FORMING CLUSTERS OF GALAXIES AS THE ORIGIN OF UNIDENTIFIED GeV GAMMA-RAY SOURCES

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ABSTRACT

Over half the GeV gamma-ray sources observed by the EGRET experiment have not yet been identified as known astronomical objects. There is an isotropic component of such unidentified sources, whose number is about 60 in the whole sky. Here we calculate the expected number of dynamically forming clusters of galaxies emitting gamma rays by high-energy electrons accelerated in the shock wave when they form, in the framework of the standard theory of structure formation. We find that a few tens of such forming clusters should be detectable by EGRET, and hence a considerable fraction of the isotropic unidentified sources can be accounted for, if about 5% of the shock energy is going into electron acceleration. We argue that these clusters are very difficult to detect in X-ray or optical surveys as compared to the conventional clusters, because of their extended angular size of about \( \sim 1^\circ \). Hence, they define a new population of “gamma-ray clusters.” If this hypothesis is true, the next generation of gamma-ray telescopes, such as the Gamma Ray Large Area Space Telescope (GLAST), will detect more than a few thousand gamma-ray clusters. This would provide a new tracer of dynamically evolving structures in the universe, in contrast to the X-ray clusters as a tracer of hydrodynamically stabilized systems. We also derive the strength of the magnetic field required for the extragalactic gamma-ray background by structure formation to extend up to 100 GeV, as observed, which is about \( 10^{-5} \) of the shock-heated baryon energy density.

Subject headings: cosmology: theory — diffuse radiation — galaxies: clusters: general — gamma rays: theory — large-scale structure of universe

1. INTRODUCTION

The deepest image of the universe in the high-energy gamma-ray band beyond 0.1 GeV has been obtained by the EGRET experiment (Hartman et al. 1999). Identified sources of the third EGRET catalog include the Large Magellanic Cloud, five pulsars, and 66 active galactic nuclei (AGNs) of the blazar class. However, over half of the EGRET sources have not yet been identified as known astronomical objects, and their origin is one of the most interesting mysteries in astrophysics. The distribution of these unidentified sources can be interpreted as the sum of the Galactic component along the Galactic disk (\(| b | \leq 40^\circ \)) and another isotropic (i.e., likely extragalactic) component (Özel & Thomson 1996; see also Fig. 2 of Mukherjee et al. 1995). Several candidates have been proposed as the origin of the Galactic unidentified sources, including molecular clouds, supernova remnants, massive stars, and radio-quiet pulsars (see, e.g., Gehrels & Michelson 1999, and references therein). However, almost no candidate has been proposed to explain the extragalactic unidentified sources, except for undetected AGNs. Recently, Mirabal et al. (2000) have performed comprehensive follow-up observations for one of the high-latitude unidentified EGRET sources (3EG J1835+5918, \( b = 25^\circ \)) in X-ray, optical, and radio wavebands. They found that no known class of GeV gamma-ray sources, including blazars and pulsars, can be the origin of 3EG J1835+5918, which suggests that this source belongs to a new class of GeV gamma-ray emitters.

There are 19 unidentified sources with high Galactic latitude of \(| b | > 45^\circ \) (about 60 in the whole sky), and seven of them are noted as “em” in the third EGRET catalog, i.e., possibly extended or multiple sources that are inconsistent with single point sources. Although this “em” designation is quite subjective and we should be careful in interpreting this result (see Hartman et al. 1999 for details), this may indicate that there is an extended and extragalactic population in the unidentified EGRET sources. Recently, Gehrels et al. (2000) chose “steady” unidentified sources from the third EGRET catalog, to eliminate any source with high variability typical of flaring AGNs. These steady sources are mostly distributed at low and mid galactic latitude (\(| b | \leq 40^\circ \)), and hence should be the Galactic origin, but seven sources are still located at \(| b | > 45^\circ \), which may be steady extragalactic sources, whose number is \( \sim 24 \) in the whole sky. Therefore, steady astronomical objects with an extended nature are worth investigating as a possible origin of unidentified EGRET sources.

It is widely believed that the observed structures in the universe have been produced via gravitational instability. Currently, the most successful theory of structure formation is the cold dark matter (CDM) scenario, in which the structures grow up hierarchically from small objects into larger ones. When an object collapses gravitationally and virializes, the baryonic matter in the object is heated by shock waves up to the virial temperature. Particles are expected to be accelerated to high energy by shock acceleration, and accelerated electrons scatter the photons of the cosmic microwave background radiation (CMB) to high-energy gamma-ray bands by the inverse-Compton mechanism. Existence of such nonthermal electrons is inferred from radio and hard X-ray observations for some clusters of galaxies (e.g., Fusco-Femiano et al. 1999), although the origin of the nonthermal electrons is not yet clear. It has also recently been argued that this radiation process in the intergalactic medium may explain the diffuse extragalactic gamma-ray background radiation (EGRB) observed in the

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EGRET range (Loeb & Waxman 2000). However, it is still highly speculative and difficult to test whether this process is really the origin of the EGRB, since the contribution by unresolved active galactic nuclei is also of the same order of magnitude (see, e.g., Mücke & Pohl 2000 and references therein).

On the other hand, if the structure formation is actually an efficient radiation process for gamma rays, clusters of galaxies should be strong emitters of gamma rays when they dynamically form, and the detectability of such forming clusters as discrete sources is of great interest as a new probe of structure formation in the universe, as well as a test for the scenario proposed by Loeb & Waxman (2000) for EGRB. In this paper we make a theoretical estimate of the number and angular size of such gamma-ray-emitting clusters detectable by EGRET, based on the standard theory of structure formation in the CDM universe. We find that a few tens of such forming clusters should have already been detected by EGRET. Detectability of such forming clusters in other wavebands, such as optical or X-ray bands, will be discussed, in comparison with the conventional clusters of galaxies identified in these wavebands. We will also calculate the EGRB spectrum from structure formation and derive a quantitative relation between the higher cutoff energy and magnetic field strength.

Throughout this paper, we assume a CDM universe with the density parameter \( \Omega_m \approx 0.3 \), cosmological constant \( \Omega_k = 0.7 \), Hubble constant \( h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7 \), baryon density parameter \( \Omega_B = 0.015 h^2 \), and density fluctuation amplitude \( \sigma_8 = 1 \). These cosmological parameters are consistent with various observations, including those of the CMB fluctuations (e.g., de Bernardis et al. 2000) and the abundance of X-ray clusters of galaxies (e.g., Eke, Cole, & Frenk 1996; Kitayama & Suto 1996b).

2. GAMMA-RAY LUMINOSITY AND FLUX FROM FORMING CLUSTERS

We first estimate the gamma-ray flux of a gravitationally bound object of total mass \( M \) that virializes at redshift \( z \). The typical radius \( r_{\text{vir}} \), density \( \rho_{\text{vir}} \), circular velocity \( V_c \), and temperature \( T_{\text{vir}} \) of the object can be computed from the spherical collapse model (Peebles 1980; Kitayama & Suto 1996b) that is widely used in study of structure formation. The total gravitational energy imparted to the baryonic gas in the forming cluster is given by \( E_{\text{baryon}} \sim (3/4)\Omega_B \Omega_m M V_c^2 \). It is reasonable to expect that a fraction \( \xi_e \sim 0.05 \) of this energy goes into accelerated electrons, since such a fraction is inferred for acceleration of cosmic-ray electrons in a supernova remnant SN 1006 from X-ray and TeV observations (Koyama et al. 1995; Tanimori et al. 1998) and is consistent with the energetics among cosmic rays, turbulent motions, and supernova rate in our Galaxy. It has also been suggested that the diffuse radio and hard X-ray emissions observed in the Coma Cluster (and possibly other several clusters) can be attributed to nonthermal electrons with an electron energy fraction of the same order (e.g., Fusco-Femiano et al. 1999). Therefore, we use \( \xi_e = 0.05 \) to determine the normalization of electron energy spectrum throughout this paper.

The maximum Lorentz factor of electrons is constrained by the competition of the Fermi acceleration time and cooling time by inverse-Compton (IC) scattering of CMB photons. The acceleration time is given by

\[
t_{\text{acc}} \sim \frac{r_{\text{min}} c}{V_c^2} \approx 1.6 \times 10^{-4} \mu \text{as} \quad \text{yr}^{-1}
\]

(1) where \( r_{\text{min}} = m_e \gamma_e/(eB) \) is the Larmor radius of electrons, \( \gamma_e \) is the electron Lorentz factor, \( e \) is the electron charge, \( B_{\mu G} = B/(1 \mu \text{G}) \) is the magnetic field, and \( V_{E \\text{,3}} = V_e/(10^3 \text{ km s}^{-1}) \) is the shock velocity that is of the same order of magnitude as the circular velocity of a halo, \( V_c \). On the other hand, the IC cooling time is

\[
t_{\text{IC}} = \frac{\gamma_e m_e c^2}{(4/3)\sigma_T \epsilon_{\text{CMB}} \gamma_e^2} \approx 2.3 \times 10^{12} \gamma_e^{-1} (1+z)^{-4} \text{ yr}^{-1}
\]

(3) where \( \sigma_T \) is the Thomson cross section and \( \epsilon_{\text{CMB}} = 4.32 \times 10^{-13} (1+z)^4 \text{ ergs cm}^{-3} \) is the CMB energy density. Equating these expressions of \( t_{\text{acc}} \) and \( t_{\text{IC}} \), we have the maximum value of \( \gamma_e \) as \( \gamma_e, \text{ max} \sim 1.2 \times 10^8 (1+z)^{-1} B_{\mu G} V_{E \\text{,3}} \). We assume the energy distribution of accelerated electrons as a power law with an exponential cutoff at \( \gamma_e, \text{ max} \), i.e., \( dN_{\gamma_e}/d\gamma_e \propto \gamma_e^{-\alpha} \exp (-\gamma_e/\gamma_{\text{e, max}}) \), with the standard particle acceleration index of \( \alpha \sim 2 \). As mentioned above, the normalization of this spectrum is set by the equation

\[
\int dN_{\gamma_e} m_e c^2 \gamma_e \frac{dN_{\gamma_e}}{d\gamma_e} = \xi_e E_{\text{baryon}}
\]

(5) with the parameter \( \xi_e = 0.05 \). The observed photon energy \( \gamma_c \), scattered by electrons is related to \( \gamma_e \) as \( \gamma_c = (4/3)\gamma_e^2 \epsilon_{\text{CMB}, \gamma} \), where \( \epsilon_{\text{CMB}, \gamma} = 6.4 \times 10^{-4} \text{ eV} \) is the mean photon energy of the CMB at \( z = 0 \).

The cooling time of electrons corresponding to photon energy \( \gamma_c \) can be written as \( t_{\text{IC}} \sim 2.1 \times 10^8 (\gamma_c/\text{GeV})^{-1/2} (1+z)^{-4} \text{ yr}^{-1} \), and this should be compared with the time for the shock wave to propagate the radius of the virialized halo, \( r_{\text{shock}} \sim r_{\text{vir}}/V_c = (4/3) r_{\text{vir}}/(4V_c/3) \). Here we have estimated the shock velocity as \( V_s = (4/3)V_c \), which is the velocity of a strong shock when a material is shocked by a supersonic piston with a velocity of \( V_c \), i.e., a typical bulk velocity of material in a collapsed halo. By using the spherical collapse model mentioned above to calculate \( r_{\text{vir}} \) and \( V_c \) for the halo, this timescale can be written as \( t_{\text{shock}} = (3/4)^{1/3} \pi^{-1/2} (G\rho_{\text{vir}})^{-1/2} \sim 1.5 (1+z)^{-3/2} \text{ Gyr} \), which is essentially the dynamical time of the halo. Note that it depends only on the redshift and not on the halo mass. From this argument, the cooling time of electrons emitting gamma rays above 0.1 GeV is always much shorter than the timescale \( t_{\text{shock}} \) during which the shock is alive and a halo is an active gamma-ray emitter. Hence, the total number of gamma rays emitted from a forming halo during the time \( t_{\text{shock}} \) is given by

\[
\frac{dN_{\gamma_c}(\gamma_c, M, z)}{d\gamma_c} = \frac{m_e \gamma_c dN_{\gamma_c}}{d\gamma_c} d\gamma_c
\]

(6) and the observed photon flux of gamma rays during the shock propagation time is

\[
\frac{dF(\epsilon_{\gamma}, M, z)}{d\epsilon_{\gamma}} = \frac{(1+z) dN_{\gamma_c}}{4\pi d_L^2} \frac{1}{\epsilon_{\gamma}} t_{\text{shock}}
\]

(7) where \( d_L \) is the standard luminosity distance.
We introduce a parameter $\xi_B$ to determine the magnetic field, which is the fraction of magnetic energy density in the total baryon energy density of the halo, i.e., $B^2/(8\pi) = \xi_B E_{\text{baryon}}/(4\pi r_{\text{vir}}^3/3)$. Then, by using the spherical collapse model again, the magnetic field of a cluster can be written as

$$B \sim 0.17 \left(\frac{\xi_B}{0.03}\right)^{1/2} \left(\frac{M}{10^{15} M_\odot}\right)^{1/3} (1+z)^2 \mu G.$$  \hspace{1cm} (8)

A magnetic field of $\sim 0.1$–1 $\mu G$ is often observed in the intracluster medium of rich clusters (Kronberg 1994; Fusco-Femiano et al. 1999; Rephaeli, Gruber, & Blanco 1999), and hence we use $\xi_B = 10^{-3}$ to be consistent with the observations. It should be noted, however, that this parameter is important only for the maximum photon energy of the gamma-ray spectrum (well beyond 10–100 GeV) measured by EGRET, which is almost insensitive to this uncertain parameter, unless the particle index $\alpha$ significantly deviates from the standard value of 2.

It is interesting to apply the above model to nearby known clusters of galaxies. For example, the Coma Cluster has the total mass of $M \sim 10^{15} M_\odot$ and is located at $z = 0.023$. The flux with these parameters becomes $F > 0.1$ GeV $\sim 6.5 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$, that is, about 10 times brighter than the observational upper limit on this cluster by EGRET, $4 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ (Sreekumar et al. 1996). This does not mean, however, that our model is incorrect. Our model is relevant for just-forming clusters of galaxies in which the violent shock generated by gravitational collapse is still alive. The Coma Cluster is thought to have formed more than a few dynamical times ago and is now hydrodynamically stable after the violent shock has disappeared. Gamma-ray flux can then be much weaker than our estimation. On the other hand, it suggests that there was an epoch during which this cluster was a strong gamma-ray emitter, and also that there may be other clusters visible by EGRET that are just dynamically forming and have not yet reached hydrostatic equilibrium.

3. EXPECTED NUMBER OF GAMMA-RAY CLUSTERS DETECTABLE BY EGRET

The number of such forming clusters of galaxies with flux stronger than $F$ can be calculated as

$$N(F > F) = \int dz \int_{M(z; F)}^{\infty} dM \frac{dV}{dz} R_{\text{form}}(M, z) t_{\text{shock}},$$  \hspace{1cm} (9)

where $dV/dz$ is the comoving volume element of the universe, $R_{\text{form}}$ is the formation rate of dark halos (or clusters) per unit mass, cosmic time, and comoving volume, and $M(z; F)$ is the mass of a cluster collapsing at redshift $z$ whose flux is $F$. Here we have taken into account that clusters are active gamma-ray emitters only during the time $t_{\text{shock}}$.

There are several formulae to calculate the formation rate $R_{\text{form}}$ in the framework of the standard theory of structure formation. As is well known, the Press & Schechter (1974, PS; Peebles 1980) formalism provides a formula of mass function (i.e., number density of halos as a function of mass and redshift) that is in reasonable agreement with $N$-body simulations. Here we want the formation rate of halos rather than the mass function at a given epoch, because we need to calculate the number of collapsing objects experiencing shock at each epoch. A naive prescription to obtain this quantity is to take a time derivative of the PS mass function, $R_{\text{dPS}}$, although this is not exactly $R_{\text{form}}$ but rather interpreted as $R_{\text{dPS}} = R_{\text{form}} - R_{\text{dest}}$, where $R_{\text{dest}}$ is the rate of destruction of halos by merging into even larger structures. Consequently, $R_{\text{dPS}}$ becomes negative at small mass scales where $R_{\text{dest}}$ is significant. As shown below, however, the number of objects visible by EGRET is dominated by massive clusters forming in the recent past ($z < 1$), which are the largest structures in the universe, and hence $R_{\text{dest}}$ is negligible. Therefore, it is a reasonable approximation to use $R_{\text{dPS}}$ in the mass range where it is positive. Alternatively, there are several extensions to the PS theory for computing $R_{\text{form}}$ (e.g., Lacey & Cole 1993; Sasaki 1994; Kitayama & Suto 1996a; Percival & Miller 1999). In the following discussion we use $R_{\text{dPS}}$ and the formulae of Sasaki (1994) and Kitayama & Suto (1996a) to take into account theoretical uncertainties in $R_{\text{form}}$.

Figure 1 shows the theoretically predicted log $N$–log $F$ of forming clusters. At least a few tens of clusters should be visible to EGRET, and a significant fraction of the isotropic unidentified EGRET sources can be accounted for. It is also interesting to note that the predicted number is similar to that of "em" isotropic unidentified EGRET sources, i.e., possibly extended sources. The predicted number at the EGRET flux limit also agrees with the number of "steady" unidentified sources with $|b| > 45^\circ$ defined by Gehrels et al. (2000). This result is robust against changes in the adopted
prescription for $R_{\text{form}}$. In the bottom panel of Figure 1, we also show mean mass, redshift, and angular radius $\theta_{\text{vir}}$ corresponding to $r_{\text{vir}}$ of such gamma-ray clusters brighter than a given flux. These quantities are $M \sim 10^{15} M_\odot$, $z \sim 0.05$, and $\theta_{\text{vir}} \sim 1^\circ$ for clusters above the EGRET sensitivity limit. Considering the EGRET angular resolution, the typical radius of $\sim 1^\circ$ is consistent with the fact that a significant fraction of isotropic unidentified sources are indicated as possibly extended.

It is predicted that more than a few thousand forming clusters will be detected by future missions such as the Gamma Ray Large Area Space Telescope (GLAST; Gehrels & Michelson 1999), and the improved angular resolution may reveal the extended profile for nearby gamma-ray clusters with higher statistical significance. Another important prediction is that GLAST will observe the flattening of the log $N$--log $F$ curve due to cosmological effects, compared with the expectation of a uniform source distribution in Euclidean space (Fig. 1, top panel, dotted line).

4. EXTRAGALACTIC GAMMA-RAY BACKGROUND

Our formulation also allows us to calculate the EGRB flux and spectrum as

$$\frac{dn_\gamma}{d\epsilon_\gamma} = \int dz \int dM \frac{dN_\gamma(e_\gamma; M, z)}{d\epsilon_\gamma} R_{\text{form}}(M, z) \frac{dt}{dz},$$

where $(dn_\gamma/d\epsilon_\gamma)$ is the gamma-ray number density that is related to the EGRB flux as $(dF/d\epsilon_\gamma) = c (dn_\gamma/d\epsilon_\gamma)/(4\pi)$, and $t$ is the cosmic time. This flux becomes $\epsilon_\gamma^2 (dF/d\epsilon_\gamma) \sim 1$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at 100 MeV, in good agreement with the observation (Sreekumar et al. 1998) as well as the previous simpler estimation assuming that the average temperature of baryons in the universe is $\sim$ keV at present (Loeb & Waxman 2000). In fact, we have checked that the mass-averaged temperature of virialized halos in the universe as a function redshift, which is calculated by the PS theory, agrees within a factor of 2 with a numerical simulation (Cen & Ostriker 1999) on which the previous EGRB estimate was based. This fact gives a justification for the use of the PS theory to calculate the gamma-ray-emitting objects. The dotted line in the bottom panel of Figure 1 shows the contribution to the EGRB at 100 MeV by objects brighter than a given flux. We predict that GLAST will resolve about 20%--30% of the EGRB as discrete gamma-ray clusters, if structure formation is the major origin of the EGRB.

The strength of the magnetic field in the shocked baryons is important for the question of whether the EGRB spectrum extends up to $\sim 100$ GeV, as observed. In Figure 2 we show the EGRB spectrum with several values of $\xi_B$. This result shows that the magnetic field strength corresponding to $\xi_B \sim 10^{-3}$ of the baryon energy density is sufficient for the EGRB to extend beyond 100 GeV. The magnetic field observed in the intracluster gas ($\xi_B \sim 10^{-3}$) is much stronger than this, and it is also theoretically reasonable to expect that the turbulent motion in collapsed objects amplifies the seed magnetic field made by the battery mechanism well beyond $\xi_B \gtrsim 10^{-3}$ within the dynamical time (Kulsrud et al. 1997). Therefore, physically reasonable magnetic field strength can explain the extension of the EGRB spectrum beyond 100 GeV, and it is likely that a considerable fraction of gamma rays above 100 GeV are absorbed by the interaction with the cosmic infrared background radiation, producing electron-positron pairs. The effect of intergalactic absorption is shown in the bottom panel of Figure 2, using the optical depth of intergalactic pair-production presented in Totani (2000). The absorbed TeV gamma rays will be reprocessed into GeV gamma rays by the produced pairs, and distort the EGRB spectrum (e.g., Coppi & Aharonian 1997). Although these secondary GeV gamma rays are not taken into account here and it is beyond the scope of this paper, it will be important to study the size of this spectral distortion in future work.

5. DISCUSSION

We here discuss the expected properties of gamma-ray clusters of galaxies. Perhaps the most natural question in this regard would be “Are they already observed in other wavebands, such as X-rays or optical surveys?” We have checked that there is no statistically significant association of the ROSAT Brightest Cluster Sample (RBSC; Ebeling et al. 1998) within the 95% error circles of the unidentified sources with $|b| > 30^\circ$ in the EGRET catalog. We have also checked the correlation with the clusters in the revised Abell catalog (Abell, Corwin, & Olowin 1989), and no statistically significant associations are found, either. However, here we argue that the gamma-ray clusters proposed in this paper are very difficult to detect in X-rays or optical bands compared to ordinary clusters identified in these wavebands, and hence our scenario is not rejected by these results.

5.1. Detectability of Gamma-Ray Clusters in X-Rays

We first estimate the expected X-ray flux from gamma-ray clusters. Baryonic gas in most clusters of galaxies observed in X-rays seems to be in approximate hydrostatic equilibrium, with the surface brightness well fitted by a density profile, $\rho_{\text{gas}}(r) \propto \left[1 + (r/r_c)^2\right]^{-1}$ (e.g., Sarazin 1988),
where $r_{\text{c}}$ is the core radius, which is typically about $\sim 10$ times smaller than the virial radius. Since the X-ray emissivity is proportional to $\rho_{\text{gas}}$, the X-ray emission is strongly concentrated into the central region. Assuming the above density profile and the self-similar model as described in Kitayama & Suto (1996b), 3 a typical gamma-ray cluster detectable by EGRET with $M \sim 10^{15} M_\odot$ and $z \sim 0.05$ would have an X-ray flux $2.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in 0.1–2.4 keV.

The inverse-Compton flux is also expected to be comparable with the thermal emission. By equating $t_{\text{IC}}$ and $t_{\text{shock}}$ in § 2, we get the cooling photon energy $\epsilon_{\text{cool}} = 2.0(1 + z)^{-3}$ keV, below which the electron cooling time is longer than the dynamical time. Then the IC spectrum extends down to around the X-ray band with $dN/d\epsilon \propto \epsilon^{-2}$, while it becomes harder at wavelengths longer than X-rays with $dN/d\epsilon \propto \epsilon^{-1.5}$. If the gamma-ray flux at 100 MeV is $\sim 10^{-7}$ photons cm$^{-2}$ s$^{-1}$, which is the EGRET threshold, the IC X-ray flux $(F_{\text{IC}})$ is $\sim 1.6 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. Therefore, the thermal and IC fluxes are well above the flux limit of $\sim 4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ of the RBCS.

However, it takes nearly the dynamical time for the cluster gas to reach hydrostatic equilibrium after the collapse, and gamma rays from the shock generated by the gravitational collapse are radiated away within that period. Then it is likely that the density profile of gamma-ray-emitting clusters is more irregular and extended than that of ordinary X-ray clusters. In fact, if the unidentified “em” sources in the EGRET catalog are actually extended, they must have typical angular size of about 1°, from the source location accuracy of EGRET. As we have shown, angular size of about 1° is theoretically reasonable if the emission is extended to the virial radius. When the density profile is not concentrated into the central region but rather is constant within the virial radius, the X-ray luminosity becomes lower than the self-similar model by a factor of $\sim 3.7$, because of the lower central density.

Furthermore, the surface brightness of such loose clusters should be drastically dimmer than that of ordinary X-ray clusters. In the self-similar model with $r_{\text{vir}} \gg r_{\text{c}}$, the core gas density is $\rho_{\text{gas,c}} = (1/3)(r_{\text{vir}}/r_{\text{c}})^2 \rho_{\text{gas,vir}} \sim 50 \rho_{\text{gas,vis}}$, where $\rho_{\text{gas,vir}} = (\Omega_{\text{m}}/\Omega_0)\rho_v$ is the virial gas density, which is the average gas density within $r_{\text{vir}}$. On the other hand, if the gas density profile of gamma-ray clusters is roughly constant at $\rho_{\text{gas,vis}}$ out to $r_{\text{vis}}$, the X-ray surface brightness of such a loose cluster is dimmer than the central surface brightness of the self-similar model by a factor of $\sim (r/v)_{\text{vis}} \rho_{\text{gas,vir}}/\rho_{\text{gas,vis}} \sim 200$, since the X-ray emissivity is proportional to $\rho_{\text{gas}}^2$. This crucially affects the detectability of X-rays from gamma-ray clusters. The detectability of X-rays should be described by the signal-to-noise ratio (S/N) against the X-ray background flux. The noise level is proportional to (image area)$^{1/2}$, and hence S/N $\propto F/r$, where $F$ and $r$ are the flux and the image radius, respectively. We have compared the value of $F/r$ of the extended gamma-ray clusters detectable by EGRET and those of the clusters in the RBCS. We found that the $F/r$ of gamma-ray clusters is smaller by a factor of 3 than the minimum $F/r$ of the RBCS clusters. The absence of association between the RBCS and the EGRET sources is therefore not in contradiction to our scenario. On the other hand, deeper observation of candidate gamma-ray clusters by XMM-Newton, for example, might detect the X-ray emission extended to about 1° with the flux estimated above, which would provide a clear test of our scenario. Such X-ray emission should reflect the structure of shocks in dynamically forming clusters, and an imaging study would be of great interest.

5.2. Detectability in the Optical Surveys

Here we again emphasize that the gamma-ray clusters are expected to be more extended than clusters that have already stabilized. It is known that the surface density profile of galaxies in a cluster can be well described by the King profile, $\sigma(r) \propto [1 + (r/r_c)^2]^{-1}$, with a core radius of $\sim 100$ kpc that is comparable to the core radius of the X-ray profile (e.g., Adami et al. 1998). If we assume a roughly constant surface density out to $\sim r_{\text{vir}}$ rather than the King profile for gamma-ray clusters, the average surface density, $\sigma_{\text{av}} \sim N_{\text{gal}}(r_{\text{vir}}/r_{\text{c}})^2$, is lower than the central surface density of the King profile, $\sigma_v \sim N_{\text{gal}}[2\ln(1/\epsilon_{\text{cool}})]$, by a factor of $\sigma_{\text{av}}/\sigma_v \sim [2\ln(1/\epsilon_{\text{cool}})]^{-1}(r_{\text{vir}}/r_{\text{c}})^2 \sim 30$. Here $N_{\text{gal}}$ is the total number of galaxies within $r_{\text{vir}}$. This dimming factor is not so significant as that for the X-ray surface brightness, but that should make the optical identification very difficult, because of the contamination by foreground and/or background field galaxies. Therefore, we consider that the absence of any statistically significant association with the known optically identified clusters does not immediately reject our scenario. Instead, it will be necessary in future to study the correlation between the EGRET sources and galaxy catalogs, taking into account the possibility that the gamma-ray clusters are considerably extended. Searching in optical bands has an advantage over searching in X-rays, in the sense that the dimming of surface number density compared to ordinary clusters is less severe than for X-rays, whose emissivity is proportional to $\rho_{\text{gas}}^2$. The typical density of such loose clusters is close to the virial density, that is, about a few hundred times higher than the mean density of the universe.

We have also noticed that there are a considerable number of ‘‘em’’ sources in the EGRET sources identified as AGNs. If they were actually extended sources, it might be speculated that some of them are also gamma-ray clusters including an AGN as a member galaxy. Time variability of these sources would be an important test to check this possibility.

5.3. On the Recent Follow-Up Observations for 3EG J1835 + 5918

Recent follow-up observations by Mirabal et al. (2000) for one of the high-latitude unidentified EGRET sources (3EG J1835 + 5918) have found diffuse X-ray emission from an uncataloged cluster of galaxies at $z = 0.102$. Although this cluster is outside the 99% error ellipse of 3EG J1835 + 5918, whose radius is 12°, the separation between the centers of the X-ray cluster and 3EG J1835 + 5918 is about 0′65, which is within our expectation of the typical angular radius of gamma-ray clusters detectable by EGRET, $\sim 1′$. As discussed above, X-ray emission is expected from a region where the intracluster gas has reached hydrodynamical equilibrium, while gamma rays are emitted from a region still hydrodynamically unstable. Therefore, it is not surprising that the positions of X-ray

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3 Here we have assumed that the core radius is proportional to the virial radius as $r_c = 0.2(h/0.7)^{-1}$ kpc $\times [r_{\text{vir}}(M, z)/10^{15} M_\odot]\times([0.05])$ with $r_{\text{vir}}(10^{15} M_\odot, 0) = 2.6$ Mpc, where the normalization is chosen to match the local observations (Abramopoulos & Ku 1983; Jones & Forman 1984).
and gamma-ray emissions are different, unless the separation is well beyond the virial radius of $\sim 1'$. 3EG J1835+5918 is not an "em" source, and may not be an extended source. The radius of the 99% confidence ellipse, 0.2, is considerably smaller than the expected angular size of gamma-ray clusters. However, high-energy electrons emitting GeV gamma rays have very short lifetimes compared to the shock propagation time ($t_{\text{prop}} \sim 10^{-2} t_{\text{shock}}$), and gamma-ray-emitting regions may be very clumpy in a cluster. (On the other hand, X-ray-emitting electrons have a cooling time comparable to or longer than $t_{\text{shock}}$ for IC and thermal radiation, and hence X-ray-emitting regions should be much less clumpy and extended with the size $\sim \theta_{\text{vir}}$, as discussed in § 5.1). Therefore, it is possible that the gamma-ray size of 3EG J1835+5918 is considerably smaller than the physical size of a whole forming cluster. This consideration also suggests a possibility that some of gamma-ray clusters may be observed as multiple sources within $\sim \theta_{\text{vir}}$, which may be revealed by future gamma-ray missions.

One characteristic that the source of 3EG J1835+5918 must have is very weak radio flux, at least 2 orders of magnitude fainter than any of the securely identified EGRET blazars (Mirabal et al. 2000). The spectrum of blazars is well understood by the two components of radiation from the same population of nonthermal electrons, i.e., synchrotron radiation in radio, optical, and X-ray bands, and inverse-Compton radiation in GeV and TeV gamma-ray bands (e.g., Inoue & Takahara 1996; Kataoka et al. 1999). The ratio of luminosities produced by the two processes is, as is well known, given by the ratio of the magnetic energy density to the target photon energy density, which is typically of order unity for blazars. On the other hand, this ratio is $U_B/U_{\text{CMB}} \sim 2.7 \times 10^{-3} (B/10^{-7}) (M/10^{15} M_\odot)^{2/3}$ for gamma-ray clusters, by using the expression for $B$ given in § 2. Therefore, the $U_B/U_{\text{CMB}}$ ratio is generally much smaller than unity, and very weak radio flux compared to identified blazars can be reasonably explained.

Based on the above arguments, we suggest that the uncataloged X-ray cluster near 3EG J1835+5918 may be a gamma-ray cluster proposed in this paper, and further observations of this cluster and the surrounding region are very important. Our model predicts that a cluster emitting a flux of $6.06 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$ above 100 MeV (the flux of 3EG J1835+5918; Hartman et al. 1999) at $z = 0.102$ should have a total mass of $7 \times 10^{15} M_\odot$ and $r_{\text{vir}} \sim 5$ Mpc ($\theta_{\text{vir}} \sim 0.7'$).

6. CONCLUSIONS

In this paper we have proposed a new candidate for unidentified EGRET sources: gamma-ray clusters that are just dynamically forming and emit gamma rays due to inverse-Compton scattering of CMB photons by shock-accelerated electrons. Based on the standard theory of structure formation and assuming the injection of $\sim 5\%$ of shock energy at the formation into nonthermal electrons, we have shown that a few tens of such clusters should have already been detected by EGRET, and a significant fraction of the isotropic component of unidentified EGRET sources can be accounted for. Such gamma-ray clusters are expected to be very extended; the X-ray surface brightness and surface number density of galaxies could be lower than those of ordinary clusters by a factor of $\sim 200$ and $\sim 30$, respectively. Therefore, it should have been very difficult to detect gamma-ray clusters in the past X-ray or optical surveys, and our scenario is in accord with the apparent lack of associations between unidentified EGRET sources and X-ray or optical clusters.

It will be of great significance to perform X-ray or optical observations to search for such loose clusters of galaxies in the regions of high-latitude unidentified EGRET sources. Future gamma-ray projects such as GLAST will provide a direct test of our scenario. If our scenario is true, a new population of "gamma-ray clusters" will provide us in the future with a new probe of dynamically evolving structures in the universe that cannot be traced by X-ray or optical clusters of galaxies.

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