Double-Double Radio Galaxies

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Abstract

We have discovered four radio sources whose radio morphology resembles that of two unequally sized FR-II type radio sources aligned along the same axis and with a coinciding radio core. We present low and high resolution radio images of these four 'double-double radio galaxies' (DDRGs) from the NVSS, WENSS and FIRST radio surveys, and from our own VLA observations, together with redshifts from optical spectroscopy. We note that, using our definition, the known radio sources 3C 445, 4C 26.35 and 1545−321 also are DDRGs.

The two-sidedness and symmetry of the inner sources strongly suggests that DDRGs are formed as the result of recurrent radio-activity in the nucleus. We discuss this in some detail and show that this leads to an evolutionary scenario in which very large radio sources can be seemingly replaced by smaller radio sources. We call this the 'metamorphosis model' of double-lobed radio sources.

1 Introduction

One of the outstanding issues concerning extragalactic radio sources is the total duration of their active phase. This physical age is not to be confused with the radiative loss age determined from radio spectral ageing arguments; most extended extragalactic radio sources probably have a physical age well surpassing the radiative loss age (e.g. van der Laan & Perola 1969, Eilek 1996). The issue of the activity lifetime is complicated by the possible presence of duty cycles in the nuclear activity. If nuclear activity is not continuous, how often do interruptions occur and how long do they last?

A small number of radio sources show characteristics that can not be fully explained by a continuous jet model. One example is the Fanaroff & Riley (1974) class II (FR-II) source 3C 219 (Clarke & Burns 1991, Clarke et al. 1992, Perley et al. 1994) in which the radio jets abruptly become undetectable at some point between the core and the hotspots. Clarke et al. (1992) propose that the jets in this source could be restarting, although numerical simulations (e.g. Clarke & Burns 1991) of this effect fail to reproduce the observed structures.

During a search for Mpc-sized radio sources in the Westerbork Northern Sky Survey (WENSS, Rengelink et al. 1997) we have found four large radio galaxies which appear to be good examples of radio galaxies with recurrent radio-activity. In the following sections we present radio maps of these sources and discuss the origin of the observed morphology. The details of all observations and of the data-reduction processes, will be presented elsewhere (Schoenmakers et al. in preparation). We will adopt $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$ throughout this paper.

2 The WENSS-sources

WNB 1834+620 stands out as a peculiar source in the unpublished 49-cm radio maps of the WENSS because of its 'four beads on a string' radio morphology (see Figure 1a). Observations of this source were made with the WSRT at 1.4 GHz on February 4, 1995. From these it could not be determined whether WNB 1834+620 is a single source or a closely aligned pair. We therefore observed it with the VLA at 8.4 GHz in its D-array configuration on August 3, 1996, and at 1.4 GHz in the A-array configuration on January 3, 1997. The radio maps from the VLA observations are presented in Figure 1b and c. The 8.4-GHz map unambiguously shows the FR-II type morphology of this source. Of the two bright inner knots, only the southern one is slightly resolved. The 1.4-GHz map shows this inner structure in more detail and shows that the two bright inner sources are clearly not knots in a jet or unrelated background sources, but form a distinct radio source. The southern inner source has an unmistakable FR-II type radio lobe structure, whose morphology resembles closely that of the southern outer lobe in the 8.4-GHz map. The northern inner source is more compact but still resolved. Because the morphology of the source as a whole is that of a small double-lobed radio galaxy within a large double-lobed radio galaxy, we have adopted the name 'double-double radio galaxies' (DDRGs) for

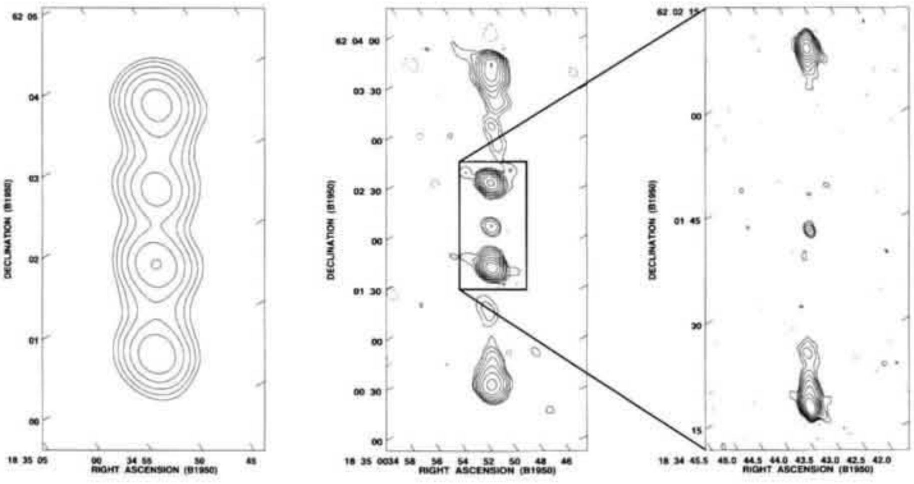

Figure 1. Radio contour plots of the source WNB 1834+620. The images have been rotated CCW by 30°. **a** Contour plot from the 49-cm WENSS survey. Contour levels are at (−10, 10, 20, 40, 80, 160, 320) mJy beam^{-1} and the FWHM beam-size is $29'' \times 33''$. **b** Contour plot from our 8.4-GHz VLA observations. Contour levels are at (−0.1, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8) mJy beam^{-1}. The FWHM beam-size is $8\farcs4 \times 6\farcs2$. **c** Contour plot of the inner region from the 1.4-GHz VLA observations. Contour levels are at (−0.16, 0.16, 0.32, 0.64, 1.28, 2.56, 5.12, 10.24) mJy beam^{-1}, and the FWHM beam-size is $1\farcs9 \times 1\farcs4$.

this type of source.
The flat-spectrum radio core ($\alpha = -0.22 \pm 0.08$) coincides with a weak optical galaxy ($R_s \sim 19.0$), which is the brightest member of a compact group of three galaxies visible on the POSS-II plates. A spectrum taken with the 2.5-m INT telescope on La Palma revealed a rich emission line spectrum, from which we determine a redshift of 0.519 ± 0.001. The projected linear size is 1660 kpc for the outer source and 428 kpc for the inner source.

WNB 1450+333 is a member of our virtually complete sample of Mpc-sized radio sources with a flux density above 1 Jy at 325 MHz (Schoenmakers et al. in preparation). Its double-double radio morphology is most striking in a radio map from the VLA FIRST survey ($5\farcs4$ FWHM; Becker et al. 1995). A con-

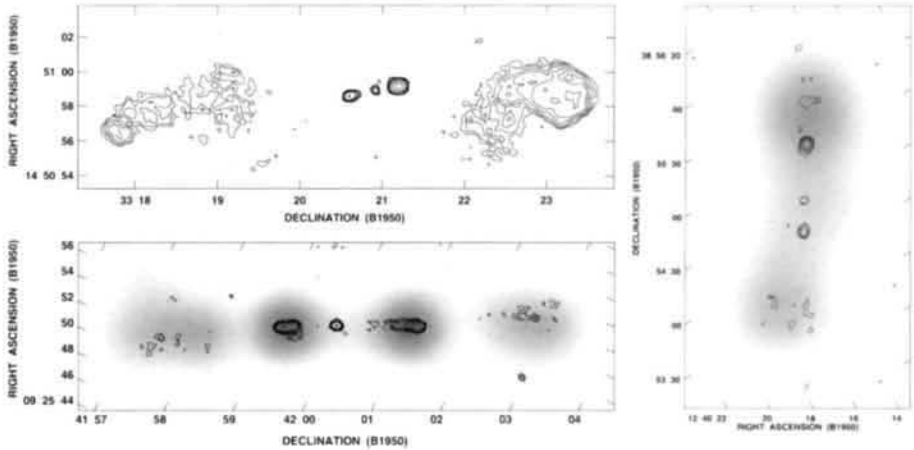

Figure 2. Radio maps of the sources WNB 1450+333 (upper left, rotated by 90° CW), WNB 0925+420 (lower left, rotated by 116° CW) and WNB 1240+389 (right, rotated by 25° CCW). Contours are from the 1435-MHz FIRST survey (beam-size of $5''.4$ FWHM) and are at (0.45, 0.64, 0.90, 1.28, 1.8, 3.6, 7.2, 14.4) mJy beam^{-1}. The grey-scale in the plots of WNB 0925+420 and WNB 1240+389 represents the flux density at 1400 MHz from the NVSS survey (beam-size of $45''$ FWHM).

tour plot of this map is shown in Figure 2 . The outer structure consists of a fat northern radio lobe without a discernible hotspot, and a narrower southern lobe with a weak, possibly double, hotspot. The radio core has been identified with a faint optical galaxy on the Digitized Sky Survey (DSS). Its R-band magnitude, according to the APM catalogue, is ∼18.3 . Spectroscopy with the 4.2-m WHT telescope on La Palma revealed no strong emission lines in the range between 5200 and 8100Å. Using the stellar Mg-b, Na-D and G-band absorption bands, we determine a redshift $z = 0.249 \pm 0.002$. As is the case in WNB 1834+620, the morphology of the outer lobes seems to be reflected in the inner lobes. The line connecting the radio core with the maximum in the southern inner lobe cuts through the emission peak in the southern outer lobe as well, suggesting that the misalignment of the inner and the outer lobes is caused by a drift of the northern outer lobe away from the radio axis. The projected linear size of the inner source is 186 kpc, that of the outer source ∼1700 kpc.

WNB 1240+389 has been discovered during a search for high ($z > 0.4$) redshift Mpc-sized radio sources from the WENSS and FIRST surveys (Schoenmakers et al. in preparation). It is recognized as a DDRG by an overlay of the FIRST and NVSS radio maps (Figure 2). The radio core is identified with a $R\sim20$ mag galaxy. An optical spectrum taken with the INT shows no emission lines, but using the 4000Å-break we find a redshift of 0.30. The projected linear size of the inner structure is 320 kpc, that of the outer structure, 860 kpc.

WNB 0925+420 is recognized as a DDRG by comparing the radio maps of the NVSS (Condon et al. 1998) and the FIRST survey (Figure 2). The large-scale outer structure is easily visible in the NVSS radio map (45″ FWHM), but is almost completely resolved in the map from the FIRST survey. The southern inner lobe is more compact than the northern one, and is closer to the radio core. We identified the radio core with a $R \approx 18.3$ mag galaxy on the DSS. An optical spectrum taken with the 2.5-m INT telescope on La Palma shows a strong 4000Å-break and the [OII]3727 emission line, for which we measure a redshift of 0.37 ± 0.01. The projected linear size of the inner source is $\sim$800 kpc, that of the outer source, $\sim$2450 kpc.

3 Discussion

We define a DDRG as a radio source consisting of two unequally sized two-sided double-lobed radio sources, roughly aligned along the same axis and with a coinciding radio core. Adopting this definition, we have found three more DDRGs in the literature. They are 3C 445 (B2221−023; Kronberg, Wielebinski & Graham 1986, Leahy et al. 1997), 4C 26.35 (B1155+266; Owen & Ledlow 1997) and 1545−321 (Subrahmanyan et al. 1996). Some basic parameters of the DDRGs can be found in Table 1.

The two-sidedness of the inner sources, and the relatively high symmetry therein, strongly suggests that the DDRG phenomenon is related to the activity of the nucleus, and almost eliminates any model which puts the primary cause well outside the nucleus. Because of the good alignment between the inner and the outer sources in six of our DDRGs, it seems unlikely that, e.g., a sudden change in the outflow direction of the jet is the primary cause of the existence of the inner sources. Only WNB 1450+333 shows a clear misalignment between the inner and the outer structure, but, as mentioned above, this can be caused by a drift of the northern outer lobe. Further, changes in the jet direction can be seen in many radio sources without any serious consequences for the jet flow.

In the case of the DDRGs, we favour a model in which the nuclear jet production

Table 1. Radio properties of the DDRGs. Column 2 gives the redshift, columns 3 and 4 the sizes of the inner and outer structure in kpc, column 5 to 8 give the 1.4-GHz flux densities and radio powers (after subtraction of the radio core). For 3C 445 the flux density of the inner component is a lower limit, measured in the FIRST survey. For 1545−321 we have, apart from the NVSS, no radio data available to measure accurate flux densities. We therefore quote only values integrated over the whole source.

(1) Source	(2) z	(3) $\mathrm{D_{outer}}$ [kpc]	(4) $\mathrm{D_{inner}}$ [kpc]	(5) $S_{\mathrm{outer}}{}^{a}$ [mJy]	(6) S_{inner} [mJy]	(7) P_{outer} [10^{25} W Hz^{-1}]	(8) P_{inner}
0925+420	0.365	2450	803	99	63.7^b	5.8	3.7
1240+389	0.30	860	320	24.1	7.8^b	1.0	0.32
1450+333	0.249	1680	180	426	33.5^b	13	0.98
1834+620	0.519	1660	428	604	200^c	84	26
3C 445	0.056^d	846	186	5260	55^b	7.3	0.08
4C 26.35	0.112^e	730	197	962	66.5^b	5.4	0.37
1545−321	0.109^f	1320	420	1775^g			10^g

Notes: *a* - Flux density measured from NVSS radio map minus S_{inner}; *b* - Flux density measured from FIRST radio map; *c* - Flux density measured from our VLA observations; *d* - Hewitt & Burbidge (1991); *e* - Owen, Ledlow & Keel (1995); *f* - Subrahmanyan et al. (1996); *g* - Integrated over the whole source

rate is temporarily strongly reduced, or even halted (see also Subrahmanyan et al. 1996). Short term variations in the energy output are known to occur in almost all AGN and it is plausible that they occur on a variety of timescales, from years to millions of years. Small changes in the jet power will most likely not disrupt the jet flow, but lead to shocks which are visible as discrete 'blobs' in the jet or become manifest only once they reach the hotspot. A large change in the jet power, and especially a large decrease, might have fatal consequences for the stability of the jet; the channel to the outer lobes – the jet – may not be able to maintain itself and will, eventually, collapse due to the pressure of the surrounding cocoon medium. As a consequence, a restarted particle outflow from the nucleus will have to clear a new channel and in doing so, may well form new inner hotspots and a new radio source. In time, the outer radio lobes will have completely faded and a new double-lobed radio source will have emerged; we have named this scenario the 'metamorphosis model' of double-lobed radio sources.

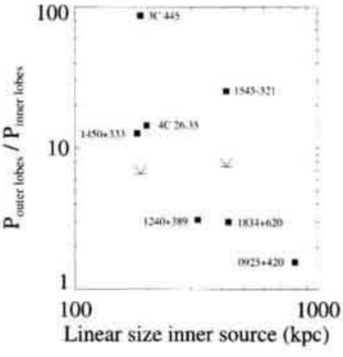

Figure 3. The ratio of the radio powers at 1.4 GHz of the outer to the inner structure of the DDRGs, plotted against the linear size of the inner structure. The flux density of the inner structure of 3C 445 and 1545−321 is not well determined from the radio data available to us. For 3C 445 we have used the FIRST flux density as a lower limit, for 1545−321 we used the contour plot presented by Subrahmanyan et al. (1996) for an estimate. As upper limits we have measured the NVSS flux density of the same region of the source. The resulting ranges are indicated by a dashed line.

Figure 3 shows the ratio of the monochromatic radio power at 1.4 GHz of the outer lobes to that of the inner lobes against the projected linear size of the inner structure. The source 3C 445 is a broad-line radio galaxy, possibly indicating that its radio axis is oriented well away from the plane of the sky and therefore its true linear size may be much larger than indicated in the figure. The radio-power ratio depends on the luminosity evolution of the inner and the outer lobes. According to a recent model for radio source evolution, continuously active radio sources are expected to slowly decrease in radio luminosity as they increase in size (Kaiser, Denett-Thorpe & Alexander 1997). Small-sized sources should therefore be more luminous than large sources. However, in all seven DDRGs the inner source is less luminous at 1.4 GHz than the outer source (see Table 1 and Figure 3). A lower radio luminosity can be the result of a lower density of the ambient medium into which the lobes expand. In the case of the DDRGs, this implies that the surrounding medium of the inner lobes is more rarified now than it was when the outer source first expanded into it. Analytical models (e.g. Cioffi & Blondin 1992) and numerical simulations (e.g. Clarke & Burns 1991, Loken et al. 1992) indeed predict that the density inside a cocoon is at least a factor of $\sim 10^{-2}$ lower than that of the original unshocked IGM. It remains to be clarified, however, if the density is not *too* low for the formation of hotspots, as has been suggested by Clarke & Burns (1991). A full discussion of this problem is beyond the scope of this contribution. A model for the successful formation of hotspots inside an intact cocoon will be presented by Kaiser et al. (in preparation).

A consequence of our model is that, once the jet is interrupted and the remainder of the jet material has reached the hotspots, the outer lobes will start to fade due the lack of inflow of energy. The observation that in all sources the inner lobes are still less powerful than the outer lobes, despite the inference that the outer lobes must be fading, implies that the time since the ceasing of the jet flow cannot be much longer than the time it takes for the outer lobes to fade significantly at 1.4 GHz. Under standard assumptions, this is a few times 10^7 yrs.

An important question is why all seven DDRGs presented here are (nearly) Mpc-sized. We believe this can be attributed to a combination of two effects. First, as said, once the jet flow to the outer lobes has ceased, they should start to fade. This will be most prominent once the break frequency in the spectrum of the outer lobes is lower than the observing frequency. Neglecting expansion, the rate of change of the break frequency per unit time $\mathrm{d}\nu_b/\mathrm{d}t \propto -B\,(B^2 + B_{MWB}^2)^{-2}$, with B the source's internal magnetic field strength and $B_{MWB} = 3.24(1+z)^2\mu$Gauss the equivalent field strength of the Microwave Background radiation at redshift z. In Mpc-sized radio sources, $B \lesssim B_{MWB}$ (e.g. Mack et al. 1998, Schoenmakers et al. 1998) which implies large (few times 10^7 yrs) radiative lifetimes of the lobes. In smaller radio sources, $B \gg B_{MWB}$ (e.g. Alexander & Leahy 1987; Leahy, Muxlow & Stephens 1989), and so their radiative lifetimes are much smaller, more like a few times 10^6 yrs. Thus, the outer lobes of small DDRGs are expected to fade much more rapidly than those of Mpc-sized DDRGs, and so it is more likely to detect large DDRGs. Second, smaller radio sources will probably lose their double-double morphology faster. After the jet stops flowing into the outer lobes, they lose their source of momentum and slow down their forward motion. This allows the inner source to overtake the outer source. If the inner source continues to grow we will probably interpret the old lobes as the manifestation of a backflow within the new lobes and we will not call such a source a DDRG anymore. Most likely, it takes less time for the inner lobes to overtake the outer lobes in a small source, and so the chance of finding a DDRG increases with increasing size of the outer source. Which of these two effects will dominate depends on the amount of time since the jet production has stopped and on the expansion velocity of the new inner source.

An outstanding problem in the evolution of radio sources is how some sources can grow to a size of a few Mpc. It has often been suggested that these Giant Radio Galaxies (GRGs) must be in extremely low density environments, but most indications for this have been obtained by measuring spectral ages (e.g. Mack et al. 1998), which might be inaccurate (e.g. Eilek 1996), and by depolarization studies which are difficult to interpret (e.g. Schoenmakers et al. 1998). As has already been suggested by Subrahmanyan et al. (1996), some

GRGs might result from multiple periods of radio activity. The DDRGs presented here indicate that such a formation scenario for GRGs might indeed be true. We note that the largest radio source known in the Universe, 3C 236 with a linear size of 5.7 Mpc, has an extremely bright radio core with a complex multiple structure (e.g. Barthel et al. 1985), and may therefore also be in a phase of recurrent activity.

4 Conclusions

We have discovered four Mpc-sized radio sources consisting of two unequally sized FR-II type radio sources aligned along the same axis and with a coinciding radio core. We believe that these three DDRGs, together with the three other sources from the literature that conform to our definition, provide very good evidence for recurrent radio-activity in AGN. DDRGs show a form of evolution of radio galaxies in which a large radio source is fading away, while at the same time a smaller radio source emerges. DDRGs are important sources to investigate the suggestion of Subrahmanyan et al. (1996) that giant radio sources may have grown to their enormous size as the result of multiple phases of radio activity. Clearly, a more detailed study of DDRGs is of key importance to learn more about duty cycles of activity in AGN and how this affects the evolution of a radio source.

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References

Alexander P., Leahy J.P., 1987, MNRAS 225, 1
Becker R., White R., Helfand D., 1995, ApJ 450, 559
Cioffi D.F., Blondin J.M., 1992, ApJ, 392, 458
Clarke D.A., Burns J.O., 1991, ApJ 369, 308
Clarke D., Bridle A., Burns J., Perley R., Norman M., 1992, ApJ 385, 173

Condon J.J., Cotton W.D., Greisen E.W., Yin Q.F., Perley R.A., Taylor G.B., Broderick J.J., 1998, AJ 115, 1693

Eilek J.A., 1996, in: Energy Transport in Radio Galaxies and Quasars, Hardee P.E., Bridle A.H., Zensus J.A. (eds.), ASP Conf. Series, p. 279

Fanaroff B.L., Riley J.M., 1974, MNRAS 167, 31

Hewitt A., Burbidge G., 1991, ApJS 75, 297

Kaiser C.R., Denett-Thorpe J., Alexander P., 1997, MNRAS 292, 723

Kronberg P.P., Wielebinski R., Graham D.A., 1986, A&A 169, 63

van der Laan H., Perola G.C., 1969, A&A 3, 468

Lacy M., Rawlings S., Saunders R., Warner P.J., 1993, MNRAS 264, 721L

Leahy J.P., Muxlow T.W.B., Stephens T.W, 1989, MNRAS 239, 401

Leahy J.P., Black A.R.S., Denett-Thorpe J., Hardcastle M.D., Komissarov S., Perley R.A., Riley J.M., Sceuer P.A.G., 1997, MNRAS 291, 20

Loken C., Burns J.O., Clarke D.A., Norman, M.L., 1992, ApJ 392, 54

Mack K.-H., Klein U., O'Dea C., Willis A., Saripalli L., 1998, A&A 329, 431

Owen F.N., Ledlow M.J., 1997, ApJS 108, 41

Owen F.N., Ledlow M.J., Keel W.C., 1995, AJ 109, 140

Perley R.A., Bridle A.H., Clarke D.A., 1994, In: Subarcsecond Radio Astronomy, Davis R.J., Booth R.S. (eds.), Cambridge University Press, p. 258

Rengelink R., Tang Y., de Bruyn A.G., Miley G.K., Bremer M.N., Röttgering H.J.A., Bremer M.A.R., 1997, A&AS 124, 259

Schoenmakers A.P., Mack K.-H., Lara L., Röttgering H.J.A, de Bruyn A.G., van der Laan H., Giovaninni G., 1998, A&A 336, 455

Subrahmanyan R., Saripalli L., Hunstead R.W., 1996, MNRAS 279, 257