Radio relics in a cosmological cluster merger simulation

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**ABSTRACT**

Motivated by the discovery of a number of radio relics we investigate the fate of fossil radio plasma during a merger of clusters of galaxies using cosmological smoothed-particle hydrodynamics simulations. Radio relics are extended, steep-spectrum radio sources that do not seem to be associated with a host galaxy. One proposed scenario whereby these relics form is through the compression of fossil radio plasma during a merger between clusters. The ensuing compression of the plasma can lead to a substantial increase in synchrotron luminosity and this appears as a radio relic. Our simulations show that relics are most likely to be found at the periphery of the cluster at the positions of the outgoing merger shock waves. Relics are expected to be very rare in the centre of the cluster where the lifetime of relativistic electrons is short and shock waves are weaker than in the cooler, peripheral regions of the cluster. These predictions can soon be tested with upcoming low-frequency radio telescopes.

**Key words:** galaxies: clusters: general – intergalactic medium – shock waves, cosmology: theory – diffuse radiation, radiation mechanism: non-thermal

1 INTRODUCTION

Active galactic nuclei (AGN) inject a large amount of magnetised, relativistic plasma into the intra-cluster medium (ICM). This radio plasma emits mainly synchrotron radiation. However, after a typical time of $10^{8}$ years the plasma has cooled radiatively such that the remaining radio emission is difficult to detect (e.g. Jaffe \textsuperscript{(1977)})\label{eq:1}). The remnants of radio lobes are called ‘radio ghosts’ or ‘fossil radio plasma’. Recently, substantial evidence for radio ghosts has come from the detection of cavities in X-ray surface brightness maps of clusters of galaxies (Boehringer et al. \textsuperscript{1993}; Churazov et al. \textsuperscript{2000}; Wilson et al. \textsuperscript{2000}; McNamara et al. \textsuperscript{2001}; Blanton et al. \textsuperscript{2001}).

Diffuse, steep-spectrum radio sources with no optical identification have been observed in a growing number of galaxy clusters. These objects have complex morphologies that show diffuse and irregular emission in combination with point-like sources. They are usually subdivided into two classes: those that are located near the centre of a cluster, e.g. in Abell 520 and Abell 2254 (Giovannini et al. \textsuperscript{1997}), and those that are located in the periphery of a cluster, e.g. Abell 85, Abell 133, Abell 3667 (Rottgering et al. \textsuperscript{1997}; See et al. \textsuperscript{2001}), denoted as ‘radio halos’ and ‘radio relics’, respectively. Unlike halos, radio relics have a filamentary morphology and show a partial polarisation of the radio emission. This distinction, however, is not free of contradictions. The cluster Abell 520, e.g., shows knotty radio structures located in the centre of the cluster’s X-ray emission. The rough classification reflects the poor understanding of the origin of the radio sources and raises the question whether halos and relics are indeed produced by different processes. Radio halos and relics show a steep spectrum $\alpha \approx 1 - 1.8$ (Kempner & Sarazin \textsuperscript{2001}; Bacchi et al. \textsuperscript{2003}) and the cut-off at high frequencies indicates that the electron population has aged (See et al. \textsuperscript{2001}; Kaiser & Cotter \textsuperscript{2002}). For more details on observations of diffuse cluster radio sources the reader is referred to (Kempner & Sarazin \textsuperscript{2001}; Giovannini \textsuperscript{1999}). The difficulty in explaining the radio emission lies in the lack of an evident source for the relativistic electrons, such as an AGN. The strongest hint for the formation of, both, halos and relics may come from the fact that both are observed in clusters that show signs of an ongoing merger, for instance significant substructures in the X-ray emission or the absence of a cooling flow (Bacchi et al. \textsuperscript{2003}; Kempner & Sarazin \textsuperscript{2001}; Feretti \textsuperscript{1993}; Schuecker & Böhringer \textsuperscript{1998}; Venturi et al. \textsuperscript{1999}; Roettiger et al. \textsuperscript{1999}). In the rest of the paper we will be primarily concerned with radio relics because their formation is believed to be quite different from that of radio halos.

Shock waves that are produced by a merger between clusters of galaxies may provide the necessary acceleration of the electrons. Several processes for the formation of radio relics have been proposed, the two most important being: (i) in-situ diffusive shock acceleration by the Fermi I process (Ensslin et al. \textsuperscript{1998}; Roettiger et al. \textsuperscript{1994}; Miniati et al. \textsuperscript{2001}) and (ii) re-acceleration of electrons by compression of existing cocoons of radio plasma (Enßlin & Gopal-Krishna \textsuperscript{1999}).
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Figure 1. The density (upper panel) and temperature (lower panel) distribution on a slice along a plane which contains the both centres of mass of the initial two clusters. The length scale is given in comoving $h^{-1}$ Mpc. The first snapshot is taken at redshift $z = 0.66$ and the later snapshots follow approximately the motion of centre of mass of the cluster. The density is given in proper mass density divided by the proton mass.

In all the aforementioned scenarios the radio emission traces the shock-front. The fact that radio relics resemble individual objects and do not trace the entire shock front, may provide some indication in favour of the last scenario. Moreover, when a radio ghost is passed by a cluster merger shock wave with a typical velocity of a few 1000 km/s the ghost is compressed adiabatically and not shocked because of the much higher sound speed within it. Therefore, diffusive shock acceleration is unlikely to be the prime mechanism that re-energises the relativistic electron population. However, it has been shown that the energy gained during the adiabatic compression together with the increase in the magnetic fields strength can cause the fossil radio cocoon to emit radio waves again. Enßlin & Gopal-Krishna (2001) showed that the spectra thus produced are consistent with an old electron population that has been adiabatically compressed. With the aid of magneto-hydrodynamical simulations Enßlin & Brüggen (2002) demonstrated that the resulting relics possess a toroidal shape and are partially polarized - in good agreement with observations. One prerequisite for this mechanism to be effective is that the electron population is not older than 0.2 - 2 Gyr (Enßlin & Gopal-Krishna 2001). The time-scale depends on the conditions in the surroundings, mainly the external pressure. In high-pressure environments, such as in cluster cores, the synchrotron losses are expected to be higher than in regions of lower pressure because the magnetic fields in the pressure-confined radio plasma is higher. This leads to a shorter synchrotron cooling time for the fossil radio plasma and a reduced probability to flare up during the passage of a shock.

In this paper we use numerical simulations to study the ICM during a merger of galaxy clusters. Here we focus on the formation of radio relics and study, in particular, whether shock waves, that are associated with the merger, can revive the fossil plasma. The main issues that we would like to address are (i) if radio cocoons that have been produced before the onset of the merger can be revived by shocks, and (ii) where the revived radio plasma is most likely found. To produce radio relics, we apply the formalism suggested by Enßlin & Gopal-Krishna (2001) to high-resolution simulations of a major merger.

2 SIMULATIONS

We performed high-resolution simulations of mergers between clusters of galaxies using the GADGET (Springel et al. 2001) code, which is a smoothed-particle hydrodynamics (SPH) code based on a tree-scheme to compute the gravitational interaction. We used the entropy conserving SPH-code as proposed by Springel & Hernquist (2002) who found that using the entropy as independent variable results in an improved representation of explosion shock waves.

GADGET provides the possibility to use particles with different masses. This allows us to simulate a cluster merger with a high mass-resolution following the scheme given by Klypin et al. (2001). The simulations are set up according to the standard ΛCDM model with $\Omega_M = 1 - \Omega_\Lambda = 0.3$, $\Omega_B = 0.039$, and $h = 0.7$, where the Hubble constant is given by $100 h$ km s$^{-1}$ Mpc$^{-1}$. For redshift $z = 50$ the initial particle positions and velocities are derived using a power spectrum normalised on the $8h^{-1}$ Mpc scale to $\sigma_8 = 0.9$. Initially, a simulation in a computational box of $80h^{-1}$ Mpc with $128^3$ particles is performed. When the simulation arrives at $z = 0$, a region with a suitable cluster is isolated. In a new simulation the mass-resolution is refined in this region by splitting the particles up into 64 sub-particles. Thus, we achieve a
Figure 2. The radio luminosity probability at a frequency of 100 MHz per mass of radio plasma in the same slice through the cluster centre as in Fig. 1. The prescription for the evolution of the relativistic electron distribution is described in Sec. 3. Here we assumed a pressure ratio between the magnetic and gas pressure of \( P_B / P_{\text{gas}} = 0.1 \) and 0.01 in the upper and lower panels, respectively.

We should note that effects of gas cooling, stellar feedback, thermal conduction, and magnetic fields are not included in this simulation. Our primary goal is to model the evolution of the merger shock waves in the ICM within a realistic cosmological setting. In order to calculate the radio emissivity of non-thermal plasma, we have to make assumptions about the strength of the magnetic field. Very little is known on the strength of the magnetic field in radio ghosts. Measurements of the large-scale magnetic field in clusters indicate a field strength of a few \( \mu \text{Gauss} \) (Carilli & Taylor 2002). In the centre of the cluster the field strength is higher and approximately thermal, i.e. \( B^2 / 8\pi = P_B \sim P_{\text{gas}} \) (Eilek 1999). However, it seems unlikely that there is enough small-scale turbulence or that there are enough powerful radio galaxies to sustain a thermal magnetic field throughout the entire cluster volume. Moreover, these measurements rely on Faraday rotation measures, to which the dilute plasma in the radio ghosts does not contribute significantly. Therefore, these measurements can only serve as a very rough guide to the actual field strength in the bubbles. In our calculations we assume that the fraction between magnetic pressure and thermal pressure is fixed at a value which yields a mass-averaged field strength of a few \( \mu \text{Gauss} \).

### 3 THE FATE OF RADIO HALOS

Relativistic electrons in radio lobes lose energy via synchrotron radiation and inverse Compton scattering with photons of the cosmic microwave background (CMB). In addition, adiabatic compression of the cocoons is able to re-accelerate the electrons. On the basis of our simulation we investigate whether the compression that the radio plasma suffers in the course of the merger can compensate for its radiative losses and is thus able to revive the fossil radio plasma. In the following, we assume that each gas particle also carries a certain amount of non-thermal radio plasma with it, whose evolution is calculated as follows.

The momentum of a relativistic electron in a radio lobe is altered by synchrotron losses that are proportional to the magnetic energy density \( u_B \), by inverse Compton losses proportional to the CMB field density \( u_{\text{CMB}} \) and by adiabatic compression of the considered volume \( V \)

\[
dp = -\frac{4}{3} \sigma_T \left( u_B + u_{\text{CMB}} \right) - \frac{1}{3} \frac{1}{\gamma} dV,
\]

where \( \sigma_T \) denotes the Thomson cross section. Enßlin & Gopal-Krishna (2001) showed that the electron distribution function \( f(p,t) dp \, dV \) can be derived from the initial distribution \( f(p,t_0) \), the compression ratio

\[
C(t) = \frac{V(t_0)}{V(t)} = \left( \frac{P(t)}{P(t_0)} \right)^{1/\gamma},
\]
where the volume $V$ of the radio ghosts is adiabatically compressed by the ambient pressure $P$ with an adiabatic exponent $\gamma$ for magnetized plasma, and the characteristic momentum

$$\frac{1}{p^*} = \frac{4}{3} \sigma_T \int_{t_0}^{t} dt' \left\{ u_B(t') + u_{\text{CMB}}(t') \right\} \left( \frac{C'(t)}{C(t)} \right)^{1/3}. \quad (3)$$

If the initial distribution is a power-law $f(p, t_0) = f_0(p/p_0)^{-\alpha}$ the spectrum at later times becomes

$$f(p, t) = f_0 C(t) (p/p_0)^{(2-\alpha)/3} (p/p_0)^{-\alpha} (1 - p/p_\gamma)^{\alpha-2}. \quad (4)$$

The luminosity of a fossil radio plasma depends thus on the age of the radio plasma, the strength of the magnetic field, the CMB density and the pressure history of the ambient gas. To set a starting time $t_0$ of the pressure history we assume that the radio plasma has been released at an early stage of the merger, more precisely when the two progenitors are still separated by 0.5 $h^{-1}$ Mpc. Those ghosts may result from the advection of the radio lobes by the merger, i.e. the merger may itself have generated the radio ghosts. The assumption that the radio plasma in the ghosts dates from the beginning of the merger yields a conservative estimate for the later occurrence of radio relics. As argued above, the magnetic field in the outer part of the cluster should be sub-thermal. We assume that the ratio $P_B/P_{\text{gas}}$ between the magnetic and thermal pressure is in the range of 1-10%.

Furthermore, we assume that the fossil radio plasma moves with gas, i.e. the plasma does not feel any buoyancy forces. This should be a tolerable assumption during the merger itself where the motion of the radio ghosts is dominated by advection by the ambient gas.

In our simulation we store the position, pressure and density for all gas particles as a function of time. We assume that each particle consists, beside the gas, of a certain amount of non-thermal radio plasma. Thus each particle represents gas whose evolution is calculated by the simulation and radio plasma whose evolution is derived from the gas properties. For the starting time $t_0$ before the merger, we assign all particles, the same power-law electron momentum distribution. The local pressure defines the local magnetic field strength due to the fixed ratio $P_B/P_{\text{gas}}$ and the compression ratio, see Eq. 2. We assume that the magnetic field within the rarefied plasma bubbles is tangled on small scales and can be approximated, together with the relativistic particles, by a $\gamma = 4/3$ equation of state. From the recorded pressure history of each particle alone, we can calculate the momentum distribution of electrons in the radio plasma, see Eq. 4. The luminosity of the radio plasma is computed for an observing frequency of $\nu = 100$ MHz and an initial spectral index of $\alpha = 2.5$ using the standard integration kernel for synchrotron radiation [Rybicki & Lightman 1979].

![Figure 3](image_url) The projected 'potential' radio luminosities for 1.13 Gyr old radio plasma, where $P_B/P_{\text{gas}} = 0.01$. The radio plasma is identically to the gas distributed, see Sec. 4. For comparison the bolometric surface X-ray luminosity, $L_X = 1.2 \times 10^{-24}$ ergs$^{-1}$ m$_{\text{gas}}/(\mu m_p) \sum n_i/(\mu m_p) (kT_i/\text{eV})^{1/2}$ [Eke et al. 1998], is given. Contours are at $10^{41}$, $10^{42}$, $10^{43}$, $10^{44}$ and $10^{45}$ ergs$^{-1}$ k$^3$ Mpc$^{-3}$. The total bolometric X-ray of the cluster is $2 \times 10^{44}$ erg s$^{-1}$ and the emission-weighted temperature is 3 keV.

4 RESULTS AND DISCUSSION

The merger produces shock waves that propagate in both directions along the line that connects the centres of the initial clusters. While the shock generates only a small jump in density, the temperature in the shocked regions is about one order of magnitude above that in regions in front of the shock (see Fig. 1). The effects of the merger on the radio plasma can be seen in Fig. 2 which shows the radio luminosity in a slice through the cluster. The slice was made along the plane which contains the both centres-of-mass of the initial two clusters. The most remarkable structure is the prominent ring-like feature with a diameter of about 1 Mpc (see Fig. 2) 1.13 Gyr after the release of the radio plasma. This structure corresponds to the outgoing shock waves seen in the temperature (see Fig. 1 lower panel). One can clearly see the flaring of radio plasma at the two outgoing merger shock waves. It is apparent that after about 1 Gyr the merger shock waves can still revive the fossil radio plasma. In contrast, it is striking that the cluster centre is virtually void of any luminous sources. Prerequisite for a reanimation of the plasma is a sufficiently low magnetic field strength. Only if the strength is as low $P_B/P_{\text{gas}} \sim 1\%$ revived structures can be seen. Higher magnetic field strengths result in too fast an ageing of the plasma, such that the shock waves cannot revive the plasma. Furthermore, in the early stage of the merger, when the shock waves pass through the centre of the cluster after about 0.5 Gyr, the even younger plasma does not flare up significantly.

The much higher occurrence of radio relics at peripheral locations in the cluster is a result of two factors: In the centre of the cluster, i.e. within a region a few hundred kpc in diameter, the radio plasma ages much faster because the pressure is much higher and, thus, also the (assumed) magnetic field. This causes considerably higher radiation losses. In the inner region of the cluster the luminosity of the plasma dies down after $\approx 0.5$ Gyr, whereas in the periphery the luminosity decreases much more slowly. The second reason is related to the shock compression. As the shocks sweep through the cluster, their strength varies with the ICM sound speed. The shock waves are relatively weak in the hotter cluster centre but steepen when they pass the cooler, outer regions of the cluster. Therefore, the compression factor of the shock in-
creases and, thus, the ability to revive radio ghosts. Under the condition that the ratio $P_B/P_{\text{gas}}$ is as low as $\approx 1\%$, the two shock waves can lighten up fossil radio plasma in the outer regions of the cluster which is about 1 Gyr old. In stronger fields, synchrotron losses are too severe and in weaker fields, higher energy electrons are required to emit at the observing frequency, which have more severe inverse-Compton losses. For $P_B/P_{\text{gas}} \approx 1\%$ the two losses roughly match. We should point out again that Fig. 2 and 3 are luminosity probability maps and not actual maps. Therefore, we do not expect radio relics over the entire shock surface.

We find additional bright spots in the periphery of the cluster which are not related to the shock fronts. These spots exist even if $P_B/P_{\text{gas}}$ is as high as $\approx 10\%$. Following the evolution of merger, one can notice that these spots appear in regions where gas from the periphery is flowing into the cluster. Since the radio plasma from regions that lie further out has aged less than more centrally located plasma, a merely moderate compression may cause a noticeable increase in the luminosity. This provides an additional mechanism to generate radio relics, which again only takes place in clusters that are not in equilibrium. Both mechanisms, gas inflow and merger shock compression, strongly favour radio ghosts that are located at least at a distances of a few hundred kpc from the cluster centre.

We now compute the radio surface brightness. For this purpose we convolve the luminosity of radio plasma with a hypothetical distribution of radio plasma. Here, we assume that the distribution of plasma follows the distribution of gas. This approach disregards the fact that there are – probably – only few individual plasma object in a cluster, but we interpret the distribution of the entire cluster as a probability that plasma is located at a certain position. We can now infer the radio luminosity of the cluster. Given that the distribution of plasma reflects the spatial probability distribution of radio ghosts, the luminosity corresponds to the probability to find radio relics at a certain position. We find that by far most of the luminosity projected onto a plane perpendicular to the shock fronts comes from the shock regions (see Fig. 4). Even the projection leaves the central region of the cluster virtually free of emission. This result indicates, that if the distribution of radio ghosts follows the distribution of the gas, i.e. if ghosts are most likely found in the centre, relics are expected to be observed almost exclusively at the location of the shock fronts.

Upcoming radio telescopes, such as GMRT, LOFAR and ALMA, will identify more radio relics and will measure their spatial distribution. They will be able to verify whether relics are predominantly found along outgoing merger shock waves at distances of a few hundred kpc from the centre of the cluster (Enßlin & Brüggen 2002). Thus, in the near future, observations of a representative sample of radio relics will put our model to test.

In summary, on the basis of cosmological high-resolution simulations of a galaxy cluster merger with two progenitors of the mass $\sim 1.6 \times 10^{13} \hinv M_\odot$, we have been able to calculate, both, the fading of non-thermal radio plasma and its re-energisation by shock waves. It was found that cluster-wide shock fronts are capable of reviving $\sim 1$ Gyr old radio ghosts if the ratio $P_B/P_{\text{gas}}$ is as low as $1\%$. Magnetic field strengths of this order are not unlikely in the cluster periphery. Finally, the vast majority of radio relics are expected to be located at typical distances of a few hundred kpc from the cluster centre.

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