RADIO PLASMA AS A COSMOLOGICAL PROBE

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Plasma containing relativistic particles appears in various forms in the inter galactic medium (IGM): As radio plasma released by active radio galaxies, as fossil radio plasma from former radio galaxies – so called *radio ghosts*–, as *cluster radio relics* in some clusters of galaxies, and as *cluster radio halos*. The impact of the different forms of radio plasma on the IGM and their use as diagnostic tools are briefly discussed.

1 Radio Galaxies

Radio galaxies produce radio cocoons, which create large cavities[1] in the IGM gas filled with magnetic fields and relativistic particles: electrons and positrons or protons. The electrons (and positrons if present) of several GeV reveal their presence by synchrotron emission at radio wavelength. From the observed radio emission the minimal energy density in the radio plasma can be deduced. Since the radio plasma has to have a higher (or equal) pressure than the environment, a direct probe of the ambient gas pressure is given[2]. Also the ram pressure effects of swept up IGM material during the expansion of the cocoon can be used to determine IGM gas densities[3,4]. The morphology of the radio galaxy can give information about relative motions of the galaxy and the IGM[5], but also allows to detect IGM shock waves[6].

The amount of energy released by radio galaxies into the gaseous Universe during the whole history of the Universe is large. Rough estimates give a ratio of 0.1 ... 1 between the energy released by radio galaxies and by the gravitationally driven structure formation[7,8]. Radio galaxies are therefore one of the best candidates in order to explain the necessary non-gravitational heating required by the observed entropy-floor of clusters and groups of galaxies[9,10]. Therefore remnant radio plasma should be a ubiquitous phase of the IGM.

2 Radio Ghosts

Radiative energy losses let the radio emitting electrons in radio cocoons become invisible to our instruments within cosmologically short times (10^8 year). Afterwards, the cocoon of fossil radio plasma is named *radio ghosts*[11]. But the electrons confined by the magnetic fields should still stay relativistic, and might reveal their presence by inverse Compton effects on the cosmic microwave background (CMB): the relativistic Sunyaev-Zeldovich (rSZ) effect. Since a CMB photon scattered by a relativistic electron gains a large factor in energy, it is practically removed from the CMB spectrum. Thus the rSZ effect is mostly an absorption at CMB frequencies. The optical depth of the total electron population residing in radio ghosts is of the order of $\tau \sim 10^{-7}$, but this number has large uncertainties[12]. Since the expansion of the radio cocoons into the IGM should at least release some pressure work to the environmental gas, the corresponding thermal SZ effect should have a Comptonization parameter of the order[13,12] of $y \sim 10^{-5\cdots-6}$.

But not only the relativistic electrons may reveal their presence by scattering of radiation. Also the magnetic fields of radio ghosts are able to deflect charged particles even at the highest energies observed in the cosmic ray spectrum. If the spatial distribution of radio ghosts is sufficiently unclustered compared to the clustering of galaxies, then the expected number densities of ghosts would be sufficient to explain the mysterious isotropy of the ultra high energy cosmic ray particles, even if the sources are as inhomogeneously distributed as the galaxies[14].

3 Cluster Radio Relics

Recently, radio ghosts were detected by X-ray deficits in cluster core regions[1]. But very likely, they already showed up as *cluster radio relics* 20 years ago. These extended radio sources in some clusters of galaxies are not specially connected to any optical galaxy[15]. Cluster radio relics are preferentially located in peripheral regions of clusters. They have usually steep radio spectra and exhibit often a high degree of linear polarization. In several cases, their locations can be associated with strong shock waves in merging clusters of galaxies[16]. In the cases of Abell 2256 and Abell 1367 temperature substructures of the hot ICM gas could be detected[17,18], which support the presence of a shock wave at the location of cluster relics in these clusters. For Abell 754[19,20], Abell 2256[21], Abell 3667[22] and also the Coma[23] cluster numerical simulations of merger events were satisfactorily fitted to the X-ray data, which also supports the shock wave-relic connection. The mechanism producing the cluster radio relics is very likely adiabatic compression of radio ghosts in an environmental shock wave[24]. This strengthens the internal magnetic fields and shifts the electron population to higher energies. If the upper cooling cutoff of the electron spectrum can be shifted above the radio emitting energies, the ghost's radio emission is revived and the ghost appears as a cluster radio relic. Cluster radio relics therefore not only allow the study of shock waves, but also give a view into the fossil Universe. Their number should be much higher at lower frequencies, due to the distribution of frequency cutoffs in their radio spectra.

4 Cluster Radio Halos

Cluster radio halos appear preferentially in the center of clusters of merging galaxies[15,25]. They have morphologies similar to the X-ray morphologies of their host clusters[26]. Radio polarization could not be reported in any case. Their large physical size ($\sim$ Mpc) require that the radio emitting electrons are accelerated or injected throughout the cluster volume.

The energy source of all non-thermal processes in clusters should be either the kinetic energy of matter falling onto clusters, or the outflows from galaxies. The latter can be divided in galactic winds, which are strongest for starburst galaxies, and ejection of radio plasma from an AGN. All these processes can produce shock waves and inject turbulence into the ICM, and therefore produce conditions where Fermi mechanisms accelerate particles. For a brief review see Enßlin (1999)[27].

A promising injection mechanism of relativistic electrons is secondary particle production from hadronic interactions of relativistic protons with the background gas[28,29,30,31]:

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

The lifetime of relativistic protons in the ICM is of the order of the Hubble time, or larger[32,33]. Thus they are able to travel large distances from their sources before they release their energy. The production of electrons via charged pions has to be accompanied by gamma ray production via neutral pions [29,33,34,31]:

$$\begin{aligned} p + p &\rightarrow 2\,N + \pi^{o} \\ \pi^{o} &\rightarrow 2\,\gamma \end{aligned}$$

Thus clusters with radio halos might have gamma-ray halos, which would be, if detected, a direct proof for a hadronic origin of radio halos.

5 Conclusions

Radio galaxies:

- probe the thermodynamical state of the gaseous Universe.
- produce large amounts of fossil radio plasma.

Radio ghosts, the invisible descendents of radio galaxies:

- may produce an relativistic Sunyaev-Zeldovich effect.
- scatter and possibly isotropize ultra high energy cosmic ray particles.

Cluster radio relics:

- trace shock waves of the large scale structure formation flows.
- are likely revived radio ghosts.

Cluster radio halos:

- indicate recent cluster merger events.
- trace non-thermal processes in the intracluster medium.

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