Radio galaxies with a ‘double-double’ morphology:
II - The evolution of double-double radio galaxies and implications for the alignment
effect in FRII sources

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ABSTRACT
A Double-Double Radio Galaxy (DDRG) is defined as consisting of a pair of double radio sources with a common centre. In this paper we present an analytical model in which the peculiar radio structure of DDRGs is caused by an interruption of the jet flow in the central AGN. The new jets emerging from the restarted AGN give rise to an inner source structure within the region of the old, outer cocoon. Standard models of the evolution of FRII sources predict gas densities within the region of the old cocoon that are insufficient to explain the observed properties of the inner source structure. Therefore, additional material must have passed from the environment of the source through the bow shock surrounding the outer source structure into the cocoon. We propose that this material is warm clouds ($\sim 10^4$ K) of gas embedded in the hot IGM which are eventually dispersed over the cocoon volume by surface instabilities induced by the passage of cocoon material. The derived lower limits for the volume filling factors of these clouds are in good agreement with results obtained from optical observations. The long time scales for the dispersion of the clouds ($\sim 10^7$ yr) are consistent with the apparently exclusive occurrence of the DDRG phenomenon in large ($\gtrsim 700$ kpc) radio sources and with the observed correlation of the strength of the optical/UV alignment effect in $z\sim 1$ FRII sources with their linear size.

Key words: galaxies: active – galaxies: evolution – galaxies: jets – intergalactic medium

1 INTRODUCTION
Double-double radio galaxies (DDRGs) are defined as consisting of two unequally sized, two-sided, double-lobed, edge-brightened (type FRII) radio sources (see also the preceding paper Schoenmakers et al. 1999a, hereafter paper I). The radio cores of the two structures coincide. This gives them the appearance of two independent FRII-type sources the smaller of which is placed inside the larger structure. This morphology distinguishes the DDRGs clearly from ‘normal’ FRII objects. Seven DDRGs in which the inner and outer structures are well aligned have been presented in paper I. In all these objects the radio axes of the two structures form angles of less than $7^\circ$. The projected linear sizes of the outer source structure of all these objects is greater than 700 kpc.

Although it is too early for final conclusions, we believe that large linear sizes of the outer source structure is an intrinsic property of the DDRGs as a sub-class of the FRII radio source population and not a selection effect. The so-called X-shape radio sources (e.g. Leahy & Williams 1984) may be further examples of DDRGs but they differ from the sources presented in paper I in that the radio axes of the two structures are not aligned.

In most of the outer lobes of the DDRGs presented in paper I no radio hot spots are detected. For the exception to this rule, B 1834+620, only one hot spot is detected (Schoenmakers et al. 1999b, hereafter paper III). This may indicate that the outer source structure of DDRGs is no longer supplied with energy from the AGN via jets.

The main aim of this paper is to show that the observed properties of the DDRGs are consistent with a model in which the jet production mechanism in the AGN in the
centre of the host galaxy of these objects is interrupted and then restarted. During the first phase of activity the outer radio structure is inflated while after the disruption the inner structure is created. The formation of the inner structure of the aligned DDRGs is only possible if some material from the outside of the outer cocoon has penetrated the cocoon boundary and forms a rather smooth density distribution within the region of the outer cocoon. We show that this material is most likely provided by the remains of warm, dense clouds which form one phase in the Inter Galactic Medium (IGM) surrounding the DDRGs and are slowly dispersed by the effects induced by the cocoon material streaming along their surface.

In Sect. 4 we briefly review the properties of the gaseous environment of FRII radio sources. Section 3.1 discusses a possible mechanism for the restarting of the jet flow and its implications for X-shaped radio sources. A brief review of the analytical model used for analysing the radio properties of the DDRGs is given in Sect. 3.2. This model is then applied to the outer, Sect. 3.3 and the inner source structure, Sect. 3.4. In this Sect. we also show that some material from the outside of the outer cocoon must have penetrated into this region. Section 3 reviews possible mechanisms for achieving this contamination. Several implications that this contamination of the cocoon has for observable properties of the DDRGs will be discussed in Sect. 5. The optical and UV continuum emission of the hosts of FRII sources at high redshift ( \( z > 0.6 \) ) has been found to be aligned with the radio source axis (for a review see McCarthy 1993). In Sect. 6 the implications for the alignment effect in FRII sources of the radio source axis (for a review see McCarthy 1993). These structures can extend over several 100 kpc. Assuming that the aligned optical line emission in radio-loud quasars is caused by the ionisation of warm gas by the central AGN, the ionizing radiation of which can be to some extent constrained from X-ray and UV observations, Heckman et al. (1991) find densities for the warm material of typically 100 cm\(^{-3}\) while the volume filling factors, \( f_{\text{cl}} \), are estimated at \( 10^{-8} \rightarrow 10^{-7} \). These low values imply the existence of warm, dense clouds embedded and in pressure equilibrium with the hot, X-ray emitting phase of the IGM. The existence of such clouds also in low redshift radio galaxies is consistent with the observations (Baum & Heckman 1989), if the volume filling factor of these clouds is roughly \( 10^{-3} \) on scales of 10 kpc and lower on larger scales in these objects. Note however, the different distances from the center of the host galaxy at which the line emission is observed in objects at low and at high redshifts. It is not clear whether the properties of the environments of FRIIs at low and at high redshift are similar in this way.

Since all currently known DDRGs are large radio sources with linear sizes \( \gtrsim 700 \) kpc, the properties of the IGM rather than those of the ISM determine the evolution and appearance of the outer source structures of these objects. The density of the hot IGM (\( T_x \sim 10^7 \) K) at distances on a scale of 100 kpc can in principle be inferred from its thermal bremsstrahlung emission in X-rays. On the properties of the IGM on scales of Mpc, which is comparable to the size of the outer structures of the DDRGs, we have no observational constraints in these sources and we therefore have to estimate these quantities. FRII radio sources at low redshift are often found in poor groups of galaxies (e.g. Prestage & Peacock 1988) and X-ray observations suggest that the density distribution of the gas in such environments is well described by a King (1972) profile with \( n_x = 10^{-2} \) cm\(^{-3}\), \( a_o = 10 \) kpc and \( \beta_{K_{n_x}} = 0.5 \) (Willott et al. 1999, based on X-ray data presented by Mulchaey & Zabludoff 1998). We will assume in the following sections that the outer lobes of the DDRGs are embedded in a hot IGM following such a density profile.

2 THE ENVIRONMENTS OF FRIIs

The radio structures of radio galaxies are embedded in the Inter Stellar Medium (ISM) of their host galaxies and, in the case of large linear sizes, the IGM in between galaxies. Extended optical line emission observed to be associated with the hosts of powerful radio galaxies at low redshift implies the existence of warm gas (\( T_x \sim 10^4 \) K) on scales of 10 kpc. Baum & Heckman (1989) find that the density of this gas is at least 0.1 cm\(^{-3}\). This assumes a volume filling factor for this material, \( f_{\text{cl}} \), close to unity. This density is a lower limit since for a ‘clumpy’ distribution of the line emitting material, i.e. smaller filling factors, higher densities are required. The gas densities and the corresponding filling factors of the gas clouds providing the extended optical emission observed in FRIIs are difficult to constrain because of the poorly constrained properties of the ionizing radiation originating in the central AGN and/or shocks in the hot IGM which illuminates the gas in radio galaxies. The gas density can in some cases be directly inferred from the flux ratios of density-dependent emission lines, e.g. [S\( \text{ii} \)] 6717, 6732. For example, van Breugel et al. (1985) find gas densities of \( \sim 300 \) cm\(^{-3}\) for the line-emitting clouds in the environment of the radio source 3C 277.3 and Heckman et al. (1989) find comparable densities for the emission line regions of galaxies at low redshift associated with cooling flows.

At high redshift (\( z > 0.6 \)) the extended optical and UV emission, line and continuum, of the host galaxies of FRII radio sources is often aligned with the axis of the radio structure (for a review see McCarthy 1993). These structures can extend over several 100 kpc. Assuming that the aligned optical line emission in radio-loud quasars is caused by the ionisation of warm gas by the central AGN, the ionizing radiation of which can be to some extent constrained from X-ray and UV observations, Heckman et al. (1991) find densities for the warm material of typically 100 cm\(^{-3}\) while the volume filling factors, \( f_{\text{cl}} \), are estimated at \( 10^{-8} \rightarrow 10^{-7} \). These low values imply the existence of warm, dense clouds embedded and in pressure equilibrium with the hot, X-ray emitting phase of the IGM. The existence of such clouds also in low redshift radio galaxies is consistent with the observations (Baum & Heckman 1989), if the volume filling factor of these clouds is roughly \( 10^{-3} \) on scales of 10 kpc and lower on larger scales in these objects. Note however, the different distances from the center of the host galaxy at which the line emission is observed in objects at low and at high redshifts. It is not clear whether the properties of the environments of FRIIs at low and at high redshift are similar in this way.

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The observation of warm gas at large distances from the host galaxies of radio sources implies that the surrounding IGM is a two-phase medium. For the evolution of the large scale radio structure of FRIIs only the hot (\( T_x \sim 10^7 \) K) phase is important. This can be seen as follows.

The expansion of the large scale structure of FRII radio galaxies is confined by the ram pressure of the material surrounding it. The warm clouds will therefore be dynamically unimportant for the expansion of the bow shock and cocoon of FRII sources as long as their volume filling factor in the hot phase of the IGM is smaller than \( (n_x/a_o) < 10^{-2} \), where \( n_x \) is the density of the hot phase of the IGM and \( a_o \) is the density of the warm clouds (Begelman & Cioffi 1989). For the warm clouds to be dynamically stable they must be in pressure equilibrium with the hot gas and from this, for the assumption of ideal gas conditions, we find \( f_{\text{cl}} < (T_x/T_x)^{1/2} \sim 0.03 \). This will hold in virtually every radio galaxy (but see for example McCarthy, van Breugel & Kapahi 1991). The expansion ve-
locity of the outer cocoon in DDRGs is therefore determined by the density distribution of the hot IGM alone.

3 THE EVOLUTION OF DDRGS

In this section we present a model for the evolution of the peculiar radio structures of DDRGs. This evolution is crucially influenced by the properties of the source environment outlined above. In this model we take the double-double appearance of the DDRGs and the absence of hot spots in most of the outer cocoons as evidence that the jet activity in these sources first inflates the outer or ‘old’ cocoon, is then stopped by some mechanism disrupting the jet production process in the central AGN and finally restarts causing the formation of the inner or ‘new’ cocoon.

Of the seven aligned DDRGs presented in paper I we exclude 3C 445 and 3C 219 from the analysis described in the following. In the case of 3C 445 sufficiently accurate radio flux measurements of the inner structure are not available. The exceptionally high asymmetry of the inner source structure of 3C 219 sets it apart from the other sources considered here. This suggests that a process different from the one described below is causing the formation of the double-double structure in this object (see also paper I).

3.1 Restarting of the jet flow

The high degree of symmetry of the inner source structures of the remaining five aligned DDRGs about the cores of the sources suggests that the jet flow must have been restarted on both sides of the sources simultaneously. The conclusions derived from the model presented here do not depend on the exact mechanism(s) that cause the disruption of the old jets and we are therefore unable to constrain them. For a brief discussion of the possibilities we refer the reader to paper I. Here we only present some further remarks on one possible scenario, the recent infall of a large amount of gas onto the AGN.

If the restarting of the jets is caused by the infall of a large mass of gas onto the AGN, there is no reason why the angular momentum vector of the new material should have a direction similar to that of the material in the original disk defining the direction of jet propagation. This may imply that in general the direction of the new jets deviates considerably from the old radio axis. In this case the new jets will quickly propagate through a part of the old cocoon and then inflate a new cocoon within the same environment as the old jets. The radio emission of the old cocoon will fade quickly as will be described in Sect. 2.4 but for some time four radio lobes will be observable; two with hot spots at their ends and two without. This is reminiscent of the so-called X-shaped or winged radio galaxies (e.g. Leahy & Williams 1984). In this scenario the aligned DDRGs of paper I are simply those sources in which the angular momentum vector of the infalling material is not very different from that of the existing accretion disk. Dennett-Thorpe et al. (1998) note that winged radio sources have radio luminosities close to the FRI/FRII break ($\sim 5 \times 10^{25} \text{ W Hz}^{-1}$, Fanaroff & Riley 1974). In paper I it is shown that this is also the case for the DDRGs with the exception of B 1834+620.

Whether the rate at which the black holes in AGN accrete and in the process launch jets is limited by the availability of fuel or otherwise is unclear. In any case it is unlikely that the efficiency of the jet production mechanism will decrease if an additional gas supply becomes available to the accretion disk if other parameters like the mass and spin of the black hole do not change. If the spin of the central black hole is responsible for the jet production (e.g. Blandford & Znajek 1977) then we expect that the new jets forming after disruption of the jet flow will have the same power as the old jets.

3.2 The evolution of FRII radio sources

To investigate the radio properties of the DDRGs we will use the dynamical model for FRII sources by Kaiser & Alexander (1997, hereafter KA) with the extension by Kaiser, Dennett-Thorpe & Alexander (1997, hereafter KDA) which allows the calculation of the radio luminosity of these objects as a function of their physical, linear size, $D$.

The observation that the optical identifications of the DDRGs are extended and the absence of broad lines in the optical spectra of the host galaxies (paper I) strongly suggest that the radio axes of the DDRGs lie close to the plane of the sky. We note that the sources 3C445 and 3C 219 are broad-line objects and thus possibly oriented differently. But, since we do not take these two sources into account here, we will therefore assume that the projected linear size of the outer sources structures is indeed equal to their physical size. The inner source structures are very closely aligned with the outer structures. Although this may be a projection effect and the radio axes of the inner and outer structure may form a rather large angle, it is unlikely that all the DDRGs found until now conspire to produce the apparent very close alignment of the two parts of the source. We therefore assume in this paper that our viewing angle of the inner source structures is also very close to 90°. In any case, all DDRGs are radio galaxies and orientation unification schemes suggest that the smallest viewing angle for a radio galaxy is 45° (e.g. Barthel 1989) which implies a maximum error in the physical linear sizes of $\sqrt{2}$.

The models of KA and KDA are based on the assumption of a constant energy transport rate, $Q_o$, from the core of the radio galaxy via the jets to the cocoon. The jets end in strong shocks which can be identified with the radio hot spots and the jet material subsequently inflates the radio cocoon. The expansion of the cocoon is supersonic with respect to the surrounding material and therefore drives a bow shock into this gas (Scheuer 1974). The jets are confined by the pressure in the cocoon. Falle (1991) showed that the expansion of the bow shock should be self-similar and the model presented in KA predicts self-similar growth of the cocoon as well. This is supported by observations (e.g. Leahy & Williams 1984).

The model of KA requires the density distribution external to the radio cocoon to be modeled by a power law: $n_x = n_o (r/a_o)^{-\beta}$, where $n_o$ is the density at a distance, $r$, of one core radius, $a_o$, from the centre of the radio galaxy. This power law is a good approximation to a King (1972) profile with central density $n_o$ and $\beta_{KING} = \beta/3$ outside a few core radii. With this assumption the age of a radio source of linear size $D$ is given by
where \( m_p \) is the mass of a proton and \( c_1 \) is a dimensionless constant (see KA). For the pressure within the cocoon, \( p_c \), KA find
\[
p_c \propto t^{(\beta - 4)/5 - \beta}.
\]  

KDA develop a more sophisticated model of the cocoon which follows the evolution of the population of relativistic electrons responsible for the radio emission via the synchrotron process in the different parts of the cocoon under the influence of energy loss processes. These include adiabatic expansion, synchrotron radiation and inverse Compton scattering of the cosmic microwave background radiation.

The model of KDA for the radio luminosity as a function of linear size or age of the radio source also depends on the aspect ratio of the cocoon, \( R \), the Lorentz factor of the bulk velocity of the jet material, \( \gamma_j \), and the index of the energy distribution of the relativistic electrons at the time of their injection into the cocoon, \( p \). Available low frequency radio maps indicate that \( R = 3 \), the median value found by Leahy & Williams 1984 in their sample of FRII sources, is reasonable for all the sources discussed here (see paper I). The aspect ratio of the cocoon is determined by the ratio of the pressure in the hot spot region and that within the cocoon, \( p_h/p_c \) (see KA). Kaiser & Alexander (1998) show that the assumption of ram pressure confinement of the cocoon perpendicular to the jet axis overpredicts the value of \( p_h/p_c \) and we use their empirical fitting formulae instead. From this for \( R = 3 \) we find \( p_h/p_c \sim 8 \) if \( \beta = 1.5 \) and \( p_h/p_c \sim 21.4 \) if \( \beta = 0 \).

We assume only mildly relativistic flow in the jet, \( \gamma_j = 2 \), and for this Heavens & Drury (1988) show that \( p = 2.14 \) at the jet shock. We set the ratios of specific heats of the jet material and of the IGM surrounding the source to 5/3 while those of the cocoon material and of the energy density of the completely tangled magnetic field within the cocoon are set to 4/3. We also follow KDA in assuming that the power law initially describing the energy distribution of the relativistic electrons in the cocoon extends to thermal energies and that the jet consists entirely of pair plasma. The inclusion of protons in the jets changes the absolute values of the quantities calculated in the following sections but has no influence on any of the conclusions of this paper.

### 3.3 The evolution of the old cocoon

The absence of hot spots in some of the outer cocoons of the DDRGs implies that in these cases the old jets are no longer active. Therefore the model discussed in the previous section is not directly applicable to DDRGs since it assumes a constant supply of energy to the cocoon by the jets. For simplicity we assume that the jet power, \( Q_o \), drops instantaneously to zero once the jet production mechanism is disrupted. The last jet material accelerated by the AGN just before the interruption occurs takes a time \( t_l \) to reach the hot spots in the old cocoon. Only after the last jet material has passed through the old hot spots the evolution of the old cocoon will start to deviate from the prediction of the models of KA and KDA. Because of the relativistic bulk speeds in extragalactic jets, we set \( t_l \sim D/2c \), where \( D \) is the total linear size of the outer cocoons and \( c \) is the speed of light.

We will assume that the evolution of the pressure of the material in the old cocoons and therefore also that of the energy density of the magnetic field in this region during the time we are interested in is given by the power law derived by KA (Eq. 2), even after the last jet material has reached the old cocoon. The information that the jets have ceased to supply the old cocoon with energy will travel through the old cocoon at the local sound speed. After roughly one sound crossing time the entire cocoon will continue to grow but now this expansion is adiabatic since there is no further energy input into the old cocoon. In the following we will justify this assumption by showing that the sound crossing time for each of the sources discussed here by far exceeds the time elapsed since the last jet material reached the old cocoon until the time at which the source is observed. Because the energy supply to the old cocoons has stopped, the pressure in the old cocoons will decrease faster than assumed here and therefore this analysis represents formally only an upper limit.

The assumption about the pressure in the old cocoon also implies that the evolution of the overall size of the cocoons during this time is indistinguishable from that of cocoons which are still supplied with energy by their jets. The total age of the source is thus given by Eq. 2.

Once the last jet material has passed through the jet shocks at the end of the old jets, the hot spots in the old cocoon will start to disperse and blend into the rest of the cocoon material at the local sound speed, \( c_s \). Using the model of KA we find that \( c_s \) is typically of order 0.5c in the hot spot region. For an upper limit of the hot spot radius of 10 kpc we find that the hot spot will disappear roughly within \( 7 \cdot 10^4 \) yr; a fraction of the time it takes the material in the jets of giant radio sources to travel from the core to the hot spots. We can therefore neglect this time and we will assume that the hot spots of the old cocoon disperse instantaneously once the last jet material has passed through them.

The relativistic electrons and possibly positrons responsible for the synchrotron emission observed in the cocoons of FRII radio sources are probably accelerated in the strong shocks at the end of the jets (e.g. Hargrave & Ryle 1974). Clearly this acceleration process stops once the last jet material reaches the old cocoons. The relativistic particles that were accelerated until this time will loose their energy because of the energy loss processes discussed by KDA. This model allows one to calculate the radio emission of parts of the cocoon identified by their injection time into the cocoon and then add up these various contributions by integrating over all injection times. In our case, the integration is stopped at the injection time of the last jet material. With the assumptions made above this allows us to determine, for a given jet power, \( Q_o \), by what factor \( \Delta \) the radio luminosity of the old cocoons has dropped during the time interval \( t_d \) from the moment the last jet material is injected into the old cocoons until the time at which we observe the source. A lower limit for the jet power, \( Q_{o,\text{min}} \), is given by the case in which no dimming has taken place and we observe the source at a time when the last jet material has not yet reached the old hot spots. Lower values for \( Q_o \) are not possible since these would imply a source luminosity below that observed even without any dimming.
For the assumptions given in Sect. 3.2 results for the minimum jet power, $Q_{\text{o,min}}$, and the corresponding maximum age of the outer cocoon, $t_{o,max}$, for the external density profile of poor groups are given in Tab. 1. Note that for B 1240+389 $Q_{\text{o,min}}$ is less than $10^{37}$ W which is roughly the dividing line between low power FRI-type sources and the more powerful FRIIs (Rawlings & Saunders 1991, KA). However, it is very likely that the old cocoon of B 1240+389 has dimmed and that the power of its old jets therefore was greater than $10^{37}$ W (see Section 4).

### 3.4 The evolution of the new cocoon

The inner source structure of all the DDRGs discussed here is fairly symmetrical about the core of the respective source. The difference of the lengths of the inner radio lobes on the two sides of a given source (paper I) is comparable with typical values found for radio galaxies without double-double structure (McCarthy, van Breugel & Kapahi 1991). This implies a density distribution in their surroundings as smooth as that of sources embedded in the unperturbed IGM. If the material in this region responsible for the development of jet shocks in the inner source structures were clumpy, we would expect the new jets to increase in luminosity if they encounter a dense clump of gas; the propagation of the hot spots is correspondingly slowed down. In all the DDRGs discussed here hot spots are detected on both sides of the inner source structure at similar distances from the core of the source and the ratio of the radio luminosity of the two sides (paper I) is also within the limits found for FRI radio galaxies without double-double morphology (McCarthy et al. 1991). The ratio of the luminosities for B 1450+333 ($\sim 6$) is somewhat higher than in the other sources. However, note that in this source the lengths of the two sides of the inner source structure are almost identical. The arm-length ratio is 1.06. We therefore consider it likely that the environment of the inner source structures of DDRGs can also be modeled by a power law density distribution similar to what is assumed for ‘normal’ FRIIs (see KA).

For all five aligned DDRGs the direction of the new jets is within 7° of the old jet axis. This implies that in each object the inner structure is expanding in a region occupied by the material of the old cocoons. The new jets all end in hot spots and the gas surrounding the inner source structures must therefore be dense enough to cause the formation of strong jet shocks.

Clarke & Burns (1991) present numerical simulations of a restarting jet. They find that their simulated jet develops a shock within the region of the old cocoon indicating that the gas within the old cocoon is dense enough to prevent the new jet becoming ‘quasi-ballistic’, i.e. with only a negligible pressure discontinuity (shock) at its end. The shock they observe in their simulations may be strong enough to cause the inner source structure of the aligned DDRGs discussed here.

Although Clarke & Burns find that mechanical instabilities along the cocoon boundary begin to grow after the jet is ‘switched’ off, the gas causing the formation of a jet shock is mainly that transported by the old jet during its activity. They find the resulting density contrast of the gas in the cocoon and the uniform density the old jet expanded into to be roughly 1/40. The model of FRII sources used here assumes that no mixing of material across the contact discontinuity delineating the cocoon of these objects takes place. For this case the only material within the old cocoons of the DDRGs is the jet material which has passed through the jet shock. The density in the old cocoon in the case of a uniform distribution is given by the model as

$$n_c = \frac{Q_o (t_o - t_d)}{(\gamma - 1) m_p c^2 V_o},$$

where $t_o$ is the total age of the source given by Eq. 1, $t_d$ is the ‘dimming time’, i.e. the time elapsed between the arrival of the last jet material at the old cocoon and the time of observation, and $V_o$ is the volume of the old cocoon. In order to be able to compare the density given by Eq. 1 with the density of the unperturbed IGM we have assumed that all the particles within the old cocoon are protons. This is contrary to our assumption that the jets consist of electrons and positrons only. However, since all model predictions for the evolution of the inner source structure depend only on the mass density and not on the particle density in the old cocoon, we can use Eq. 2 for purposes of comparison in its given form. If we assume that the old cocoon expanded in a uniform density environment ($n_o \sim 10^{-2}$ cm$^{-3}$, $\beta = 0$) as in the numerical simulations of Clarke & Burns (1991), then we find from Eq. 3 that our model predicts density contrasts of the gas in the cocoon and the ambient medium comparable to those found in the simulations for short lengths of the old cocoon (of order 1 kpc). This is consistent with the numerical simulations since they only extend to short life times equivalent to short lengths of the jet.

Clarke & Burns (1991) also point out that the formation of relatively strong shocks at the end of the inner jets should be accompanied by the formation of a bow shock within the old cocoon material of similar strength in front of the hot spots. Since the old cocoon volume is filled with magnetic fields this bow shock could be visible due to synchrotron emission if electrons are accelerated to relativistic velocities by the bow shock. In none of the sources discussed here a distinct bow shock around the inner source structure has been observed. This may indicate that the acceleration of particles to relativistic velocities at this bow shock is not efficient. Note here that the strength of the bow shock around the inner source is decreasing away from the hot spots. This implies that although the shock ending the inner jet is strong enough to accelerate particles ‘lighting up’ the cocoon of the inner sources the associated bow shock may be too weak along most of its length to produce enough relativistic particles for it to be detectable. However, the non-detection of any emission from this bow shock is somewhat puzzling.

In the case of short life times of the old jets before the jet flow is interrupted and of uniform density distributions of the external gas we showed above that the gas in the region of the old cocoon may indeed be dense enough to force the formation of significant shocks at the end of the new jets. However, for the profile of the density in the environment used here and for the considerably larger life times of the old jets derived in the previous section, Eq. 3 predicts much smaller density contrasts. We will show in the following that the density in the region of the old cocoon created by the material transported by the old jets alone is insufficient for the formation of strong shocks at the end of the new jets in DDRGs.
Numerical simulations predict the presence of backflow in the cocoon (e.g. Norman et al. 1982) which implies that most of the material within the cocoon will ‘pile up’ towards the core of the source. This suggests that the new jets are propagating along a negative density gradient, the exact shape of which is difficult to determine. However, an upper limit for the density in front of the hot spots of the new source is given by the assumption that all the jet material which has passed through the old jets during their lifetime is uniformly distributed over the volume of the old cocoon. If, within the confines of the inner source, the same amount of material is arranged in such a way that it forms a monotonically decreasing density profile, the density in front of the hot spots of the inner source will be always less than in this limiting case. For calculation of the density in the region of the old cocoon in this limiting case we can therefore use Eq. (3). The solid lines in Fig. 1 show the results as a function of the power of the old jets. We did not consider jet powers above a value for which the radio luminosity at 178 MHz of the respective source would reach $2 \cdot 10^{27}$ W Hz$^{-1}$ sr$^{-1}$, if no dimming of the emission had taken place. This is the luminosity of the most luminous source with a linear size greater than 700 kpc, 3C 292, in the sample of Laing, Riley & Longair (1983) which includes the most luminous radio sources in the observable universe at any redshift.

Analogous to the analysis of the old cocoon, we can use the model of KDA to determine the density of a uniform environment, $n_{oi}$, required to produce the observed linear sizes and radio fluxes of the inner sources for a given jet power. We use the same source parameters as for the old cocoon except for the exponent of the external density which in a uniform environment $\beta_{e} = 0$ (note that the exponent of the power law density distribution surrounding the inner source structure, $\beta_{i}$, is in general not equal to $\beta$, the equivalent exponent of the material the outer cocoon is embedded in). The dashed lines in Fig. 1 show $n_{oi}$ as a function of the power of the inner jets. The cut-off at high jet powers for these lines in the figure is given by the limit that the inner source can not expand faster than the speed of light. It is now also possible to calculate the age of the inner source, $t_{i}$, as a function of the jet power of the inner source. This is shown as the dashed lines in Fig. 1.

The time during which the AGN was quiescent, $t_{off}$, is given by

$$t_{off} = t_{i} + t_{d} - t_{f},$$

where $t_{f}$ is the time it takes the last jet material to reach the end of the old cocoon after it leaves the AGN, $Q_{o,min}$ is the minimum jet power required for the outer cocoon assuming that it is still supplied with energy by the old jets. $t_{o,max}$ is the corresponding age of the outer cocoon. $t_{d,max}$ is the maximum length of time during which the old cocoon could have dimmed to be still consistent with the observations.

### Table 1. Source parameters for the double-double radio sources from observations and derived from the models of KA and KDA. $D_{o}$ and $D_{i}$ are the linear sizes of the outer and inner source structure respectively. $S_{o}$ and $S_{i}$ are the core-subtracted flux density measurements at 1.4 GHz for the outer and inner source structure respectively. $z$ is the cosmological redshift (linear sizes, flux measurements and redshifts are taken from paper I). $t_{f}$ is the light travel time from the core of the radio source to the tip of the old cocoon, i.e. roughly the time it takes the last jet material to reach the end of the old cocoon after it leaves the AGN. $Q_{o,min}$ is the minimum jet power required for the outer cocoon assuming that it is still supplied with energy by the old jets. $t_{o,max}$ is the corresponding age of the outer cocoon.

| Source         | $D_{o}$ / kpc | $D_{i}$ / kpc | $S_{o}$ / mJy | $S_{i}$ / mJy | $z$ | $t_{f}$ / Myr | $Q_{o,min}$ / W | $t_{o,max}$ / Myr | $t_{d,max}$ / Myr |
|----------------|---------------|---------------|---------------|---------------|-----|---------------|----------------|----------------|-------------------|
| B0925+420      | 2450          | 803           | 99            | 63.7          | 0.365 | 4.0          | 8.1 $\cdot 10^{37}$ | 321             | 35.1              |
| B1240+389      | 860           | 320           | 24.1          | 7.8           | 0.30  | 1.4          | 8.2 $\cdot 10^{36}$ | 203             | 32.1              |
| B1450+333      | 1680          | 180           | 426           | 33.5          | 0.249 | 2.7          | 7.3 $\cdot 10^{37}$ | 214             | 34.5              |
| B1834+620      | 1660          | 428           | 604           | 200           | 0.519 | 2.7          | 3.7 $\cdot 10^{38}$ | 122             | 17.7              |
| 4C 26.35       | 730           | 197           | 962           | 66.5          | 0.112 | 1.2          | 1.9 $\cdot 10^{37}$ | 127             | 26.4              |

$t_{off}$ must always be greater or equal to zero and this implies that $t_{f} \leq t_{i} + t_{d,max}$. This condition defines a minimum jet power for the new jets which is shown as the cut-off of the dashed lines in Fig. 1 at low jet powers for two of the DDRGs. For the other three sources this cut-off is below $10^{27}$ W which is roughly the jet power where the transition from FRII to FRI-type sources occurs (Rawlings & Saunders 1991, KA).

From Fig. 1 it is clear that in the cases of B0925+420, B1240+389 and 4C 26.35 the properties of the inner source structure could be caused alone by the presence of the material transported by the old jet during its life time. B1240+389 and 4C 26.35 are also the sources with the smallest outer structures in our sample for which Eq. (3) predicts the highest densities in the old cocoon. Note however, that for all three objects this requires the somewhat favorable assumption that this material is distributed uniformly. It also implies that even if the power of the new jets in B1240+389 and 4C 26.35 is lower by a factor of 5 to 10 than that of the old jets the current expansion velocity of the inner structure is very close to the speed of light, which is unlikely. We therefore conclude that the old cocoons of the DDRGs can not be filled solely with the old jet material but that they must be ‘dirty’ in the sense that some other material must have penetrated the cocoon boundary from the outside.

If the power of the new jets in B1450+333 is equal to that of the old jets, then the observations of this source are consistent with the old cocoon still being supplied with energy. This would imply the existence of hot spots in the old cocoon of this source. The observational evidence is unclear, but a rather diffuse hot spot may have been detected in the southern radio lobe (paper I). In this scenario we find...
The evolution of DDRGs

Figure 1. Densities within the region of the old cocoon of the DDRGs. Vertical solid line: $Q_{o,\text{min}}$ of the jets which inflated the old cocoon. Solid line: The uniform density produced in the old cocoon by the material of the old jet alone (Eq. 3) as a function of the power of the old jets. Dashed line: The uniform density required to produce the observed properties of the inner source as a function of the power of the inner jets. Dotted line: The central density, $n_{oi}$, required within the old cocoon region if $\beta_i = 1.5$ and $a_o = 10$ kpc.

$t_{\text{off}} \sim 10^6$ years for B 1450+333. Assuming that the power of the inner jets, $Q_o$, is equal to that of the old jets as suggested in Sect. 3.1 and that $t_{\text{off}} \sim 1$ Myr for all sources, we can calculate $Q_o$ required for each source by the observed properties of the inner and outer source structure. Tab. 2 lists the results for the assumption of a uniform density in the region of the old cocoon along with the required densities and resulting source ages. The assumption of $t_{\text{off}} = 1$ Myr gives plausible results for $Q_o$ but other values for $t_{\text{off}}$ may be reasonable as well. B 1834+620 shows a radio hot spot at one end of its old cocoon but not at the other (paper III). This implies that the radio emission of the old cocoon in this source has not dimmed significantly and the small value for $t_d$ listed in Tab. 2 for the assumption of $t_{\text{off}} = 10^6$ years for this source is within the limitations of the model consistent with this.

The sound crossing time for the old cocoon, $t_{\text{sc}}$, is also given in Tab. 2. For all five sources the time during which
Figure 2. Time scales in the DDRGs. Solid vertical line: The minimum jet power derived from the model of KDA (see text and Tab. 1). Solid line: The sum of $t_t$ and $t_d$ as a function of the power of the old jets. $t_t$ is given by the intersection of this curve with the solid vertical line. Dashed line: The age of the inner source structure as a function of the power of the inner jets for the assumption of a uniform density in the environment. Dotted line: The age of the inner source structure for $\beta_i = 1.5$.

the radio emission of the cocoon has dimmed is of order a few percent of the sound crossing time. Our assumption that most of the old cocoon continues to dynamically evolve during $t_d$ as if the jets were still supplying it with energy is therefore justified.

4 ‘CONTAMINATING’ THE OLD COCOON

Several possibilities for the contamination of the cocoon with material from the outside exist. In this section we consider entrainment of material into the old cocoon across the contact discontinuity by Kelvin-Helmholtz and/or Rayleigh-Taylor instabilities, the replacement of the old cocoon by the surrounding IGM by buoyancy and the disruption and dis-
Table 2. Derived source parameters for the assumption of constant jet power, uniform density within the region of the old cocoon and $t_{off} \sim 10^8$ years. $Q_o$ is the jet power of the old and the new jets. $n_{oi}$ is the density within the old cocoon region. $f'_c$ is the initial filling factor of line emitting clouds within the old cocoon necessary to produce this density if all of the cloud material is spread over the volume of the cocoon. $t_i$ is the age of the inner source structure. $t_o$ is the age of the outer source structure. $t_d$ is the time during which the old cocoon has dimmed. $\Delta$ is the factor by which the radio emission of the old cocoon has dimmed since the last jet material reached the old hot spots. $t_{sc}$ is the sound crossing time of the old cocoon for the density $n_{oi}$.

| Source          | $Q_o / W$   | $n_{oi} / cm^{-3}$ | $f'_c$   | $t_i / Myr$ | $t_o / Myr$ | $t_d / Myr$ | $\Delta$ | $t_d/t_{sc}$ |
|-----------------|------------|--------------------|----------|------------|------------|------------|---------|-------------|
| B 0925+420      | 1.2 $\times 10^{38}$ | 1.3 $\times 10^{-6}$ | 1.3 $\times 10^{-8}$ | 16.0 | 281 | 13.0 | 1.8 | 0.033 |
| B 1240+389      | 1.1 $\times 10^{37}$ | 5.8 $\times 10^{-6}$ | 6.0 $\times 10^{-8}$ | 12.8 | 184 | 13.3 | 1.5 | 0.054 |
| B 1450+333      | 7.2 $\times 10^{37}$ | 1.4 $\times 10^{-6}$ | 1.4 $\times 10^{-8}$ | 1.6 | 215 | 0.0 | 1.0 | 0.0 |
| B 1834+620      | 4.3 $\times 10^{38}$ | 4.1 $\times 10^{-6}$ | 4.0 $\times 10^{-8}$ | 5.4 | 117 | 3.7 | 1.2 | 0.017 |
| 4C 26.35        | 2.0 $\times 10^{37}$ | 3.5 $\times 10^{-6}$ | 3.5 $\times 10^{-8}$ | 3.9 | 125 | 4.2 | 1.1 | 0.037 |

4.1 Entrainment across the contact discontinuity

Numerical simulations indicate that the contact discontinuity delineating the cocoon is stable against hydrodynamic instabilities, if the backflow within the cocoon is supersonic with respect to the ambient medium (Norman et al. 1982). In the simulations the backflow is found to be initially supersonic whenever the bulk velocities in the jets inflating the cocoon are highly supersonic with respect to the speed of sound in the unperturbed IGM. For the five DDRGs and the assumed isotermal density profile of poor groups of galaxies we find that even if the power of the old jets is close to their lower limit, $Q_o_{min}$, their Mach numbers just before they stop supplying energy to the old cocoon are equal or greater than about 5.

In FRII sources which do not show large off-axis gas flow within their cocoon the backflow of gas must eventually be decelerated to velocities below the external sound speed (Norman et al. 1982). This may lead to the development of fluid instabilities along the contact discontinuity of the inner cocoon. This is also seen in numerical simulations. However, most simulations are confined to a two dimensional treatment of the problem and include reflective boundary conditions at the limits of the computational grid where we would expect the instabilities to be strongest. The predictions of numerical simulations in this flow region should therefore be treated with caution. A simple analytical estimate of the time scale for the growth of Kelvin-Helmholtz and Rayleigh-Taylor instabilities of length scale $l$ at the boundary of two fluids with large density contrast $\chi$ and relative velocity $v_{rel}$ is given by $t_{KH} \sim \sqrt{l/v_{rel}}$ and $t_{RT} \sim \sqrt{l/g}$, where $g$ is the acceleration of one fluid with respect to the other (Chandrasekhar 1961). To replace large parts of the cocoon of FRII sources large-scale instabilities would be most efficient. However, for $l$ comparable to the cocoon size the instability growth is slow and the mixing of material from the ambient IGM with the gas in the cocoon on small scales, say $l \sim 1$ kpc, may be sufficient if it proceeds fast enough. We have mentioned already that the relative velocity for the two gas streams for fluid instabilities to grow must be of the order of or smaller than the sound speed in the unshocked IGM, which for $T_e \sim 10^7$ K is about $370$ km s$^{-1}$. From the previous section we note that $\chi \sim 10^4$ for the outer cocoon at a few 100 kpc from the centre of the assumed density distribution of the unshocked IGM. From this we find that $t_{KH} \sim 2 \times 10^8$ years which is longer than the life time of most of the outer cocoons in the sources discussed here. Kaiser & Alexander (1999) show that there should be a backflow not only within the cocoon but also in the shocked IGM in between bow shock and contact discontinuity. Both flows show similar velocities and decelerate on similar length scales. This implies that $g$, the acceleration of the flow within the cocoon with respect to that of the shocked IGM, is small and $t_{RT} \sim t_{KH}$. Entrainment of dense material from the IGM into the old cocoon across the contact discontinuity even in the regions of the cocoon where the backflow velocity is not supersonic with respect to the unshocked IGM should therefore be rather inefficient. This makes it unlikely that the additional material in the old cocoons has been entrained.

4.2 Replacement of the old cocoon by the IGM

During most of the life time of FRII sources the cocoon will be overpressured with respect to the surrounding IGM. The expansion of the cocoon will be supersonic and therefore it will drive a strong bow shock into the IGM. However, the pressure within the cocoon decreases with time and will eventually become comparable to the pressure of the ambient medium and the bow shock will vanish. If the IGM in the vicinity of the cocoon is isothermal with a density distribution close to a King (1972) profile, this will first occur close to the core of the radio source. Once the cocoon is no longer protected by its bow shock over its entire length, buoyancy will set in and the denser IGM will push the lighter material filling the cocoon outwards thereby starting to replace it in the inner regions of the cocoon. Assuming the minimum jet power for each source given in Tab. 1, the model of KA predicts that for a temperature of $10^7$ K for the IGM the pressure in the old cocoons of all of the DDRGs discussed here, except in that of B 1834+620, should be slightly lower than about half the value of the ambient pressure close to the core of the respective source. In the case of B 1834+620 the old cocoon should still be overpressured with respect to the IGM over its entire length. The low value for the pressure in the old cocoon in the other sources implies that their cocoons may be in direct contact with the unshocked IGM close to the core. However, this estimate depends strongly on the assumed temperature of the IGM and also on whether this material really is isothermal. If the power of the old jets is higher than their minimum value...
used here, then their old cocoons will still be overpressured and they will still be surrounded by a bow shock over their entire lengths.

The replacement of the cocoon material by the IGM due to buoyancy proceeds at the sound speed of the IGM and is therefore a slow process. For the temperature of the IGM assumed here, the relevant sound speed is of order 370 km s\(^{-1}\). At this speed we find that the replacement of a cylindrical volume of 100 kpc length and the width of the old cocoon by the IGM takes of order a 100 Myrs. This almost corresponds to the maximum ages of the old cocoons (see Tab. 1). This implies that there is enough time for the IGM to replace a considerable fraction of the volume of the old cocoon only if the replacement started early in the evolution of the radio source. Of course, a higher temperature of the IGM causing a higher sound speed in this material would shorten the relevant time scales. Although in principle this mechanism may therefore be fast enough we present further arguments against the replacement of large fractions of the cocoon material by the IGM in the following.

It is not straightforward to determine the density distribution in the region of the old cocoon resulting from such a buoyant replacement of the old cocoon material. We can, however, make two very crude approximations. If the IGM has had enough time to replace the old cocoon material and settle into an equilibrium configuration, its density distribution may closely resemble that of the unperturbed IGM. In this case the inner sources in the aligned DDRGs are embedded in essentially the same environment as the old cocoons (see Tab. 1). This implies that there is enough time for the IGM to replace a considerable fraction of the volume of the old cocoon only if the replacement started early in the evolution of the radio source. Of course, a higher temperature of the IGM causing a higher sound speed in this material would shorten the relevant time scales. Although in principle this mechanism may therefore be fast enough we present further arguments against the replacement of large fractions of the cocoon material by the IGM in the following.

As we have seen in Sect. 2, optical observations of FRII radio galaxies suggest the existence of warm, dense clouds embedded in the hot gas of the IGM in the vicinity of the host galaxy. They can potentially provide the additional material needed to explain the observed properties of the inner source structures in the aligned DDRGs. This is only possible if they can pass through the contact discontinuity into the old cocoon and if most of their material is subsequently dispersed over the volume of the old cocoon.

When the bow shock of an FRII radio source encounters one of these warm clouds embedded in the hot IGM, it drives a shock into it. The cloud is small and will therefore quickly re-establish pressure equilibrium with its surroundings. This implies that the Mach number of the shock within the cloud can be set equal to the Mach number of the bow shock within the hot IGM, \(M_b\) (McKee & Cowie 1975). Note that because of its shape \(M_b\) is not uniform along the length of the bow shock. In the following \(M_b\) therefore refers to an ‘average’ Mach number of a given bow shock. Because of its large density the cloud is not efficiently accelerated by the passage of the shock and is therefore quickly overtaken by the contact discontinuity and passes through this surface into the cocoon.

It has been suggested that after the cloud has passed through the bow shock it will collapse and possibly form stars if radiative cooling is efficient (Rees 1989, Begelman & Cioffi 1989, Foster & Boss 1996). Because of the low temperature of the cloud material the bow shock of FRII sources will be radiative and the compression of the cloud is an almost isothermal process. For strong shock conditions this implies \(n_{cl} = M_b^2 n_{cd}\), where \(n_{cd}\) is the pre-shock density of the cloud (Rees 1989). We will use dashed variables for quantities describing the cloud after the shock has passed through it. The temperature of the warm cloud will initially increase by a factor \(\sim 30\) for \(M_b = 10\). The cloud material then cools radiatively back to a temperature of \(10^4\) K within \(10^3 \rightarrow 10^4\) years (Sutherland & Dopita 1993). During this phase the optical line emission of the clouds will be enhanced because of the passage of the bow shock. Once the temperature within the cloud reaches \(10^4\) K, cooling via radiation becomes inefficient and the subsequent evolution of the cloud will be adiabatic. In this regime the numerical simulations predict the shredding of the cloud due to growing Kelvin-Helmholtz and Rayleigh-Taylor instabilities on its surface within a few ‘cloud crushing times’ (Klein, McKee & Colella 1994)

\[
t_{cc} = \frac{\sqrt{3 v_t^3}}{v_b},
\]

where \(\chi\) is the ratio of the density of the warm cloud and that of its surroundings, \(r_c^3\) is the radius of the cloud and \(v_b\) is the velocity of the bow shock with respect to the unshocked IGM. Here we have made use of the fact that the warm cloud is not very effectively accelerated by the passage
of the bow shock and that $v_b$ is therefore similar to $v_{rel}$, the relative velocity of the shocked hot IGM with respect to the cloud.

For this and in the following we assume that the density of the cloud is uniform over its volume. This is a simplification and the cloud will be denser close to its centre than further out. In this case the core of the cloud may collapse under the influence of the radiative shock within the cloud and form stars. Such shock induced star formation may play an important role in the explanation of the alignment effect in FRII sources at $z > 0.6$ (see Sect. 3). However, most of the gas in the cloud will become adiabatic before it can collapse to form stars and this is the material which will subsequently be spread out over the volume of the old cocoon. Super novae and stellar winds of the stars formed in the core of the cloud will contribute to the dispersion of the outer cloud regions as well. The exact details of the evolution of the warm cloud can probably only be determined with the help of numerical simulations taking into account radiative cooling and feedback from star formation.

Immediately after passing through the bow shock the warm cloud is surrounded by the shocked gas of the hot IGM. For the hot IGM the bow shock is adiabatic and for strong shock conditions $\chi'$ is therefore equal to $\sim \frac{M_b^2}{4(T_s/T_{cl})}$, where $M_b$ is the local Mach number of the bow shock. This implies the shredding of the cloud within a few $t_{cc} \sim \frac{M_b}{\sqrt{T_s/T_{cl}}r_{cl}'/(2c_s)}$. The acceleration of the cloud by the shocked IGM outwards, away from the contact discontinuity, proceeds on at least similar if not longer time scales (Klein et al. 1994). Consider now a 'typical' FRII source with a total linear size of $D = 400$ kpc embedded in a density distribution appropriate for a poor group. According to Eq. (3) this source has an age of roughly $2 \cdot 10^7$ years if the aspect ratio of its cocoon, $R$, is equal to 3. From this we find the advance speed of the hot spots for this source $v_b \sim 0.03c$. If we assume that the shape of the cocoon is cylindrical the expansion speed perpendicular to the jet axis is $5 \cdot 10^{-2}c$ thereby implying a Mach number of the bow shock in this direction of 3.8. Assuming $r_{cl}' = 10$ pc (e.g. Osterbrock 1989) we find that for this cloud in these conditions $t_{cc} \sim 1.6 \cdot 10^9$ years. From Kaiser & Alexander (1999) we note that the stand-off distance between the bow shock and the contact discontinuity is roughly $5 \cdot 10^{-2}D$. If the cloud is not accelerated at all by the passage of the bow shock, it will take the contact discontinuity roughly $10^6$ years to overtake the cloud. The cloud is therefore just able to reach the safety of the cocoon before it is dispersed within the layer of shocked IGM. Since the shape of the cocoons of FRII sources is not cylindrical, the conditions for clouds closer to the hot spot should be more favorable than estimated here because the Mach number of the bow shock will always be higher than in the above scenario and also the different direction of expansion of the cocoon causes the contact discontinuity to overtake the cloud earlier. We therefore conclude that 'average' clouds are not disrupted or accelerated efficiently by the bow shock and the shocked IGM.

The pressure within the cocoon is the same as that in the shocked layer of gas between bow shock and contact discontinuity but the density is much lower. For an estimate we use Eq. (3) with the same parameters as above. Again we assume that the warm clouds supplying the material for the environment of the inner source structures are not displaced by the passage of the bow shock. Therefore to determine the disruption time scale of these clouds we have to consider the properties of the bow shock around the outer source structure at the time when it had a linear size of typically $400$ kpc. We find $n_e \sim 1 \cdot 10^{-7}$ cm$^{-3}$ which implies $t_{cc} \sim 5 \cdot 10^7$ years. A warm cloud is therefore stable for a long time within the cocoon during which its outer layers may be ionized by the UV emission of the central AGN and/or the emission of the shocked hot phase of the IGM (see Sect. 3). This material may then produce the observed line emission.

Roughly a time $t_{cc}$ after an ensemble of clouds have passed through the bow shock they are finally broken up into smaller fragments and their material is spread out over large fractions of the cocoon volume. It is not straightforward to estimate the size of the volume over which the cloud material is dispersed because this is determined by the mixing of the cloud material with the gas already present in the cocoon. While the break-up of the warm clouds is mainly driven by the fluid instabilities on large scales, mixing proceeds on much smaller scales which are difficult to resolve in numerical simulations (Klein et al. 1994). As was mentioned above, instabilities grow faster on smaller scales and so significant fractions of the gas mass of the clouds may be already mixed with the other cocoon material by the time the clouds finally break up on larger scales after a time $t_{cc}$.

A rough estimate for the volume over which the cloud material is spread may be obtained by calculating the volume 'swept-out' by a given cloud during one cloud crushing time. Assuming that the cloud expands adiabatically in pressure equilibrium with its surroundings in the cocoon we find from Eq. (3) that the cloud cross sectional area, $\sigma_{cl}$, increases proportional to $t^{2(\beta+\gamma)/3\beta}$. If we again assume that the velocity of the cloud relative to its surroundings is roughly equal to the advance speed of the hot spot we find for the volume swept-out by the cloud $\int \sigma_{cl} v_B dt$. If the cloud material is distributed over this swept-out volume this corresponds to an increase in the cloud volume of a factor $\sim 3 \cdot 10^5$ for the cloud and source parameters introduced above. Of course this estimate is very simplistic and neglects many of the complicated processes involved. However, we note that since the cloud disruption is a continuous process the density of the gas in the cocoon responsible for the disruption of newly incoming clouds is already enhanced by the shredding of clouds which were earlier overtaken by the expansion of the cocoon. This means that the time scales for the cloud dispersal and mixing of cloud material with the cocoon gas may be shorter than estimated above. From this we see that the volume filling factor of the former cloud material may increase substantially when compared to that of the intact clouds. In the following we will make the approximation that the material of all clouds is spread out uniformly over the entire volume of the cocoon, i.e. the filling factor of the former cloud material is unity after the disruption of the clouds. The resulting density within the cocoon is approximately $f_{off}' n_{cl}'$. This then provides the environment for the inner source structures of the aligned DDRGs.

In Sect. 3.4 we have calculated the uniform density within the region of the old cocoon required to explain the properties of the inner source structure for the assumption that $t_{off} \sim 10^6$ years and that the jet power of the old and new jets is the same. If this density profile is provided by the shredding of line-emitting clouds we can estimate their ini-
tial volume filling factor, $f_{cl}$, within the cocoon before they are dispersed. The results which are given in Tab. 2 agree very well with the filling factors derived from observations of the line emission (Heckman et al. 1991). Note that because we assume a filling factor of unity of the former cloud material the calculated values of $f_{cl}$ are only lower limits since some of the clouds will not be dispersed completely. Of course this is also true if the cloud cores collapse and form stars.

The distribution of warm, line-emitting clouds within the hot IGM must be quite smooth to explain the symmetry of the inner source structures. In some FRII sources observations indicate a rather clumpy distribution of these clouds (e.g. Johnson, Leahy & Garrington 1995). A concentration of a large number of warm, dense clouds in the IGM in the path of one of the jet may even become dynamically important for the evolution of this jet (McCarthy et al. 1991). The volume filling factor of the clouds must be locally increased in such regions so that $f_{cl} \sim \sqrt{T_e/T_c} \geq 0.03$. However, the distribution of clouds in these sources is observed at a time when they are still intact within the cocoon. The time available for the cloud to disrupt and the cloud material to smooth out over the volume of the old cocoon in DDRGs is probably sufficient to provide a more homogeneous environment for the inner source structures than suggested by the observations of the intact clouds.

5 IMPLICATIONS OF CLOUD-SHREDDING FOR ALIGNED DDRGS AND OTHER LARGE FRII SOURCES

The dispersion of warm, dense clouds by the bow shock of the outer cocoon of aligned DDRGs can explain the formation of the observed peculiar structures of these objects. There are some further implications of this model which we will discuss in this section.

5.1 Internal depolarisation by the cloud material

Any thermal material, like the warm, dense clouds inside the outer cocoon prior to their dispersion, threaded by magnetic field will contribute to the depolarisation of the radio synchrotron emission of the cocoon material by Faraday rotation. In some FRII sources a clear spatial association between the line emitting clouds and the depolarisation is observed (e.g. Pedelty et al. 1989). As long as the clouds are still intact their contribution to the depolarisation can not be distinguished from any depolarisation occurring outside the radio cocoon. However, in DDRGs and other large radio galaxies the cloud material should be spread out over most of the volume of the cocoon and in this case the depolarisation should show the characteristics of internal depolarisation. Garrington & Conway (1991) find no evidence for the presence of thermal material in the cocoons of a sample of 47 FRII radio galaxies with a maximum linear size of 625 kpc. They give an upper limit of $5 \cdot 10^{-3}$ $\mu$G for the product of the strength of the magnetic field along the line of sight in the cocoon, $B_c$, and the number density of electrons, $n_e$, in this region. From the model of KA we find the pressures in the old cocoons of the DDRGs to be of order $\sim 10^{-13}$ erg cm$^{-3}$. Assuming equipartition between the energy density of the magnetic field and that of the relativistic particles in the cocoon we find $B \sim 3$ $\mu$G. The upper limit of Garrington & Conway (1991) then corresponds to densities of roughly $2 \cdot 10^{-3}$ cm$^{-3}$ for the cocoon material. The densities within the old cocoons of the DDRGs necessary to explain the properties of the inner source structures are about three orders of magnitude lower than this (see Tab. 2). The internal depolarisation of the radio emission of large radio galaxies caused by the material of the dispersed warm clouds should therefore be unobservable. However, the model presented here predicts that as more and more of the warm clouds are shredded within the cocoons, the radio depolarisation observed towards the cocoon of FRII radio sources should decrease with increasing linear size. This effect may be masked by the additional decrease in depolarisation caused by the fact that for large FRII sources a larger fraction of the radio lobes is surrounded by material of low density at large distances from the core which causes less depolarisation than the material closer in (e.g. Strom & Jägers 1988). However, the shredding of warm clouds should lead to a decrease in the number of ‘clumpy’ regions of depolarisation, possibly associated with optical line emission, in large FRIIs and this difference may be detectable in high resolution depolarisation maps of sources of different size.

5.2 The large size of DDRGs

For the cloud in the example presented in the previous section the final dispersion takes place when the outer cocoon has a linear size of 670 kpc. If the shredding of line emitting clouds is the mechanism which contaminates the cocoon of FRII radio sources then, because of the long time it takes to disrupt these clouds, we expect to see large aligned DDRGs only. Indeed, all aligned DDRGs mentioned in paper I have large linear sizes ($\geq 700$ kpc).

If the jet flow in younger sources is disrupted without significantly changing the direction of the jets, the new jets will pass through the old cocoons at the bulk velocity of the jet material without developing a strong jet shock because the warm clouds are still intact and can not influence the dynamics of the new jets. Those sources will most likely follow a evolution much like that predicted by Clarke & Burns (1991), in which a restarted jet travels unhampered through the old cocoon without a clear trace of its doing so. Because of the relativistic velocities of the jet material, the time it takes the new jets to reach the edge of the old cocoon is about the light travel time along the cocoon. Since the old hotspots will fade extremely fast after the energy input has stopped, such sources would only be noticed during the short time their radio lobes do not show any hot spots.

It is unclear how such a source will evolve further once the jet has reached the old cocoon boundary again. During the time that the jet was off, the old cocoon will have continued to expand and it will probably have a lower length-to-width ratio, since mainly the forward, jet-driven motion will have slowed down and not the sideways expansion. The new hotspot, since it is driven by the restarted jet, will advance much faster than the head of the old cocoon and it will probably form a protrusion at the head of the old lobe (see also the simulations of Clarke & Burns 1991). There are a number of radio sources which clearly show protrusions in one or both radio lobes (e.g. 3C 79, Spangler, Myers & Pogge

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5.3 The velocity of the inner lobes

Since the density in the old cocoon is lower than that of the unperturbed IGM, it is expected that the inner structures advance much faster than the outer structures would have at a similar distance from the core.

Finding direct evidence for such high advance velocities, for instance through spectral ageing studies, is difficult and often ambiguous (e.g. Alexander & Leahy 1987). If the inner structures indeed are the result of a restarted jet, then the fact that we still detect the outer radio lobes in the DDRGs already indicates that the inner lobes must be advancing relatively fast. Radio lobes which are not being refuelled anymore are expected to fade away quickly, in a few times $10^7$ yr, at most. Since the radio powers of the outer structures are quite normal for sources of their size (see paper I), the length of time elapsed since the disconnection of the outer lobes from the jet flow must be relatively short compared to their age. Hence, the inner structures must have grown relatively fast to their currently observed size, certainly faster than the outer lobes would have advanced at the time they had a similar size.

In the case of B1834+620 we have been able to constrain the advance velocity and age of the inner structure (see paper III). We find that the velocity must lie within the range $0.2 - 0.3c$, depending only on the orientation of the source. This is much higher than what is usually found in powerful radio galaxies ($0.01 - 0.1c$; e.g. Alexander & Leahy 1987, Scheuer 1995). The age is constrained to the range between 2.6 and 5.8 Myr, which is in good agreement with the prediction of the model presented in this paper (see Tab. 2). Also, we have estimated an ambient density of the inner lobes of $\sim 8 \times 10^{-7} \text{ cm}^{-3}$, three orders of magnitude below what is generally found around the lobes of radio galaxies (e.g. Alexander & Leahy 1987), but in reasonable agreement with the prediction from the model in this paper (see Tab. 3).

6 IMPLICATIONS FOR THE ALIGNMENT EFFECT

The alignment of the UV and optical line emission with the radio axis in FRII sources at high redshift, $z \geq 0.6$, is usually explained by ionisation of the warm clouds by either the radiation from the AGN (McCarthy 1993 and references therein) or by the emission of gas shocked and heated by shocks (e.g. Dopita & Sutherland 1995). Aligned optical continuum emission is partly caused by the nebular continuum emitted by the ionized clouds (Dickson et al. 1995) and may include contributions by scattering of the AGN emission by the cloud material (Tadhunter et al. 1987) and shock induced star formation (Rees 1989, Begelman & Cioffi 1989). It is interesting to note that all of the explanations mentioned above postulate the existence of a two phase IGM; warm ($T_w \sim 10^4 \text{ K}$), dense clouds embedded in a hot ($T_h \sim 10^7 \text{ K}$), less dense background.

The model for the shredding of the warm, dense clouds presented here is consistent with all of the explanations for the alignment effect. The cores of the clouds may very well collapse after the compression of the cloud by the bow shock while the outer cloud regions are stable for a significant fraction of the life time of the radio source. The material in this region can be ionized but will also scatter the light of the AGN. The hot phase of the IGM may provide some of the ionizing radiation after passing through the bow shock. The following considerations show that the model is consistent with the observed properties of the alignment effect.

We have shown in Sect. 4.3 that the properties of the warm, line-emitting clouds can change significantly when they pass through the bow shock of an FRII source. Most optical emission from FRII sources is observed in regions overlapping with the radio cocoon which is the basis of the alignment effect. All physical quantities derived from such observations for the warm clouds therefore apply to their post-shock state within the cocoon of the FRII source. This has important implications for their confinement in the hot IGM before they are shocked.

To be stable the pre-shock cloud must be in pressure equilibrium with the hot IGM. For the typical temperatures involved this implies $n_{cl}/n_h \sim 10^3$, where $n_h$ is the density of the hot IGM. The densities of these clouds derived from the observed line emission coming from regions overlapping with the radio cocoon would then imply much higher densities of the hot IGM than are derived from X-ray observations of this material (e.g. Fabian et al. 1987). However, because the clouds, for which these observations have been made, may have been compressed by the bow shock their pre-shock densities are much lower than those indicated by the observations. For $M_h \sim 10$ we find that the pre-shock clouds are stable within the density profile of the hot IGM in poor groups of galaxies assumed above out to roughly 50 kpc from the centre of the group. This explains the stability of the warm clouds in their hot environment without the need to invoke additional contributions to the thermal pressure of the hot IGM by cooling flows or other processes.

In some radio galaxies Lyα emission is detected well beyond the radio cocoon but still aligned with the radio axis forming the so called Lyα halo (Chambers, Miley & van Breugel 1990, McCarthy et al. 1990, Eales et al. 1993, van Ojik et al. 1996, Pentericci et al. 1997). The source of ionizing photons for the Lyα emission cannot be due to recently formed stars and must be caused by the illumination of warm material by the obscured AGN or by the shocked hot phase of the IGM (e.g. Meisenheimer & Hippelein 1992). However, the warm clouds causing the observed emission of the Lyα halos must still be in their pre-shock state. This can explain observed differences in velocity spread and ionisation parameter between the material in the halo and that of the region of the cocoon.

Velocities of the warm clouds in regions overlapping with the cocoon and in the more extended halo can be inferred from their Doppler-broadened emission lines. In the Lyα halos typical velocities are of order 500 km s$^{-1}$ which is comparable to the sound speeds within the hot IGM and may indicate some large scale movement like rotation (van Ojik et al. 1996). For the line-emitting regions within the radio cocoons velocities of order 1000 km s$^{-1}$ are measured (McCarthy 1993 and references therein). These somewhat higher velocities of the clouds within the cocoon may be caused by the acceleration of the clouds by the passage of the...
bow shock and the continuing momentum transfer from the material in the cocoon to the clouds. The velocities within the cocoon should be similar to the advance speed of the hot spots (Norman et al. 1982). These are typically a few times 1000 km s$^{-1}$ which agrees well with the observations. This may indicate that the clouds observed in regions overlapping with the cocoon are indeed located within the cocoon.

Furthermore the ratio of ionizing photons arriving at a warm cloud to the number density of electrons available to absorb these photons within the cloud, the ionisation parameter, $U$, will also change when the cloud passes through the bow shock (e.g. Lacy et al. 1998). The warm clouds in the cocoon will have been compressed by the bow shock but the ionizing flux from the core is roughly the same for clouds within the cocoon and those in front of it. This will lead to a smaller value of $U$ for the clouds within the cocoon compared to those in front of it. This can in principle be tested observationally using line ratios like $\text{[O III]}{\lambda}5007 / \text{[O II]}{\lambda}3727$.

All models of the dynamical evolution of the radio cocoons of FRII sources predict a correlation of linear size with age of the source. The exact age of a source of a given linear size depends of course on the power of its jets and also on the density of the surrounding material. However, larger sources will in general be older than smaller sources. Once the line-emitting clouds within the cocoon are completely disrupted, the resulting temperatures (a few 10$^8$ K) and densities in this region imply a drastic decrease in the line emission of these clouds. In the picture of the slow dispersion of the line-emitting clouds within the radio cocoon sketched above we therefore expect the strongest aligned emission in small FRII sources while in larger sources the effect should be weaker and may vanish in large sources. The same is true for the aligned optical and UV continuum emission because the nebular continuum emission (Dickson et al. 1995) of the warm clouds will decrease as the cloud material starts to be spread out over the volume of the cocoon. If the cores of the warm clouds collapse and form stars, their emission will also fade because of the aging of the stellar population. Best, Longair & Röttgering (1996) find in a sample of 8 FRII radio galaxies, all at a redshift $z \sim 1$ and of similar radio luminosity, that the alignment effect depends on the linear size and therefore presumably on the age of the radio source. Sources with larger linear sizes show a weaker alignment effect than smaller objects as predicted by our model.

7 CONCLUSIONS

Based on the observed properties of aligned DDRGs we have developed a model for their evolution. The symmetry of the inner source structure strongly suggests that the interruption of the jet flow takes place in the central AGN. One possible physical process is the infall of large masses of gas onto the accretion disk, possibly caused by a (repeated) interaction with a companion galaxy (see paper I). This scenario may explain the existence of so-called X-shaped or winged FRII radio galaxies, if similar processes have taken place in these sources and the angular momentum vector of the infalling gas is very different to that of the pre-existing accretion disk. These objects may then constitute the ‘mis-aligned’ DDRGs.

We extended the model of the radio luminosity evolution of FRII sources of KDA to allow for sources in which the jets have stopped supplying the cocoon with energy. We used this model to investigate the evolution of the outer and the inner source structure. This analysis suggests that the density in the outer cocoon created by the old jets is insufficient to explain the observed properties of the inner source structure. We argue that the most likely contamination of the old cocoon with additional gas is the slow dispersion by the effects of the bow shock surrounding the old cocoon of warm, dense clouds embedded in the otherwise hot IGM.

The observation of optical and UV emission aligned with the radio axis in many FRII sources at high redshift implies that the clouds must survive for a long time in the cocoon. They are, however, eventually destroyed and provide the environment for inner source structures in DDRGs. The long survival times for these clouds derived here are consistent with the observation that the currently known aligned DDRGs are all large ($\gtrsim 700$ kpc). Also, it is consistent with the observation that in $z \sim 1$ 3CR radio galaxies the strength of the alignment effect anti-correlates with the linear size of the radio sources. The lower limits for the volume filling factors for the warm, dense clouds derived from the density requirements of the inner source structures are in good agreement with those obtained from optical observations.

The problem of the confinement of the warm clouds within the hot IGM previously pointed out by various authors (e.g. Fabian et al. 1987) can be resolved by taking into account the effects of the bow shocks on these clouds. The properties of the clouds are derived from optical observations of clouds which may already be located inside the radio cocoon. This implies that they have been compressed by the bow shock leading to an increased density and pressure for the cloud material compared to pre-shock clouds.

Polarization measurements of the radio emission from the cocoons of FRII sources indicate a spatial association of peaks in the depolarisation and concentrations of line-emitting material. Once the cloud material has been spread out over the volume of the radio cocoon, its depolarisation signature will be too weak to be detected.

The available data on the currently known DDRGs have not allowed us to put strong constraints on the model. Only in the case of the source B 1834+620 have we been able to limit the age and to estimate the ambient density of the inner source. These values are in rough agreement with the predictions from the model.

Many of the physical quantities we have derived for the DDRGs discussed here are model dependent. The shape of the density distribution within the region of the old cocoon in particular is unknown. Moreover, we have assumed a density profile for the environment of the outer source structures which may be typical for low redshift FRII sources but in the absence of X-ray data we do not have the means to test the validity of this assumption. The numerical values of the derived source parameters should therefore be treated with caution. However, we arrived at the main conclusions of this paper, namely that the cocoons of aligned DDRGs and possibly other FRII sources contain material additional to that supplied by their jets, using only limiting cases of the models. This material is most likely the remains of shredded line-emitting clouds. In view of the observational evidence we believe that the contamination of the cocoons of FRII
sources by warm, dense clouds located in the IGM is an important process in the evolution of these objects.

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