Particles and Fields in Radio Galaxies
ASP Conference Series, Vol. , 2001
Robert A. Laing and Katherine M. Blundell

Are Cluster Radio Relics Revived Fossil Radio Cocoons?

Torsten A. Enßlin

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str.1, 85740 Garching, Germany

Gopal-Krishna

National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune University Campus, Ganeshkhind, Pune 411007, India

Abstract. A new model for the, so called, *cluster radio relics* is presented (Enßlin & Gopal-Krishna 2000). Fossil radio cocoons, resulting from the former activity of radio galaxies, should contain a low energy relativistic electron population and magnetic fields. Electrons with an age of even up to 2 Gyr can be re-accelerated adiabatically to radio emitting energies, if the fossil radio plasma gets compressed in an environmental shock wave. Such a wave can be caused by a merging event of galaxy clusters, or by the accretion onto galaxy clusters. An implication of this model is the existence of a population of diffuse, ultra-steep spectrum, very low-frequency radio sources located inside and possibly outside of clusters of galaxies, tracing the revival of aged fossil radio plasma by the shock waves associated with large-scale structure formation.

1. Introduction

The radio cocoons of radio galaxies become rapidly undetectable after the central engine of the active galactic nucleus ceases to inject fresh radio plasma. Although undetectable, the aged radio plasma should still be an important component of the inter-galactic medium (IGM). We investigate the possibility of reviving patches of such fossil radio plasma (also called *radio ghosts*, Enßlin (1999)) by compression in a shock wave produced in the IGM by the flows associated with cosmological large-scale structure formation. Such shock waves re-energize the electron population in the fossil radio cocoons, which can lead to observable synchrotron emission. This is probably the mechanism responsible for the, so called, *cluster radio relics*, which are patches of diffuse, sometimes polarized radio emission typically found at peripheral locations in clusters of galaxies. These cluster radio relics can not be simply relic radio galaxies, as their name suggests. The spectral ages of the electron population are usually too short to admit even the nearest galaxy to have been the parent radio galaxy, which has moved to its present location with a velocity typical for cluster galaxies. Therefore, a recent enhancement of the nonthermal radio output of the cluster relic sources is mandatory.

For reviews on diffuse cluster radio emission (cluster radio relics and halos, which are believed to be distinct phenomena), see Jaffe (1992), Feretti & Giovannini (1996), Enßlin et al. (1998), Giovannini et al. (1999), Feretti (2000), and Enßlin (2000).

The connection between the presence of a shock wave and the appearance of the cluster radio relic phenomenon was assumed to be due to Fermi-I shock acceleration of electrons, in Enßlin et al. (1998) and Roettiger et al. (1999). While this process might work within the normal IGM, several arguments favor the possibility that indeed old fossil radio plasma is revived in the case of cluster relic sources:

- Cluster radio relics are extremely rare, whereas shock waves should be very common within clusters of galaxies. The dual requirement of a shock wave and fossil radio plasma, for producing a cluster radio relic, would be an attractive explanation for the rareness of the relics.
- Fossil radio plasma with existing relativistic electron population and fairly strong magnetic field appears to have ideal properties for being brightened up during the shock's passage.
- The radio relic 1253+375 near the Coma cluster of galaxies appears to be fed with radio plasma by the nearby galaxy NGC 4789 (Enßlin et al. 1998).

But, if indeed the fossil radio plasma and not the normal IGM were to become radio luminous at a shock wave, the expected very high sound velocity of that relativistic plasma should forbid the shock in the ambient medium from penetrating into the radio plasma. Thus, shock acceleration is not expected to occur there. Instead, the fossil radio plasma would get adiabatically compressed, and the energy gain of the electrons is expected to be mainly due to adiabatic heating. It is the purpose of this work to demonstrate that this process is sufficient to account for the cluster radio relics.

2. The Model

Between the release from a radio galaxy and the reappearance as a cluster radio relic the radio plasmon undergoes several different phases of expansion and contraction:

Phase 0: Injection. The radio galaxy is active and a large expanding volume is being filled with radio plasma. The expansion of this cocoon is likely to be supersonic with respect to the outer medium

Phase 1: Expansion. After the central engine of the radio galaxy becomes inactive, the radio cocoon might still be strongly over-pressured compared to its gaseous environment and expands until pressure equilibrium with environment is reached. The radio cocoon probably becomes undetectable during this phase, and therefore becomes a fossil radio cocoon or a so called radio ghost.

Phase 2: Lurking. Due to the previous adiabatic energy losses of the electrons, they are at low energies. Their radiation losses, which strongly depend on the particle energies, are therefore strongly diminished. Furthermore, the synchrotron losses are reduced due to the weaker magnetic field during the expanded state of the radio cocoon. The adiabatic losses are reversible, and will be reversed during the subsequent compression phase.

Phase 3: Flashing. The fossil radio plasma gets dragged into a environmental shock wave. The relativistic electron population and the magnetic field gain energy adiabatically, leading to a steep enhancement of the synchrotron emissivity.

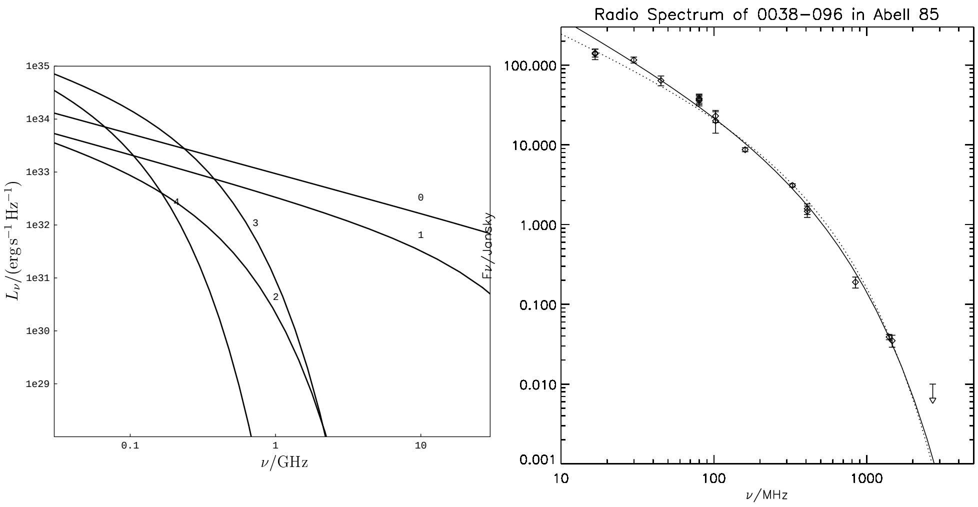

Figure 1. Left: Radio spectrum of the radio cocoon in scenario A at the end of phases 0-4. Right: Radio spectrum of the radio relic in A85, compared to spectra resulting from this model (lines).

The fossil appears as a 'relic'.
Phase 4: Fading. The radio plasma is in pressure equilibrium with the post-shock ambient medium. The radio emission of the relic now fades away due to the heavy radiation losses.

We followed the evolution of a cocoon of radio plasma for different scenarios (A, B, and C) and calculated the resulting radio emission. In A, the relic is located at the cluster center, while in B, its location is near the cluster boundary, i.e., in the proximity of the accretion shock wave. In both scenarios the duration of phase 2 was chosen to be so long that the shocked radio plasma could be barely observed as a weak ultra-steep spectrum source: 0.1 Gyr in A and 1 Gyr in B. Scenario C demonstrates that a shorter phase 2 can lead to a moderately steepened spectrum of the cluster radio relic. The different scenarios and the calculations of the radio spectra are described in detail in Enßlin & Gopal-Krishna (2000). The resulting radio spectra of the radio fossil/relic in scenario A are displayed in Fig. 1 together with the spectrum of an observed relic.

3. Discussion

We have argued here that adiabatic compression in cluster shocks can revive fossil radio plasma to radio detection, even up to 2 Gyr after the cessation of the nuclear activity and thus explain the observed cluster radio relics. Below, we summarize some merits of this model (also, see Sect 1.):

- The observed connection of cluster radio relics to shock waves arises naturally in this model.
- The presence of the radio galaxy NGC 4789 and the morphological connection of its radio tails to the relic 1253+275 seems to be the *smoking gun* of cluster radio relic formation by compression of fossil radio plasma.

- The expected very high sound speed within the radio plasma should virtually forbid shock waves of the ambient medium to penetrate into radio cocoons. This renders adiabatic compression as a more plausible means of reviving the fossil plasma.
- Cluster radio relics are rare. Not only a shock wave and fossil radio plasma are both required in this model, in order to produce a cluster radio relic, but also the fossil radio plasma cannot grow too old (of the order of 0.1 Gyr in the center of clusters and 1 Gyr at their boundaries). Otherwise, the depletion of the high energy end of the electron population would be too severe for the adiabatic gains during the compression phase to be able to shift them to radio emitting energies. Since radio fossils should be very common (Enßlin & Kaiser 2000), these requirements help to explain the observed rarity of cluster radio relics.
- The observed tendency of relics to appear at peripheral locations in clusters follows in this model from the much shorter synchrotron lifetimes of the radio emission and, consequently, much shorter ages which the revive-able fossil radio cocoons can have near the centers.

We conclude that the model presented here provides a fairly natural and promising explanation for the phenomenon of cluster radio relics. It predicts the existence of a population of diffuse, ultra-steep, very low frequency radio sources inside and possibly also outside of clusters of galaxies, due to the age dependence of the upper frequency cutoff of the radio emission arising from the revivable fossil radio plasma. The ongoing rapid improvements in the sensitivities at low radio frequencies (Giant Meterwave Radio Telescope: (GMRT), Low Frequency Array (LOFAR)) may therefore open a new window on cosmological structure formation by detecting shock waves marked by such relic radio sources.

References

Enßlin, T. A., Biermann, P. L., Klein, U., and Kohle, S., 1998, A&A 332, 395

Enßlin, T. A., 1999, in 'Diffuse Thermal and Relativistic Plasma in Galaxy Clusters', MPE Report 271, p. 275, astro-ph/9906212

Enßlin, T. A., and Gopal-Krishna, 2000, A&A submitted

Enßlin, T. A., 2000, in IAU Symp. 199: 'The Universe at Low Radio Frequencies', in press, astro-ph/0001433

Enßlin, T. A. and Kaiser, C. R., 2000, A&A 360, 417

Feretti, L. and Giovannini, G., 1996, in IAU Symp. 175: Extragalactic Radio Sources, p. 333

Feretti, L., 2000, in IAU Symp. 199: 'The Universe at Low Radio Frequencies', in press, astro-ph/0006379

Giovannini, G., Tordi, M., and Feretti, L., 1999, New Astronomy 4, 141

Jaffe, W., 1992, in Clusters and Superclusters of Galaxies, p. 109

Roettiger, K., Burns, J. O., and Stone, J. M., 1999, ApJ 518, 603