Shock Acceleration and gamma radiation in Clusters of Galaxies

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Abstract

The nonthermal radiation observed from a handfull of clusters of Galaxies is the proof that particle acceleration occurs in the intracluster medium. It is often believed that shock surfaces associated with either mergers of clusters of galaxies, 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 intracluster medium, stressing that merger related shocks are typically weak, at least for the so-called major mergers. We investigate the implications of shock strengths for gamma ray emission from single clusters of galaxies and for their detectability with future gamma ray experiments such as GLAST. We also discuss the contribution of clusters of galaxies to the extragalactic diffuse gamma ray background.

1. Merger shocks and particle acceleration

Nonthermal radiation is observed from several clusters of galaxies, showing that accelerated particles are present in the intracluster medium. Although the processes responsible for the acceleration are poorly known, there are some hints that they may be related to the merging processes that build up the clusters from smaller substructures. During cluster mergers, shock waves are formed due to the supersonic relative motion, and particle acceleration may take place through the first order Fermi process [1,2]. In [3], shock acceleration during cluster mergers was investigated without *ad hoc* assumptions on the strength of the shocks. The compression factors of these shocks were instead calculated from the physical properties of clusters involved in the process of hierarchical structure formation. In Fig. 1 we plot the distribution of Mach numbers of shocks formed during mergers that end up in a cluster of mass $10^{15} M_{\odot}$ at the present cosmic time. This plot shows that the large majority of mergers have Mach numbers below 2, which correspond to spectra of accelerated particles which are much steeper that those that can explain nonthermal observations in the radio band. Only $\sim 6\%$ of the mergers have spectra flatter than $E^{-2.4}$ (corresponding to Mach numbers larger than 3), which suggests that Fermi acceleration at merger shocks may not

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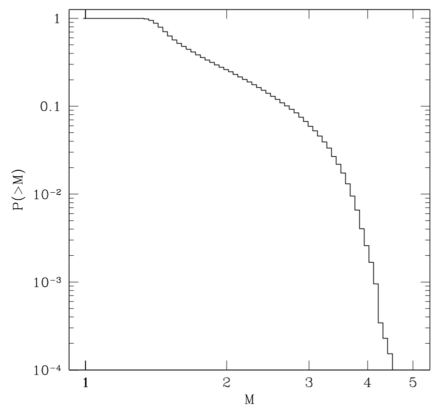

Fig. 1. Distribution of Mach numbers during mergers of two clusters of galaxies, as obtained in [3].

be the main process for the generation of nonthermal particles in the intracluster medium.

2. Clusters as single gamma ray sources

Shock fronts are formed in clusters of galaxies either due to merger events, or due to accretion of matter onto the potential well of a forming cluster. The latter shocks are called accretion shocks, and by definition are very strong, since they propagate in a cold non-virialized medium. Their Mach number can be up to several hundreds and Fermi acceleration generates particle spectra $\propto E^{-2}$. We concentrate here upon electrons accelerated at both merger and accretion shocks, and calculate the gamma ray emission that may be produced by these electrons as a result of their inverse Compton scattering (ICS) on the cosmic microwave background (CMB) radiation. This mechanism is efficient if diffusion of the particles around the shock front is well described by Böhm diffusion and if the magnetic field is large enough in the shock upstream proximity. If these conditions are not fulfilled, it may happen that the maximum energy of the accelerated electrons is too low, and the CMB photons cannot be upscattered to gamma ray energies. In Fig. 2a we show the results of [4], where the $\log N - \log S$ for the gamma ray emission above 100 MeV from merging (dashed line) and accreting (solid line) clusters was calculated, following the merger and accretion histories. In the same plot we also indicated the sensitivity levels of gamma ray telescopes such as EGRET, AGILE and GLAST. While no cluster was predicted to be detectable by EGRET (and none has in fact been detected [5]), a few clusters should be visible with AGILE and ~ 50 clusters should be identified by GLAST. The mergers are on average brighter, because they release a large amount of energy

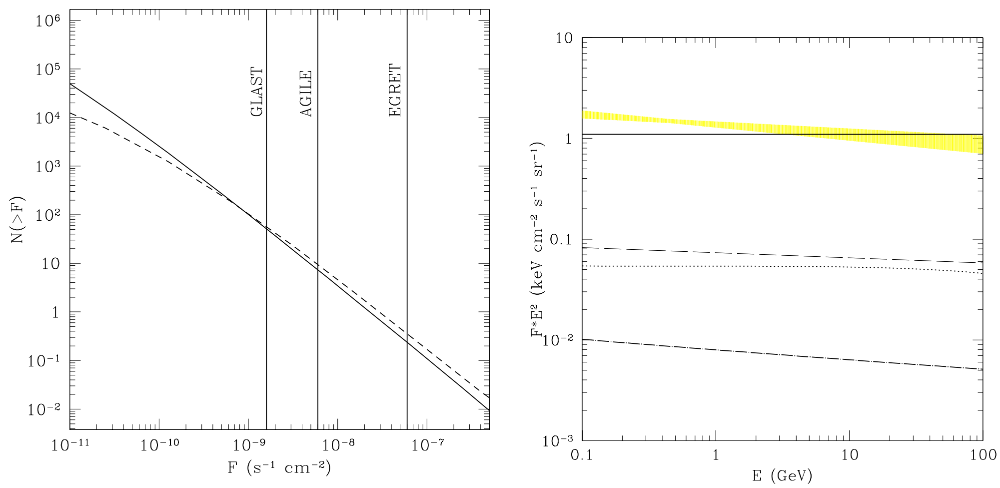

Fig. 2. *a) LogN − LogS* for mergers (dashed line) and for accretion (solid line). *b)* The diffuse gamma ray background from clusters of galaxies. See text for more information.

in a short time (about a billion years), but have spectra which are typically steep. Only for minor mergers, namely mergers involving two clusters with very different masses, the spectra are flat enough to imply a considerable gamma ray emission. For particles accelerated at accretion shocks, the opposite is true: accretion occurs over the all lifetime of a cluster and the energy involved is smaller than that released during a merger event. However, the spectra of accelerated particles are as flat as (E^{-2}) and the gamma ray signal may be detectable. These effects play together to make the $\log N - \log S$ curves for mergers and accretion roughly similar in the region accessible to current and future gamma ray telescopes. It is worth stressing however, that while mergers should become bright gamma ray sources only during the merger event itself, accretion provides a steady gamma ray emission, although limited to nearby clusters. Here we are neglecting the contribution of hadronic gamma rays, namely those produced through production and decay of neutral pions, that are the result of inelastic proton-proton collisions. This contribution can be evaluated only by carefully accounting for the injection of cosmic rays during the whole lifetime of the cluster, due to the confinement effect found in [6,7].

3. The Diffuse Gamma Ray Background

The superposition of the gamma ray emission from single clusters results in a diffuse gamma ray emission. Our results [8] are plotted in Fig. 2b, where the dashed and dot-dashed lines represent the contribution of cluster mergers to the diffuse gamma ray background (DGRB) when the minimum mass of the merging clusters is taken to be 10^{12} and $10^{13} M_\odot$ and the shaded region reflects EGRET observations [9]. Being $10^{12} M_\odot$ the mass of a galaxy, the shocks described here are not expected. In fact gas stripping is likely to occur in this case. We consider therefore the dot-dashed line as the most realistic prediction for the contribution of cluster mergers to the DGRB. The dotted line represents instead the contribution of accretion to the DGRB, and it is clear that this is the dominant contribution. The solid line in Fig. 2b is the result of a previous estimate [10] in which the shocks were all assumed strong (namely with Mach numbers $\gg 1$). As we stressed above, this is not the case. This, together with several other factors discussed in [8] explains their larger predicted DGRB. In all these curves the fraction of the kinetic pressure converted at the shocks into nonthermal electrons is taken to be $\sim 5\%$.

4. Conclusions

In [3] we first found that merger related shocks were typically weak and the corresponding spectra of shock accelerated particles steep. We included the effects of the stronger accretion shocks in [8]. This result that seemed initially in disagreement with the results of N-body numerical simulations, that predicted a peak in the Mach number distribution of merger shocks at ~ 4, was instead recently confirmed by improved numerical calculations [11].

Electrons accelerated at both merger and accretion shocks may upscatter the photons of the CMB to gamma ray energies and be detected by upcoming space-borne gamma ray telescopes, such as AGILE and GLAST. The diffuse gamma ray background generated by clusters of galaxies is about 10 times smaller that that observed by EGRET.

5. References

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