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COSMIC RAY ACCELERATION DURING LARGE SCALE STRUCTURE FORMATION

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ABSTRACT

Clusters of galaxies are storage rooms of cosmic rays. They confine the hadronic component of cosmic rays over cosmological time scales due to diffusion, and the electron component due to energy losses. Hadronic cosmic rays can be accelerated during the process of structure formation, because of the supersonic motion of gas in the potential wells created by dark matter. At the shock waves that result from this motion, charged particles can be energized through the first order Fermi process. After discussing the most important evidences for non-thermal phenomena in large scale structures, we describe in some detail the main issues related to the acceleration of particles at these shock waves, emphasizing the possible role of the dynamical backreaction of the accelerated particles on the plasmas involved.

Key words : acceleration of particles – cosmology: large scale structure – shock waves

I. INTRODUCTION

The non-thermal pressure support in galaxy clusters is currently unknown and historically considered as negligible compared with the thermal pressure contributed by the material fallen in the gravitational potential well of dark matter and thereby heated to approximately the virial temperature. On the other hand, the discovery of the confinement of cosmic rays in clusters (Volk et al. 1996, Berezinsky, Blasi, & Ptuskin 1997) implied that the energy content of these structures in the form of cosmic rays should increase with time. It is therefore a natural conclusion that, if cosmic rays are efficiently accelerated in the cluster neighborhood, they will be confined therein for cosmological time scales and eventually represent some sizeable fraction of the total pressure support. The inelastic proton-proton interactions of these cosmic rays with the intracluster gas are the most direct channel for the production of gamma rays, through the generation and decay of neutral pions, and in fact current gamma ray observations have already been used to constrain the cosmic ray energy density in a limited set of clusters, for different assumptions on the spatial distribution of the non-thermal pressure (Blasi 1999). Additional limits have been obtained more recently from the comparison of the newly measured flux of radio emission from the Coma cluster at a few GHz (Thierbach et al. 2003) and the predicted radio emission from secondary electrons produced in pp scatterings (Reimer et al. 2004). Most of these limits are rather model dependent and sensitive to the spatial distribution and energy spectrum of cosmic rays in the intracluster medium.

More recently it has become clear that the role of electrons accelerated at shocks arisen during the formation of the large scale structure of the universe is crucial for the generation of gamma radiation (Loeb & Waxman 2000) because of the relatively short lifetime of these particles for inverse Compton scattering (ICS) off the photons of the cosmic microwave background (CMB). This emission is expected to contribute to an uncertain extent to the extragalactic diffuse gamma ray background (EDGRB): in (Loeb & Waxman 2000) it was argued that all of the EDGRB could be explained in terms of ICS of relativistic electrons, while later estimates led to numbers one order of magnitude lower (Gabici & Blasi 2003b). Contrary to some statements appeared in the literature (Colafrancesco 2002; Kawasaky & Totani 2002), no association of clusters of galaxies with unidentified EGRET gamma ray sources could be assessed in a statistically significant way (Reimer et al. 2003; Scharf & Mukherjee 2003).

Despite the absence of firm proof of gamma ray emission from clusters of galaxies or more in general from large scale structures, strong evidences exist now of the presence of non-thermal phenomena in this class of objects. Extended radio emission in the form of radio halos and radio relics have been found (see (Feretti et al., 2004) and references therein for a review of these phenomena), while some clusters of galaxies also appear to be sources of hard X-ray emission (see (Petrosian, 2004) and references therein for a review). There are hints of a correlation between the presence of radio halos in rich clusters of galaxies and the occurrence of a recent merger event (Buote, 2001).

The models that attempt to explain the observations fall in three classes, that we refer to as *primary* electron models (Fujita & Sarazin 2001, Blasi 2001, Miniati et al. 2001a), *secondary* electron models (Dennison 1980, Colafrancesco & Blasi 1998, Blasi & Co-

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lafrancesco 1999, Dolag & Ensslin 2000), and *reacceleration* models (Schlickeiser, Sievers & Thiemann 1987, Brunetti et al. 2001, Petrosian 2001, Brunetti et al. 2004). The first two are distinguished depending on whether the radiating electrons are directly accelerated through some kind of mechanism, or rather generated as a result of production and decay of charged pions in inelastic proton-proton scatterings. In the reacceleration models the radiating electrons are re-energized through the interaction of MHD waves with a population of relic electrons, pre-existing the formation of the radio halo.

Present observations, mainly those in the radio band, seem to suggest that the extended diffuse radio halos are best explained by the reacceleration models, while many arguments can be identified against the primary and secondary electron models, as discussed below and by Brunetti in these proceedings (Brunetti 2004).

This paper is structured as follows: in section II we describe the main attempts to explain the observations and the diagnostic tools that can be used to discriminate among them. In section III we describe our view of the perspective for detection of gamma rays from clusters of galaxies. In section IV the process of particle acceleration at shock waves created during the formation of clusters of galaxies and filaments is described. We show there that the backreaction of the accelerated particles on the shock itself is likely to be strong. We conclude in section V.

II. NON-THERMAL PHENOMENA IN CLUSTERS AND THEIR EXPLANATION

The richest set of data on non-thermal activity in clusters is related to radio halos (Feretti et al. 2004) and the best studied radio halo is that of the Coma cluster, despite the fact that it is certainly not one of the brightest. Observations show a roughly power law spectrum extending to a few GHz with a steepening that appears to be a cutoff, as confirmed by the recent measurement of Thierbach et al. (2003). The surface brightness of the Coma cluster has also been measured at different frequencies: the extension of the radio halo has been shown to be smaller at high frequencies than it is at low frequencies. In the inner part of the cluster, the spectrum of the radio emission is as flat as $\nu^{-0.8}$ (Giovannini et al. 1993). This spectral steepening as a function of the distance from the center of the cluster is one of the most challenging pieces of information to be explained. This wealth of information on the radio emission contrasts with the poorness of the data on the hard X-ray excess, which appears to be present only in a few clusters (Petrosian 2004). The models that attempt to explain the observations fall in three classes, that we will refer to as *primary* electron models, *secondary* electron models, and *reacceleration* models. The first two are distinguished depending on whether the radiating electrons are directly accelerated through some kind of mechanism, or rather generated as a result of production and decay of charged pions in inelastic proton-proton scatterings. In the reacceleration models the radiating electrons are re-energized through the interaction of MHD waves with a population of relic electrons, pre-existing the formation of the radio halo.

In the following we will concentrate our attention on the extended radio emission rather than on the X-ray excess, since it provides a much richer set of constraints on the physics of the acceleration and propagation of cosmic rays in the intracluster medium.

The *primary* models are those in which electrons are directly accelerated at shock waves formed during merger events or other violent processes in the cluster volume (Fujita & Sarazin 2001, blasi 2001,Miniati et al. 2001a). While these models can easily reproduce the shape of the volume-integrated spectrum of the radio radiation, as generated through synchrotron emission of electrons with an *ad hoc* spectrum, the morphology of the generated radio halo is unlike that observed in radio halos: the short lifetime of the required electrons, due to ICS energy losses, implies that the emission should be concentrated in rim-like regions around the sites where the electrons are accelerated (for instance the merger related shock waves), while the observed radio emission appears to be spread out over Mpc scale structures. In addition to the extended emission, radio radiation is sometimes also observed in the vicinity of shock waves (Markevitch 2004, these proceedings).

In the inner part of the clusters, where the radio halos are brighter, the merger related shock waves have very low Mach numbers (Gabici & Blasi 2003a) and the spectra of accelerated particles are therefore too steep to explain observations (similar results were obtained by Berrington & Dermer (2003) and by Inoue (these proceedings)). Moreover, the efficiency of acceleration at these shocks is expected to be very low (see for instance Fig. 6 of (Ryu et al. 2003) and Fig. 3b here), although this expectation depends somewhat on the injection recipe assumed for the calculations. On this basis it appears unlikely that electrons accelerated as primaries at merger related shocks can explain the spectrum and morphology of the observed radio halos.

In this perspective, *secondary electron models* appear to be very appealing: in these models, electrons are generated through the decays of charged pions, resulting from inelastic proton-proton interactions. The confinement of cosmic rays within the cluster volume (Volk et al .1996, Berezinsky et al. 1997) over cosmological time scales enhances the energy density in the form of cosmic rays in the intracluster medium and this increases the probability for these particles to interact and produce secondaries. It is worth reminding that the protons confined in the intracluster medium also include most of the cosmic rays accelerated outside the clusters and eventually advected inside through the accretion flow, driven by gravity. This accretion process results in the formation of shock waves with potentially very high Mach numbers, since they propagate in a cold non-virialized medium (Bertschinger 1985). These shocks were considered as sites for particle acceleration by Volk et al. (1996) and by Berezinsky et al. (1997), while clear evidence is found of spatially extended filamentary-like shock surfaces in numerical simulations (Ryu et al. 2003). Protons accelerated at these shock waves would finally end up being accumulated within clusters of galaxies, and the spectrum of these cosmic rays is expected to be as flat as E^{-2}, as predicted by the linear theory of particle acceleration. This expectation is satisfied only as far as the fraction of the energy dissipated by the shock is very small, while non-linear effects modify this prediction in a substantial way when an appreciable fraction (even of the order of 10%) of the kinetic energy crossing the shock is converted into accelerated particles. Note that even in the strongly non-linear regime, the fraction of particles which are accelerated can be very small, of the order of $\sim 10^{-4}$.

Secondary electron models were first proposed by Dennison (1980) and considered in detail by Colafrancesco & Blasi (1998) and by Blasi & Colafrancesco (1999). More recently these models have been revived by many authors (e.g. Dolag & Ensslin (2000) and Miniati et al. 2001b) for radio halos and (Pfrommer & Ensslin 2004) for radio mini-halos). It has been known for some time now that the very general features of the observed radio halos could be reproduced by secondary electron models (see for instance (Blasi 2001) for a calculation involving both primary and secondary electron models). What is hard or impossible to explain through these models are the details, which therefore become the tool to discriminate among different explanations.

The maximum energy of accelerated protons depends on many unknown quantities, and on the specific acceleration process responsible for the injection of protons. Within clusters, as discussed in (Berezinsky et al. 1997), there are many potential sources of cosmic rays: normal galaxies are expected to provide only a small fraction of the cosmic rays in the intracluster medium; active galaxies and shock waves associated with the process of structure formation are expected to be the dominant sources of cosmic rays in large scale structures. In all these cases the estimates of the maximum energy of the accelerated particles are large enough that no cutoff in the GHz region of the synchrotron emission of the secondary electrons should be expected. Secondary electrons generate power law radio spectra that extend way beyond the GHz region. This point was recently used in (Reimer et al. 2004) to impose a limit on the energy density in the form of cosmic rays in the intracluster medium of the Coma cluster.

The spectrum of the synchrotron emission in the context of the secondary electron model is expected to be rather independent of the spatial location in the cluster, so that no spectral steepening is expected, while the observations show it, at least in the case of the Coma cluster and in some other cases in which spatially resolved spectra are available. Both these issues point strongly against the secondary electron models. One could play with the maximum energy of the protons and try to obtain the spectral steepening as well as the steepening in the volume integrated spectrum, by lowering this maximum energy way below the existing estimates. However, even assuming that this procedure has any physical motivation, it was shown by Brunetti (2003) and more recently in (Brunetti 2004) that the energetic requirements for the model to work are unacceptably large and therefore to be discarded on the basis of the observations listed above. In addition, if the evidence (Buote 2001) that seems to be emerging of a correlation between recent or ongoing mergers and the presence of radio halos is confirmed by future observations, the secondary electron model has an additional problem in that the radio emission would be dominated at any time by the electrons produced by the pile up of cosmic ray protons during the merger history of the cluster, rather than by the last merger event. No correlation should therefore be expected. It is worth stressing once more that all these conclusions have been derived on the basis of observations carried out in very few clusters. As such, these conclusions are hardly extendable to a more general context at the present time.

The third class of models of the non-thermal activity in the intracluster medium is that based on the possibility that low energy electrons, relics of the past activity of the cluster or injected in a past flare event from an active galaxy in the intracluster medium, could be reenergized due to resonant or non-resonant interactions of these electrons with MHD turbulence, possibly associated with the merger history of the cluster. These models were first introduced by Schlickeiser, Sievers & Thiemann (1987), and later investigated in great details by Brunetti et al. 2001, and by Petrosian (2001).

The nice feature about these models is that electrons develop a so-called inverse spectrum, with a bump at high energy. This bumpy structure cuts off at the maximum Lorentz factor of the electrons which is typically of the order of $\sim 10^5$, as determined by the balance between the acceleration rate and the rate of energy losses for ICS. The maximum energy is relatively low since the acceleration process is alike a second order Fermi process and is therefore rather inefficient compared with shock acceleration. The presence of a bump in the spectrum implies that the synchrotron emission at a given frequency is dominated by electrons with different energy (and therefore with different spectrum) depending upon the local strength of the magnetic field. This process easily accounts for the spectral steepening, while the volume integrated spectral cutoff is naturally produced by the presence of the maximum Lorentz factor. The time during which the process is effective is of only a few hundred million years, so that the emission is expected to correlate with the most recent or even ongoing merger event, and gradually dies out with time after the merger (Brunetti et al. 2004).

The rather disappointing aspect of this explanation is the complexity of the mechanism: despite the basic physics involved is rather simple, the details of the development of the MHD turbulence and its interaction with the relic electrons is all but understood. Each type of MHD turbulence has its own channels of wave-particle interactions and there are numerous different types of turbulent modes that can be excited (Alfven waves, slow and fast magnetosonic modes, Whistler modes, and so on). When fluid turbulence is injected in the intracluster medium, the mechanism for its conversion to MHD turbulence is not established as yet, although several possibilities have been investigated: one of the channels which are used most often in the recent literature is the so-called Lighthill mechanism (Fujita, Takizawa & Sarazin 2003), which couples the fluid and MHD turbulence and therefore allows to carry out detailed calculations of the development of the MHD waves and their interaction with charged particles. The cascading process from large to small spatial scales, those most relevant for the acceleration process (at least for Alfven turbulence), is also matter of much investigation in plasma physics, but it would be an underestimate of the complexity of the situation to say that it is by now clear how this non-linear process works.

All these different pieces of the model need to be further investigated and probably much input can come from the study of turbulence in environments in which we have more control, such as in the solar system or near the Earth or again in the Galaxy, where second order Fermi processes are also expected to be at work. Despite the complexity of the mechanism however, the basic features of the observations can easily be accomodated within the *reacceleration models*, which makes them unique at the present time.

Until recently, the calculations involved in the reacceleration model were carried out in a stationary regime, namely assuming that both the spectra of electrons and waves were time-independent. Moreover there was the hidden assumption that electrons were the only population of charged particles present in the intracluster medium. These assumptions were both relaxed in a recent work (Brunetti et al. 2004), where the fully time-dependent coupled equations for electrons, protons and waves were solved, in the case of Alfvèn waves as the main channel of MHD turbulence. The presence of the protons (thermal and non-thermal) is crucial for understanding the effects of the interactions of electrons with Alfvèn waves, because these waves can resonate with thermal protons and relativistic protons, while they only resonate with suprathermal electrons. The net effect of the presence of the protons is to reduce the transfer of energy from waves to electrons, and therefore damp the acceleration process. It was calculated that if more than $\sim 5\%$ of the thermal energy of the cluster is in the form of relativistic protons with a power law spectrum, the radio halos would not be effectively generated (Brunetti et al. 2004). This constraint can be substantially relaxed in the case of magnetosonic waves (Cassano and Brunetti, in preparation). More work is being carried out on the role of turbulent reacceleration on the secondary electrons and positrons generated from pp collisions (Brunetti and Blasi, in preparation), which represents a realistic situation in which the radio emission would be generated by reaccelerated secondary electrons, but the gamma ray signal may still be present because of a substantial presence of hadrons.

III. GAMMA RAYS FROM CLUSTERS OF GALAXIES

The main motivation for interest in the gamma ray emission arose as a consequence of the possibility of cosmic ray confinement in the intracluster medium, and consequently the possibility that radio halos could be the result of synchrotron emission from secondary electrons. A natural by-product of the model is the copius production of gamma radiation as a result of the decay of neutral pions. Calculations of this emission from single clusters of galaxies have been carried out by Ensslin et al. (1997), Blasi & Colafrancesco (1998) and Blasi (1999).

Gamma radiation in the intracluster medium can also be generated as a result of the ICS of high energy electrons off the universal photon background. This finding was proposed by Loeb & Waxman (2000) as a possible explanation of the extragalactic diffuse gamma ray background. In (Gabici & Blasi 2003b) it was shown that the contribution of clusters of galaxies to the diffuse gamma ray background was actually limited to $\sim 10\%$ of the measurement reported by Sreekumar et al. (1998) (see (Strong, Moskalenko & Reimer 2004) for a revised estimate of the extragalactic gamma ray background). This contribution is dominated by the accretion process, rather than by the acceleration of electrons during merger events, as a consequence of the weakness of the typical shocks involved in merger events in the central parts of clusters (Gabici & Blasi 2003a). This new estimate appears to be close to the results reported in (Keshet et al. 2004).

The detectability of the gamma ray signal from the electrons accelerated at either merger or accretion related shocks also depends on the strength of the shocks formed in either one of these cases. In (Gabici & Blasi 2004) the LogN-LogS of clusters of galaxies as gamma ray sources was calculated, as it is shown in Fig. 1a, where the typical sensitivities of GLAST, AGILE and EGRET are also indicated. The calculations refer to the case of a constant efficiency of electron acceleration of 5%, independent of the Mach number of the shocks. The electrons accelerated in this way provide a negligible contribution to the diffuse radio emission and to the hard X-ray emission.

Although the initial motivation to believe that there may be a gamma ray emission from clusters of galaxies was related to the need to explain the non-thermal ac-

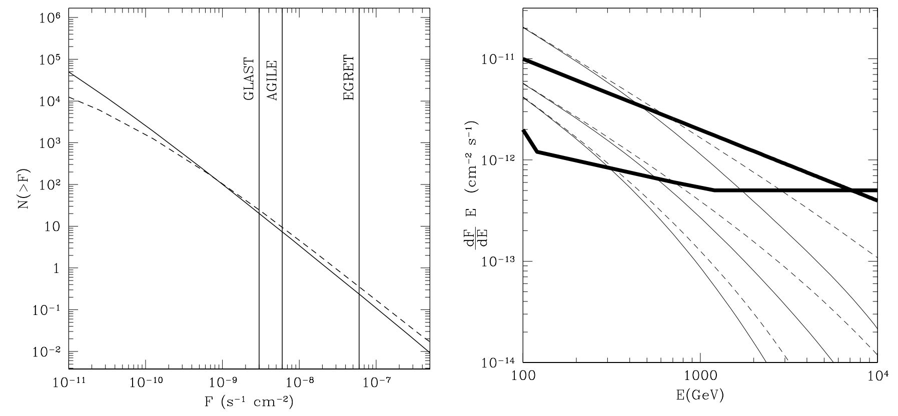

Fig. 1.— a) Number of accreting (solid line) and merging (dashed line) clusters with gamma ray flux greater than F. The vertical lines represent the GLAST, AGILE and EGRET sensitivity for point sources. b) Gamma ray emission in the 100 GeV - 10 TeV region. The thick solid lines represent the sensitivities of a IACT for point sources (lower curve) and extended sources (upper curve). The predicted gamma ray fluxes from a Coma-like cluster at a distance of 100 Mpc with and without absorption of the infrared background are plotted as dashed and solid lines respectively.

tivity of such clusters at other wavelengths, the present situation appears to be quite different: secondary electron models appear to be inadequate to properly describe observations, at least in those few cases in which the data are good enough, as for the Coma cluster. As a consequence, in those cases the present observations can only be used to impose limits on the amount of non thermal protons confined in the intracluster medium, and therefore on their gamma ray signal. In addition to this possible pp signal, as illustrated in Fig. 1a, GLAST should be able to identify the ICS signal, if the efficiency for particle acceleration of electrons is large enough.

The corresponding signal in the TeV region is much more uncertain: the decay of neutral pions may provide a flux in this energy region, as shown for instance by Blasi (1999). However the energy density in the form of cosmic rays required for a measurable flux is close to or even in excess of the equipartition level. As for the ICS signal from electrons accelerated at shocks during structure formation, the maximum energy and the efficiency for electron acceleration are the crucial quantities. Assuming that the magnetic field in the acceleration region is large enough (or amplified enough) to allow for the acceleration up to multi-TeV energies, then the ICS emission may extend up to a few TeV.

In Fig. 1b we plot the results of our calculations for the high energy gamma ray spectrum generated from a Coma-like cluster of galaxies at 100 Mpc distance for the case of merger and accretion. The effect of the gamma ray absorption in the infrared background (IRB) is illustrated by the difference between the solid lines (with absorption) and dashed lines (without absorption).

From top to bottom, the lines refer to three different cases: 1) a merger between two clusters with masses $10^{15}M_{\odot}$ and $10^{13}M_{\odot}$; 2) an accreting cluster with mass $10^{15}M_{\odot}$ with a magnetic field at the shock in the upstream region $0.1\mu G$; 3) an accreting cluster with mass $10^{15}M_{\odot}$ with a magnetic field at the shock in the upstream region $0.01\mu G$.

The thick solid lines represent the sensitivities for a generic Cherenkov telescope as calculated in (Aharonian et al. 1997). These results are obtained considering an array of imaging atmospheric Cherenkov telescopes (IACT) consisting of n cells, each consisting of a 100×100 m^2 quadrangle with four '100 GeV' class IACTs in its corners. The two thick curves in Fig. 1b represent the minimum detectable fluxes for point sources (lower curve) and an extended 1° wide source (upper curve) for an exposure time of 1000 hours. The exposure time here is defined as the product between the observation time and the number of cells that form the array. For instance, an exposure of 1000 hours can be achieved with a 100 hours observation performed by an array consisting of 10 cells.

IV. SHOCK ACCELERATION DURING STRUCTURE FORMATION

The supersonic motion of baryon-loaded dark matter clumps results in the formation of shock waves, if there is enough magnetic field in the background medium to mediate the build-up of a collisionless shock. At least in the case of mergers between clusters, these shocks are indeed observed (Markevitch, these proceedings). More problematic is the detection of shock waves in the intergalactic medium outside the virialized regions, since the gaseous environment is much less dense and the temperatures are much lower there. On the other hand these external shocks are crucial for understanding the role of cosmic rays in large scale structures, because most cosmic rays accelerated in these outskirts are finally advected in the central parts, where they get confined for cosmological times (Volk et al. 1996, Berezinsky et al. 1997).

In recent times, much interest has arisen on the distribution of Mach numbers of the shock waves related to structure formation, since the spectrum of the accelerated particles is fully determined by the Mach number, at least in the context of the linear theory of shock acceleration. In (Miniati et al. 2000) a histogram was presented of the number of shocks per unit Mach number in the central Mpc of a cluster, which showed a pronounced peak at Mach number $M = 5$, while practically no shock was *detected* at lower values of M. A simple model for the development of merger related shocks in the hierarchical picture of structure formation (Gabici & Blasi 2003a) showed that in fact a pronounced peak at $M \sim 1.5$ was to be expected. This conclusion appears to be confirmed, at least qualitatively, even from observations: for all cases in which the Mach number of merger related shocks could be measured, the inferred Mach number is $M \sim 1 - 3$ (Markevitch, these proceedings).

It is sometimes argued that in the approach of Gabici & Blasi (2003a) strong shocks are not correctly accounted for. However, strong shocks are associated very seldomly with merger events, and more often with phenomena occurring in the outskirts of the cluster. These shocks were included in (Gabici & Blasi 2003a, 2004) where the accretion processes were accounted for.

The fact that simulations were missing the weak shocks was confirmed by the work of Ryu et al. (2003), in which simulations were carried out for different choices of the spatial resolution in the simulations. That work showed that: 1) an increasing number of weak shocks was *visible* when increasing the resolution; 2) most energy was dissipated at Mach numbers $M \sim 2 - 4$. Both conclusions have been confirmed by more recent simulations by the same authors.

The second finding actually hides several complex pieces of information: in (Ryu et al. 2003), the dissipation in the form of cosmic rays was evaluated by adopting a simple but physically motivated recipe for the injection, namely the so-called *thermal leakage injection.* This recipe adopts an injection momentum p_{inj} as a multiple of the momentum of thermal particles p_{th} and assumes that the particles that take part in the acceleration process are those with momenta in excess of p_{inj}. The choice of p_{inj} is a guess, since the details of particle injection still represents one of the most serious problems of particle acceleration at shock waves. With the reasonable choice made by Ryu et al. (2003), the shocks that dissipate most energy in the form of cosmic rays are those with Mach numbers $M \sim 2 - 4$. Unfortunately, in this narrow range of Mach numbers, the spectra of accelerated particles change from very steep ($E^{-3.3}$) to very flat ($\sim E^{-2.26}$) in the linear theory of shock acceleration, so that it becomes crucial to understand which shocks take most of the energy. The question is therefore *what is the role of weak shocks?* Weak shocks can certainly contribute to heat the gas in the intracluster medium, but they also play an important role in reaccelerating the pre-existing cosmic rays. The role of re-acceleration was considered by Gabici & Blasi (2003a) but is ignored in other calculations. Moreover, their role in the acceleration of fresh particles from the thermal pool depends very sensibly on the recipe for the injection (Blasi, Gabici and Vannoni, in preparation), and this recipe is all but established: the conclusion that shocks with Mach number ~ 2 are inefficient accelerators depends on this recipe and should not be taken as a model independent and universally true statement.

The most important recent developments in the study of particle acceleration at newtonian shock waves are related to the effects of the backreaction of the accelerated particles upon the shock itself. For a strong shock, linear theory implies that the particle spectrum approaches E^{-2}, which is energy divergent, unless a maximum momentum is adopted. Even doing so, it can happen that the pressure in the form of cosmic rays can approach or exceed the available kinetic energy ρu^2. As a consequence, the backreaction of the accelerated particles cannot be neglected any longer. Moreover, the escape of the particles at the maximum momentum make the shock *radiative* and therefore more compressible. All these effects go in the direction of making the shock a more efficient accelerator, therefore implying a stronger backreaction. This is a typical example of a non-linear run-away system. The main effects of this non-linear backreaction are 1) the production of a cosmic ray mediated precursor in the upstream section; 2) the acceleration of particles to non-power-law spectra; 3) reduced efficiency of the shock in the heating of the background plasma.

The implications of these effects for large scale structures were suggested by Kang (2003), Gabici & Blasi (2004a) and Kang & Jones (2004) and are now recognized as crucial to understand the role of cosmic rays in clusters of galaxies and their neighborhood.

Several approaches, both analytical (Malkov 1997, Malkov, Diamond & Volk 2000, Blasi 2002, Blasi 2004) and numerical (Ellison 1991, Kang, Jones & Gieseler 2002) exist in the literature to treat the non-linear effects of particle acceleration. In order to illustrate the main results, we adopt here the approach first introduced by Blasi (2002), and generalized by Blasi (2004), while adding the recipe of thermal leakage for the injection (see (Gabici and Blasi 2004a) for further details). This calculation allows us to calculate analytically and in a relatively simple way the spectrum of the accelerated particles, the shape of the precursor and the temperature of the gas at any point upstream and downstream. The details of the calculations will be published elsewhere (Blasi and Gabici, in preparation).

In the calculations, the injection is chosen in such a way that all the particles with momentum larger than $p_{inj} = \xi p_{th}(T_2)$, with $\xi = 3.5$ are injected in the accelerator. It is worth stressing that the thermal momentum is fixed by the temperature of the downstream gas, which is not a free parameter but an output of the non-linear calculations. In this way, the system regulates the amount of energy to be transferred to the

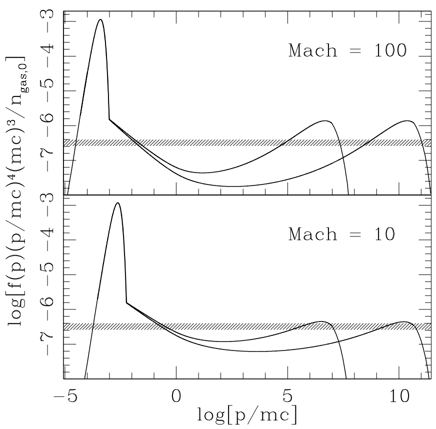

Fig. 2.— Proton spectra at the shock location for different values of the shock Mach number and of the maximum momentum of the accelerated particles.

non-thermal particles. The only parameter left free is the maximum momentum p_{max} of the accelerated particles which is determined by either the finite size of the shock or by energy losses.

In Fig. 2 we plot the spectra of protons at the shock location for Mach number $M = 100$ (upper panel) and $M = 10$ (lower panel) and for $p_{max}/(m_c c) = 10^7$ and $p_{max}/(m_c c) = 5 \times 10^{10}$. The normalization of the curves is such that these spectra reproduce those expected for protons accelerated at the accretion shock of a Coma-like cluster and therein confined (see (Gabici and Blasi 2004a)). The concave shape of the spectra, typical of non-linear particle acceleration at shocks, is clear in the figures. It is also worth stressing that in current numerical simulations it is difficult to achieve maximum momenta larger than ~ 100 GeV (Kang & Jones 2004), while for the application to clusters of galaxies much larger values are expected. In this respect, analytical calculations represent a unique tool to tackle the problem of evaluating the non-linear backreaction of cosmic rays on the shocks in large scale structures. The maxwellian distribution in Fig. 2 represents the spectrum of the particles in the downstream fluid, at the temperature determined through the calculations.

As stressed above, one of the consequences of the non-linear backreaction of cosmic rays on the shocks induced by large scale structures is that the gas is heated less than it would be at shocks where cosmic rays are absent (if there were anything like that). In Fig. 3a, we plot the temperature ratio between downstream infinity and upstream infinity T_2/T_1 for an ordinary shock (dotted line) and for a cosmic ray modified shock for $p_{max} = 10^2$, 10^6 and 5×10^{10} GeV (from top to bottom) as a function of the Mach number of the shock. It is possible to see that typically the heating is not affected appreciably for low Mach number shocks, while it is considerably suppressed for strongly modified shocks.

In Fig. 3b we also plot the fraction of flux (in units of $(1/2)\rho u^3$) which is effectively advected downstream, the fraction of flux which escapes at p_{max} and the sum of the two, which saturates to a number very close to unity for large Mach numbers. It is important to recognize that the relevant flux which is later confined in the cluster volume is that advected downstream, rather than the total flux. The latter is in fact dominated for large Mach numbers by the escaping flux, which by definition does not end up at downstream infinity.

V. CONCLUSIONS

There is now clear evidence of the existence of non-thermal phenomena associated with the formation of the large scale sctructure of the Universe. Most information on the mechanisms responsible for the acceleration of the radiating particles can be gathered from observations of the diffuse radio emission from the intracluster medium. In the few cases in which we have enough information about the radio emission, as for the Coma cluster, the data on the volume integrated spectrum, on the spectral steepening as a function of the distance from the center of the cluster, and the correlation between radio halos and recent merger events all seem to play against the so-called secondary electron models. The morphology of these radio halos also contradicts the possibility that the radiating electrons are accelerated as primary particles in merger related shock waves. The possibility that currently is favored by observations is that the radiating electrons are the result of reacceleration of relic electrons, possibly due to MHD turbulence.

Shock acceleration at the collisionless shocks formed during structure formation is a very important issue in the study of non-thermal phenomena in clusters of galaxies, as it has already been recognized to be in the case for particles acceleration at shocks in supernova remnants. Indeed the typical Mach numbers and velocities of the shocks involved in the two cases are very similar. The confinement of cosmic rays in clusters might provide us with a unique tool to explore the non-linear mechanism of shock acceleration (see for instance (Gabici & Blasi 2004a) for an investigation of the generation of gamma rays in this regime).

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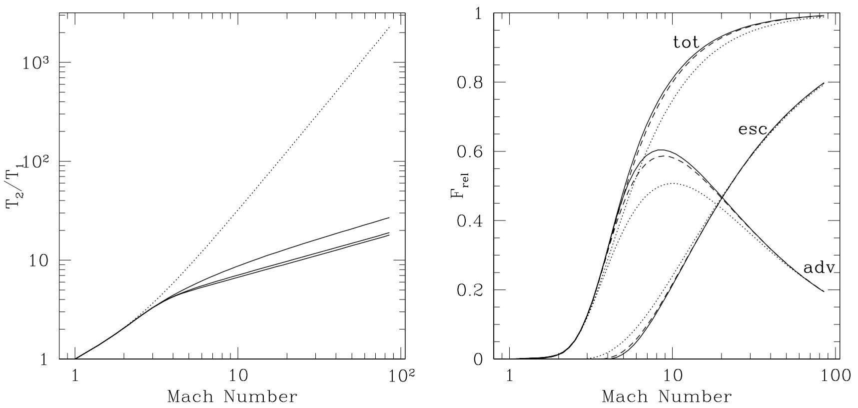

Fig. 3.— a) Temperature ratio between downstream and upstream infinity as a function of the Mach number (see text). b) Efficiencies for advected particles, escaping particles and total efficiency as functions of the Mach number.

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