Gamma Rays from Clusters of Galaxies

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Abstract

The nonthermal radiation observed from a handful of clusters of galaxies (CG) is the proof that particle acceleration occurs in the intracluster medium (ICM). It is often believed that shock surfaces associated with either mergers of CG, or with the cosmological inflow of matter onto clusters during structure formation may be the sites for acceleration. We discuss here the effectiveness of shock acceleration in the ICM, stressing that merger related shocks are typically weak, at least for the so-called major mergers. We investigate the implications of shock strenghts for gamma ray emission from single CG and for their detectability with future gamma ray satellites (such as GLAST and AGILE) and ground based Cherenkov telescopes. We also discuss the contribution of clusters to the extragalactic diffuse gamma ray background (EDGRB).
Cluster Mergers

The relative velocity of two merging clusters, $V_r$, can be easily calculated from energy conservation:

$$-\frac{G M_1 M_2}{r_{\text{vir},1} + r_{\text{vir},2}} + \frac{1}{2} M_r V_r^2 = -\frac{G M_1 M_2}{2 r_{12}}$$

where $M_r$ is the reduced mass and $r_{12}$ is the turnaround radius, where the clusters are supposed to be at rest (in fact, the final value of $V_r$ is quite insensitive to the exact initial conditions).

The sound speed of the halo $i$ is given by:

$$c_{s,i}^2 = \frac{5}{9} \frac{G M_i}{r_{\text{vir},i}}$$

where we used the virial theorem to relate the gas temperature to the mass and virial radius.
Following Lacey & Cole (1993) we can construct the merger tree of a cluster with present mass $10^{15}$ solar masses. The big jumps here represent major merger events while the small jumps corresponds to accretion events. For each merger event we can estimate the relative velocity between the two clusters and the ICM sound speed.
Distribution of the Mach numbers $V_r/c_{s,i}$ of merger related shocks as a function of the mass ratio of the merging clusters. We consider here 500 different realizations of the merger tree for a cluster with present mass $10^{15}$ solar masses. The upper strip is the distribution of mach numbers in the smaller cluster, while the lower strip refers to the bigger cluster. (Gabici & Blasi, 2003a).
We plot here the probability to have a merger with a shock having Mach number larger than a certain value. The greatest part of the merger shocks are weak \((M \sim 1.5)\). This is a consequence of the fact that these shocks propagate in the hot, virialized ICM. Accretion shocks, located at the cluster periphery and propagating in the cold, nonvirialized external medium, are characterized by high Mach numbers \((M \sim 100-1000)\) (Gabici & Blasi, 2003c)
Particle Acceleration

At merger or accretion shocks particles are accelerated to relativistic energies via first order Fermi process. Requiring that acceleration (in the Bohm diffusion approximation) occurs faster than losses (inverse compton on the CMB photons) we obtain the following expression for the maximum energy:

\[ E_{\text{max}} \sim 63 \ B (\mu G)^{1/2} h(R)^{-1/2} V_8 \ \text{TeV} \]

that correspond to a maximum energy for the upscattered photons equal to:

\[ \epsilon_{\text{IC}} \sim 10 \ B (\mu G) h(R)^{-1} V_8^2 \ \text{TeV} \]

Here \( B \) is the magnetic field, \( V_8 \) is the upstream velocity in \( 10^8 \) cm/s and \( h(R) \) is a function of the compression factor of the shock.
The accelerated particles have a power law spectrum in momentum with slopes related to the shock Mach number $M$ through:

$$\alpha = 2 \frac{M^2 + 1}{M^2 - 1}$$

For major mergers, involving clusters with comparable masses, the Mach numbers are of order unity and the spectra of accelerated particles are steep. In order to obtain flat spectra ($M > 3$) we have to consider mergers between clusters with very different masses. Electron spectra are normalized assuming that a fraction $\eta = 0.05$ of the energy passing per unit time and unit area through the shock is converted to relativistic electrons.

Recently Loeb & Waxman (2000) have proposed a connection between the EDGRB and the process of large scale structure formation. The claim is that the whole EDGRB can be explained in terms of inverse Compton scattering of electrons accelerated up to ultrarelativistic energies at shocks during structure formation. We reevaluated here this contribution and we conclude that at most $\sim 10\%$ of the observed EGRBR can be explained by invoking the process described above (Gabici & Blasi, 2003b).
Diffuse emission

The diffuse gamma ray emission from merging clusters is:

\[
I_\gamma(\epsilon_\gamma) = \frac{c}{4 \pi H_0} \int_0^{z_{\text{max}}} \frac{dz}{S(z)} \int_0^\infty dM \, n(M, z) \int_0^M dM' \, R(M, M', z) Q_\gamma(\epsilon, (1+z), M, M') \Delta t_{\text{mer}}
\]

where \(n(M, z)\) is the differential comoving number density of clusters with mass \(M\) at redshift \(z\) (Press & Schechter, 1974) and \(R(M, M', z)\) is the rate at which clusters of mass \(M\) merge at a given redshift \(z\) in function of the final mass \(M'\) (Lacey & Cole, 1993). \(S(z)\) depends on cosmology, \(Q_\gamma\) is the rate of \(\gamma\)-ray production for each merger and \(\Delta t_{\text{mer}}\) is the duration of a merger event.

For accreting clusters (we assume here that a spherical strong shock forms approximately at the virial radius) we have:

\[
I_\gamma(\epsilon_\gamma) = \frac{c}{4 \pi H_0} \int_0^{z_{\text{max}}} \frac{dz}{S(z)} \int_0^\infty dM \, n(M, z) Q_\gamma(\epsilon(1+z), M, z)
\]
Diffuse $\gamma$-rays from accreting (red line) and merging (green line) clusters. The blue line is a more realistic estimate of the diffuse flux from merging clusters in which we have considered only the clusters with mass greater than $10^{13} M_\odot$. The shaded yellow region represents the EGRET observations of the extragalactic background.

Accreting clusters contribute at most $\sim10\%$ of the extragalactic $\gamma$-ray diffuse emission while mergers can account only for $\sim1\%$ of the background (Gabici & Blasi, 2003b).
We make here predictions on the number of clusters that could be detected by future gamma ray telescopes such as GLAST and AGILE. The number of accreting clusters with flux stronger than $F_{\text{min}}$ can be calculated as:

$$C(F_{\text{min}}) = \int_0^\infty dz \frac{dV}{dz} \int_{M(F_{\text{min}}, z)}^\infty dM n(M, z)$$

where $M(F_{\text{min}}, z)$ is the mass of a clusters accreting at redshift $z$ whose flux is $F_{\text{min}}$. While for merging cluster we have:

$$C(F_{\text{min}}) = \int_0^\infty dz \frac{dV}{dz} \int_{M_{\text{min}}}^\infty dM n(M, z) \int_{M_{\text{min}}}^M dM' R(M, M + M', z) \Delta t_{\text{mer}} \theta[F_{\text{min}} - F_{\text{y}}]$$
The solid line represents the number of accreting clusters with flux greater than $F_{\text{min}}$ while the dashed line refers to merging clusters. The three vertical lines represent the EGRET, AGILE and GLAST sensitivity for point sources. None of the unidentified EGRET sources should be associated with a cluster (and none has in facr be detected, see Reimer et al. 2003), while AGILE and GLAST should detect respectively ~10 and ~50 objects (Gabici & Blasi, 2003c).
TeV emission.

The maximum energy for the $\gamma$-ray photons falls in the TeV range, so that clusters could be potentially detected by Cherenkov telescopes. The thick lines represent the sensitivities for a generic telescope as calculated in Aharonian et al. (1997). The thin dashed lines represent the predicted spectra for (from top to bottom): a merger between a $10^{15}$ and a $10^{13} M_\odot$ cluster, a $10^{15} M_\odot$ accreting cluster with magnetic field at the shock equal to 0.1 and 0.01 $\mu$G. The assumed distance is 100 Mpc. The thin solid lines are the spectra of clusters calculated taking into account the absorption of $\gamma$-rays due to pair production in the infrared background.
Conclusions

✔ Shock Mach numbers are often weak, following a distribution strongly peaked at $M \sim 1.5$ (result confirmed by simulations; see Ryu et al. 2003);

✔ Merging and accreting clusters of galaxies can account at most for $\sim 10\%$ of the diffuse extragalactic $\gamma$-ray background. Our estimate is in agreement with recent results of numerical simulations (Miniati, 2002; Keshet et al., 2002);

✔ None of the unidentified EGRET sources should be associated with clusters of galaxies, in agreement with observations (Reimer et al. 2003) while AGILE and GLAST will be able to detect respectively $\sim 10$ and $\sim 50$ clusters.

✔ The perspective of detecting inverse Compton emission with Cherenkov telescopes does not appear to be optimistic.
References.