Cosmic ray transport in galaxy clusters: implications for radio halos and gamma-rays

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Abstract. Observations of giant radio halos provide unambiguous evidence for the existence of cosmic ray (CR) electrons and magnetic fields in galaxy clusters. The physical mechanism generating radio halos is still heavily debated. We critically discuss the proposed models for the radio halo emission and highlight the weaknesses underlying each explanation. We present an idea how the interplay of CR propagation and turbulent advection selects a bimodal spatial CR distribution that is characteristic for the dynamical state of a cluster. As a result, strongly turbulent, merging clusters should have a more centrally concentrated CR energy density profile with respect to relaxed ones with very subsonic turbulence. This translates into a bimodality of the expected diffuse radio and gamma ray emission of clusters. Thus, the observed bimodality of cluster radio halos appears to be a natural consequence of the interplay of CR transport processes, independent of the model of radio halo formation, be it hadronic interactions of CR protons or re-acceleration of low-energy CR electrons.

Key words. Galaxies: clusters: intracluster medium – Astroparticle physics – Gamma rays: galaxies: clusters – Radio continuum: galaxies – Acceleration of particles – Magnetic fields

1. Introduction

Cluster radio halos are our primary evidence for the existence of CRs in galaxy clusters. They are spatially extended regions of diffuse radio emission, have regular morphologies, and are unpolarised due to Faraday depolarisation. They come in two sizes: giant Mpc-sized halos (found in merging clusters) and radio mini-halos (found in cool cores). The radio (mini-)halo luminosity correlates with

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the X-ray emissivity of the cluster (see Fig. 1). A large fraction of clusters is radio quiet and half of the radio deficient clusters, for which we have Chandra data, show clear evidence for some level of cool core structure ($K_0 \lesssim 40\,\mathrm{keV\,cm^2}$) as can be seen in Fig. 1. This could either imply that these clusters are in the intermediate state between having giant radio halos because of merging activity and having mini halos due to strongly developed cool cores. On the other hand there could be two populations of clusters – cool cores and non-
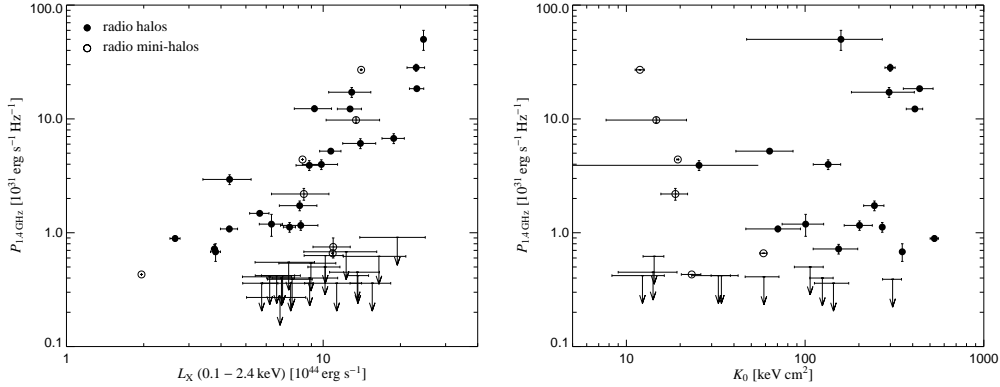
Fig. 1. Correlation of radio halo luminosities with cluster properties (Enßlin et al. 2011, reproduced with permission © ESO). *Left:* Radio halo luminosity vs X-ray luminosity. *Right:* Radio halo luminosity vs central entropy indicator K_0 for the subsample of clusters for which high resolution Chandra data are available.

cool cores – and the corresponding radio luminosity responds sensitively to the level of injected turbulence by either AGN or cluster mergers, respectively (see Enßlin et al. (2011) for an extended list of references).

1.1. Hadronic models

In the hadronic model the accumulated CRps continuously inject radio emitting CRes into the ICM due to well known hadronic process $p_{CR} + p \rightarrow \pi^{\pm} + \ldots \rightarrow e^{\pm} + \nu_e/\bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu + \ldots$ The hadronic model has *advantages*:

- all required ingredients available: shocks to inject CRp, target protons, magnetic fields
- predicted luminosities and morphologies as observed without tuning
- power-law spectra as observed

There are also *issues* with the hadronic model:

- all clusters should have radio halos [will be addressed here]
- does not explain all reported spectral features [will be addressed here]

The hadronic model makes a testable prediction: the radio halo emission should always be accompanied by weak diffuse gamma-ray emission, due to the hadronic production of neutral pions and their decay into gamma-rays, $p_{CR} + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$ The current upper limits on diffuse gamma-ray flux from cluster of galaxies by the Fermi collaboration (Ackermann et al. 2010) are still well above the predictions of expected fluxes, even for the most optimistic assumptions about the CR acceleration efficiency (Pinzke & Pfrommer 2010). They are far off the minimal gamma-ray flux expected in the limit of strong magnetic field strength ($\gg 3\mu$G; Pfrommer 2008; Aleksić et al. 2010).

1.2. Re-acceleration models

In re-acceleration models, a pre-existing CRe population at lower energies of about 0.1 GeV gets re-accelerated into the radio emitting regime of about 10 GeV by plasma waves. These are generated by the turbulence during and after a cluster merger event. Some level of re-acceleration has to happen most of the time or frequently enough in order to prevent the CRe population in the cluster center from loosing its energy completely due to Coulomb losses on a timescale of about 1 Gyr. The *advantages* of the re-acceleration model are:
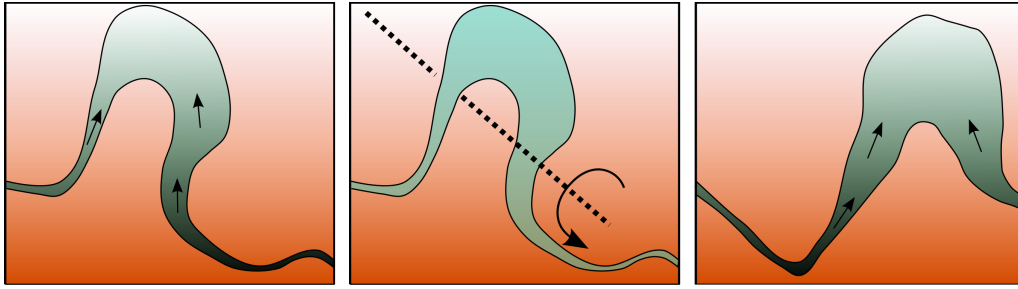
Fig. 2. Sketch of the interplay of CR streaming and turbulent advection for a single flux tube in a stratified atmosphere with gravity pointing downwards (Enßlin et al. 2011, reproduced with permission © ESO). *Left:* The dense CRs at the center stream along the tube towards the CR depleted regions at larger atmospheric height. *Middle:* CR streaming stops as soon as a homogeneous CR space density is achieved. A turbulent eddy (represented by its angular momentum axis) starts to turn the magnetic structure upside down. *Right:* The former outer parts of the flux tubes are compressed at the center, and harbor now an overdense CR population, whereas the former inner parts are expanded at larger atmospheric scale height and therefore have now an underdense CR population. Again CR streaming sets in.

- all required ingredients available: radio galaxies and relics to inject CRe, plasma waves to re-accelerate
- clusters without halos are less turbulent
- reported complex radio spectra emerge naturally

The *issues* with the re-acceleration model are:

- Fermi II acceleration is inefficient and currently fitted to match data
- CRe cool rapidly in the core regions
- power-law spectra require fine tuning
- current models neglect advective energy losses by waves that propagate outwards and dissipate
- intermittency of turbulence might be difficult to reconcile with the observed regularity of radio halos

2. Cosmic ray transport

2.1. Confined cosmic rays

To begin, we consider an isolated magnetic flux tube with CRs confined to it to illustrate the interplay of advection and streaming with a basic picture. This represents the limiting case of *confined CRs* and will be generalised in the next section. Imagine a magnetic flux tube frozen into the plasma which is distributed in a stratified pressure atmosphere of a cluster as shown in Fig. 2 on the left. Any central concentration of CRs will escape due to CR streaming on a timescale of $\tau_{st} = L_B/v_{st}$, where L_B is the magnetic bending scale and v_{st} the CR streaming velocity along the magnetic field which is of order the sound speed in the cluster plasma.[1] This leads to a homogeneous CR distribution within the flux tube (Fig. 2, middle). Turbulence turns the magnetic structure upside down on half an eddy turnover time. If this is comparable to, or less than, the CR escape time,

$$\frac{\tau_{st}}{\tau_{tu}} \equiv \gamma_{tu} \sim O(1), \tag{1}$$

[1] In a low-β plasma, the CR streaming velocity is linked to the Alfvén velocity, which exceeds the sound speed there. However, this can obviously not be true in a high-β plasma. It would imply that in the limit of vanishing magnetic field strength the CRs get completely immobile due to the vanishing Alfvén speed. However, for disappearing magnetic fields, the coupling of CRs to the plasma gets weaker and therefore the CRs should stream faster. Thus, there must be a characteristic velocity, below which the Alfvén velocity is not limiting the streaming velocity any more. Plasma physical arguments indicate that this is roughly the sound speed (Felice & Kulsrud 2001; Enßlin et al. 2011).
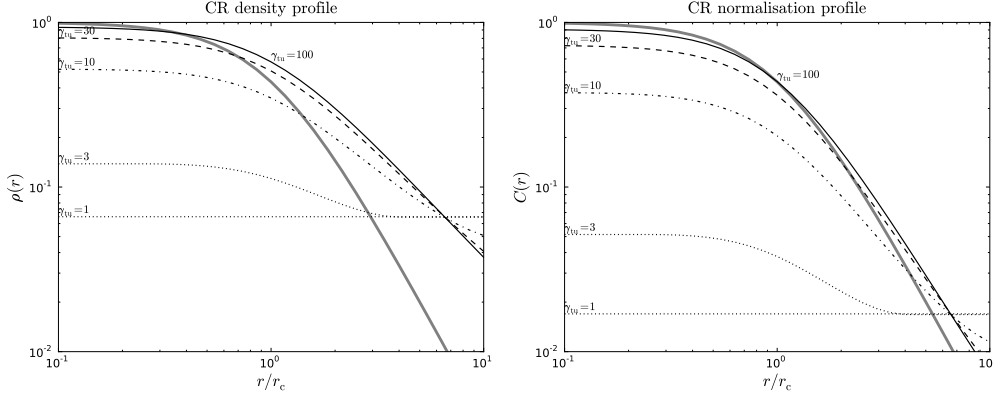
Fig. 3. *Left:* CR density profiles for $\gamma_{tu} = 1, 3, 10, 30$, and 100 (from bottom to top at small radii) including the same number of CRs each. Profiles are normalised to $\varrho(0)|_{\gamma_{tu}=\infty}$. Also the more narrow gas density profile is shown (thick grey line). *Right:* CR normalisation profiles for the same parameters and the gas density profile for typical cluster conditions (Enßlin et al. 2011, reproduced with permission © ESO).

a good fraction of the CRs from larger radii will be compressed towards the center, from where they again start streaming to larger radii. *The transonic turbulence is therefore able to maintain a centrally enhanced CR density by pumping expanded CR populations downwards.* As soon as the turbulent velocities become significantly subsonic, this pumping becomes inefficient, since the streaming will be faster than the advection. At this point a nearly constant volume density of CRs establishes within a closed flux tube, meaning that most CRs are residing at larger cluster radii. Depending on the level of turbulence, we obtain either a CR distribution peaked towards the center or a homogeneous CR distribution.

2.2. Mobile cosmic rays

In reality, CR diffusion perpendicular to the mean magnetic field enables CRs to change between magnetic flux tubes and thereby find paths to more peripheral regions. The accessible distance is determined by the level of turbulent pumping, magnetic topology, and available time to stream. In principle, CRs can even reach the outskirts of galaxy clusters, where the infall of matter onto the cluster behind the ac-

cretion shocks prevents further escape which motivates our term *mobile CRs*.

We assume a power-law CR spectrum,

$$f(\boldsymbol{r}, p, t) = C(\boldsymbol{r}, t)\, p^{-\alpha}, \qquad (2)$$

where $\alpha \approx 2.1 - 2.5$ is the spectral index and $C(\boldsymbol{r}, t)$ the spectral normalisation constant. First, we derive the equilibrium profile that CRs attain if turbulent advection dominates the CR transport (and CR streaming is negligible). To this end, we assume that (i) the cluster is characterised by a mean pressure profile and (ii) that CR propagation operates on small scales, permitting CR exchange between nearby gas volume elements, but not on large scales. Whenever two volume elements come close, CRs can be exchanged which establishes a constant CR population in any given radial shell. During radial advective transport from radius r to r', the ICM gas with the entrained CRs is compressed or expanded by a factor $X(r \to r') = (P(r')/P(r))^{1/\gamma}$, where $P(r)$ is the pressure profile and $\gamma = 5/3$. The CR rest-mass density $\varrho(\boldsymbol{r}) = m \int dp\, f(\boldsymbol{r}, p)$ thus establishes – under the influence of advection alone – a profile according to

$$\varrho(r) = \varrho_0 \left(\frac{P(r)}{P_0} \right)^{\frac{1}{\gamma}} = \varrho_0\, \eta(r), \qquad (3)$$

where $\eta(r) = (P(r)/P_0)^{1/\gamma}$ is the advective CR target profile.

The CR continuity equation for ϱ in the absence of sources and sinks can be written as

$$\frac{\partial \varrho}{\partial t} + \nabla \cdot (\boldsymbol{v}\,\varrho) = 0, \tag{4}$$

with $\boldsymbol{v} = \boldsymbol{v}_{\mathrm{ad}} + \boldsymbol{v}_{\mathrm{di}} + \boldsymbol{v}_{\mathrm{st}}$ the CR transport velocity, which is composed of the advective ($\boldsymbol{v}_{\mathrm{ad}}$), diffusive ($\boldsymbol{v}_{\mathrm{di}}$), and steaming ($\boldsymbol{v}_{\mathrm{st}}$) transport velocities. These are defined by

$$\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{st}} \frac{\nabla \varrho}{|\nabla \varrho|},$$

$$\boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}} \frac{1}{\varrho} \nabla \varrho = -\kappa_{\mathrm{di}} \nabla \ln(\varrho), \tag{5}$$

$$\boldsymbol{v}_{\mathrm{ad}} = -\kappa_{\mathrm{tu}} \frac{\eta}{\varrho} \nabla \frac{\varrho}{\eta} = -\kappa_{\mathrm{tu}} \nabla \ln\left(\frac{\varrho}{\eta}\right),$$

where κ_{di} is the macroscopically averaged CR diffusion coefficient and the passive, advective transport via turbulence can be described by an additional diffusion process with diffusion coefficient $\kappa_{\mathrm{tu}} = L_{\mathrm{tu}}\,v_{\mathrm{tu}}/3$. We note that the appearance of the target density profile $\eta(\boldsymbol{r})$ in the gradient for $\boldsymbol{v}_{\mathrm{ad}}$ ensures that any deviation of the CR distribution from target density causes a restoring term towards this equilibrium configuration. The CR space density becomes stationary for $\boldsymbol{v} = \boldsymbol{0}$, and this reads in spherical symmetry with radially outstreaming CRs

$$v_{\mathrm{st}} = \kappa_{\mathrm{tu}} \frac{\partial}{\partial r} \ln\left(\frac{\varrho}{\eta}\right) + \kappa_{\mathrm{di}} \frac{\partial}{\partial r} \ln(\varrho). \tag{6}$$

Enßlin et al. (2011) provide an analytical solution of this equation which is shown in Fig. 3 for different values of γ_{tu}.

3. Radio and gamma-ray bimodality

The gamma-ray emissivity and luminosity of a power law CRp spectrum as in Eqn. (2) is

$$\dot{\varepsilon}_\gamma \propto C\,\varrho_{\mathrm{gas}}, \quad \text{and } L_\gamma = \int dV\,\dot{\varepsilon}_\gamma. \tag{7}$$

The radio luminosity in the hadronic model is

$$\dot{\varepsilon}_\nu \propto C\,\varrho_{\mathrm{gas}} \frac{\varepsilon_B^{(\alpha+2)/4}}{\varepsilon_B + \varepsilon_{\mathrm{ph}}}, \quad \text{and } L_\nu = \int dV\,\dot{\varepsilon}_\nu. \tag{8}$$

As shown in Figs. 4 and 5, L_γ and L_ν inherit the strong dependence on the advective-to-streaming-velocity ratio, $\gamma_{\mathrm{tu}} = v_{\mathrm{tu}}/v_{\mathrm{st}}$. Thus, a rapid drop in radio luminosity after the turbulent merger phase by one order of magnitude or more is actually expected in the *hadronic halo model* on a timescale of 0.1–1 Gyr, depending on magnetic topology and the macroscopic CR streaming speed (Enßlin et al. 2011).

4. Conclusions

CR streaming (and CR diffusion) aims at establishing a spatially flat CR profile; hence explaining why radio halos are not found in every cluster. *CR advection* tends to produce centrally enhanced CR profiles. Thus, CR advection and streaming are counteracting transport mechanisms. Whenever the former dominates, centrally enhanced profiles are established, and whenever streaming is more important, a flat profile results.

During a cluster merger, advective velocities in galaxy clusters are comparable to the sound speed and drop when the cluster relaxes after the merger. Plasma physical arguments suggest that the microscopic CR streaming velocity in clusters might of the order of the sound speed. Macroscopically it is reduced due to magnetic trapping of CRs in flux tubes (which is larger for a stronger turbulence) and slow cross field diffusion required to escape.

As a result of this, merging clusters should have a much more centrally concentrated CR population than relaxed ones. This leads naturally to a *bimodality of their gamma-ray and radio synchrotron emissivities due to hadronic interactions of CR protons*. Also in the re-acceleration model of cluster radio halos these transport processes should be essential, since the re-accelerated CR electron populations in the dense cluster centers is probably too vulnerable to Coulomb losses, to survive periods without significant re-acceleration. Transport of the longer living electrons at the cluster
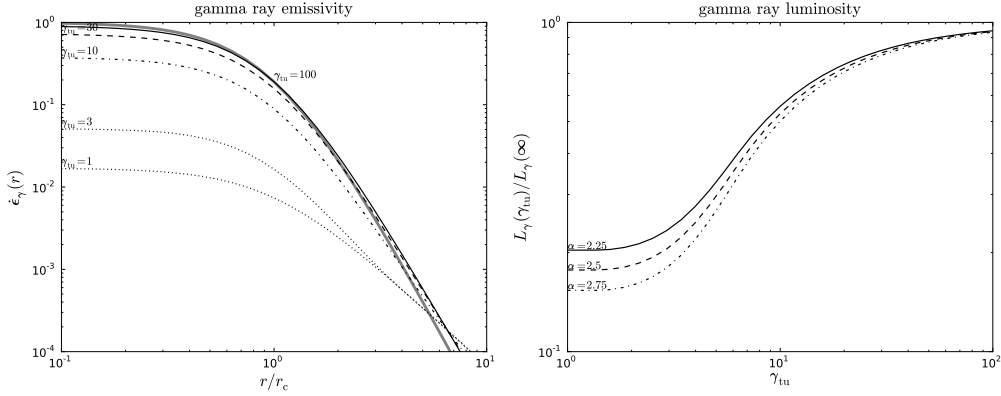
Fig. 4. *Left:* Gamma-ray emissivity profiles for the CR distributions in Fig. 3 and X-ray emissivity profile of the ICM in grey. Emissivities are normalised to the central emissivity of a cluster with $\gamma_{tu} = \infty$. *Right:* Total gamma-ray flux due to hadronic CRp interactions with the ICM nucleons as a function of $\gamma_{tu} = \tau_{st}/\tau_{ad}$ and for $\alpha = 2.25$, 2.5, and 2.75 (solid, dashed, and dashed-dotted lines, respectively). Normalised to L_γ for $\gamma_{tu} = \infty$ (Enßlin et al. 2011, reproduced with permission © ESO).
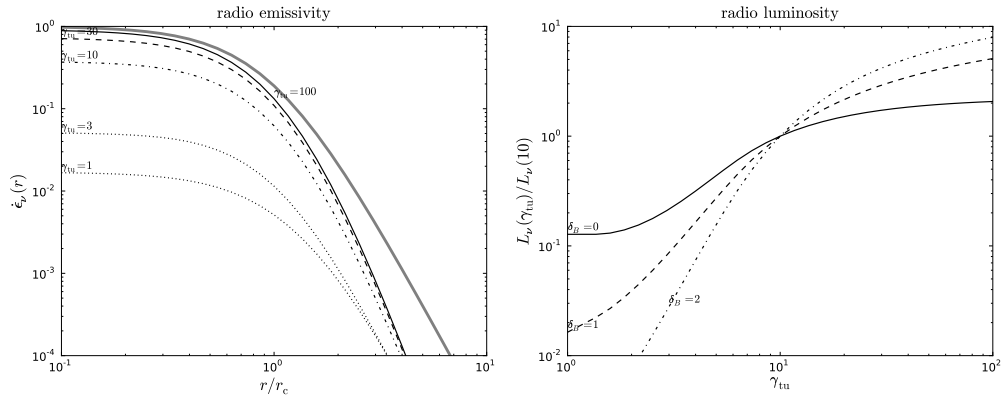

Fig. 5. *Left:* Radio emissivity profiles for the cluster shown in Fig. 3 assuming the same magnetic field profiles with $B_0 = 6\,\mu G$ and $\delta_B = 0$. Emissivities are normalised to the central radio emissivity of a cluster with $\gamma_{tu} = \infty$. The X-ray profile is shown in grey (Enßlin et al. 2011, reproduced with permission © ESO). *Right:* Total radio flux due to hadronic CRp interactions with the ICM nucleons as a function of $\gamma_{tu} = \tau_{st}/\tau_{ad}$ and for different dependencies of the magnetic energy density on the turbulence level, $\varepsilon_B \propto n(r)\gamma_{tu}^{\delta_B}$ and parametrised by $\delta_B = 0$, 1, and 2 (solid, dashed, and dashed-dotted lines, respectively). Normalised to L_ν for $\gamma_{tu} = 10$. (Central field strength $B_0 = 6\,\mu G$, $\alpha = 2.5$).

outskirts into the cluster center during cluster merger would circumvent this problem.

We also expect an energy dependence of the macroscopic CR streaming speed, which then should lead to a spatial differentiation of the spectral index of the CRp population and any secondary radio halo emission. Such spectral index variation in the radio halo should become especially strong during phases of out-

streaming CRps, i.e. when a radio halo dies due to the decay of the cluster turbulence.

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