Particle Acceleration in Clusters of Galaxies

Motokazu Takizawa,[1] Tsuguya Naito,[2] Hiroshi Ohno,[3], and Shinpei Shibata[1]
(1) Department of Physics, Yamagata University, Yamagata 990-8560, Japan
(2) Yamanashi Gakuin University, Koufu, Yamanashi, 400-8575, Japan
(3) Yamagata Junior College, Yamagata 990-2316, Japan

Abstract

Clusters of galaxies have non-thermal high energy particles as well as the thermal intracluster medium in the intracluster space. One bit of direct evidence is the existence of non-thermal synchrotron radio halos and relics. However, it is still unclear how they are accelerated. Here, we consider two kinds of acceleration processes which likely work in the intracluster space and introduce models based on them. One is shock acceleration associated with cluster mergers. We calculate evolution of non-thermal electrons during cluster merger based on N-body + SPH simulations. Radio emission is localized near the shocks. This is qualitatively similar to radio relics. The other is resonant scattering of random Alfvén waves. We calculate steady state electron distribution functions when Alfvén wave power spectra are power-law. We successfully reproduce the Coma cluster radio halo spectrum.

1. Introduction

Clusters of galaxies have not only the thermal intracluster medium (ICM), but also non-thermal high-energy particles in intracluster space. One bit of direct evidence is the existence of non-thermal synchrotron radio halos and relics[6]. This indicates that there are non-thermal electrons with energy of $\sim$ GeV in intracluster space. Recently, an excess of hard X-ray radiation over thermal emission has been detected from several clusters and groups[3,4,5], although their emission mechanism is still unclear[9].

Some observational evidence strongly suggests that such non-thermal phenomena are associated with thermal ICM, especially dynamical motion of the ICM. Radio luminosity is strongly correlated with X-ray luminosity and temperature of ICM[7]. Giovannini et al.[6] confirmed the positive correlation between the absence of cooling flow and the presence of radio halos and relics. Buote[1] shows that radio luminosity is correlated with asymmetry of X-ray image. Furthermore, most of clusters where hard X-ray is detected are merging clusters. In this paper, we consider two kinds of acceleration process, shock[10] and turbulent[8]

pp. 2059–2062

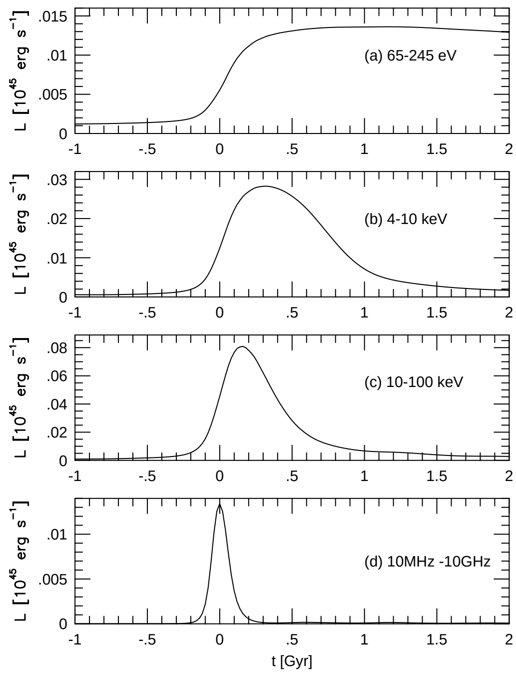

Fig. 1. The time evolution of non-thermal emission for various energy bands: from top to bottom, inverse Compton scattering of EUVE band (65-245 eV), soft X-ray band (4-10 keV), and hard X-ray band (10-100 keV), and synchrotron radio emission (10 MHz - 10 GHz). The times are relative to the most contracting epoch.

acceleration, which likely work in the intracluster space.

2. Merger Shock Acceleration

We have investigated evolution of non-thermal emission from relativistic electrons accelerated around the shock fronts during cluster merger. Dynamical evolution of cluster merger is simulated by an N-body + smoothed particle hydrodynamics code. We assume that 5% of energy dissipated at shocks is transformed into non-thermal electrons. We calculate evolution of energy spectra of non-thermal electrons taking account of Inverse Compton (IC) cooling, synchrotron loss, and Coulomb loss.

Figure 1 shows the time evolution of non-thermal emission for various energy bands: from top to bottom, IC emission of the Extreme Ultraviolet Explorer (EUVE) band (65-245 eV), soft X-ray band (4-10 keV), and hard X-ray band (10-100 keV), and synchrotron radio emission (10 MHz - 10 GHz). The times are relative to the most contracting epoch. Since cooling time is roughly proportional to E_e^{-1} in these energy range, the higher the radiation energy of IC emission is, the shorter duration of luminosity increase is. In other words, luminosity maximum comes later for lower energy band. Hard X-ray and radio emissions come from the electrons with almost the same energy range. The luminosity maximum in the hard X-ray band, however, comes slightly after the most contracting epoch. On the other hand, radio emission becomes maximum at most contracting epoch since the change of magnetic field due to the compression and expression plays an more crucial role than the increase of relativistic electrons. In any case, radio halos and hard X-ray are well associated with merger phenomena. They are observable only when thermal ICM have definite signatures of mergers such as complex temperature structures, non-spherical and elongated morphology, or substructures. Soft X-ray emission, which is observable only in clusters (or groups) with relatively low temperature ($\simeq 1$ keV) ICM, is still luminous in ~ 1 Gyr after the merger. Thus, the association with mergers in this band is weaker than in the hard X-ray band. Moreover, EUV emission continues to be luminous after the signatures of the merger have been disappeared in the thermal ICM.

3. Turbulent Acceleration

The resonant scattering condition for an electron of velocity along the magnetic field $v_{//}$ with a Alfvén wave of a frequency ω_A and wave number k is $\omega_A = kv_{//} + \Omega_e$, where Ω_e is the electron cyclotron frequency. Under this condition, the electron travels with the wave along the mean field at a locked phase. When the electron is extremely relativistic, the condition can be simplified to be $k \sim (r_l \gamma)^{-1}$, where r_l and γ are the electron's larmor radius and relativistic gamma factor, respectively. This process can be regard as a random walk process in the electron momentum space. Therefore, Fokker-Planck equation can be applied to calculate evolution of the electron distribution function.

We calculate the steady state radio spectra when the power spectra of random Alfvén wave are power-law $P(k) \propto k^{-w}$, and compare the results with Coma cluster. Figure 2 shows examples reproducing the observed radio spectrum. The observational data are drawn from Deiss et al.[2]. The best fit model is obtained when $w = 2.8$ (Figure 2a). However, a model with $w = 4.5$ (Figure 2b) cannot be ruled out considering that it is still controversial whether the spectrum break near a few GHz is real or not[2]. In any case, our results imply a steeper power spectrum of Alfvén waves than what is expected from MHD turbulence theory. This strongly suggests that the wave power spectrum is significantly modified by the back reaction of the particle acceleration.

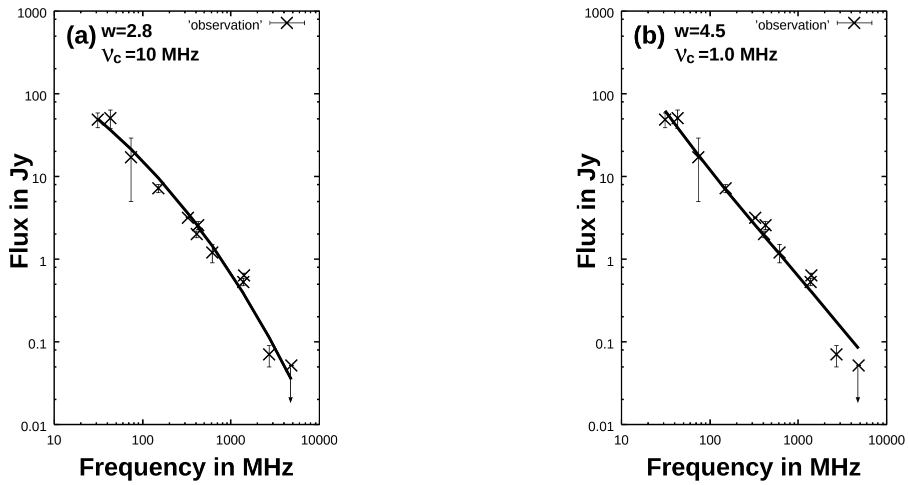

Fig. 2. Two examples reproducing the observed radio spectrum. (a) $w = 2.8$; (b) $w = 4.5$; The observed intensity is drawn from Deiss et al.[2].

4. Discussion

We consider shock and turbulent acceleration in the intracluster space. How do they work in a realistic situation? In shock acceleration model, non-thermal electrons tend to be localized near the shocks. Thus, it is good for radio relics in views of morphology. However, it is very difficult to reproduce halos with shock acceleration only. On the other hand, turbulence acceleration can occur in principle everywhere in the intracluster space. Thus, turbulence acceleration is better for radio halos.

5. References

1. Buote, D. A. 2001, ApJ, 553, L15
2. Deiss, B. M. et al. 1997, A&Ap, 321, 55
3. Fukazawa, Y. et al. 2001, ApJ, 546, L87
4. Fusco-Femiano, R. et al. 1999, ApJ, 513, L21
5. Fusco-Femiano, R. et al. 2000, ApJ, 534, L7
6. Giovannini, G. et al. 1999, New Astronomy, 4, 141
7. Liang, H. et al. 2000, ApJ, 544, 686
8. Ohno, H., Takizawa, M., Shibata, S. 2002, ApJ, 577, 658
9. Takizawa, M. 2002, PASJ, 54, 363
10. Takizawa, M., Naito, T. 2000, ApJ, 535, 586