Relativistic Particles in Clusters of Galaxies

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A brief overview on the theory and observations of relativistic particle populations in clusters of galaxies is given. The following topics are addressed: (i) the diffuse relativistic electron population within the intra-cluster medium (ICM) as seen in the cluster wide radio halos and possibly also seen in the high energy X-ray and extreme ultraviolet excess emissions of some clusters, (ii) the observed confined relativistic electrons within fresh and old radio plasma and their connection to cluster radio relics at cluster merger shock waves, (iii) the relativistic proton population within the ICM, and its observable consequences (if it exists), and (iv) the confined relativistic proton population (if it exists) within radio plasma. The importance of upcoming, sensitive gamma-ray telescopes for this research area is highlighted.

1 Introduction

Even though the study of relativistic particle population is more than three decades old, it has recently received a significant increase in attention by various researchers. Here, a brief and, therefore, incomplete and personally biased overview of this field is provided. A guide through the lines of argumentation is given by Fig. 1, which sketches the main dependencies of the components of the theory and their observational consequences. This figure is explained in the following.

The main energy sources of the relativistic particle population in clusters are outflows from galaxies (galactic winds, radio jets) and/or the energy released in accretion on galaxy clusters. The first sources can directly eject relativistic particles into the ICM [1,2], whereas the latter produce shock waves and turbulence, which can accelerate particles via the Fermi mechanisms [3,4,5,6,7,8,9]. Also the termination shocks of galaxy winds were proposed as shock acceleration sites [10]. A different source of relativistic particles may be the annihilation of certain dark matter particles [11].

The relativistic particles loose energy via various radiative and non-radiative processes, allowing to measure or constrain their spectral energy distribution observationally. The most important loss channels are discussed in the following.

2 Relativistic Electrons

2.1 Diffuse Population: Radio Halos

The existence of relativistic electron populations in galaxy clusters is known since Willson's [12] (1970) detection of extended diffuse radio emission from the intra-cluster medium of Coma. Today, there exists a much larger sample of similar detections [13,14,15,16,17]. This radio emission

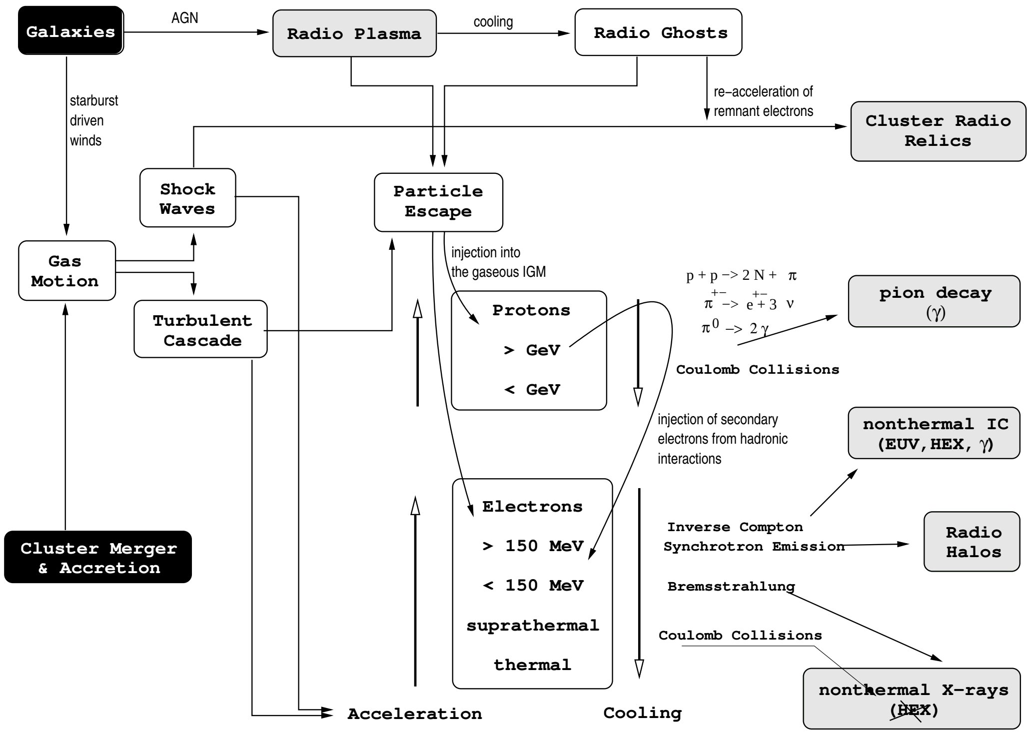

Figure 1: Basic theory building blocks covering most of the proposed scenarios for the production and maintenance of relativistic particle populations in galaxy clusters and their observational consequences. For details see text.

is believed to be synchrotron emission from highly relativistic ($\gamma \sim 10^4$) electrons spiraling in intra-cluster magnetic fields of $\sim \mu$G strength. The origin of the fields and particles were unclear at the time of the first detection, and are still a puzzle, although substantial progress has been made in their understanding. A clue is the obvious correlation of the presence of extended radio emission with the presence of cluster substructure as an indication for ongoing or recent cluster merger activity [18]. This indicates that the main energy source of the electron population are merger shock waves and possibly merger induced turbulence [19].

Extended cluster radio emission, which is not associated with individual galaxies, is nowadays classified as *cluster radio halos* and *cluster radio relics*. Cluster radio halos are steep spectrum radio sources, which often have morphologies very similar to the X-ray emission of the cluster [20] indicating that there is a direct link between their energetics and that of the ICM. It is therefore likely that the emitting electrons occupy the same subvolume as the thermal X-ray emitting ICM gas, which we assume in the following. We denote this population as the *diffuse population of relativistic electrons* in galaxy clusters. It is worth noting, that the cluster wide radio halos cannot be the direct result of passing merger shock waves, since the cluster crossing time of a shock wave is much larger ($\sim 10^9$ years) compared to the radio emitting electron cooling time ($\sim 10^8$ years). Since there is some indication that radio halos only appear in regions which were passed by a merger shock wave [21,22] one can speculate if some agent stores some fraction of the shock released energy and provides it successively to the radio electron population. Possible natures of such an agent are plasma turbulence [7] or a shock accelerated population of relativistic protons [23] (see below).

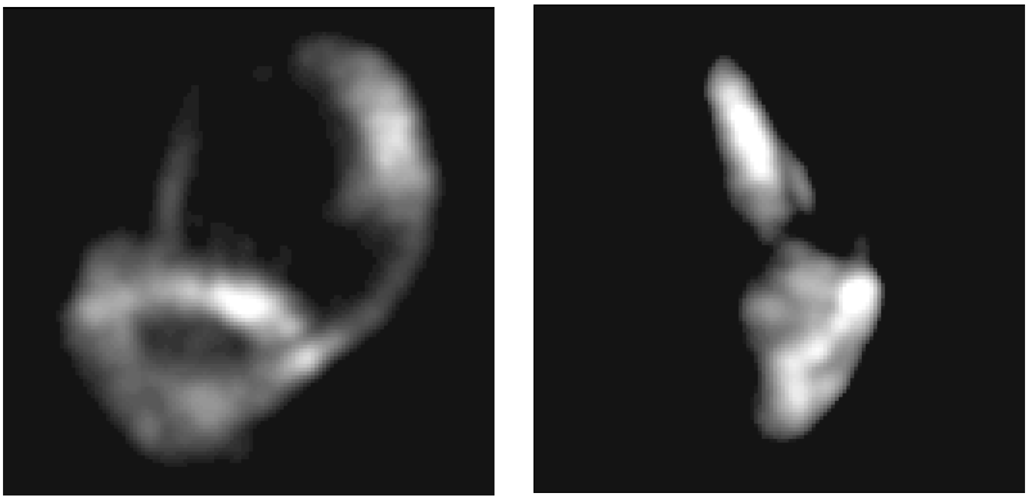

Figure 2: Simulated cluster radio relic: radio emission of a radio ghost after shock passage. Left: face on view on the shock plane, right: edge on view on the same relic.

2.2 *Confined Populations: Radio Cocoons, Radio Ghosts, & Cluster Radio Relics*

In contrast to the radio halo electrons spatially *confined populations of relativistic electrons* exist in galaxy clusters: There are the electrons released by outflows from radio galaxies and confined from the thermal ICM by strong magnetic fields within the so called *radio cocoons*. Since the higher energy electrons rapidly lose energy by synchrotron and inverse Compton (IC) emission, the observable radio emission of an old radio cocoon disappears after $\sim 10^8$ years. Afterwards, the relativistic electrons (and any other particle population) should still be confined by the magnetic fields. Recent support for the existence such of non-emitting *radio ghosts* [24] is given by the rapidly growing number of detections of cavities [25,26] in the X-ray emitting gas of clusters of galaxies, sometimes filled with observable radio emission, sometimes not.

Furthermore, another class of objects with possibly confined electron populations are the cluster radio relics. They are typically located at the periphery of clusters, sharply edged, and sometimes of a filamentary morphology. Their steep spectrum radio emission is often highly polarized, which highlights their physical distinctness from the unpolarized radio halos.

There are now several examples of a spatial co-location of relics and cluster merger shock waves [6,21,27,28,29] indicating that the electrons observed there in radio were directly accelerated by the shock. Two shock acceleration mechanisms were proposed so far for relics: direct diffusive shock acceleration out of the thermal pool [6,9,28], and adiabatic compression of an old electron population in a radio ghosts [30,31]. Both processes may be realized in nature: E.g. the giant radio relics in Abell 3667 seem to be of the first type [6,28,32], whereas the small, filamentary relics in Abell 85 are probably of the second type [31,33] (see Fig. 2).

2.3 *Observational Constraints on the Spectrum*

Relativistic electrons should reveal their presence via a variety of emission processes. They can up-scatter a present photon population to higher energies. They can produce non-thermal bremsstrahlung, and they emit synchrotron radiation if located in magnetic fields.

Fig. 3 is a compilation of the available observational information on the electron spectrum in Coma [34,a]. The line on the left hand side is the thermal distribution. The line on right hand

[a] The compilation was done in 1997, but since then only the upper limit on the HEX excess by OSSE was accomplished by a detection of a only slightly lower flux by Beppo-Sax in 1998. Therefore the figure can still be regarded to be up to date.

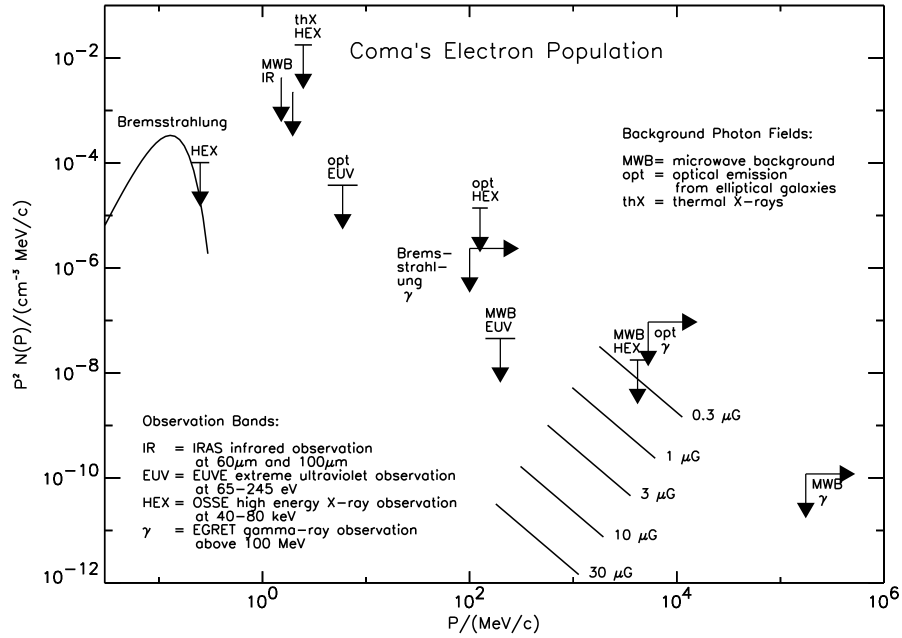

Figure 3: The central electron spectrum in the Coma cluster of galaxies. For details see text.

side gives the required electron populations in order to produce the observed radio halo of Coma with the labeled magnetic field strengths. The given upper limits result from observational upper limits to bremsstrahlung or IC scattering fluxes in various wave-bands. Two of them correspond to actual detections: the extreme ultraviolet (EUV) [35] and the high energy X-ray (HEX) [38] excess fluxes. Some of the corresponding upper limits (labeled by EUV and HEX) on the electron spectra could therefore be data points. For further details of this figure see Enßlin & Biermann [34].

The explanation of the HEX excess is problematic. An IC interpretation in terms of up-scattered CMB photons requires magnetic field strength of $\sim 0.1\mu$G in order to be consistent with the observed radio halo flux level [36,37,38,39]. This is much lower than the $\sim 1\mu$G fields suggested by Faraday rotation measurements [40,41,42]. There might be ways to reconcile these measurements, e.g. by inhomogeneously and anti-correlated relativistic electron and magnetic field distributions [43], but they seem to be a little contrived. Another proposal, that the HEX excess is actually due to a supra-thermal electron population producing bremsstrahlung [43], is even less likely due to the inefficiency of bremsstrahlung compared to the unavoidable huge Coulomb losses [44].

It is worth noting, that gamma-ray observations of up-scattered optical photons will probe exactly the same energy range as probed by HEX observations of up-scattered CMB photons. The sensitivity of upcoming gamma-ray telescopes should therefore allow to give important insight into this puzzle. In addition to this, such gamma-ray observation will also probe for the presence of TeV electrons [45,46,47].

3 Relativistic Protons

3.1 Diffuse Populations: Origin of Radio Halos?

Today, a direct proof of the presence of a relativistic proton populations in galaxy clusters is still lacking although our knowledge of the galactic cosmic rays suggests the presence of a much more energetic proton population compared to the electrons. Protons are long-lived in the ICM, with lifetimes of the order of a Hubble time. Since spatial diffusion of moderate energy protons (say below 10^{15} eV) is slow, even on a cosmological timescale, they should basically be stored within the cluster [10,48,49].

A diffuse relativistic proton population can, in principle, be observed by secondary particle produced in hadronic interactions with the background gas nucleons. The hadronic production of neutral pions leads to gamma-ray emission from galaxy clusters [50], which may be detectable with upcoming gamma-ray telescopes. The non-detection of the Coma cluster by the EGRET telescope limits the energy density of protons to be below the thermal electron density of the ICM at least in the case of Coma [10,48,51,52,53]. Upcoming gamma-ray instruments will either detect such emission, or further constrain the relativistic proton population.

The hadronic production of charged mesons leads to the injection of electrons and positrons [23,50,53,54] into the ICM and to the emission of neutrinos [53]. The neutrinos are practically undetectable with present and planned telescopes, but the injected electrons could be the ones seen in radio halos.

3.2 Confined Populations: Undetectable?

A population of relativistic protons within radio plasma if it exists, is practically unobservable by direct means. However, improvement in the understanding of radio jets, or detailed analysis of the mechanical properties of radio plasma [55] may lead to firmer conclusions in the future.

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