To appear in Large Scale Structure in the X-ray Universe, edited by M. Plionis & I. Georgantopoulos (Paris: Editions Frontieres), in press.

Thermal and Nonthermal Effects of Merger Shocks in Clusters of Galaxies

Craig L. Sarazin

Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22901, USA; cls7i@virginia.edu

Abstract. Cluster mergers drive shocks into the intracluster medium which heat and compress the thermal gas. X-ray observations of shocks can be used to determine the geometry and kinematics of the merger. Merger shocks should also accelerate relativistic particles. Electrons with $\gamma \sim 300$ ($E \sim 150$ MeV) are expected to be particularly common. Relativistic particles produce observed EUV emission, hard X-ray tails, and diffuse radio emission. The predicted gamma-ray fluxes of clusters should make them easily observable with GLAST.

1 Introduction

Major cluster mergers are the most energetic events in the Universe since the Big Bang. In these mergers, the subclusters collide at velocities of $\sim 2000$ km/s, and shocks are driven into the intracluster medium. In major mergers, these hydrodynamical shocks dissipate energies of $\sim 3 \times 10^{63}$ ergs; such shocks are the major heating source for the X-ray emitting intracluster medium. Mergers shocks should heat and compress the X-ray emitting intracluster gas, and increase its entropy. We also expect that particle acceleration by these shocks will produce nonthermal electrons and ions, and these can produce synchrotron radio, inverse Compton (IC) EUV and hard X-ray, and gamma-ray emission.

2 Thermal effects of merger shocks

Merger shocks heat and compress the intracluster gas, and these effects can be used to determine the geometry and kinematics of the merger. ASCA X-ray temperature maps and ROSAT images have been used in an initial effort to apply this technique. The cluster containing the radio source Cygnus A is a particularly simple case (Fig. 1). This appears to be a fairly symmetric merger with a low impact parameter. The merger is at an early phase, with the merger shocks being located between the two subcluster centers. A hydro/N-body simulation of the merger is shown at the right in Fig. 1 (not to the same scale). Presumably, the fact that the merger shocks have not yet passed through the subcluster centers is the reason why the merger hasn’t disrupted the Cygnus A radio source or...
The surrounding cooling flow. The simple geometry of this merger makes it easy to apply the shock jump conditions to determine the merger velocity. From the Rankine-Hugoniot jump conditions, the velocity change across the merger shock is

$$\Delta u_{sh} = \left[ \frac{kT_0}{\mu m_p} (r - 1) \left( \frac{T_1}{T_0} - \frac{1}{r} \right) \right]^{1/2} \gamma, \quad (1)$$

where $T_0$ and $T_1$ are the pre- and post-shock temperature, and the shock compression $r$ is given by

$$\frac{1}{r} = \left[ \frac{1}{4} \left( \frac{\gamma + 1}{\gamma - 1} \right)^2 \left( \frac{T_1}{T_0} - 1 \right)^2 + \frac{T_1}{T_0} \right]^{1/2} - \frac{1}{2} \left( \frac{\gamma + 1}{\gamma - 1} \right) \left( \frac{T_1}{T_0} - 1 \right). \quad (2)$$

For a symmetric merger, the merger velocity of the two subclusters is just $\Delta u_{cl} = 2\Delta u_{sh}$. When the ASCA temperatures are used, this gives $\Delta u_{cl} \approx 2200 \text{ km/s}$. The radial velocity distribution of the galaxies in this cluster is bimodal\(^3\) and consistent with a merger velocity of 2400 km/s.

Interestingly, the collision velocity found above is close to the free-fall velocity of $\sim 2200 \text{ km/s}$ for the two subclusters if they had fallen from a large distance to their observed separation. This consistency suggests that the shock energy is effectively thermalized, and that a major fraction does not go into turbulence, magnetic fields, or cosmic rays.
Figure 2: (a) A typical model for the relativistic electron population in a cluster of galaxies. The lower energy electrons are due to all of the mergers in the cluster history, while the high energy electrons are due to a small current merger. (b) The IC spectrum from the same model (solid curve). The dashed curve is a 7 keV thermal bremsstrahlung spectrum.

3 Nonthermal effects of merger shocks

Radio observations of supernova remnants indicate that at least a few percent of the shock energy goes into the acceleration of relativistic electrons in shocks with \( v \gtrsim 10^3 \) km/s. Even more energy may go into relativistic ions. Given that all of the thermal energy of the intracluster gas in clusters is due to shocks with such velocities, it seems likely that relativistic electrons with a total energy of \( \gtrsim 10^{52} \) ergs are produced in clusters, with perhaps even higher energies in ions. Clusters are also very good storage locations for cosmic rays. Under reasonable assumptions for the diffusion coefficient, particles with energies \( \lesssim 10^9 \) GeV have diffusion times which are longer than the Hubble time. Although high energy electrons lose energy rapidly due to IC and synchrotron emission, electrons with Lorentz factors of \( \gamma \sim 300 \) have long lifetimes. Thus, clusters of galaxies can retain low energy electrons (\( \gamma \sim 300 \)) and nearly all cosmic ray ions for a significant fraction of a Hubble time.

Recently, I have calculated models for the relativistic electrons in clusters, assuming they are primary. Fig. 2(a) shows the electron spectrum in a cluster with a typical history. Most of the electron energy is in electrons with \( \gamma \sim 300 \), which have the longest lifetimes. These electrons are produced by mergers over the entire history of the cluster. This cluster also has a small ongoing merger which produces the high energy tail on the electron distribution.

Most of the emission from these electrons is due to IC, and the resulting spectrum is shown in Fig. 2(b). For comparison, thermal bremsstrahlung with a typical rich cluster temperature and luminosity is shown as a dashed curve. Fig. 2(b) shows that clusters should be strong sources of extreme ultraviolet (EUV) radiation. Since this emission is due to electrons with \( \gamma \sim 300 \) which have very long...
lifetimes, EUV radiation should be a common feature of clusters[14]. In fact, the EUVE satellite appears to have detected all of the clusters it observed[4],[6],[7],[9].

In clusters with an ongoing merger, the higher energy electrons will produce a hard X-ray tail; the same electrons will produce diffuse radio synchrotron emission. Such radio halos are seen in a number of clusters, all of which show evidence for ongoing mergers[3]. BeppoSAX observations show hard X-ray excesses in the Coma[2] and Abell 2199 clusters. Coma has a radio halo and is undergoing at least one merger; on the other hand, Abell 2199 has no radio halo[5] nor any evidence for a merger. It is possible that the hard tail in Abell 2199 has some other explanation; for example, it might be due to nonthermal bremsstrahlung[13].

Relativistic electrons and ions in clusters are also expected to produce strong gamma-ray emission. The region near 100 MeV is particularly interesting, as this region includes bremsstrahlung from the most common electrons with $\gamma \sim 300$ and gamma-rays from ions produced by $\pi^0$ decay. The predicted fluxes are such that nearby clusters should be easily detectable with GLAST.

Acknowledgements. This work was done in collaboration with Josh Kempner, Maxim Markevitch, Paul Ricker, and Alexey Vikhlinin. It was supported by NASA grant NAG5-8390.

References
[1] Colafrancesco, S., & Blasi, P. 1998, APh, 9, 227
[2] Fusco-Femiano, R., et al., 1999, ApJ, 513, L21
[3] Giovannini, G., et al., 1993, ApJ, 406, 399
[4] Kaastra, J. S., et al., 1999, ApJ, 519, L119
[5] Kempner, J., & Sarazin, C. L. 2000, ApJ, in press
[6] Lieu, R., et al., 1996, Science, 274, 1335
[7] Lieu, R., et al., 1996, ApJ, 458, L5
[8] Markevitch, M., Sarazin, C. L., & Vikhlinin, A. 1999, ApJ, 521, 526
[9] Mittaz, J. P. D., Lieu, R., & Lockman, F. J. 1998, ApJ, 498, L17
[10] Owen, F. N., et al., 1997, ApJ, 488, L15
[11] Ricker, R., & Sarazin, C. L. 2000, in preparation
[12] Sarazin, C. L. 1999, ApJ, 520, 529
[13] Sarazin, C. L., & Kempner, J. 2000, ApJ, in press
[14] Sarazin, C. L., & Lieu, R. 1998, ApJ, 494, L177