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A CLUSTER SURVEY AROUND THE UNIDENTIFIED EGRET SOURCES

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ABSTRACT

Based on optical galaxy data, we executed a systematic search for galaxy clusters around the 15 steady unidentified EGRET GeV gamma-ray sources in high Galactic-latitude sky ($|b| > 30°$). We found a strong correlation with 3.7σ level between close cluster pairs (merging cluster candidates) and the unidentified EGRET sources, though, in contrast, no correlation with single clusters. This result implies that merging clusters of galaxies are a possible candidate for the origin of high galactic-latitude, steady unidentified EGRET gamma-ray sources.

Key words : galaxies: clusters: general — gamma rays: unidentified sources — large-scale structure of universe — surveys

I. INTRODUCTION

It is more than 30 years since the first astronomical observation in gamma-rays, and yet the unidentified gamma-ray sources are one of the major mysteries in high energy astrophysics: more than 60% (170/271) of the gamma-ray sources listed in the Third EGRET (hereafter 3EG, Hartman et al. 1999) Catalog, the largest GeV gamma-ray sources catalog ever made, are not identified in any other wavelengths and their nature are still unclear.

The distribution of the unidentified EGRET sources can be explained as the sum of the Galactic ($|b| \lesssim 40°$) component and another isotropic (likely extragalactic) component (Mukherjee et al. 1995; Özel & Thompson 1996). While variety of candidates were proposed for the origin of Galactic sources, no astronomical object except for active galactic nuclei (AGNs) has been proposed as the origin of the isotropic component. All AGNs identified as EGRET sources belong to the blazar class, and there is no evidence that other types of AGNs are emitting gamma-rays detectable by EGRET.

Clusters of galaxies have been studied as a possible source of high-energy gamma-rays, since high-energy cosmic rays are expected to exist in intracluster medium (ICM), which could be emitted by member galaxies, or could be generated by AGNs or shocks in cosmological structure formation. Most previous studies concentrated on the hadronic processes, i.e., pion-decay gamma-rays produced by interaction between cosmic-ray protons/hadrons with intracluster matter (e.g. Colafrancesco & Blasi 1998), and predictions are well below the detection sensitivity of EGRET even for the case of the Coma cluster, for which only an upper limit has been set by EGRET (Sreekumar et al. 1996).

Also, attention to high-energy emission from nonthermal electrons is recently increasing. Loeb & Waxman (2000) pointed out that the extragalactic gamma-ray background in the GeV band may be explained by the inverse-Compton (IC) scattering of the cosmic microwave background (CMB) photons by electrons accelerated in large-scale shocks generated in structure formation, if about 5% of the shock kinetic energy is converted into nonthermal electrons.

Totani & Kitayama (2000, hereafter TK00) calculated the expected gamma-ray source counts by this process and found that a few tens of sources are expected above the EGRET sensitivity from nearby dynamically forming clusters, and a part of unidentified EGRET sources may be accounted for (see also Waxman & Loeb 2000). TK00 estimated that "gamma-ray clusters" detectable by EGRET should have a typical redshift of 0.1 and mass of $10^{15} M_\odot$. However, no statistically significant correlation between the unidentified EGRET sources and known clusters has been found.

There are several possible reasons for this result. First, only a small fraction of clusters should be emitting gamma-rays by the process considered by TK00, since the cooling time of electrons emitting high-energy gamma-rays is very short ($10^6 yr$), and hence only clusters that are dynamically forming with active shocks can emit GeV gamma-rays. The lack of detection from the Coma cluster is thus explained. We may not be able to observe gamma-rays even from clusters with merging signatures in X-ray or radio bands, which remain on much longer timescales than the gamma-ray emission. It is also difficult to select the candidates of gamma-ray clusters from all unidentified EGRET sources, since the Galactic gamma-ray sources extend to relatively high galactic latitude of $|b| \sim 45°$ (Gehrels et al. 2000); a portion of the sources at even higher latitude seem

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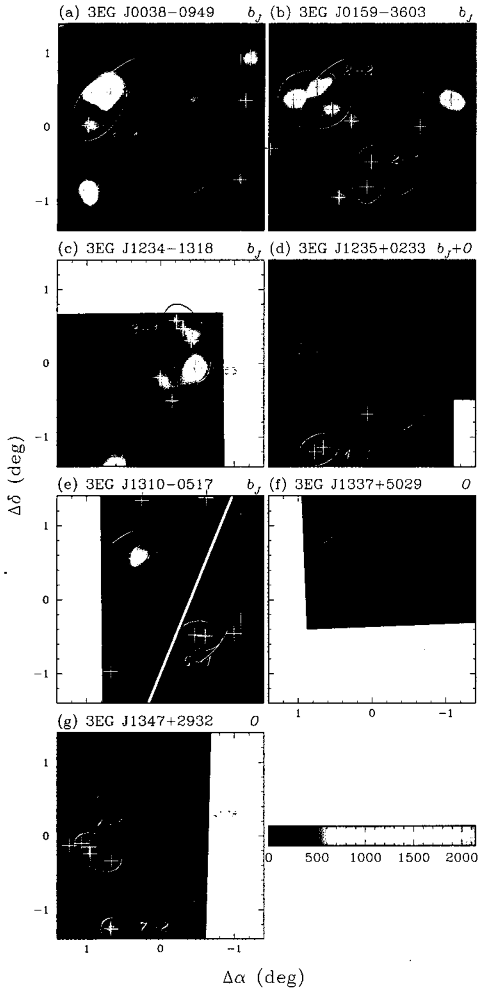

Fig. 1.— Matched filter "richness maps" for the seven regions centered at the steady unidentified EGRET sources at $|b| > 45°$. The EGRET source name and the bandpass of the galaxy data are shown at the top of each panel. The plus signs denote the Abell-like cluster candidates with $z_{est} \leq 0.15$ and Abell Richness Class ≥ 0 detected by a matched filter. (for other symbols, see the caption of Fig. 2.)

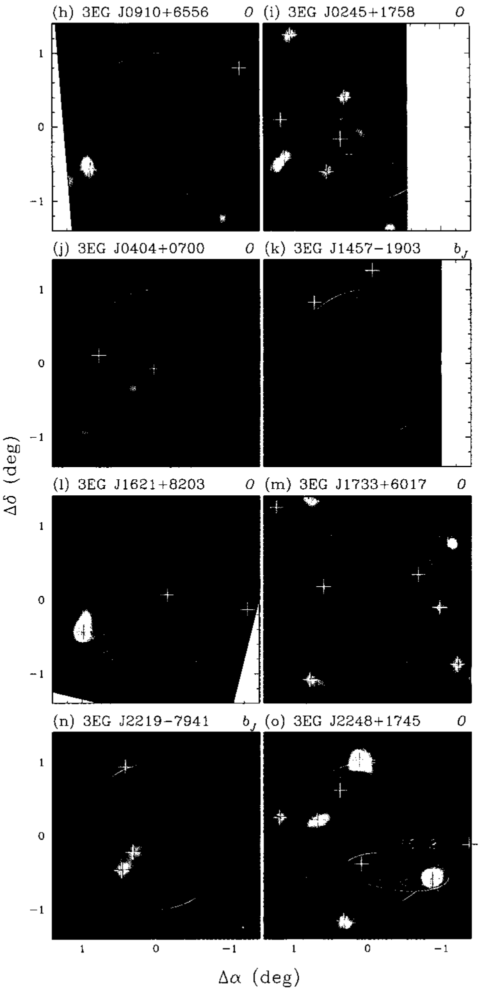

Fig. 2.— Same as Fig. 1, but for the ones at $30° \leq |b| < 45°$. The small open circles are Abell/ACO clusters. Close cluster pairs or groups (CPGs) are shown as the green ellipses enclosing their member clusters. The VES boundary is shown with large yellow circles (solid line). The yellow dotted ellipses denote the best-fit ellipses for 95% confidence regions of the EGRET sources by Mattox et al. (2001).

to be variable, and hence they are likely to be AGNs. Even if the candidates are appropriately selected, the typical redshifts reached in the existing all-sky cluster catalogs in optical (Abell, Corwin, & Olowin 1989) or X-ray (Ebeling et al. 1998) are not much greater than the expected redshift of gamma-ray clusters ($z \sim 0.1$), and hence a portion of the gamma-ray clusters detected by EGRET could have been missed by past cluster surveys. These facts make it difficult to search the correlation efficiently. Furthermore, TK00 pointed out that, since gamma-rays can be emitted only from dynamically forming clusters, their structure may be considerably different and extended when compared with stable, well-established clusters detected by X-rays or optical surveys. This effect might make the correlation search with known clusters even more inefficient.

However, most of such forming gamma-ray clusters should have some substructure or merging signature within them, as expected by the hierarchical structure formation in the cold dark matter (CDM) universe. Therefore, an intensive search for these signatures in the regions around the unidentified EGRET sources, with sensitivities better than existing all-sky catalogs of galaxy clusters, is a straightforward test of the gamma-ray cluster hypothesis.

In this paper, we report the results from our project to systematically examine the gamma-ray cluster hypothesis using optical galaxy data. Among the 31 unidentified EGRET sources at $|b| > 30°$, we focus here on the 15 sources classified as "steady" (Gehrels et al. 2000; D. Macomb 2000, private communication) since the remaining 16 variable sources should be other objects such as flaring AGNs. To perform a correlation analysis between the EGRET sources and galaxy clusters more efficiently than past studies, we make a new sample of galaxy clusters detected automatically based on the matched filter cluster finding algorithm (Kawasaki et al. 1998). This catalog should be better for statistical study of correlation than the past optical cluster catalogs selected by eyes that inevitably induce some systematic bias.

II. DATA

We use the galaxy sample extracted from the APM catalog. The data around the seven EGRET sources were obtained via APMCAT service, while the data near the south Galactic pole (SGP) were kindly distributed from S. Maddox and M. Irwin. Only blue passband (O or b_J) data have been used, since the red passband data seemed much noisier for some EGRET source regions, especially at the edge of photographic plates. Both O and b_J data were available and analyzed for 3EG J1235+0233. After correcting galaxy dimming due to Galactic absorption using the extinction maps and tools by Schlegel, Finkbeiner, & Davis (1998), galaxies within magnitude range of $14 \leq m \leq 20$ were selected as the input data for cluster-finder. The seven 4° x 4° areas centered at each EGRET source are searched. For comparison, a 100 deg^2 area near the SGP is also used as a control field.

III. CLUSTER IDENTIFICATION

To make an original cluster sample, we employed a revised version of the matched filter method by Kawasaki et al. (1998), an automated and objective cluster-finding technique based on maximum-likelihood method (see Kawasaki & Totani 2002 for details).

Fig. 1 and Fig. 2 show central 2.°8 x 2.°8 areas of the "richness maps" around the 15 EGRET sources. Cluster candidates are seen as local peaks of color contour. It should be noted that this color contour just indicates the amplitude of the "best-fit" filter with a fixed redshift parameter ($z_{\rm fil} = 0.14$) and does not directly reflect cluster's richness except for the ones at $z = 0.14$. Only the clusters with $z_{\rm est} \leq 0.15$ and Abell richness class ≥ 0, which we utilize below, are marked with the pluses.

Using this cluster sample, we search for close cluster pairs or groups (CPGs) as candidates of merging clusters. If there are close clusters satisfying the two criteria that (1) their estimated redshifts equal one another within the uncertainty of redshift estimation (20%) and (2) their transverse separation at that redshift is less than 2 h-1 Mpc, we regard them as a CPG.

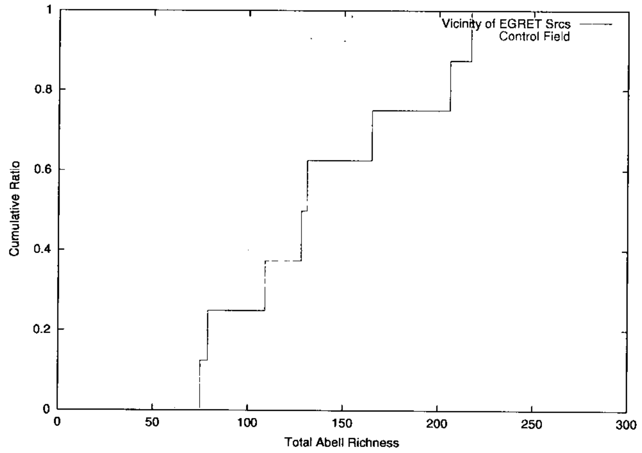

Fig. 3.— Cumulative distribution of the optical Abell Richness (defined as the number of galaxies within 2 mags from the third brightest galaxy)of the CPGs. The solid line is for the ones in the vicinity (within 1°) from the 3EG sources. The dashed line is for the ones in the control field.

IV. RESULTS

We here try two statistical tests for the correlation between clusters and the 15 EGRET sources.

(a) Projected Number Density

We examine if there is an excess overdensity of clusters or CPGs in the vicinity of the EGRET sources (VES). VES is defined as the sum of all areas within 1° of the 15 EGRET sources, and the boundary is shown as the yellow solid circles in Fig. 1. Considering the extended nature of CPGs, the VES radius is fixed at 1° rather than the EGRET error radius; the value is close to the typical size of both EGRET error circle and expected gamma-ray clusters detectable by EGRET (TK00). The rest of the data area (the EGRET region outside VES plus the SGP region) is hereafter referred to as "control field". Simply counting all clusters, we see that there is almost no density excess of clusters in VES.

However, the situation changes greatly for CPGs. Seven among the 15 EGRET sources have CPGs within 1° from them. The number excess of CPGs in VES amounts to 3.7σ level (99.8% confidence level), which is in sharp contrast to the case for single clusters.

(b) Estimated Richness

We also found that the eight CPGs within the VES of EGRET sources seem to be systematically richer compared with the ones not associated with EGRET sources. Fig. 3 shows the cumulative distribution of the optical Abell Richness, defined as the number of the spatial correlation shown in the previous section. If this result is added to the spatial correlation, significance would be further increased.

V. SUMMARY

We performed a correlation analysis between the 15 steady unidentified EGRET sources in the high-latitude sky ($|b| > 30°$) and a quasi 3-dimensional catalog of galaxy clusters newly generated with a matched filter algorithm. While there is no correlation between the EGRET sources and the individual clusters, in sharp contrast we found a strong (maximally 99.8% CL level) correlation between the EGRET sources and close pairs/groups (CPGs). This result is consistent with the gamma-ray cluster hypothesis proposed by TK00, which expect that the gamma-ray emission comes from only ongoing mergers with active shocks but not from the usual ones in dynamically "quiet" regimes where the violent shock has subsided. Because of the short timescale of energy dissipation, gamma-ray luminosity should rise more rapidly with the generation of the shock, and decay with the disappearance of the shock, compared with the thermal or nonthermal emission in longer wavelength. This suggests that some clusters may have strong gamma-ray emission with still weak or only early signatures of merging in other bands, and others may have weak gamma-ray flux but with still remaining merging signature in longer wavelength. Confirmation of the merging signatures in CPGs found in this paper is important for further verification, but deep observation is necessary when the merging is still in the early stage.

Clearly, the weak point of our analysis is small sample (15) of the steady unidentified gamma-ray sources due to the flux limit of 3EG catalog (although it is the deepest to date). However, TK00 predicted that future gamma-ray telescopes such as GLAST could find hundreds to thousands of gamma-ray clusters up to $z = 0.2 - 0.3$. The coming three-dimensional deep galaxy catalogs from ongoing SDSS and 2dF survey projects will be ideal resources to directly compare with the GLAST gamma-ray sources. When it is established that a part of the extragalactic steady gamma-ray sources are from forming (merging) clusters, large-scale distribution of gamma-ray clusters will offer unique and valuable information about the dynamical side of cosmological structure formation, in contrast to the more stationary side that has been probed by conventional galaxy clusters in X-ray and optical bands.

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