Cosmic Rays in Clusters of Galaxies

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Abstract. We argue that clusters of galaxies have an intergalactic medium, which is permeated by strong magnetic fields and also has a contribution of pressure from cosmic rays. These two components of total pressure are probably highly time dependent, and range probably between 1/10 of the gas pressure up to equipartition between gas pressure and the sum of the two other components. Radio galaxies are likely to provide the main source for both magnetic fields and cosmic rays. In this concept it becomes easy to understand the occasional mismatch between the total mass inferred from the assumption of hydrostatic equilibrium derived purely from gas, and the total mass derived from lensing data. We also suggest that the structure and topology of the magnetic field may be highly inhomogeneous - at least over a certain range of scales, and may contain long twisted filaments of strong magnetic fields, as on the Sun. The analogy with the interstellar medium may be fruitful to explore further, where we do not know where magnetic fields come from, but suspect that the cosmic rays derive from supernova explosions. In such an analogy it becomes useful to refer to “radio galaxy explosions” in clusters of galaxies. A full scale exploration of all the implications, especially of the notion that occasionally complete equipartition may be reached, is a task for the future.
1. Introduction

For a long time it has been recognized that clusters of galaxies have intergalactic gas, which actually dominates in baryonic mass over the stars in galaxies; this gas is enriched in heavy elements. The assumption of hydrostatic equilibrium can be used to infer in the case of a nearly spherical cluster the total gravitating mass of a cluster; this inferred mass can in turn be tested with strong lensing observations which also give the gravitating mass; for spherical clusters with high accuracy. It had been believed for some time that this intergalactic gas in clusters appeared to be much simpler than interstellar gas in the sense that magnetic fields and cosmic ray particles did not seem to matter much for the overall energetics, the overall pressure, and the emission. We can refer to the ensemble of magnetic fields and energetic particles, i.e. cosmic rays, as the “nonthermal component”. In recent years this view has begun to be demonstrated to be false, and we now have to take these two other components into account, leading to the same questions and uncertainty as for the interstellar medium, for which we are just beginning to appreciate the difficulties in understanding its physics, as, for instance, in searching for the origin of the interstellar magnetic field.

Here we discuss what is known today about the nonthermal component of the intergalactic medium in clusters. We outline a range of possibilities, and tasks. These questions are all the more important since we now suspect that the missing baryonic mass in the universe is all in gas, usually outside of clusters of galaxies, in groups, filaments and sheets of the galaxy distribution.

The order of the paper is as follows: 1) First we outline some basic parameters of the intergalactic medium in clusters, in this introductory section. 2) We discuss the recent detection of rather strong magnetic fields in clusters. 3) We discuss cosmic rays in clusters, as derived from normal galaxies and starburst galaxies. 4) Then we discuss the cosmic rays from accretion shocks. 5) Mergers between clusters and structural rearrangements of un-relaxed clusters can also produce shock waves and cosmic rays. 6) Finally, cosmic rays from radio galaxies can surely provide sufficient energy to provide cosmic rays, and also magnetic fields to clusters of galaxies, and do so to the stability limit of the medium. 7) Then, we describe the attempts to understand where cosmic magnetic fields come from. 8) We discuss explosions into a homogeneous medium, so as to describe the effective cooling in either the interstellar medium or intergalactic medium, subject to the buffeting of supernova explosions or radio galaxy explosions. We discuss to what limit this analogy may help to understand the physics of these two media. 9) Also, the recent XMM-Newton findings illustrate the necessity to consider the heating from radio galaxies in the cores of clusters. 10) Then, we describe some cosmological simulations that show what happens with magnetic fields. 11) We then explore the topology of magnetic fields in a medium subject to continuous excitement of turbulence, again as an example for both the interstellar and the intergalactic medium. 12) We furthermore discuss the two sources of leptons so as to predict the lepton energy distribution,
critical to understand the inverse-Compton and synchrotron emission in clusters; leptons are expected both from the primary acceleration of electrons starting from the thermal tail, as well as from pion decay following p-p collisions between energetic protons and the medium itself. 13) We then outline some predictions as regards the various possible limits of the model proposed here, namely that radio galaxies dominate both the source of magnetic field and the source of energetic particles, the cosmic rays. 14) We conclude with some final summary of the present status of this field, and define some tasks for the future.

1.1. Basic properties of clusters

First we outline some basic parameters of the intergalactic medium in clusters, in this introductory section.

Clusters of galaxies cover an enormous range of properties, some probably still unrecognized. But “typical” values for the most massive clusters are by order of magnitude:

- Total mass about $10^{15}$ solar masses, mostly dark matter of unknown nature. Dark matter seems to be non-interacting, except through gravitation.

- Gas mass about $10^{14}$ solar masses. This gas is enriched, and so has been reprocessed through stars to some degree, since it is often about 1/3 of solar abundances. The temperature of the gas is between 5 - 10 keV, or up to about $10^8$ K. The density of the gas at the center is about $3 \times 10^{-4}$ cm$^{-3}$. The X-ray luminosity from thermal bremsstrahlung emission of the hot gas is about $10^{44}$ erg/s, and the energy content in the gas is about $10^{62}$ erg.

- The total stellar mass is considerably less than the gas mass.

- The radial scale of the density profile of the cluster is about 300 kpc. The “outer edge” is at a few Mpc. This is where the accretion shock becomes visible through reacceleration of an old quiescent population of energetic particles, and subsequent radio emission (Enßlin et al. 1998).

- The cooling time of the gas is usually larger than the Hubble time, of about $5 \times 10^{17}$ s. There are some clusters for which the central cooling time is shorter than the Hubble time and for those a cooling flow is inferred. This cooling flow can reach some $10^3$ solar masses per year in accretion, of which few traces are visible anywhere. XMM-Newton data suggest that much of this cooling is compensated by heating, to be discussed below, and as had been suspected for some time; references are given below.

Groups of galaxies (e.g., Biermann et al. 1982, Biermann & Kronberg 1983, Biermann & Kronberg 1984a, Biermann & Kronberg 1984b, Schmutzler & Biermann 1985, Wu & Xue 2001), and also the large sheets and filaments in the large scale distribution of galaxies also appear to harbor much gas, often at lower temperature than in rich clusters, and so is very difficult to detect. This gas is suspected to constitute the missing baryonic matter, inferred from comparing nucleosynthesis results and
microwave background fluctuation data with the baryonic mass directly detectable in stars.

1.2. Magnetic fields

Here we discuss the recent detection of rather strong magnetic fields in clusters (Clarke et al. 1999, Clarke et al. 2000).

Magnetic fields have now been firmly detected in clusters of galaxies, and as a rule appear to have the following properties:

- Strength at or above 5 - 10 $\mu$G normally.
- In two known cases the magnetic field strength reaches equipartition, with 20 - 30 $\mu$G (see, e.g., Enßlin et al. 1997).
- The reversal scale is small, 10 kpc or less. The field is highly chaotic.
- The scale of the magnetic region in the cluster gas has a radius of at least about 500 kpc. This means that the magnetic field is detectable through Rotation Measure data throughout the inner one Mpc.

2. Sources of cosmic rays in clusters

Here we discuss the various possible sources of cosmic rays in clusters of galaxies.

2.1. Cosmic rays: Starburst and normal galaxies

Here we discuss cosmic rays in clusters, as derived from normal galaxies and starburst galaxies (Popescu et al. 2000, Völk et al. 1999, Völk et al. 2000).

Galaxies and especially starburst galaxies produce an enormous power in cosmic rays, as evidenced through the far-infrared/radio correlation. The far-infrared luminosity is therefore a direct measure of the creation of cosmic rays,

$$L_{CR} \simeq 10^{-3} L_{FIR}.$$  

These cosmic rays are generally believed to drive a wind from the galaxy, and so lose their power in adiabatic expansion to the wind. These cosmic rays can then be captured by the environment in a cluster. These cosmic rays then outside have little total power left, only a small fraction of their original power, but lots of ionizing capital (Nath et al. 1993). However, Volk, Aharonian, & Breitschwerdt (1996) argued that the termination shock waves of such galactic winds can re-accelerate the escaping cosmic rays.

Since galaxies in clusters are usually early Hubble type galaxies their far-infrared luminosity is relatively weak, and so their starburst activity and a fortiori cosmic ray power is diminished (Popescu et al 2000, Völk et al. 1999, Völk et al. 2000).
If the galaxies get stripped on their path through the cluster (e.g., Himmes & Biermann 1980, Toniazzo & Schindler 2001), then their cosmic ray contribution may not suffer from driving any wind, and so their contribution may be larger.

However, on balance the cosmic ray power from galaxies is not expected to dominate over other sources of cosmic rays in clusters of galaxies.

2.2. Cosmic rays: Accretion shocks

Here we discuss the cosmic rays from accretion shocks (Kang et al. 1997, Enßlin 1998).

Accretion shocks around clusters of galaxies, now detected through the re-energization of fossil clouds of energetic particles (Enßlin et al. 1998), can certainly also accelerate cosmic rays, and do so to very high particle energy (Kang et al. 1997). These accretion shocks, however, sample the potential well at a large distance, several Mpc, and so cannot contribute very large power.

There is probably a similar feature around filaments and sheets in the galaxy distribution (Enßlin et al. 2001), in one example detected through the reenergization of an extended radio jet.

These arguments strengthen the case for the validity of the cosmic simulations, which show shocks around clusters, filaments and sheets in the galaxy distribution.

2.3. Cosmic rays: Mergers and relaxation

Mergers between clusters and structural rearrangements of un-relaxed clusters can also produce shock waves and so cosmic rays (Donnelly et al. 2001, Schindler 2002).

When two clusters merge, as e.g. in the case of the Perseus cluster, they rearrange themselves over some time - about one to two crossing times, causing widespread shock waves and highly anisotropic phase and real space distributions of galaxies (e.g. Donnelly et al. 2001, Schindler 2002). The group around NGC383 is another example where the group appears as a cigar in projection on the sky, contains only early Hubble type galaxies, and the radio galaxy 3C31 (the host galaxy of which is NGC383 itself) shoots its radio jets along the cigar figure in projection. Again cosmic rays can be accelerated by the shocks caused by mergers, but as these shocks are low Mach number, the spectrum of the accelerated particles is steep, i.e. will not contribute much at high energy. On the other hand, their total energy content could approach the thermal energy.

2.4. Cosmic rays: Radio galaxies

Finally, cosmic rays from radio galaxies can surely provide sufficient energy to provide cosmic rays, and also magnetic fields to clusters of galaxies, and do so to the stability limit of the medium (Enßlin, et al. 1997).

Radio galaxies can easily provide lots of energy in relativistic particles and also in magnetic fields, all derived from the accretion power of
Figure 1. Two-dimensional cut of the simulated universe at $z = 0$ from a cosmological simulation. The plot shows a region of $32h^{-1} \times 20h^{-1}\text{Mpc}^2$ with a thickness of $0.25h^{-1}\text{Mpc}$, although the simulation was done in a box of $(32h^{-1}\text{Mpc})^3$ volume. The first panel shows baryonic density contours, the second panel shows velocity vectors, and the third panel shows magnetic field vectors. In the third panel, the vector length is proportional to the log of magnetic field strength. (Ryu et al. 1998)
Figure 2. Here we show how we might interpret the configuration around the radio galaxy NGC315, as influenced by the accretion shocks around the local filaments. The top figure shows the peculiar radio morphology of the radio galaxy. The western radio trail exhibits a sharp bending and a flat (color-coded) spectral index. This can be understood as signatures of a environmental shock wave, as sketched in the bottom figure (Enßlin et al. 2001).
Figure 3. Jet-power versus the radio emission for radio galaxies, demonstrating the enormous power residing in the jet output. (Enßlin et al. 1997)

their central black hole. The jet-disk symbiosis picture developed by Falcke over the past ten years (Falcke & Biermann 1995, Falcke et al. 1995a, Falcke et al. 1995b, Falcke & Biermann 1999) can be used to derive the total power injected by radio galaxies over time, and can easily be seen to surpass all the thermal energy in the cluster, which obviously taps the gravitational potential well. This means that radio galaxies can push the thermal stability of the cluster gas to its limit, thus at least in principle ensuring to keep it at threshold of stability, just as has been argued for the interstellar medium. In the case of Hydra A this limit appears to be reached, because the nonthermal bubble has broken through to the outside (McNamara et al. 2000, David et al. 2001, Nulsen et al. 2001). What is not so clear is whether radio galaxies can do this frequently enough in time to continuously keep the intergalactic medium at the threshold of stability with respect to the content in magnetic fields and in energetic particles.

3. Magnetic fields in the cosmos

Then, we describe the attempts to understand where cosmic magnetic fields come from.

Magnetic fields are known to exist almost everywhere in the cosmos, with the Earth and the Sun the most prominent examples (Kronberg 1994, Beck et al. 1996, Kulsrud et al. 1997, Blasi et al. 1998, Kul-
Figure 4. Integrated jet-power versus time in a cluster of galaxies, showing the total energy as compared to the thermal energy. (Enßlin et al. 1997)

The Sun demonstrates that a dynamo mechanism can twist, fold, and turn back on itself magnetic loops and so strengthen the magnetic field, a mechanism proposed by Steenbeck & Krause (Steenbeck & Krause 1965, Steenbeck et al. 1966, Steenbeck & Krause 1966, Krause & Steenbeck 1967, Steenbeck et al. 1967, Krause 1967, Steenbeck & Krause 1969a, Steenbeck & Krause 1969b, Rädler 1968a, Rädler 1968b, Rädler 1969a, Rädler 1969b, Rädler 1970, Krause 1969) as well as Parker (Parker 1969, Parker 1970a, Parker 1970b, Parker 1970c, Parker 1971a, Parker 1971b, Parker 1971d, Parker 1971e, Parker 1971f, Lerche & Parker 1971, Lerche & Parker 1972, Parker 1973, Parker 1975a, Parker 1975b) many years ago. This mechanism requires a seed field, and a simple plasma physics mechanism was proposed by L. Biermann (Biermann 1950, Biermann & Schlüter 1951) more than fifty years ago; this is based on the idea that in the equation of motion for electric currents the non-coincidence between the surfaces of constant pressure and the surfaces of constant density drives a current, which cannot be compensated by any electric field; this is normally expected for almost any rotating system such as a galaxy or a star. This provides a seed field, which is very weak, and any normal dynamo mechanism requires many rotation periods to reach any interesting strength for the magnetic field. In the Sun this is believed to be possible at the base of the convective layer (Cowling 1953, Mestel & Roxburgh 1962), as in massive star cores; massive stars have been observed to show in some examples nonthermal radio emission, clearly demonstrating the existence of non-
negligible magnetic fields on the radiative surface, and at the base of their winds (Biermann & Cassinelli 1993, Seemann & Biermann 1997). In a galaxy there may not be sufficient time to develop appreciable magnetic fields by this mechanism.

The observations of galaxies, however, indicate strong constraints for any mechanism to strengthen magnetic fields:

- In our Galaxy the time scale of “turnover” of the interstellar medium as derived from cosmic ray studies is about 30 million years; this is the time scale to replenish the cosmic ray population. This means that any geometric order in the homogeneity of the magnetic field is destroyed with such a time scale, and yet, the magnetic field is of order half ordered.

- The observation of starburst galaxies that also have characteristic time scales of also a few tens of millions of years, and yet with an ordered magnetic field in near equipartition with the interstellar medium, again indicates a very fast mechanism to strengthen and so regenerate the magnetic field.

This means that the mechanism, whatever it may be, works basically on the Alfvénic time scale through the thickness of the hot disk (Kaneda et al. 1997, Snowden et al. 1997). This is also the limiting time scale for any inverse cascade model, which may be hard to reach (Stribling & Matthaeus 1991, Stribling & Matthaeus 1994, Stribling & Matthaeus 1995, Matthaeus et al. 1996, Matthaeus et al. 1998, Matthaeus et al. 1999).

Once the magnetic fields in galaxies are understood (Han & Qiao 1994, Han et al. 1997, Han et al. 1997, Krause & Beck 1998), the universe can be “filled” with magnetic fields and cosmic rays (Ryu et al. 1998, Enßlin et al. 1998, Kronberg et al. 1999, Birk et al. 2000, Kronberg et al. 2001).

4. Explosions in a homogeneous medium

We then discuss explosions into a homogeneous medium, in the spirit of Kellermann & Pauliny-Toth (1968), and McKee & Ostriker (1977) and so as to describe the effective cooling in either the interstellar medium or intergalactic medium, subject to the buffeting of supernova explosions or radio galaxy explosions.

We also discuss to what limit this analogy may help to understand the physics of these two media. Also, the recent XMM-Newton findings illustrate the necessity to consider the heating from active galaxies in clusters.

In this section we first wish to consider the inhomogeneity of the intergalactic medium, just as implied already by the irregular explosions that take place, and so fully explore the analogy with the interstellar medium.

Following the treatment of explosions in the interstellar medium originally proposed by McKee & Ostriker (1977) we wish to derive here a
crude estimate of the effective cooling rate of medium riddled with explosions. The line of reasoning also follows the argument for the Compton catastrophe in Active Galactic Nuclei (Kellermann & Pauliny-Toth 1968).

Consider first a homogeneous medium, subject to aperiodic explosions which carve out a spherical bubble, surrounded by a shell of density four times higher, caused by the strong shock. We adopt the adiabatic limit, and so one can describe these explosions approximately by a self-similar Sedov solution. Then the shock velocity \( v_{sh} \) scales with radius \( r \) as \( r^{-3/2} \), while the radius itself decreases with time \( t \) as \( t^{-2/5} \). The shell has a thickness of \( \Delta r = r/12 \), and has a density relative to the reference density \( n_0 \) of \( 4n_0 \). We then consider multiple explosions, which overlap, and so in a very simple description have from a first level \( 1/4 \) the volume with 4 times the density, and so this contributes to the thermal X-ray emission in incremental X-ray luminosity

\[
\Delta L_{X,1} \sim \frac{1}{4} (4)^2 f(T_1). \tag{2}
\]

From the second and higher level \( n \) the contribution is

\[
\Delta L_{X,n} \sim \left(\frac{1}{4}\right)^n (4)^{2n} f(T_n). \tag{3}
\]

At each level the emission coefficient corresponds to the local temperature \( T_n \), but as the emissivity varies rather weakly with temperature compared to the dependence of emission on density, we can approximate this as a general average emission coefficient \( f(T_{av}) \), and write

\[
\Delta L_{X,\Sigma} \sim Vol n_0^2 \left( 1 + \frac{1}{4} (4)^2 f(T_1) + \left(\frac{1}{4}\right)^2 (4)^4 f(T_2) + \ldots \right), \tag{4}
\]

which is

\[
\Delta L_{X,\Sigma} \sim Vol n_0^2 f(T_{av}) \Sigma \left(\frac{1}{4}\right)^m (4)^{2m}. \tag{5}
\]

The sum is broken off as soon as the local cooling time becomes shorter than the repetition time scale for explosions. This may be the case already after the second level. The second level increases the emission by more than an order of magnitude.

The energy content in the same approximation is modified as follows

\[
Vol n_0^2, k_B \Sigma \left(\frac{1}{4}\right)^m (4)^m T_m \approx Vol n_0^2, k_B T_{av}, \tag{6}
\]

where \( k_B \) is the Boltzmann gas constant. Therefore the total X-ray luminosity may be increased by the strong inhomogeneity of the medium easily by a factor of order ten. Applying this to the interstellar medium the cooling time inferred from the assumption of homogeneity using the numbers of Snowden et al. (1997), Kaneda et al. (1997), Valinia & Marshall (1998), of a density of \( 3 \times 10^{-3} \) per cm\(^3\), and a temperature of \( 4 \times 10^6 \) K, we find a cooling time of about \( 3 \times 10^8 \) years, and then using
the argument on inhomogeneity derived here, the cooling time may well be very much shorter, and could be only $3 \times 10^7$ years. Interestingly, this suggests that the time scales for heating and cooling of the hot medium of the interstellar gas, the time scale for magnetic field regeneration, and also the time scale for cosmic ray transport may all be the same. This then would lead to an understanding why we may on average always be at a limit of stability. Surely these considerations may apply to the present day interstellar medium. On the other hand, we have to realize, that these arguments may be less important in today’s clusters of galaxies due to the scarcity of active phases of galaxies, but they were probably critical in the early evolution, when the activity level in the Universe was very much higher, by about a factor of 30 near redshift near 1.7 (e.g., Pugliese et al. 2000); some clusters of galaxies are known to harbour two radio galaxies, even today.

4.1. Reheating of gas in clusters of galaxies

Repeating the same argument for clusters of galaxies the cooling time may be shorter than the Hubble time in many cases, especially locally, but would then just lead to a refueling of an Active Galactic Nucleus, which then through the action of its jet, reheats the local environment; and we know from the work of Falcke et al. (Falcke & Biermann 1995, Falcke et al. 1995a, Falcke et al. 1995b, Falcke & Biermann 1999) that the jet carries a power equivalent to the visible electromagnetic radiation, and so easily can provide substantial heating. Also, the recent XMM-Newton findings illustrate the necessity to consider the heating from radio galaxies in the cores of clusters (Churazov et al. 2002, Böhringer et al. 2002, Brüggen et al. 2002). As almost all galaxies are now known to harbor a central black hole, this threshold argument should work with most galaxies in a cluster.

5. Cosmological structure of magnetic fields

Here we describe some cosmological simulations that show what happens with magnetic fields (Biermann et al. 1997, Ryu et al. 1998). We then explore the topology of magnetic fields in a medium subject to continuous excitement of turbulence, again as an example for both the interstellar and the intergalactic medium (Lee et al. 2002).

As shown in the large scale simulations by Ryu et al. (Biermann et al. 1997, Ryu et al. 1998), the baryonic flow in the large scale structure formation draws the magnetic fields along, so as to reproduce the galaxy distribution also in the magnetic field distribution. The magnetic field is strongest in clusters of galaxies, somewhat weaker in the filaments, even weaker in the sheets, and very weak in the voids. The flow is along the filaments and sheets towards the next cluster or supercluster, pulling the magnetic fields along. The clusters, filaments and sheets are all bounded by shocks; the existence of these shocks is supported by observational data (Enßlin et al. 1998, Enßlin et al. 2001).
5.1. Topology of magnetic fields

In any otherwise homogeneous medium continuously excited by turbulence the magnetic field can form long flux tubes, depending on the intermittency, a measure of the Alfvénic Mach number of the turbulence injection. The weaker the magnetic field on average, the stronger the inhomogeneity of its distribution.

Therefore we have to consider a highly inhomogeneous medium in density, in magnetic fields, and probably also in cosmic rays. And yet, on average the time scales for their supply and decay are so close to each other, that an apparent regularity is reached.

6. Lepton energy distribution

We furthermore discuss the two sources of leptons so as to predict the lepton energy distribution, critical to understand the inverse-Compton and synchrotron emission in clusters; leptons are expected both from the primary acceleration of electrons starting from the thermal tail, as well as from pion decay following p-p collisions between energetic protons and the medium itself (Falcke & Biermann 1995, Falcke et al. 1995a, Falcke et al. 1995b, Falcke & Biermann 1999, Enßlin & Biermann 1998).

There are two basic modes of lepton energy distribution; we consider two modes using diffusive shock acceleration as an example to illustrate:

First, those electrons accelerated outwards in phase space from the thermal tail, i.e. starting with a power law from somewhere near the peak of the Maxwellian; this Maxwellian itself could be relativistic, since electrons get thermally relativistic from temperatures near $10^{10}$ K already. Also, this power law might have several different slopes, as a function of energy, in response to losses, or in response to changes of the diffusion coefficient as a function of energy in the acceleration region. This latter effect might happen if the electrons at first sample an electric field in the case that their Larmor radius is actually smaller than the thermal proton Larmor radius, which is likely to define the thickness of a shock (and then with the post-shock temperature). The first effect might happen if synchrotron and inverse Compton losses cut on immediately after the acceleration is finished, or even inside the acceleration region. Also, if the shock is relativistic itself, further modifications to the spectrum might exist (e.g. Bednarz & Ostrowski 1998).

Second, the electrons might be the decay products from pion decay, and in this case there would be an equal number of positrons; if neutrons are also produced in collisions, and their subsequent decay is far away in distance, then locally the electrons and positrons would differ slightly in number density. In this second case the energy distribution starts near the pion mass, and is strongly suppressed at lower energies (only inelastic collisions fill this part of phase space, an effect which is well known from anti-protons). Following pion decay the peak of the energy in the population is near pion mass in most cases, as opposed to the thermal case (above), where that peak is normally near the rest mass of the electron (i.e. for spectral indices near to or steeper than -2 in the energy

Figure 5. Grey scale images of density (left panels) and contours of magnetic field lines (right panels) at an epoch from simulations with various field strength of intermittent turbulence in a 2D case, with a magnetic field, stretched along into long flux tubes. In the density images, brighter regions represent higher values and the gray scale has been set arbitrarily to highlight structures. (Lee et al. 2002)
distribution, written in transrelativistic momentum $pc$: $4\pi (pc)^2 f(pc)$, where $f(pc)$ is the 3D distribution function. As a consequence, for instance, given the same energy content in the lepton population, the radio emission may be very different between the two cases, since the electrons responsible for radio emission usually are those far above either threshold, but have a very different flux.

Obviously, adiabatic losses can shift these spectra around in phase space, synchrotron and inverse Compton losses can truncate them at the top energies, while ionization losses can truncate or weaken it at the lower energies, all subsequent to acceleration.

In earlier work we have argued that radio galaxies typically use the second mode, and derive all the leptons visible through radio synchrotron emission from pion decay. The pions are created near the base of the jet (Biermann et al. 1995, Falcke & Biermann 1995, Falcke et al. 1995a, Falcke et al. 1995b, Falcke & Biermann 1999).

7. Tests

High spatial resolution Rotation Measure data should give a clue on intermittency and Alfvén number of turbulence, a key ingredient in understanding both the interstellar medium and the intergalactic medium.

Comparison of soft/hard X-rays, line emission and absorption should show whether we are in the convective or diffusive limit for cosmic ray transport and, consequently, will delimit the effect of cosmic ray heating. $\gamma$-rays will provide another test, as will the connection to low frequency
radio emission (e.g. Enßlin et al. 1997, Enßlin & Biermann 1998, Brüggen et al. 2002).

8. Summary

Clusters of galaxies probably have a chaotic relaxation cycle with their input of thermal energy, magnetic energy, and cosmic ray energy; we predict that radio galaxies provide the bulk, when considered the long term effect.

The maximum of the sum of the energy density of magnetic fields and cosmic rays is probably near equipartition with the thermal gas, due to the relaxation cycle probably being extended to a factor of order ten below equipartition.

Energy input may occur from radio galaxies at random rare times, mergers, the accretion shocks, and possibly even starbursts in merged galaxies.

So there are two limits that we consider to be possible. Consider the energy distribution:

\[ E_B + E_{CR} \simeq (1/10)^{1 \ldots 1} E_{th} \]  

(7)

where \( E_B, E_{CR}, \) and \( E_{th} \) are the total energy content in the cluster intergalactic medium for magnetic fields, cosmic rays, and the thermal energy.

1) The evolution of the ratio of the two sides is highly time dependent, with occasional deep dips, or
2) The ratio is only slowly varying.

Obviously, considering the dependencies on location in the gas this ratio will be extremely time-dependent, and vary by powers of ten.

The extreme cases of complete equipartition, and the case of highly intermittent injection of cosmic rays and magnetic fields, along with the heating provided by jets, in a mode where the intergalactic medium is pushed to its stability limit, might be well worth exploring. Also, the case, when the magnetic field is relatively weak at injection, but then stretched into long flux tubes that enhance its effect, should be considered. The medium is also likely to be extremely inhomogeneous, with filaments and folded sheets of higher density, different temperature, and different cosmic ray particle density. And yet, in all its complexity, it is plausible that simple rules govern its average behavior. Such is suggested by the radio-far infrared correlation of the thermal dust emission with the non-thermal radio emission, and the presumably thermal X-ray emission from normal galaxies and starburst galaxies. Taking radio galaxy explosions in place of supernova explosions, and considering clusters of galaxies in place of the interstellar medium, it appears plausible that similar simple relationships govern the intergalactic gas - we just need to discover them.

Acknowledgments. PLB appreciates the diligent work of making suggested improvements to the manuscript by the editor St. Bowyer,
and my colleague P.P. Kronberg. PLB would like to thank P.P. Kronberg and T. W. Jones for many years of very inspiring discussions. High energy work with PLB is funded through grant 05 CU1ERA/3 from DESY/BMBF. The collaboration between HK, DR and PLB has been funded by the DFG in Germany and KOSEF in Korea.

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