Evolution of Intracluster Cosmic Rays and Gamma-Ray Emission

Shin-ya TSUBAKI, Tetsu KITAYAMA[2], and Katsuhiko SATO[1,3]
(1) Department of Physics, School of Science, University of Tokyo. 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033.
(2) Department of Physics, School of Science, Toho University
(3) Research Center for the Early Univese, School of Science, University of Tokyo

Abstract

The effect of merger history of clusters of galaxies on intra-cluster cosmic rays (ICCRs) is investigated. Though the effect of merger shock, which is responsible for (in-situ) acceleration of ICCRs, is ignored here, the effect of evolution is important for ICCRs and induced gamma-rays. Taking star formation history into account, we find 1) the gamma-ray flux from a cluster of galaxies is consistent with EGRET observation, and the detection by the GLAST is possible, and 2) the contribution of clusters of galaxies to the diffuse gamma-ray background is not so large, with reasonable parameter range.

1. Introduction

Based on measurements of Faraday rotation, it is confirmed that clusters of Galaxies have strong ($\sim \mu$G) magnetic fields. It means that clusters of galaxies have enough ability to confine cosmic ray particles. The existence of these particles leads non-thermal emissions.

Hard X-ray tails from non-thermal electrons is observationally established. Merging of clusters is promising model not only for X-ray emission [1,2] but also γ-ray emission [3,4]. These authors treat shocks generated by cluster merging as accelerator for cosmic ray electrons.

On the other hand, merger event means accumulation of cosmic ray particles. Larger objects have stronger effect on cosmic ray confinement. We treat merger events as only accumulator for cosmic ray particles. In addition, star formation history is also taken into account. There is possibility of tracing these histories by γ-ray observation.

2. Methods

In our calculation, cosmological parameters are set as

$$\Omega_0 = 0.3,\ \lambda_0 = 0.7,\ \sigma_8 = 1.0,\ h = 0.7. \quad (1)$$

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Our calculation is based on the simplified diffusion equation:

$$\frac{dN(t)}{dt} = -\frac{N(t)}{\tau} + Q(t), \tag{2}$$

where $N(t)$ is number of cosmic ray particles in an object, τ is typical diffusion timescale, and $Q(t)$ is particle injection rate. τ is estimated by a diffusion coefficient D as

$$\tau = \frac{R^2}{6D}, \quad D \equiv \frac{1}{3}c\ell_{\mathrm{MFP}}, \tag{3}$$

where R is typical size of an object, which is taken as virial radius here. We translate the diffusion coefficient D to another parameter ℓ_{MFP}, which means the mean-free path of a cosmic ray particle.

The particle injection rate Q is determined by

$$Q(M, z) = q_{\mathrm{gal}} SFR(z) \left(\frac{M}{M_{\mathrm{gal}}}\right). \tag{4}$$

This means: 1) the cosmic ray emission rate of our galaxy q_{gal} is taken as a standard, and 2) star formation rate is taken into account. We use this rate $SFR(z)$ provided by [5]:

$$SFR(z) = \frac{R(z)}{R(0)}, \quad R(z) = 0.15 h_{65} \frac{\exp(3.4z)}{\exp(3.4z) + 22}. \tag{5}$$

Probability of merger event is evaluated by using extended Press-Schechter theory [6]. The probability of making an object with mass M_2 at time t_2 from an object with mass $M_1 (< M_2)$ at time $t_1 (< t_2)$ is

$$\frac{dP_1}{dM_1}(M_1, t_1 | M_2, t_2) = \frac{1}{\sqrt{2\pi}} \frac{\delta_{c1} - \delta_{c2}}{(\sigma_1^2 - \sigma_2^2)^{3/2}} \left|\frac{d\sigma^2}{dM_1}\right| \exp\left[-\frac{(\sigma_{c1} - \sigma_{c2})^2}{2(\sigma_1^2 - \sigma_2^2)}\right]. \tag{6}$$

Using these formalism, our calculation scheme is as follows.

1. At the initial redshift z_{ini}, all objects have no particles: $N(z_{ini}) = 0$.
2. During a given interval $\Delta t = t_{dyn}(z)$ (t_{dyn} means a dynamical time), particles will escape from objects.
3. After leaking, all objects are mixed up. The mixing ratio is estimated by

$$N(M_2, t + \Delta t) = \int_{M_{min}}^{M_2} N(M_1, t) \frac{dP}{dM_1}(M_1, t | M_2, t + \Delta t) dM_1. \tag{7}$$

4. Step 2 and 3 will be repeated up to present time ($z = 0$).

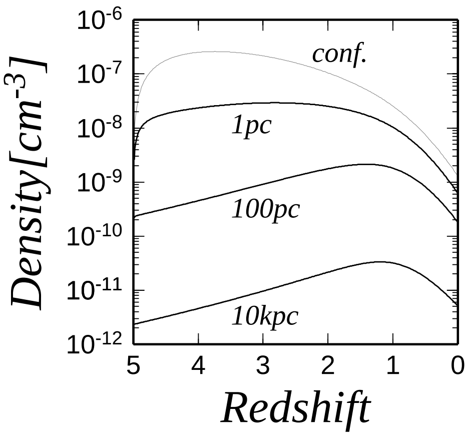

Fig. 1. Evolution of particle density in a Coma-like cluster. "conf." means completely confined case ($\ell_{MFP} = 0$), and another lines are $\ell_{MFP} = 1, 100, 10$kpc, respectively.

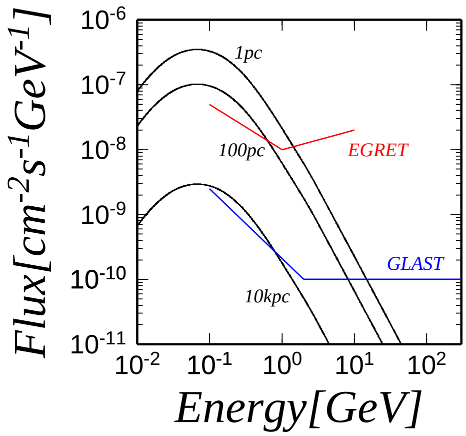

Fig. 2. γ-ray emission from a Coma-like cluster. The detection limit for EGRET and GLAST(in design) is also superposed.

3. Results

Figure 1 shows our result for a Coma-like cluster. Here $z_{ini} = 5$ and the variance of this parameter is less effect on the density. When clusters of galaxies has the same ability of confinement as our galaxy ($\ell_{MFP} \sim 1$pc), the cosmic ray density at present is similar to fully confined case, so the "universal-flux" model is approximately valid. Universal flux model (*i.e.* the cosmic ray flux in our galaxy is universal in the universe) predicts γ-ray detection from the Coma cluster, which contradicts observational data.

Figure 2 shows the γ-ray flux from a Coma-like cluster. This shows that when we set $\ell_{MFP} \leq 100$pc, EGRET should detect some flux from the Coma cluster. The adequate value of ℓ_{MFP} may be some $10^3 - 10^5$pc.

Figure 3 shows the contribution these γ-ray fluxes from various objects to the diffuse γ-ray background. When we take $\ell_{MFP} = 1$pc, the predicted flux obviously exceeds observed flux by EGRET.

4. Discussion

The re-acceleration of cosmic ray particles by merger shock is ignored in our model, our result can be thought as "lower limit". Of course, when shock acceleration is taken into account, γ-ray flux will increase much more.

Here flux distortion of leaked cosmic rays from objects is also ignored. When outer space is sparse and the magnetic field strength is well small, cosmic rays will be cooled by adiabatic expansion. But this is not the case for our model.

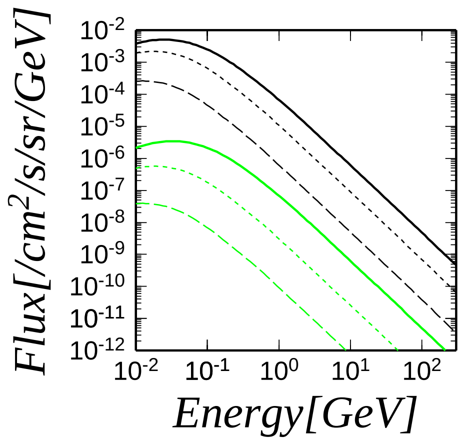

Fig. 3. Contribution to the diffuse γ-ray background. Upper 3 lines are for $\ell_{MFP} = 1$pc, and lower 3 lines are $\ell_{MFP} = 10$kpc. Solid, dotted and dashed lines mean $z = 0, 2, 4$.

Magnetic fields in outer space is rather strong. If adiabatic cooling is not so effective, we should these leaked cosmic rays taken into account.

5. Conclusion

We introduce new treatment of cluster merger effect on intracluster cosmic rays. The leaked cosmic rays from normal galaxies affect on γ-rays from clusters of galaxies and diffuse γ-ray background. Thus the mean free path ℓ_{MFP} should be large as $\ell_{MFP} \geq 100$pc.

References

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