Journal of The Korean Astronomical Society
37: 1 ~ 5, 2004

The quest for cosmic ray protons in galaxy clusters

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(Received October 31, 2004)

ABSTRACT

There have been many speculations about the presence of cosmic ray protons (CRps) in galaxy clusters over the past two decades. However, no direct evidence such as the characteristic γ-ray signature of decaying pions has been found so far. These pions would be a direct tracer of hadronic CRp interactions with the ambient thermal gas also yielding observable synchrotron and inverse Compton emission by additionally produced secondary electrons. The obvious question concerns the type of galaxy clusters most likely to yield a signal: Particularly suited sites should be cluster cooling cores due to their high gas and magnetic energy densities. We studied a nearby sample of clusters evincing cooling cores in order to place stringent limits on the cluster CRp population by using non-detections of *EGRET*. In this context, we examined the possibility of a hadronic origin of Coma-sized radio halos as well as radio mini-halos. Especially for mini-halos, strong clues are provided by the very plausible small amount of required CRp energy density and a matching radio profile. Introducing the *hadronic minimum energy criterion*, we show that the energetically favored CRp energy density is constrained to 2% ± 1% of the thermal energy density in Perseus. We also studied the CRp population within the cooling core region of Virgo using the TeV γ-ray detection of M 87 by *HEGRA*. Both the expected radial γ-ray profile and the required amount of CRp support this hadronic scenario.

Key Words : galaxies: cooling flows – galaxies: cluster: general – galaxies: cluster: individual: Perseus (A426), Coma (A1656) – intergalactic medium – cosmic rays – radiation mechanisms: non-thermal

I. Galaxy clusters as a window to non-thermal intra-cluster medium components

Cooling cores in galaxy clusters are especially well suited places to find traces of otherwise nearly invisible non-thermal components of the intra-cluster medium (ICM) due to the extreme gas densities observed in these central regions. The faded and therefore invisible remnants of radio galaxy cocoons, so-called *radio ghosts* (Enßlin 1999) or *ghost cavities*, were first detected in cooling cores by the absence of X-ray emissivity in the ghost's volume in contrast to the highly X-ray luminous cooling cores gas surrounding it (Böhringer et al., 1993; Fabian et al., 2000, and many recent Chandra observations). Cosmic ray electrons (CRes) are seen in cooling cores by their radio synchrotron radiation within strong magnetic fields. Cosmic ray protons (CRps) in the ICM are most likely to be detected for the first time within cooling cores via their hadronic interaction with the dense cooling core gas leading to γ-rays and CRes.

A better knowledge of these non-thermal components of the ICM – especially in the cooling core regions – is highly desirable, since they play important roles in the heat balance of the gas through heating by CRps, radio ghost buoyant movements, and suppression of heat conduction by magnetic fields. Additionally, such non-thermal components are tracers of the violent dynamics of the ICM and may help to solve some of the puzzles about cooling cores.

In this article, we present our recent progress in constraining CRps by using limits on the γ-ray emission as well as the observed radio emission of nearby galaxy clusters (Sect. III and Sect. IV). Finally, we present the novel concept of the hadronic minimum energy condition which should serve as unambiguous energetic criterion for the applicability of the hadronic model of radio synchrotron emission in galaxy clusters (Sect. V). We focus on ideas and results, leaving the technical details to the publications given in the reference list.

II. Hadronic interactions of cosmic ray protons

Approximately once in a Hubble time, a CRp collides inelastically with a nucleon of the ambient ICM gas of non-cooling core clusters. Within cooling cores, such collisions are much more frequent due to the higher target densities. Such inelastic proton (p) nucleon (N) collisions hadronically produce secondary particles like relativistic electrons, positrons, neutrinos and γ-rays according to the following reaction chain:

$$\begin{aligned} p + N &\rightarrow 2N + \pi^{\pm/0} \\ \pi^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} \rightarrow e^{\pm} + \nu_e/\bar{\nu}_e + \nu_{\mu} + \bar{\nu}_{\mu} \\ \pi^0 &\rightarrow 2\gamma\,. \end{aligned}$$

The resulting γ-rays can be detected directly with current and future γ-ray telescopes. The relativistic electrons and positrons (summarized as CRes) are visible due to two radiation processes: inverse Compton scattering of background photon fields (mainly the cosmic microwave background, but also starlight photons) and radio synchrotron emission in ICM magnetic fields. Especially the latter process provides a very sensitive observational signature of the presence of CRps in cooling cores not only because of the tremendous collecting area of radio telescopes, but also due to the strong magnetic fields in cooling cores, as Faraday rotation measurements demonstrate.

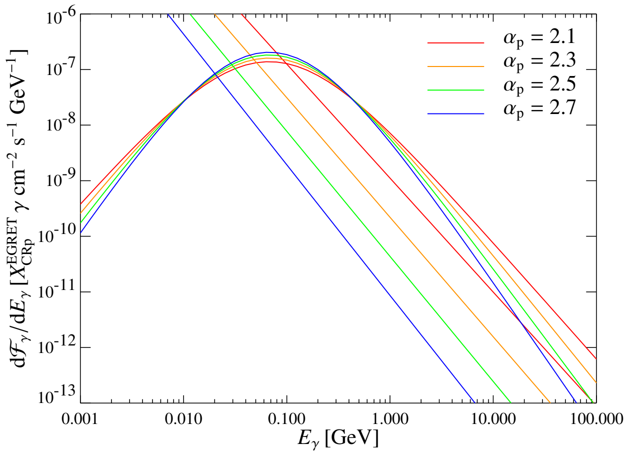

Fig. 1.— Theoretical γ-ray spectra of the Perseus cluster resulting from CRp hadronic interactions with the cooling core gas. The assumed CRp spectra are normalized to be marginally consistent with the *EGRET* $E_\gamma > 100$ MeV non-detection limits. Results for different proton spectral indices are shown. The π^0-decay bump is clearly visible. Secondary CRes scatter cosmic microwave background photons into the γ-ray regime by the inverse Compton process. The resulting power-law emission dominates the low energy part of the spectrum. The CRe population was calculated neglecting synchrotron radiation energy losses. Thus, realistic inverse Compton spectra due to this process will exhibit a lower normalization than displayed here.

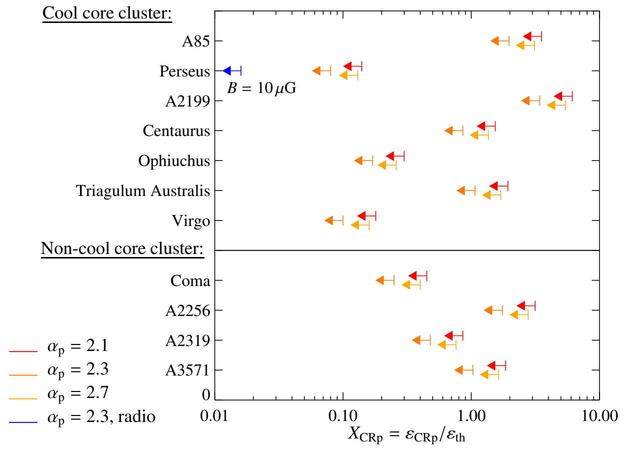

Fig. 2.— *EGRET* γ-ray constraints on the (central) CRp energy density ($\varepsilon_{\rm CRp}$, for various CRp spectral indices) in terms of the cluster central thermal energy density ($\varepsilon_{\rm th}$) for cooling core and non-cooling core clusters. The constraint from the Perseus cluster radio mini-halo observation is also displayed while assuming a typical cooling core cluster magnetic field strength (blue arrow). If radio mini-halos are entirely produced hadronically by CRps then the constraint derived for the Perseus cluster is an actual measurement for $X_{\rm CRp}$ and not only an upper limit.

III. Gamma-ray emission

(a) Gamma-ray constraints from *EGRET*

Assuming that the CRp population can be described by a power law distribution in momentum, Pfrommer & Enßlin (2004a) developed an analytical formalism to describe the secondary emission spectra from hadronic CRp interactions which exhibit the simplicity of textbook formulae. This formalism was applied to a sample of nearby X-ray luminous galaxy clusters which are also believed to be powerful γ-ray emitters owing to the present high target densities. Synthetic γ-ray spectra of the Perseus cooling core cluster, which are calculated using this formalism, are shown in Fig. 1. Assuming that the CRp population follows the spatial distribution of the thermal ambient intra-cluster gas, we can define the CRp scaling ratio

$$X_{\rm CRp} \equiv \frac{\varepsilon_{\rm CRp}}{\varepsilon_{\rm th}}, \tag{1}$$

where $\varepsilon_{\rm CRp}$ and $\varepsilon_{\rm th}$ denote the CRp and thermal energy density, respectively. This scaling effectively implies an *isobaric* compression of the CRps during the formation of the cooling core. The parent CRp spectra, which give rise to the hadronically induced γ-ray spectra, are normalized to upper limits on the γ-ray emission obtained by *EGRET* observations for energies $E_\gamma > 100$ MeV. For nearby cooling core clusters, this analysis constrains CRp energy densities relative to the thermal energy density to $X_{\rm CRp} \sim 10\%$. For the full sample of nearby X-ray luminous clusters, upper limits of the same order of magnitude were obtained (cf. Fig. 2).

It is obvious from this compilation that cooling core clusters are extremely well suited to visualize even small CRp populations.

The real γ-ray spectra are not expected to be far below these spectra: many processes like supernova driven galactic winds, structure formation shock waves, radio galaxy activity, and in-situ turbulent particle acceleration support this expectation. These processes should have produced a CRp population characterized by an energy density relative to the thermal energy density of at least a few percent.

(b) Gamma-rays from the central region of the Virgo cluster

Recently, the *HEGRA* collaboration (Aharonian et al., 2003) announced a TeV γ-ray detection from the giant elliptical galaxy M 87 which is situated at the center of the cooling core region of the Virgo cluster. Using imaging atmospheric Čerenkov techniques, this γ-ray detection was obtained at a 4-σ significance level. On the basis of their limited event statistics, it is inconclusive whether the detected emission originates from a point source or an extended source. Despite testing for intermittent behavior of M 87, no time variation of the TeV γ-ray flux has been found.

Pfrommer & Enßlin (2003) applied the previously described analytical formalism (Sect. (a)) of secondary γ ray emission spectra resulting from hadronic CRp interactions to the central cooling core region of the Virgo cluster. While combining the observed TeV γ-ray emission to *EGRET* upper limits, they constrain the CRp spectral index $\alpha_{\rm GeV}^{\rm TeV} < 2.3$

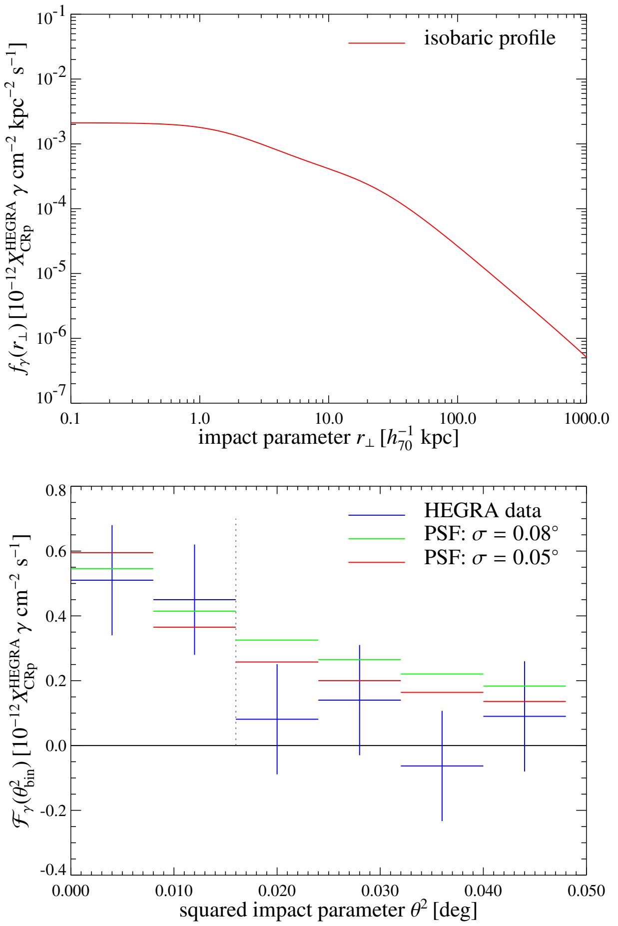

Fig. 3.— Upper panel: Modeled γ-ray surface flux profile of the cooling core region within the Virgo cluster. The profile is normalized by comparing the integrated γ-ray flux above 730 GeV to *HEGRA* data of M 87 within the innermost two data points. **Lower panel:** Comparison of detected to predicted γ-ray flux within the central aperture and the innermost annuli for two different widths of the PSF. The red lines correspond to an optimistic PSF of $\sigma = 0.05°$ whereas the green lines are calculated for a conservative $\sigma = 0.08°$ for a soft γ-ray spectrum. The vertical dashed line separates the data from the noise level at a position corresponding to $r_\perp = 37.5$ kpc.

provided the γ-ray emission is of hadronic origin and the population is described by a single power-law ranging from the GeV to TeV energy regime.

A comparison of the observed to the predicted γ-ray emissivity profiles is shown in Fig. 3. In order to allow for finite resolution of the Čerenkov telescope, the real profile was convolved with the point spread function (PSF) of the *HEGRA* instrument. The more optimistic PSF of $\sigma = 0.05°$ for harder γ-ray spectra being favored by our model as well as the conservative choice of a PSF derived from softer Crab-like spectra are both consistent with the observed data. Considering an aged CRp population which has already suffered from significant Coulomb losses, CRp scaling ratios of the order of $X_{\rm CRp} \sim 50\%$ are obtained for the innermost region of Virgo within $r_\perp = 37.5$ kpc.

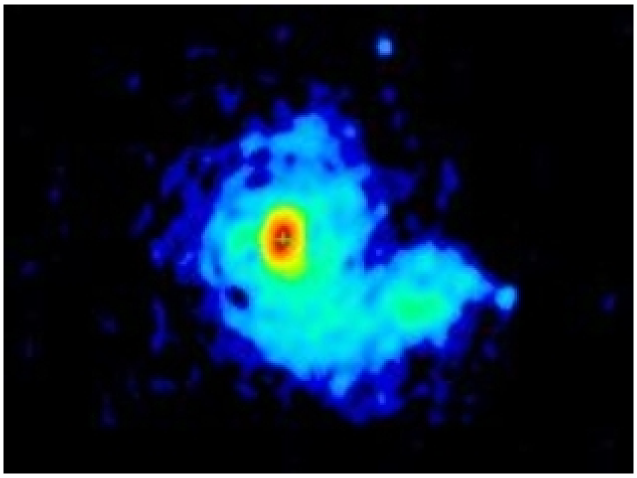

Fig. 4.— The Perseus radio mini-halo at 1.4 GHz from Pedlar et al. (1990) with an extent of $160\,h_{70}^{-1}$ kpc in diameter. At the very center is an extremely bright flat-spectrum core owing to relativistic outflows of the radio galaxy NGC 1275. This outflow was subtracted from this image to make the extended structure more visible. The position of the radio galaxy is marked by the green cross in the center of the red region.

Since the emission region is dominated by the giant radio galaxy M 87, other mechanisms like processed radiation of the relativistic outflow or dark matter annihilation could also give rise to the observed γ-ray emission. Nevertheless, the hadronic scenario probes the CRp population within a mixture of the inter stellar medium of M 87 and the ICM of the center of Virgo yielding either an upper limit or a detection on the CRp population, provided this scenario applies.

IV. Radio mini-halos

The Perseus radio mini-halo at 1.4 GHz is shown in Fig. 4 as observed by Pedlar et al. (1990). The emission due to the relativistic jet has been subtracted to make the extended structure more visible. The spatial extent of the radio mini-halo of $160\,h_{70}^{-1}$ kpc in diameter is too large to be accounted for by synchrotron emission of direct accelerated CRes in structure formation or accretion shocks. Thus one needs to consider other injection processes of CRes into the ICM which are responsible for the observed diffuse radio emission. Besides the reacceleration scenario of mildly relativistic CRes ($\gamma \simeq 100-300$) which are accelerated in-situ by turbulent Alvén waves (Gitti et al., 2002), the hadronic injection scenario of CRes is a promising alternative.

Azimuthally averaging the radio emission shown in Fig. 4 yields the radio emissivity profile as displayed in Fig. 5. For comparison, we overlaid synthetic radio surface brightness profiles resulting from the hadronic scenario. There is a perfect morphological match between observed and predicted profiles. Assuming a typical magnetic field strength for cooling cores of $10\,\mu$G, we derive an upper limit for the

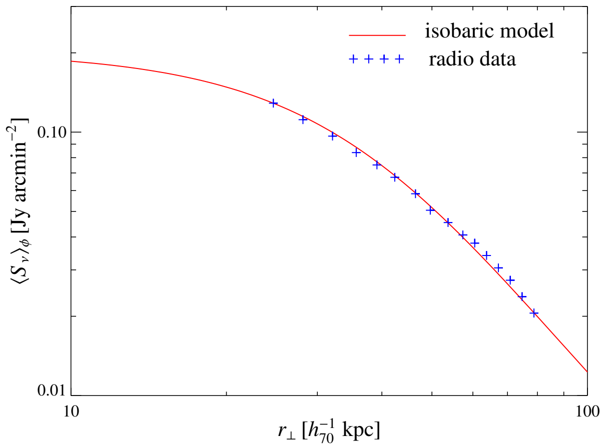

Fig. 5.— Radio emissivity profile of the Perseus mini-halo at 1.4 GHz observed by Pedlar et al. (1990) (crosses) and predicted due to hadronic interactions of CRp by Pfrommer & Enßlin (2004a). Both the required CRp scaling ratio $X_{\rm CRp} \simeq 2\%$ and the morphological match of the observed and predicted radio emissivities strongly indicate the hadronic origin of radio mini-halos.

CRp population of $X_{\rm CRp} \simeq 2\%$ by normalizing our simulated to the observed profile (cf. Fig. 2).

The radio emissivity of hadronically generated CRes depends on the assumed magnetic field strength. Thus, upper limits on $X_{\rm CRp}$ rely on the same assumption. However, in the case of strong magnetic fields (above 3 μG), the dependence of $X_{\rm CRp}$ on the assumed field strength is very weak, since synchrotron losses dominate in this regime. If radio mini-halos are entirely produced hadronically by CRps, then the constraint derived for the Perseus cluster is an actual measurement for $X_{\rm CRp}$ and not only an upper limit. Alongside the perfect morphological match of the radio synchrotron profiles, the comparably small number of CRps required to account for the observed radio mini-halo suggests a hadronic origin of the radio mini-halo in Perseus.

V. Hadronic minimum energy criteria

As an extension of the previous work, we estimated magnetic field strengths of radio emitting galaxy clusters by minimizing the non-thermal energy density — contained in relativistic electrons, protons, and magnetic fields — with respect to the magnetic field strength (Pfrommer & Enßlin, 2004b). As one boundary condition, the implied synchrotron emissivity is required to match the observed value. Additionally, a second boundary condition is required mathematically which couples CRps and CRes. For the *classical* case, a constant scaling factor between CRp and CRe energy densities is assumed. However, if the physical connection between CRps and CRes is known or assumed, a physically better motivated criterion can be formulated. As such a case, we introduce the minimum energy criterion within the scenario of *hadronically* generated CRes. The work by Pfrommer & Enßlin (2004b) provides simple self-consistent recipes for applying the classical and hadronic minimum energy criterion in typical observational situations.

Alongside, we provide theoretically expected tolerance regions which measure the deviation from the minimum energy states by one e-fold: We use logarithmic measures of the curvature radius at the extremal values in order to characterize the 'sharpness' of the minima. These regions have the meaning of a quasi-optimal realization of the particular energy densities.

The philosophy of this approach is to provide a criterion for the energetically least expensive radio synchrotron emission model possible for a given physically motivated scenario. There is no first principle enforcing this minimum state to be realized in nature. However, our minimum energy estimates are interesting in two respects: First, these estimates allow scrutinizing the hadronic model for extended radio synchrotron emission in clusters of galaxies. If it turns out that the required minimum non-thermal energy densities are too large compared to the thermal energy density, the hadronic scenario will become implausible to account for the extended diffuse radio emission. In this respect, our criteria is a way to test the robustness of the previous results with respect to the observationally available parameter space spanned by the CRp spectral index and the (unknown) distribution of the magnetic field strength. Secondly, should the hadronic scenario be confirmed, the minimum energy estimates allow testing for the realization of the minimum energy state for a given independent measurement of the magnetic field strength.

Application to the radio halo of the Coma cluster and the radio mini-halo of the Perseus cluster yields equipartition between cosmic rays and magnetic fields within the expected tolerance regions. In the hadronic scenario, the inferred central magnetic field strength ranges from 2.4 μG (Coma) to 8.8 μG (Perseus), while the optimal CRp energy density is constrained to $2\% \pm 1\%$ of the thermal energy density (Perseus) (cf. Fig. 6). Pfrommer & Enßlin (2004b) discuss the possibility of a hadronic origin of the Coma radio halo while current observations favor such a scenario for the Perseus radio mini-halo. Combining future expected detections of radio synchrotron, hard X-ray inverse Compton, and hadronically induced γ-ray emission should allow an estimate of volume averaged cluster magnetic fields and provide information about their dynamical state.

VI. Conclusions

- We argue that cooling cores of galaxy clusters are well suited to reveal or constrain any cosmic ray proton population via radiation from hadronic interactions with the ambient gas nuclei. Such collisions lead to γ-rays and cosmic ray electrons. The former would have been seen above 100 MeV by the *EGRET* telescope if the cosmic ray protons had energy densities relative to the thermal gas exceeding 10% (Pfrommer & Enßlin, 2004a).

- The giant elliptical galaxy M 87 in the center of the

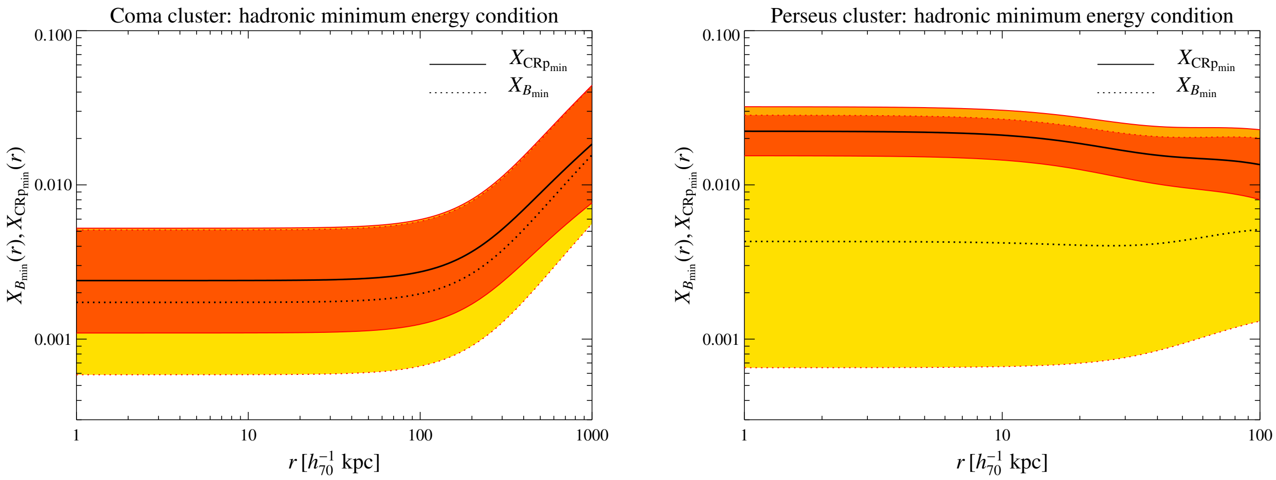

Fig. 6.— Profiles of the CRp-to-thermal energy density $X_{\mathrm{CRp}_{\mathrm{min}}}(r)$ (solid) and magnetic-to-thermal energy density $X_{B_{\mathrm{min}}}(r)$ (dotted) as a function of deprojected radius are shown. The different energy densities are obtained by means of the hadronic minimum energy criterion. The **left panel** shows profiles of the Coma cluster while the **right panel** represents profiles of the Perseus cluster. The light shaded areas represent the logarithmic tolerance regions of $X_{B_{\mathrm{min}}}(r)$ and $X_{\mathrm{CRp}_{\mathrm{min}}}(r)$, respectively, while the dark shaded regions indicate the overlap and thus the possible equipartition regions in the quasi-optimal case.

Virgo cluster cooling core region has recently been detected at TeV energies by the *HEGRA* instrument (Aharonian et al. 2003). These γ-rays could be produced by hadronic interactions of a cosmic ray proton population if its spectral index $\alpha_{\mathrm{GeV}}^{\mathrm{TeV}} < 2.3$ and its energy density is of the order of 50% of the gas within the transition/mixture of inter-stellar and intra-cluster medium within M 87 (Pfrommer & Enßlin, 2003).

- Cosmic ray electrons produced in hadronic interactions are a very sensitive indicator of cosmic ray protons due to their strong emissivity. Radio synchrotron emission of such electrons in strong cooling core magnetic fields of $\sim 10\,\mu$G limit the cosmic ray proton energy density to $\sim 2\%$ or less compared to the thermal one in the Perseus cluster cooling core (Pfrommer & Enßlin, 2004a).
- Diffuse radio emission from the Perseus cluster cooling core was detected – the so called Perseus *radio mini-halo*. This radio synchrotron emission may be induced by cosmic ray proton interactions in the intra-cluster medium. This scenario is strongly supported by the very moderate energy requirements (2% of the thermal energy) and the excellent agreement between the observed and the theoretically predicted radio surface profile (Pfrommer & Enßlin, 2004a).
- Introducing the *hadronic minimum energy criterion*, we show that the energetically favored cosmic ray proton energy density is constrained to $2\% \pm 1\%$ of the thermal energy density in Perseus. Application to the radio halo of the Coma cluster and the radio mini-halo of the Perseus cluster yields equipartition between cosmic rays and magnetic fields within the expected tolerance regions (Pfrommer & Enßlin, 2004b).

ACKNOWLEDGEMENTS

We thank Francesco Miniati, Björn Malte Schäfer, and Sebastian Heinz for discussion and collaboration, Alan Pedlar for the permission to reproduce the Perseus mini-halo image, and the conference organizers for an excellent meeting.

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