Modeling radio mini–halos in cooling flow clusters

Myriam Gitti, Gianfranco Brunetti, Giancarlo Setti, Luigina Feretti

Dip. Astronomia Univ. di Bologna, v. Ranzani 1, 40127 Bologna, Italy
Ist. di Radioastronomia del CNR, v. Gobetti 101, 40129 Bologna, Italy

Abstract. We have developed a model in which the diffuse synchrotron emission from radio mini–halos, observed in some cooling flow clusters, is due to a relic population of relativistic electrons reaccelerated by MHD turbulence via Fermi–like processes. In this model the energetics is supplied by the cooling flow itself. Here, the model (successfully applied to the Perseus cluster, A426) is preliminarily applied to the possible mini-halo candidate A2626, for which we present VLA data.

1. Introduction

Several clusters of galaxies show extended (∼ Mpc size) synchrotron emission not directly associated with the galaxies but rather diffused into the intracluster medium (ICM): these radio sources are called radio halos. In some cooling flow clusters with a central dominant galaxy, the diffuse radio emission is extended on a smaller scale, forming the so–called mini–halos (Feretti & Giovannini 1996). The radiative life–time of an ensemble of relativistic electrons losing energy by synchrotron emission and Inverse Compton (IC) scattering off the CMB photons is given by τ(yr) = 24.3/[B^2 + B'^2_{CMB}]^γ, where B is the magnetic field intensity (in G), γ is the Lorentz factor and B_{CMB} = 3.18(1 + z)^2 μG. In a cooling flow region (i.e. for distances r < r_c, the cooling radius) the compression of the thermal ICM is expected to produce a significant increase of the strength of the frozen–in intracluster magnetic field: B ∝ r^{−2} for radial compression (Soker & Sarazin 1990) or B ∝ r^{−0.8} for isotropic compression (Tribble 1993). Therefore, in absence of a reacceleration or continuous injection mechanisms, relativistic electrons injected at a given time in these intense fields (of order of some tens of μG, e.g. Ge & Owen 1993) should already have lost most of their energy and the radio emission would not be observable for more than ∼ 10^{7÷8} yr. This short lifetime contrasts with the diffuse radio emission observed in mini–halos, hence it seems plausible that the electrons have been reaccelerated.

2. Model for electron reacceleration in cooling flows

The time evolution of the energy of a relativistic electron is determined by the competing processes of losses and reaccelerations (both related to the magnetic field) and it is important to study the efficiency of these processes in the cooling flow region as a function of x = r/r_c (isotropic compression of the field is
Figure 1. **Left panel:** $\dot{\gamma} = d\gamma/dt$ is plotted for the processes in Eq. 1 and 2 as a function of $\gamma$. The value of $\gamma_b$ is shown for synchrotron losses with $B = 7\,\mu G$. **Right panel:** Evolution of $\gamma_b$ inside the cooling flow region for three different cases of reacceleration (see Eq. 2): $\bullet\alpha_+\approx\text{Fermi-like processes related to the MHD turbulence in the cooling flow (bold line); \bullet\alpha_+\approx\text{constant (dashed line); \bullet}\alpha_+\approx 0$, assuming $\Delta t \approx 4 \times 10^9\,\text{yr from injection (solid line).}$

\begin{align*}
\dot{\gamma}_- &= -\beta\gamma^2 - \chi \approx -1.3 \times 10^{-9} \left[ \left( B_c^2 x^{-1.6} + B_{CMB}^2 \right) \gamma^2 + \frac{n_e}{930} x^{-1.2} \right] \\
\dot{\gamma}_+ &= +\alpha_+ \gamma = f(x) \gamma
\end{align*}

(1)

(2)

where $\beta$ is the coefficient of synchrotron and IC losses, $\chi$ the Coulomb losses term, $\alpha_+$ the reacceleration coefficient, $B_c = B(r_c)$ and $n_e$ is the electron number density at $r_c$. Since the characteristic time of radiative losses is proportional to $\gamma^{-1}$, while that of reacceleration is independent of $\gamma$, the losses dominate the time evolution of the electrons for energies higher than $\gamma_b$, the break energy (Fig. 1, left panel). In our model (Gitti, Brunetti & Setti 2002) we assume that the relativistic electrons are continuously reaccelerated by MHD turbulence via Fermi-like processes. This kind of reacceleration has the correct radial dependence on the parameters in the cooling flow region to naturally balance the radial behaviour of the radiative losses (Fig. 1, right panel). Under these assumptions, the stationary spectrum of the relativistic electrons is:

\[ N(\gamma) \propto \left(\frac{\gamma}{\gamma_b}\right)^2 x^{-s} \exp\left(-2\gamma/\gamma_b\right) \]

(3)

which is essentially peaked at $\gamma_b$ and where we have parameterized the electron energy density as $\propto x^{-s}$, $s$ being a free parameter. The other free parameters in the model are $B_c$ and $l_c$, the leading MHD turbulence scale at $r_c$. 
3. Model results for the Perseus cluster

The first observed and well studied case of radio mini-halo is that in the Perseus cluster (A426, at \( z = 0.0183 \)), which hosts also a massive cooling flow. The diffuse radio emission (see left panel in Fig. 2) has a total extension of \( \sim 15' \) (comparable with that of the cooling flow region, \( r_c \sim 210 \) kpc), a steep spectrum with spectral index \( \alpha = 1.4 \) (between 327 MHz and 609 MHz, \( S_\nu \propto \nu^{-1.4} \)) and its morphology is correlated with that of the cooling flow X-ray map (Ettori et al. 1998). On smaller scales (\( \sim 1' \)), Böhringer et al. (1993) showed evidence of interaction between the radio lobes of the central radiogalaxy 3C84 and the X–ray emitting intracluster gas. More recent results confirmed this interaction (Fig. 2, right panel) and support the interpretation of the holes in the X–ray emission as due to buoyant old radio lobes (Fabian et al. 2002). We notice that the spectral index in the lobes ranges from \( \sim 0.7 \) in the centre to \( \sim 1.5 \) in the outer regions of Fig. 2 (right panel), i.e. a value similar to the spectrum of the mini–halo extended over a scale \( \sim 10 \) times larger. Thus it is impossible to find a direct connection between the radio lobes and the mini–halo in terms of simple particle diffusion or buoyancy. The relativistic electrons of the mini–halo should then be reaccelerated and the morphological connection with the cooling flow suggests a leading role of the cooling flow itself in powering the reacceleration process.

Therefore, we have applied our model to the Perseus cluster, whose radio properties (brightness profile, integrated spectrum and radial spectral steepening) can be well reproduced assuming isotropic compression of the field (Gitti et al. 2002). In this case, the necessary energy rate to reaccelerate the relic population...
of electrons in a typical time of few $10^9$ yr is $\sim 3 \times 10^{42}$ erg s$^{-1}$, while the energy rate supplied by the cooling flow is of the order of $10^{44}$ erg s$^{-1}$, so only a small fraction of it is required. The number of relativistic electrons in the cooling flow region is $\sim 10^{62}$. This is comparable to the number of the electrons in a typical radiogalaxy and may suggest an important role of the AGNs (and possibly of the central AGN) in the injection of the electron relic population.

4. Why are radio mini-halos so rare?

In the framework of our model, large–scale turbulence in the cluster volume is required to balance the radiative losses of the electrons at $r_c$ (for Perseus we found $\gamma_b(r_c) \sim 1500$), however at the same time the turbulence can not be too high in order to avoid the disruption of the cooling flow. This scenario is similar to that of the extended radio halos where, however, higher energy electrons (with $\gamma_b \sim 10^4$) are required (e.g. Brunetti et al. 2001): this means that the turbulence efficiency would have to be correspondingly greater hence bringing to the disruption of a possible cooling flow, in agreement with the observed anti-correlation between radio halos and cooling flows.

Based on these considerations, we suggest that the physical conditions of the ICM in a cooling flow cluster with a radio mini–halo are intermediate between those which lead to the formation of extended radio halos, hosted by clusters without cooling flows, and those holding in cooling flows clusters without radio halos. This could explain, at least qualitatively, the rarity of radio mini–halos. In this scenario, where the energetics of the turbulence plays the main part in discriminating between the two opposite situations, Perseus may represent a borderline case: indeed there is evidence for a relatively recent merger event (Dupke & Bregman 2001) which may have left a fossil turbulence, not energetic enough to produce an extended radio halo, but sufficient for reaccelerating the electrons producing the mini–halo.

5. Abell 2626: a possible radio mini-halo candidate?

In order to extend the application of our model, we have undertaken the analysis of A2626 ($z = 0.0604$). This cluster has a radio emission extended on a scale comparable to that of the cooling flow region (e.g. Rizza et al. 2000), and thus it is one of the best mini–halo candidates.

We present preliminary results for this cluster, obtained from VLA archive data at 1.5 GHz and 330 MHz at different resolutions. The 1.5 GHz map (Fig. 3, left panel) shows an unresolved core (with a flux density $\sim 15$ mJy, in agreement with Roland et al. 1985) and a diffuse emission extended by $\sim 2'$ ($S_{1.5} \sim 27$ mJy); we have estimated a polarization level $< 2\%$. At 330 MHz we do not detect the emission of the core (for which we estimated an inverted spectral index $\leq -0.6$) while the flux density of the diffuse emission is $S_{330} \sim 1$ Jy. The spectral index of the diffuse emission between $\nu = 330$ MHz and $\nu = 1.5$ GHz is $\alpha \simeq 2.4$. These results indicate that the radio source observed in A2626 shows an amorphous structure which is likely to be not related to the central radiogalaxy. Thus it appears as a good candidate to apply our model for electron reacceleration in cooling flows. In Fig. 3 (right panel) we report a preliminary comparison
Figure 3. **Left panel:** 1.5 GHz VLA map of A2626 at a resolution of 17″ × 17″. The r.m.s. noise is 0.02 mJy/beam. The cross indicates the position of the cluster centre. **Right panel:** Flux densities of the diffuse emission of A2626 compared with the total spectrum of the synchrotron emission predicted by our reacceleration model. The flux density at 609 MHz is obtained by subtracting the estimated core emission from the total flux given by Roland et al. 1985.

between the observed flux densities and the total synchrotron spectrum predicted by our reacceleration model.

**References**

Böhringer H., Voges W., Fabian A.C., Edge A.C., & Neumann D.N. 1993, MNRAS, 264, L25
Brunetti, G., Setti, G., Feretti, L., & Giovannini, G. 2001, MNRAS, 320, 365
Dupke R.A., & Bregman J.N. 2001, ApJ, 547, 705
Ettori S., Fabian A.C., & White D.A. 1998, MNRAS, 300, 837
Fabian, A. C., Sanders, J. S., Ettori, S., Taylor, G. B., Allen, S. W., Crawford, C. S., et al. 2000, MNRAS, 318, 65
Fabian, A. C., Celotti A., Blundell K.M., Kassim N.E., & Perley R.A. 2002, MNRAS, 331, 369
Feretti, L., & Giovannini, G. 1996, IAUS, 175, 333
Ge, J.P., & Owen, F.N. 1993, AJ105, 3
Gitti, M., Brunetti, G., & Setti, G. 2002, A&A, 386, 456
Rizza E., Loken C., Bliton M., Roettiger K., & Burns J.O. 2000 AJ, 119, 21
Roland, J., Hanish, R.J., Véron P., & Fomalont, E. 1985, A&A, 148, 323
Sijbring, D. 1993, Ph.D. Thesis, Groningen
Soker, N., & Sarazin C.L. 1990, ApJ, 348, 73
Tribble, P.C. 1993, MNRAS, 263, 31