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Anomalous radio-loudness of Cygnus A and other powerful radio galaxies

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ABSTRACT

The nearby, extremely powerful radio galaxy Cygnus A stands out as having an atypically low far-infrared/radio luminosity ratio. It is demonstrated that in objects displaying such a low ratio the radio-loudness is anomalously high, which fact is connected to these objects inhabiting dense X-ray haloes. The enhanced radio emission is most likely due to strong radiation losses in the dense environment. It must be concluded that radio luminosity is not a good measure of AGN power.

Key words: galaxies: active – intergalactic medium – infrared: galaxies – radio continuum: galaxies.

1 INTRODUCTION

By virtue of its extreme radio luminosity, being the third brightest radio source in the sky after the Sun and the supernova remnant in Cassiopeia, Cygnus A (3C 405) was one of the first extragalactic radio sources to be discovered (Hey, Phillips & Parsons 1946; Baade & Minkowski 1954). In fact, the radio source luminosity function was later determined to be so steep at its high-luminosity end that comparable radio sources are only found at redshifts approaching 1, i.e., at truly cosmological distances. Cygnus A has been recognized as the archetypal luminous radio galaxy, displaying the edge-brightened double-lobed morphology of FR2 (Fanaroff & Riley 1974) class 2 radio sources. However, Cygnus A is roughly 1.5 orders of magnitude more radio luminous than any other nearby FR2 radio galaxy.

Renewed interest in these powerful FR2 galaxies arose with the proposition that they may harbour QSOs in their nuclei, hidden from direct view, and evidence is mounting that such is the case in Cygnus A (e.g. Carilli & Barthel 1996). Prime questions in the study of Cygnus A are the nature of its energy source, the physics of the double-lobed radio source (including its orientation and its interaction with the intergalactic medium), and the connection with the equally luminous high-redshift radio galaxies (e.g. McCarthy 1993). The latter class is characterized by spectacularly aligned extended continua and emission-line nebulae as well as high optical polarization, indicative of both scattering and starburst phenomena. A crucial issue in active galaxy research is whether or not Cygnus A can be considered as a local example of these high-redshift ($z \gtrsim 1$) radio galaxies. We demonstrate here that Cygnus A is anomalous in its radio-loudness because of its location in an extended, hot, X-ray emitting halo. Comparison with high-redshift objects will therefore need to take this into account.

Our investigation was motivated by the finding that Cygnus A has an unusually steep radio–far-infrared spectral index, $\alpha^{178\,\mathrm{MHz}}_{60\,\mu\mathrm{m}}$. In contrast to the (about 20) *IRAS*-detected FR2 radio galaxies, which display well-correlated radio and far-infrared emission (Hes, Barthel & Hoekstra 1995) with a 60-μm far-infrared luminosity (W Hz^{-1}) typically 1 per cent of the 178-MHz radio luminosity, this value is about 0.02 per cent for Cygnus A. Most of the far-infrared emission in lobe-dominated quasars and radio galaxies originates in circumnuclear dust being heated by the nuclear continuum (Sanders et al. 1989; Hes et al. 1995; Hoekstra, Barthel & Hes 1996) and this thermal emission – provided optically thin – should reflect the central engine luminosity. Radio (lobe) emission, on the other hand, reflects the combination of active galactic nucleus (AGN) power (through the jet kinetic energy flow) and the conversion efficiency of this energy into radiation (e.g. Pacholczyk 1977). The optical extended narrow-line radiation (ENLR) is also a crude measure of the total AGN luminosity (Baum & Heckman 1989; McCarthy 1993; Hes, Barthel & Fosbury 1993; Zirbel & Baum 1995). The ratio of extended line emission to 178-MHz radio emission is unusually low in Cygnus A (table

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3 in Baum & Heckman 1989). It is therefore tempting to attribute the origin of the high $\alpha_{60\,\mu\mathrm{m}}^{178\,\mathrm{MHz}}$ value to a high radio, rather than to a low infrared, luminosity. In fact, the AGN X-rays from Cygnus A have average strength (Ueno et al. 1994), fully supporting this view.

Another extremely radio luminous galaxy is 3C 295, at $z=0.46$. Being about an order of magnitude more radio luminous than any other radio galaxy at $z\sim0.5$, 3C 295 is comparable in radio power to Cygnus A, but even lower in it relative emission-line power (Baum & Heckman 1989). 3C 295 has a 60 μm over 178 MHz power ratio of <0.06 per cent where we have used the upper limit to its 60-μm flux from Golombek, Miley & Neugebauer (1988). Now, both Cygnus A and 3C 295 are known to be located in dense, extended X-ray haloes (Arnaud et al. 1984; Henry & Henriksen 1986; Dreher, Carilli & Perley 1987; Perley & Taylor 1991; Reynolds & Fabian 1996). Obvious questions to ask, therefore, are whether in general a low far-infrared/radio luminosity ratio reflects anomalously high radio-loudness, and whether this property is indeed related to a dense source environment. We will argue that the answer to both these questions is yes and that luminous radio sources in dense intracluster media are more efficient radiators of their AGN power than those in less dense environments.

2 SAMPLE SELECTION AND ANALYSIS OF PHOTOMETRIC DATA

To test this hypothesis we have selected a sample of 18 high-luminosity 3CR radio galaxies, having redshifts $z<0.2$, 408-MHz radio luminosities in excess of 10^{26} W Hz^{-1},[1] and measured 60-μm flux densities or upper limits (Golombek et al. 1988). Note that 3C 295, due to its intermediate redshift value, does not belong in this sample. We have subsequently searched the literature and examined on-line archives for X-ray observations of the sample objects. With the exception of 3C 33.1 which has not been observed by the *Einstein Observatory* or *ROSAT*, and will not be considered further, the sample objects are listed in Table 1. We have classified X-ray cluster members, defining cluster membership as having extended X-ray emission with a luminosity exceeding 2×10^{43} erg s^{-1}. This classification was done blind by one of us (KAA), without knowledge of the infrared and emission-line data. In addition to radio, far-infrared and X-ray properties, we have assembled optical emission-line flux values for the isotropically (Hes et al. 1993) emitted [O II] λ3727 line. References for the X-ray and emission-line data are given in the table caption. We were not able to locate [O II] flux values for 3C 61.1, 3C 111, 3C 130 or 3C 315. X-ray cluster members (seven objects) appear in the top part of Table 1 followed, for comparison, by 3C 295. Non-cluster inhabitants (10 objects) are listed in the bottom part of the table.

Fig. 1(a) shows the distributions of the radio–far-infrared 'spectral index', log (L_{408}/L_{60}) for the cluster and non-cluster subsamples. Indeed, those radio galaxies residing in dense X-ray emitting environments have stronger radio emission relative to their far-infrared luminosity than do objects in less dense environments. Using, respectively, the Gehan and log rank tests (Feigelson & Nelson 1985) to compare the two subsamples gives probabilities that the two subsamples are drawn from the same parent population as 2.5 and 1.8 per cent (3C 295 was excluded from the statistical analysis).

Fig. 1(b) shows the distributions of the ratio of emission-line and radio power. The cluster sources again stand out with considerably higher radio luminosity: the average values for $P_{[\mathrm{O\,II}]}/P_{408}$ are 3.8 versus 21.7 per cent, respectively. The Gehan test, which in this case reduces to the standard Mann–Whitney test, gives a probability for one parent population of 1.2×10^{-3}. The distributions of emission-line over far-infrared luminosity, however (Fig. 1c), show considerably less difference (albeit few 60-μm detections), implying that the radio emission is the dominant variable. Here the Gehan and log rank tests yield probabilities of 6.1 and 7.2 per cent. 3C 295 is seen to closely follow the behaviour of the low-redshift cluster sample. We conclude that radio sources in dense environments experience a substantial boost in their radio luminosity, whereas their emission-line and far-infrared luminosity more reliably reflect the actual central engine luminosity.

3 DISCUSSION

Before addressing the possible origin of this radio luminosity boosting, we note that some [O II] emission from sources in X-ray clusters may be associated with a cooling flow rather than the AGN (e.g. McNamara & O'Connell 1989). This could explain the difference between the two samples for the ratio of emission-line to infrared power. It will, however, make the difference for the ratio of (AGN) emission-line to radio power even more significant.

The cluster and non-cluster samples display significantly different high-frequency (GHz) radio spectral index distributions, the cluster distribution being steeper. We determine a Gehan probability for one spectral index parent population of 2.7×10^{-3}, and average values for $\alpha_{1.4\,\mathrm{GHz}}^{5\,\mathrm{GHz}}$ are found to be -1.01 and -0.82 for the cluster and non-cluster objects, respectively. It is well known that in double-lobed radio sources the cores display considerably flatter radio spectra than the lobes. Leaving out the mildly core-dominated objects 3C 236 and 3C 315 in the non-cluster sample does not however, change its spectral index value. This finding recalls earlier work on the radio emission of cluster objects. Compared with field sources, cluster radio sources generally have steeper radio spectra (Baldwin & Scott 1973) and strong radio sources are more likely to be found in luminous X-ray clusters than in other clusters (McHardy 1978). However, the normalization by the actual AGN power, demonstrating anomalous radio-loudness, is an entirely new aspect.

What is the cause of the enhanced radio emission? Radio spectral steepening is believed to be the result of synchrotron losses (e.g. Myers & Spangler 1985), and the steep spectra of cluster radio sources have successfully been modelled as being due to confinement (e.g. Roland et al. 1985). Confinement will prevent adiabatic expansion of the radio source. Hence a larger fraction of the energy of the electrons is lost through frequency-dependent synchrotron losses than through frequency-independent expansion losses. In other words, whereas in field sources which are subject to expansion the lobe synchrotron emission is the result

[1]We adopt $H_0=75$ km s^{-1} Mpc^{-1} and $q_0=0.5$.

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Table 1. 3C radio galaxies – radio, far-infrared, and emission-line photometry.

3C-source	IAU-name	z	$\log L_{408}$ (W/Hz)	$\alpha_{1.4}^{5}$	F_{60} (mJy)	$F_{[OII]}$ (erg/s/cm^2)	$\log P_{60}$ (W)	$\log P_{[OII]}$ (W)	$\log(L_{408}/L_{60})$	$P_{[OII]}/P_{60}$ (×1000)	$P_{[OII]}/P_{408}$ (×100)
3C 28	0053+261	0.195	26.76	−1.13	<80	1.5×10^{-15}	< 37.49	34.08	> 1.96	> 0.38	5.1
3C 130	0448+519	0.109	26.33	−0.88	<200		< 37.37		> 1.64		
3C 218	0915−118	0.055	26.81	−0.92	155	2.1×10^{-14}	36.66	34.10	2.85	2.71	4.7
3C 219	0917+458	0.174	27.15	−0.98	<25	4.5×10^{-15}	< 36.89	35.45	> 2.95	> 3.60	5.0
3C 348	1648+050	0.154	27.85	−1.06	<40	2.5×10^{-15}	< 36.98	34.09	> 3.56	> 1.25	0.4
3C 388	1842+455	0.091	26.36	−0.94	<35	4.0×10^{-15}	< 36.45	33.82	> 2.59	> 2.29	7.1
3C 405	1957+405	0.056	28.44	−1.17	2847	1.2×10^{-13}	37.94	34.87	3.19	0.84	0.7
3C 295	1409+524	0.461	28.49	−1.01	<80	6.0×10^{-16}	< 38.28	34.47	> 2.90	> 0.15	0.2
3C 61.1	0211+860	0.186	27.12	−0.90	<280		< 38.00		> 1.82		
3C 111	0415+379	0.049	26.18	−0.52	321		36.87		1.99		
3C 236	1003+351	0.099	26.10	−0.71	72	7.1×10^{-15}	36.84	34.15	1.95	1.97	27.3
3C 303	1441+522	0.141	26.42	−0.78	<150	4.3×10^{-15}	< 37.48	34.24	> 1.63	> 0.57	16.4
3C 315	1511+263	0.108	26.40	−0.93	<55		< 36.80		> 2.29		
3C 321	1529+242	0.096	26.23	−0.83	1067	1.2×10^{-14}	37.99	34.35	0.94	0.22	31.9
3C 327	1559+021	0.104	26.65	−0.92	670	1.5×10^{-14}	37.85	34.51	1.49	0.45	17.9
3C 381	1832+474	0.161	26.76	−0.88	66	1.3×10^{-14}	37.24	34.84	2.21	3.94	29.8
3C 390.3	1845+797	0.056	26.33	−0.77	250	2.7×10^{-14}	36.88	34.22	2.14	2.16	19.1
3C 433	2121+248	0.102	26.76	−0.91	299	1.1×10^{-14}	37.49	34.36	1.96	0.74	9.8

The columns list, from left to right: (1) 3C-source name; (2) object name in IAU convention; (3) redshift; (4) radio luminosity at 408 MHz; (5) radio spectral index from 1.4 to 5 GHz, with values taken from Kellermann, Pauliny-Toth & Williams (1969) brought to the Baars et al. (1977) scale; (6) 60-μm far-infared flux density, or upper limit, taken from Golombek et al. (1988); (7) [O II] λ3727 emission-line flux; (8) 60-μm far-infrared power; (9) [O II] emission-line power; (10) radio to far-infrared spectral slope; (11) ratio of emission-line and far-infrared power; (12) ratio of emission-line and radio power. The emission-line flux values were taken from Baum & Heckman (1989) for 3C 295, 3C 327, 3C 405 and 3C 433; McCarthy (1988) for 3C 28 and 3C 381; Rawlings et al. (1989) for 3C 303; Saunders et al. (1989) for 3C 219, 3C 236, 3C 321; 3C 388 and 3C 390.3; and Tadhunter et al. (1993) for 3C 218 and 3C 348, with appropriate Galactic foreground extinction corrections. In some cases we used the standard conversions (McCarthy 1988) $F_{[O II]}/F_{H\alpha+N II}=0.25$ and $F_{[O II]}/F_{[O III]}=0.3$. X-ray literature data, used to address cluster membership, were taken from Fabbiano et al. (1984) for 3C 28, 3C 303, 3C 315, 3C 321, 3C 381, 3C 388, 3C 390.3 and 3C 433; Wilkes et al. (1994) for 3C 61.1 and 3C 111; Miley et al. (1983) for 3C 130; David et al. (1990) for 3C 218; Feigelson (private communication) for 3C 348; Arnaud et al. (1984) for 3C 405; and Henry & Henriksen (1986) for 3C 295. Data for 3C 219 were drawn from the *ROSAT* archive, and data for 3C 236 and 3C 327 from the *Einstein Observatory* archives. Cluster members, including 3C 295, appear in the top part of the table.

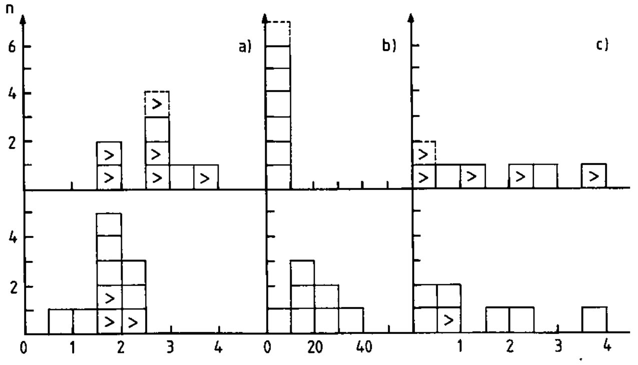

Figure 1. Photometric ratios for cluster (top) and non-cluster radio galaxies (bottom). (a) The left panels display the radio to far-infrared spectral slope $\log(L_{408\,\mathrm{MHz}}/L_{60\,\mu\mathrm{m}})$; (b) the middle panels display the emission-line over radio ratio $100 \times P_{[\mathrm{O\,II}]}/P_{408}$; (c) the right panels display the emission-line over infrared ratio $1000 \times P_{[\mathrm{O\,II}]}/P_{60}$. 3C 295 – formally not a sample member – is indicated with dashed boxes.

of recently accelerated electrons, the confined cluster sources radiate comparatively more through the old electron population, the expansion losses being considerably smaller. The low level of expansion losses implies efficient transfer of AGN power into radio emission.

We conclude that FR2 radio galaxies similar to and including Cygnus A owe their high radio luminosity to their location in a dense, extended X-ray cluster, which causes efficient transfer of AGN power into radio radiation. In analogy to Baum & O'Dea (1991), in which a similar computation for the cooling-flow cluster source PKS 0745 − 191 was made, we argue that if Cygnus A were located in the field, its lobes might have been larger by a factor of 2, implying a radio luminosity decrease with a factor 2^6 (e.g. Pacholczyk 1977), which is roughly the 1.5 orders of magnitude luminosity excess that we observe. We stress that the physical connection between the presence of a hot gaseous environment for a radio galaxy and its associated cluster richness is not understood (e.g. Burns 1996), so that the effects of the inferred radio boosting mechanism on the radio luminosity functions remains to be determined.

The sample that we have analysed was drawn from the large number of radio galaxies studied at far-infrared wavelengths by Golombek et al. (1988) and as such is incomplete. However, the Golombek et al. (1988) sample is representative of the radio galaxy population. The only bias that we could have introduced is through our criteria of 3CR membership. As demonstrated by Laing, Riley & Longair (1983), 3CR misses a few large, low surface brightness radio sources with flux densities above the sample limit. Because of this incompleteness and the small number statistics in the present analysis, the true occurrence rate of environmental radio boosting (and its cosmic evolution) also remains to be determined.

4 IMPLICATIONS

We now address the question of whether Cygnus A can be considered a local example of high-redshift radio galaxies. We first examine the emission-line–radio power ratio for the latter class. High-redshift ($z \gtrsim 1$) 3CR galaxies have radio luminosities $L_{408} \sim 10^{28.5}$ W Hz^{-1} (basically implied by their 3C membership). Emission-line imaging and spectroscopic studies have shown that the spread in [O II] luminosities for these objects is substantial (e.g. fig. 2 in McCarthy 1993), and these result in $P_{[\mathrm{O\,II}]}/P_{408}$ ratios ranging from less than one to several tens of per cent. It is, however, possible that the high-redshift $P_{[\mathrm{O\,II}]}/P_{408}$ figures, which resemble the figures in our table, reflect the very same radio luminosity boosting phenomenon as inferred in the local Universe. Some high-redshift radio galaxies have been hypothesized to lie in X-ray emitting clusters (Crawford & Fabian 1995), but X-ray measurements with *AXAF* will be needed to address that issue in depth. Forthcoming *ISO* data may be used to construct far-infrared to radio spectral index values. In the meantime we concur with Tadhunter, Scarrott & Rolph (1990) and Eales (1996) that it is at least careless to consider Cygnus A as a local example of a high-redshift radio galaxy.

Given the above discussion, it will be clear why, besides Cygnus A, the early, 'classical' radio sources Hydra A (3C 218) and Hercules A (3C 348) appear in our cluster sample. That fact nicely illustrates an important consequence of this study: the Fanaroff and Riley (Fanaroff & Riley 1974) division into low radio luminosity FR1 morphology and high radio luminosity FR2 morphology is affeted by environmental radio boosting. Both Hercules A, which was already noted early to have very weak emission lines (Schmidt 1965), and Hydra A have FR1 radio morphologies (Dreher & Feigelson 1984; Baum et al. 1988) but radio luminosities above the Fanaroff and Riley break at $\sim 10^{26}$ W Hz^{-1}. They are both in our cluster sample, so their apparent FR2 luminosity is due to the environmental radio boost. The same effect also explains the somewhat lower average line luminosity values for the cluster galaxies in comparison to the non-cluster objects: because the transfer of AGN power into radio emission is highly efficient, intrinsically weaker AGN make it into the cluster sample. We note with interest that quasar optical continuum luminosity appears to be a more reliable tracer of AGN luminosity than is radio lobe luminosity (Wills & Brotherton 1995), and similarly that cosmologically evolving gaseous haloes have been postulated to cause enhanced radiative efficiency with increasing redshift (Gopal-Krishna & Wiita 1991).

5 CONCLUSIONS

It has been supposed for many years that the radio luminosity of extragalactic radio sources is affected by the source environment. We have provided the first straightforward observational proof of this hypothesis. Cygnus A is a prime example, experiencing a radio luminosity boost of roughly 1.5 orders of magnitude in comparison with objects having comparable central engine power. This environmental effect renders AGN selection and classification on the basis of radio luminosity *alone* less accurate and hence less attractive. Knowledge of far-infrared, emission-line and/or hard X-ray luminosity is essential in order to address the true AGN power of extragalactic radio sources.

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