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Multi-messenger Constraints on Particle Acceleration in the Formation History of Galaxy Clusters

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Galaxy Clusters are considered to be efficient containers of cosmic rays (CRs). In their formation history, CRs are accelerated by active galactic nuclei (AGNs) and cosmological shocks and turbulence and accumulated in the intra-cluster space. Diffuse radio emission found in massive clusters is important to probe the magnetic field and cosmic ray electrons, while the content of cosmic ray protons is highly uncertain. The variety seen in the radio emission suggests that the CR acceleration is closely related to the formation processes such as cluster mergers and mass accretion. We study the CR acceleration in galaxy clusters by modeling the multi-wavelength emission in various clusters with different formation histories. We use the so-called merger tree method to simulate the merger history of clusters. We particularly focus on the re-acceleration by merger-induced turbulence, since it is considered to be the dominant mechanism of the diffuse radio emission. We find that the combination of radio surveys and the stacking analysis of neutrino background can constrain the parameters in the re-acceleration model for the radio halos in galaxy clusters.

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1. Introduction

Galaxy clusters (GCs) are possible sources of high-energy neutrinos observed in IceCube [1, 2]. They can work as reservoirs of cosmic rays (CRs), within which cosmic-ray protons (CRPs) are accumulated over a cosmological timescale and emit gamma rays and neutrinos through the inelastic pp collisions with the nuclei in the intra-cluster medium (ICM) [e.g., 3, 4]. On the source of CRs in the ICM, previous studies compared two possibilities; cosmological (accretion) shocks, and internal sources such as AGNs [5, 6]. The intensity of the isotropic neutrino background is estimated to be almost 100 % of the IceCube flux in the internal source models [4, 5, 7, 8]. However, the density of CRPs in the ICM is highly uncertain due to the lack of diffuse gamma-ray emission from the ICM [9].

On the other hand, direct evidence of relativistic electrons in the ICM has been achieved with the observations of cluster-scale diffuse radio emission, such as giant radio halos (GRHs) [e.g., 10]. The most plausible mechanism of GRHs is so-called turbulent re-acceleration, where the non-thermal electrons are re-energized by the stochastic interaction with the merger-induced turbulence permeating the cluster volume [e.g., 11]. On the other hand, the pure hadronic model, which explains the radio emission with the secondary CRE injection from the pp collision, is challenged by the discovery of GRHs with ultra-steep spectral indexes, and the non-detection of gamma-rays from the ICM [e.g., 9, 12, 13].

The re-acceleration model requires the “seed" population of relativistic CREs that are injected before the onset of the re-acceleration. The seed population can be either directly accelerated/injected at the accelerators, such AGNs or cosmological shocks, or provided through the pp collisions of CRPs. It is shown that the re-acceleration of secondary CRe from the pp collisions can explain the radio emission of Coma without violating the gamma-ray limit [13, 14]. The limits on the hadronic emission from the ICM, i.e., gamma-rays and neutrinos, provide important constraints on the parameters of the re-acceleration model, such as the magnetic field B and the electron-to-proton ratio of primary CRs $f_{\rm ep}$.

Recently, [15] reported an upper limit on the contribution of massive GCs to the isotropic muon-neutrino background derived from a stacking analysis of *Planck* clusters. The contribution from the nearby massive clusters ($10^{14}M_{\odot} < M_{500} < 10^{15}M_{\odot}$, $0.01 < z < 0.2$) is limited to be less than $\sim 5\%$ at 100 TeV. In this work, we show that the neutrino upper limit by [15] is deep enough to provide a meaningful constraint on the re-acceleration model, especially for the case where the seed CREs originated from the pp collisions. We estimate the neutrino background from GCs using the method of [16]. We consider the re-acceleration of CRs due to the merger-induced turbulence by numerically solving the Fokker–Planck (FP) equations. The merger history of GCs is simulated with the so-called merger tree method [17, 18]. Most importantly, our model is consistent with the statistical properties of the observed GRHs, such as their occurrence and the luminosity function (LF).

2. Re-acceleration Model and Luminosity–Mass Relation

We solve the Fokker–Planck (FP) equations to follow the evolution of the CR distribution in the ICM. We consider one-dimensional distributions of CRs, ICM density, and the magnetic field.

For the magnetic field profile, we adopt the following scaling with the ICM density

$$B(r) = B_0 \left(\frac{n_{\rm ICM}(r)}{n_{\rm ICM}(0)} \right), \tag{1}$$

where $n_{\rm ICM}(r)$ is the ICM density profile, and B_0 and η_B are the parameters. We fix $\eta_B = 0.5$ [19]. The diffusion in the radial direction is neglected, since it is not significant at least for the $\lesssim 10$ GeV CRs that are responsible for the radio emission. A further discussion on the radial distribution can be found in [14]. For CRPs, the FP equation can be written as

$$\frac{\partial N_p}{\partial t} = \frac{\partial}{\partial p}\left[N_p \left(b^{(p)} - \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D_{pp}) \right) \right] + \frac{\partial^2}{\partial p^2}[D_{pp}N_p] + Q_p - \frac{N_p}{\tau_{pp}}, \tag{2}$$

where N_p is the distribution function of CRPs, $b^{(p)}$ is the momentum loss rate, D_{pp} is the momentum diffusion coefficient due to turbulent re-acceleration, Q_p is the injection rate, and τ_{pp} is the pp collision timescale [see 16, for the detail]. For CREs, it becomes

$$\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial p}\left[N_e \left(b^{(e)} - \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D_{pp}) \right) \right] + \frac{\partial^2}{\partial p^2}[D_{pp}N_e] + Q_e, \tag{3}$$

where Q_e includes both the primary CREs and the secondary electron from the pp collisions; $Q_e = Q_e^{\rm pri} + Q_e^{\rm sec}(t, p; N_p)$. In our fiducial model, we neglect the primary CREs, i.e., $f_{\rm ep} \equiv \frac{Q_e^{\rm pri}(p=1\ {\rm GeV})}{Q_p(p=1\ {\rm GeV})} = 0$. Our model is normalized with the observation of the Coma cluster. For example, we adopt the magnetic field profile with the central magnetic field of $B_0 = 4.7\ \mu$G, which is the best-fit value measured with the Faraday rotation [19]. See [16] for further details.

We consider the second-order Fermi acceleration of CRs due to the interaction with the merger-induced turbulence. Considering the resonant (transit-time) interaction between turbulent eddy and CRs, the acceleration efficiency can be estimated as

$$D_{pp} = \frac{\pi I_\theta(c_s/c)}{8c} p^2 \int_{k_L}^{k_{\rm cut}} dk k \mathcal{W}(k), \tag{4}$$

where $c_{\rm s}$ is the sound velocity of the ICM, $\mathcal{W}(k)$ is the spectrum of turbulence, $k_{\rm cut}$ is the cut-off scale, k_L is the injection scale, and $I_\theta(x) = \frac{x^4}{4} + x^2 - (1 + 2x^2)\ln x - \frac{5}{4}$ [20]. Assuming that a fraction of the gravitational energy turns into turbulent energy, one can show that the acceleration efficiency scales with the cluster mass as $D_{pp} \propto M^{1/3}$.

We obtain the luminosity–mass (LM) relation of radio and neutrino emission by solving the FP equations using the above scaling of D_{pp}. We find that the LM relation of synchrotron emission at 1.4 GHz becomes $L_{\rm radio} \propto M^{3.5}$, which is consistent with the observation [e.g., 21]. We also obtain the LM relation for high-energy neutrinos. We find $L_{E_\nu} \propto M^{5.1}$ for the 100 TeV neutrino luminosity (in the unit of [GeV/s/GeV]) in our re-acceleration model, whose index is steeper than those assumed in previous studies that do not include the re-acceleration.

3. Merger Tree and Luminosity Function

We use the merger tree build with the Monte Carlo algorithm explained in [16] and follow the evolution of cluster mass and luminosities of synchrotron and neutrino emission. We simulate the

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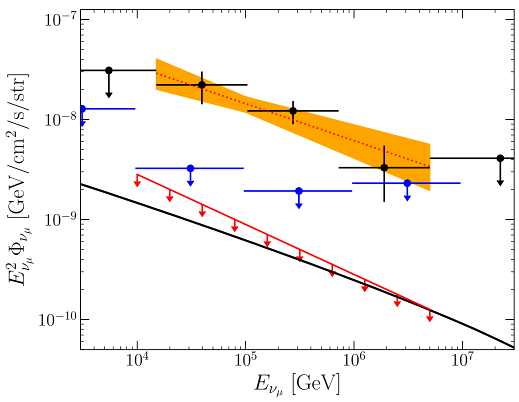

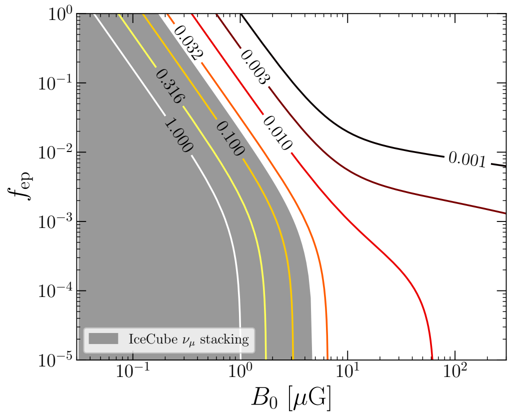

Figure 1: *Left:* Spectrum of diffuse muon-neutrino background expected in the re-acceleration model (black). The black points and the orange band shows the intensity estimated with IceCube track events [23]. The red line shows the 90% CL upper limit derived from the stacking analysis [15]. *Right:* Constraints on the model parameters in the re-acceleration model. The contour shows the fractional contribution to the total background intensity.

evolution of 4,000 halos from redshift $z = 2.0$ to $z = 0.0$. We simplify the evolution of luminosities by assuming that they have a finite value only after the mergers with a mass ratio larger than a threshold value $\xi_{\rm th}$. The mass ratio ξ is defined to be smaller than 1. We take into account the LM relation studied with the FP equations in Sect. 2, by assigning the peak luminosity as a function of the cluster mass. Further details are explained in [16].

We find that the occurrence of GRHs can be explained when $\xi_{\rm th} \approx 0.15$, in line with the expectation in [22]. The radio luminosity function (LF) in our model is compatible with the observation. We also obtained the neutrino luminosity function. one can define the effective luminosity $L^{\rm eff}_{E_\nu}$ as the luminosity that maximize $L_{E_\nu}(dN/dV_{\rm c}d\log L)$, where $dN/dV_{\rm c}d\log L$ is the neutrino LF. Due to the steep LM relation in our re-acceleration model, $L^{\rm eff}_{E_\nu}$ is as large as 10^{42} [GeV/s/GeV], which corresponds to the luminosity of clusters with $M_{500} \approx 1.5 \times 10^{15}\ M_\odot$. Thus, the neutrino background is dominated by a few nearby clusters in the re-acceleration model.

4. Neutrino Constraints on the Re-acceleration Model

Using the neutrino LF obtained above, the intensity of the isotropic neutrino background can be calculated as

$$E_\nu\Phi_\nu = \frac{1}{4\pi}\int dz\frac{dV_{\rm c}}{dz}\int dL_\nu\frac{dN}{dL_\nu dV_{\rm c}}L_\nu\frac{1+z}{4\pi D_L^2(z)}, \tag{5}$$

where $V_{\rm c}(z)$ is the comoving volume at redshift z, $\frac{dN}{dL_\nu dV_{\rm c}}$ is the luminosity function, and $D_L(z)$ is the luminosity distance.

In the left panel of Fig. 1, the spectrum of the neutrino background is compared with the observations. We find that the expectation in our re-acceleration model with $B_0 = 4.7\ \mu$G and $f_{\rm ep} = 0$ is comparable to the upper limit by [15]. This means that the neutrino upper limit already excludes the re-acceleration models that result in larger neutrino intensity, and thus the limit can be used to constrain the parameters. We especially focus on two parameters B_0 and f_{ep}, as these strongly affect the ratio between synchrotron and neutrino luminosities. The ratio of the luminosities scale as

$$\frac{L_{E_\nu}}{L_{\rm radio}} \propto \left(\frac{f_{\rm ep}^0}{f_{\rm ep}+f_{\rm ep}}\right) B^{-\frac{q+1}{2}} \left(1+\left(\frac{B}{B_{\rm cmb}^2}\right)^2\right), \tag{6}$$

where $f_{\rm ep}^0 \approx 10^{-2}$, $q \approx 3.4$ is the spectral index of CREs, and $B_{\rm cmb}(z) \approx 3.25(1+z)^2\ \mu$G [24].

In the right panel of Fig. 1, we show the constraints on the parameters B_0 and $f_{\rm ep}$. The values of parameters in the shaded region are excluded since they result in larger neutrino intensity than our fiducial model and thus in tension with the upper limit by [15]. [13] derived a similar limit, considering the gamma-ray upper limit of Coma. The central magnetic field measured with Faraday rotation ranges $B_0 \approx 1-10\ \mu$G [25], and our limit still allows the secondary seed model within this range. A neutrino limit as deep as 1% of the IceCube level will significantly constrain the scenario, where the seed population originated from the pp collisions.

5. Discussion and Conclusions

The turbulent re-acceleration model is consistent with various observational properties of GRHs, such as their steep spectral indexes, and the correlation with cluster mergers [e.g., 11]. While the pure hadronic model without re-acceleration is in tension with the gamma-ray upper limits on the Come cluster [e.g., 13], the secondary electrons from the pp collision can be the seed population for the re-acceleration [14]. In this work, we show that the limit on the neutrino background from GCs by the IceCube observation gives a meaningful constraint on the CRP content in the re-acceleration scenario.

The steep luminosity-mass relation of the observed GRHs can be explained with the re-acceleration through the resonant interaction between compressible turbulence and CRs [26]. By solving the FP equations for clusters with various masses, we find that this model predicts a steep LM relation for neutrinos. We follow the mass evolution of clusters with the merger tree and build the LFs for synchrotron and neutrino emission. We find that nearby massive GCs contribute most to the isotropic neutrino background in the re-acceleration model.

The flux of the neutrino background is only $\sim 5\%$ of the IceCube level when $B_0 = 4.7\ \mu$G and $f_{\rm ep} = 0$, which is consistent with the recent stacking analysis of *Planck* clusters [15]. The neutrino upper limit is so deep that it can constrain the central magnetic field strength B_0 and the electron-to-proton ratio of primary CRs $f_{\rm ep}$. We find that the current neutrino limit does not completely exclude the secondary scenario, where most of the seed electrons originate from the pp collisions of CRPs, considering B_0 obtained from the Faraday rotation. The combination of neutrino and radio observations is important to clarify the origin of relativistic electrons distributed over the cluster volume.

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