A STATISTICAL DETECTION OF GAMMA-RAY EMISSION FROM GALAXY CLUSTERS: IMPLICATIONS FOR THE GAMMA-RAY BACKGROUND AND STRUCTURE FORMATION

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ABSTRACT

The origin of the diffuse extragalactic high-energy gamma-ray background (EGRB) filling the universe remains unknown. The spectrum of this extragalactic radiation, as measured by EGRET on board the Compton Gamma Ray Observatory, is well fitted by a power law across nearly four decades in energy, from 30 MeV to 100 GeV. It has been estimated that not more than a quarter of the diffuse gamma-ray background could be due to unresolved point sources. Recent studies have suggested that much of the diffuse background could originate from the upscatter of cosmic microwave background photons by relativistic electrons. In some scenarios, the shock radii for clusters could be large, with gamma rays detectable in the form of 5–10 Mpc diameter ringlike emission tracing the cluster virialization shock (Keshet et al. 2002). Other work has suggested that some 0.5%–2% of the EGRB could arise solely from the formation shock (Keshet et al. 2002). The association of gamma rays from pion decay. Recent simulation studies of a ΛCDM universe suggest that future high-energy gamma-ray experiments such as the Gamma-Ray Large Area Space Telescope (GLAST) or the next generation of atmospheric Cerenkov telescopes should be able to resolve gamma rays from individual clusters in the local universe (z ≳ 0.025; Keshet et al. 2002). The association of the EGRB with the large-scale structure of the universe can be then tested by cross-correlating gamma-ray maps with known galaxy clusters.

Subject headings: galaxies: clusters: general — gamma rays: observations — large-scale structure of universe

1. INTRODUCTION

During the 9 years (1991–2000) that EGRET was operational on board the Compton Gamma-Ray Observatory (CGRO), it detected a diffuse gamma-ray emission above 30 MeV filling the universe. This gamma-ray background is composed of an intense Galactic component, due to cosmic-ray interactions with local interstellar gas and radiation (Hunter et al. 1997), as well as a diffuse and isotropic extragalactic component. The extragalactic radiation is well described by a simple power law with the energy per unit solid angle and the energy, corresponding to a typical nonthermal bolometric luminosity of $L_\gamma \sim 1 \times 10^{44}$ ergs s$^{-1}$ ($>100$ MeV), where we conservatively estimate that $\sim 1\%–10\%$ of the EGRB could originate from clusters with $z < 1$. For this cluster population, the predicted nonthermal luminosity is in excellent agreement with our measurement, suggesting that the clusters have experienced mass accretion within the last $10^9$ yr. If correct, then future gamma-ray missions, such as the Gamma-Ray Large Area Space Telescope, should be able to directly detect nearby galaxy clusters.

So far, individual galaxy clusters have not been found to be correlated with discrete gamma-ray sources detected by EGRET, although it has been suggested that they may be candidates for unidentified EGRET sources (Totani &
Kitawaki (2000), which may be correlated with cluster pairs (Kawasaki & Totani 2002). In most cases, the predicted gamma-ray fluxes from nearby individual clusters (Dar & Shaviv 1995; Colafrancesco & Blasi 1998) are below the sensitivity limit of EGRET, and indeed, no excess gamma-ray emission is seen from any individual cluster. For example, a 2 upper limit of $4 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ at energies greater than 100 MeV can be derived for Coma, the closest rich cluster (Sreekumar et al. 1996). However, in the case of Coma, Ensslin et al. (1997) find that for equipartition of cosmic-ray photons with thermal gas, the gamma-ray production would exceed this limit.

Previous efforts to constrain the gamma-ray emission of clusters used a small sample (58) of X-ray–luminous clusters (Reimer 1999) and found no significant signal when the EGRET data centered on the clusters were co-added. Corrections for Galactic diffuse emission were not made, and a likelihood analysis of the data found no statistically significant emission associated with the clusters. Colafrancesco (2002) recently has reported preliminary evidence of the association of unidentified EGRET sources with galaxy clusters at high latitudes, claiming that these sources also show strong radio emission. Relativistic particles responsible for the radio emission are probably also the source of inverse Compton gamma rays. However, the number of claimed associations is small, and no account was taken of the known deviation from Poissonian statistics due to cluster–cluster correlations. As we discuss below, even at high Galactic latitudes—and even with the removal of the best model of Galactic emission—residual Galactic signatures remain, which is a known feature of these models (Hunter et al. 1997). Furthermore, by utilizing the much larger (albeit more inhomogeneous) optical Abell catalog of clusters and evaluating emission in radial bins, we increase our search sensitivity by a factor of 100–1000.

In the present analysis, we search for angular correlations of the EGRET extragalactic diffuse emission with cluster position, using the complete Abell catalog of clusters (§2) and radially binning the gamma-ray emission around the Abell clusters (§3 and 4). We then estimate the average gamma-ray luminosity per cluster and address the question of whether this is consistent with recent predictions of the gamma-ray energy flux arising from intergalactic shocks, based on semianalytic predictions and hydrodynamical cosmological simulations (§5 and 6).

2. DATA ANALYSIS

We have used archival gamma-ray data from all 9 years of EGRET observations for our present analysis. The maps were generated by summing data over phases 1–3 and cycles 4–9 of the EGRET observations, using only photons with inclinations angles of less than 30°. EGRET covers an energy range of 30 MeV to over 20 GeV. Details of the EGRET instrument and capabilities can be found in Kanbach et al. (1988). The point-spread function (PSF) of EGRET is strongly energy dependent and varies from nearly 6° (FWHM) at 100 MeV to 0.1 at greater than 1 GeV (Thompson et al. 1993). EGRET has proved to be a highly successful gamma-ray experiment, comprehensively surveying the gamma-ray sky from 1991 to 2000. The Third EGRET (3EG) Catalog (Hartman et al. 1999a) lists the 271 point sources detected by EGRET during the first four cycles of its mission (1991–1995). Since cycle 4, EGRET has been operated in a narrow field-of-view mode for instrumental reasons (Hartman et al. 1999b). Of the 271 point sources in the 3EG Catalog, more than 60% are unidentified.

The diffuse gamma-ray emission detected by EGRET consists of two components, one Galactic and the other assumed to be extragalactic and isotropic. A model for the Galactic diffuse gamma-ray emission was calculated using EGRET data from 1991 to 1993 (Hunter et al. 1997); a diffuse model using all 9 yr of EGRET data is not yet available. Other models of the diffuse galactic gamma-ray emission, also using subsets of the EGRET data, have been presented by Strong, Moskalenko, & Reimer (2000) and Pohl & Espósito (1998; for greater than 1 GeV emission). The model of Hunter et al. (1997) assumes that cosmic rays are coupled to the interstellar matter density. The gamma rays are produced mainly by the interaction of cosmic-ray protons and electrons with the interstellar medium (ISM). The Galactic diffuse component is found to be highly peaked along the Galactic plane. This model generally describes the EGRET data well on larger scales but is less successful for individual regions of the sky. Hunter et al. (1999) discuss the residual (observed minus best-fit model) intensity in their analysis of the EGRET galactic diffuse emission. The large-scale residual distributions for energies greater than 100 MeV are less than $\pm 2 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and are roughly distributed around zero intensity. For our analysis, we subtract the modeled Galactic component of the gamma-ray emission from the EGRET gamma-ray intensity skymaps (see below).

The EGRET data used here have been projected into a 720 × 360 (0.5 pixel size in coordinate units) equatorial grid containing intensities (photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$; Fig. 1). We also utilize the maps of raw photon counts in the same projection in order to evaluate the Poisson noise associated with each pixel (see below). Our primary data set contains photons from all energies greater than 100 MeV. We also have analyzed the greater than 1 GeV data set (which has a correspondingly smaller PSF), although the increased photon shot noise results in no statistically significant measurements.

Prior to evaluating the cluster-EGRET cross-correlations, we typically perform three sets of clipping or corrections to the data, unless described otherwise below. First, 27 radius regions (on the sphere of the sky) are excised around the 100 identified EGRET sources to reduce the overall shot-noise level. This corresponds to the 90% enclosed flux radius of the full energy-weighted (>100 MeV, $E^{-2}$ spectrum) EGRET PSF. Using the 99% enclosed flux radius of 7:1 has a negligible effect on our results. The identified sources consist of 67 blazars and six pulsars, as well as 27 sources marginally identified as gamma-ray blazars.

An additional 171 unidentified faint EGRET sources have been cataloged. However, the majority of these are close to the Galactic plane within the Galactic plane cut we describe below (only 41 of all EGRET sources have $|b| > 45°$; of those, 22 are identified and 19 unidentified). Excising these additional unidentified sources has a negligible effect on our results, and we therefore have chosen to remove only those

1 As directly available from the HEASARC archives, http://heasarc.gsfc.nasa.gov/.
sources of known origin. As described above, no sources are identified with known clusters of galaxies.

Second, the region with $|b| < 45^\circ$ is removed to eliminate the high-intensity Galactic plane emission. The choice of this cut is determined by a combination of the desire to minimize the Galactic contamination and the latitude-dependent incompleteness of the Abell catalog (see below) and to maximize the number of Abell clusters used in evaluating the cross-correlation function (thereby maximizing sensitivity and keeping shot noise to an acceptable level). Variations of $\leq 10^\circ$ on this cut have a negligible effect on our results.

Third, the detailed model of the diffuse Galactic emission intensity in the EGRET data (as described above; Hunter et al. 1997) is subtracted from the masked skymap. Since this model has small residuals, in some instances (5%) in which the EGRET data is nonzero, the subtraction results in a negative intensity in a given pixel. The values of the residuals of the model are scattered about zero (relative to the mean subtracted Galactic emission) but do seem to exhibit some correlation with Galactic latitude, especially at lower energies, being more negative at lower $b$ and away from the Galactic center (Hunter et al. 1997). In our analyses, we also utilize the raw EGRET photon count maps to estimate the Poisson, or shot noise, due to finite photon statistics. Specifically, we always construct weighted means in which weights are assigned as $A_i \sqrt{N_i}$, where $N_i$ is the raw photon number in a given pixel and $A_i$ is the pixel solid angle, which varies with latitude. Consequently, all pixels with zero photons acquire zero weight in the calculation of the mean (an unweighted mean, which simply excludes the zero photon pixels, is found to have a negligible difference from the weighted mean for our purposes).

For most of the analyses described below, we are left with a total of $\sim 40,000$ usable EGRET pixels ($\sim 10^4$ deg$^2$). The effect of any remaining Galactic emission on our results is discussed below. The final EGRET data set is shown in Figure 2. The mean intensity is $2.88 \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

The catalog of Abell clusters we utilize consists of the original Abell catalog of 2712 systems, plus the southern ACO extension of 1364 clusters (Abell, Corwin, & Olowin 1989). Figure 3 plots the clusters for comparison to the EGRET data. We have used the basic Abell parameters of richness ($R$) and distance class ($D$) in the analysis presented below. Specifically, we have split the sample between $R \geq 2$ (Fig. 3) and $R < 2$ and among various distance classes. We have also utilized the X-ray–selected Brightest Cluster Survey (BCS) of 206 clusters (Ebeling et al. 1998), combined with the extended BCS catalog of an additional 108 fainter systems (Ebeling et al. 2000), although as described below, the larger shot noise of this smaller X-ray sample prohibits robust measurements.

2.1. Cross-Correlation

The most rigorous cross-correlation analysis of a surface brightness map and a collection of points (clusters) would involve a direct summation over sky cells, smoothing the point distribution by the same kernel (PSF) as the surface brightness (e.g., as is applied to all-sky X-ray data [Jahoda et al. 1991; Lahav et al. 1993; Miyaji et al. 1994]). In the case of the EGRET data, however, we have chosen a cruder approach of summing or stacking gamma-ray emission in radial annuli centered on all Abell clusters and then determining the statistical mean in each angular bin. Ostensibly, this does not differ much from the cell summation approach, and unlike cell summation, we obtain a direct estimate of the excess emission associated with clusters by explicitly including the cluster coordinate information. Using the cell summation technique would require more extensive modeling to extract this measure (Lahav et al. 1993). In addition, given the potentially complex residual contamination by

Fig. 1.—Greater than 100 MeV EGRET all-sky intensity map in rectangular equatorial projection. The Galactic plane is clearly seen as the brightest region in the sky; some individual bright sources are also evident. Galactic south is toward the bottom center of this image.
Fig. 2.—EGRET data as in Fig. 1 but with all mask cuts and the diffuse Galactic model intensity subtraction applied. Two of the excised bright sources (center and left) clearly have remaining extended flux in this map. However, this flux has negligible impact on our analysis, since by area it is small.

Fig. 3.—Top: All 4076 Abell clusters are plotted in rectangular equatorial coordinates as for the EGRET data. The strong selection bias away from the Galactic plane is reflected in the sparsity of clusters in those regions. Bottom: The 447 richest ($R \geq 2$) Abell clusters are plotted.
diffuse or unresolved Galactic emission and the known selection biases of the Abell catalog, the stacking approach allows for more intuitive modeling (see §3.1 below).

Given an equatorial pixel size of 0:5′ for the EGRET data and the 68% flux enclosure at 1° radius for the energy-weighted greater than 100 MeV PSF, we choose annular bins of width 1° in our analysis. We note that the energy-dependent PSF can be described as θ ≤ 5°85(E/100 MeV)^{-0.336}, where θ is the energy-dependent radius for 67% flux enclosure (Thompson et al. 1993; Esposito et al. 1999). The area-noise–weighted mean flux excess (hereafter referred to as the mean; see §2) above the global mean (calculated from all unmasked Galactic-corrected pixels) is then evaluated by using all unmasked pixels in each radial bin, out to 20° for each cluster, and then averaging over all clusters used. Pixels are used if their centers lie within a given annulus; consequently, there is some variation in the number of pixels counted between different cluster centers. However, this variation is negligible on averaging over many objects. We refer to this angular function as \( w_c(θ) \) or \( \langle ΔI \rangle = \langle I - \bar{I} \rangle \) in the results in §3 below. In §3.1, we assess its significance.

3. RESULTS

In Figure 4, we plot our principal results. The curve for all 2469 Abell clusters with \(|b| > 45°\) peaks at a value of \(6.2 \times 10^{-7} \text{photons s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\) in the 1° bin and gently declines with θ. This is generically the behavior expected for a positive correlation between the two data sets. Top and bottom heavy curves are for the richest (\( R ≥ 2 \)) and poorest (\( R < 2 \)) Abell subsets. We note that, based on the theoretical predictions, more massive cluster systems are expected to be the sites of higher gamma-ray emission (Loeb & Waxman 2000). Consequently, the increased amplitude of the rich cluster \( w_c \) relative to that of the poorer clusters goes in the expected sense if clusters are indeed diffuse gamma-ray sources. The peak amplitude for the rich cluster subset, in the 1° bin, is \(1.19 \times 10^{-6} \text{photons s}^{-1} \text{cm}^{-2} \text{sr}^{-1}\).

We have also investigated the effect of using subsets of the Abell catalog divided using the distance parameter \( D \), which is based on the brighter galaxy magnitudes in a cluster. The increased noise of using smaller subsets of clusters makes these measurements less significant. Using only the more distant (\( D > 4 \)) subset, which is still large, has little effect on the results presented here, with variations well within the noise.

In addition, since X-ray–selected clusters are considered to be more robust in terms of being real gravitationally relaxed systems, we have run our cross-correlation using the 304 clusters of the BCS (Ebeling et al. 1998, 2000). However, only 159 systems remain after the Galactic cuts are applied, and the resulting \( w_c(θ) \) is too noisy to draw any conclusions.

Finally, at energies above 1 GeV, the EGRET PSF has a FWHM of only 0′1. In principle, this could help reduce the effect of Galactic contamination and enhance the cross-correlation measure for compact resolved sources associated with clusters. In practice, though, the increased photon shot noise of the greater than 1 GeV data results in a statistically insignificant (although still positive) \( w_c(θ) \).

3.1. Monte Carlo Tests

The strongly energy-dependent EGRET PSF (Thompson et al. 1993), in combination with a complex diffuse Galactic emission contribution and local large-scale structure traced by galaxy clusters (e.g., the super-Galactic plane), indicates that the most direct way to assess the significance of any measurement is via Monte Carlo simulations.

Our primary goal is to determine the significance of any positive correlation between the centroids of local galaxy clusters and the EGRET intensity map. We therefore perform two sets of Monte Carlo simulations. First, we retain the true sky distribution of galaxy clusters but use “fake” EGRET data. Pixel values are assigned by drawing values randomly from the real (masked and Galactic model–subtracted) data, repeats are allowed, and photon shot noise is carried with the surface brightness. Second, we retain the true EGRET data but randomize the galaxy cluster positions. In both cases, we generate 1000 random realizations and perform an identical angular cross-correlation analysis to that made on the real data. The population distribution of the angular cross-correlation in each angular bin is then determined, and limits containing 90%, 95%, and 99% of the realizations, centered about the means, are obtained.

The first approach removes all residual Galactic emission correlations and all PSF effects, and we consider this to be the true baseline for the case of uncorrelated noise. The second approach is more conservative, since any residual Galactic structure is still present and the precise noise characteristics of the EGRET data are retained. Our second set of Monte Carlo simulations generate random position clus-
ter catalogs with the same number of entries as the real data, although without the measured cluster-cluster correlation properties. The Abell catalog has a known angular selection function because of increasing absorption and increasing star-galaxy confusion toward the Galactic plane. This has been fitted to a simple law: \( f = 10^{(\alpha - \text{csc}|b|)} \), where \( b \) is Galactic latitude and \( \alpha \) has values ranging from \( \alpha \approx 0.3 \) (Bahcall & Soneira 1983) to \( \alpha \approx 0.53 \) (Romani & Maoz 1992), depending on the particular subset of clusters modeled. Here we conservatively apply the larger correction to our simulated catalogs in order to reproduce the gross features of the Abell cluster selection.

In Figures 5 and 6, the results from the first set of Monte Carlo simulations (randomly resampled EGRET data) are presented for all clusters and for just rich clusters, respectively. In Figures 7 and 8, the results for the second set of simulations (random Abell catalogs) are presented in the same format.

For all cases shown in Figures 5, 6, 7, and 8, the measured \( w_c(\theta) \) in the \( 1^\circ \) bin is significant at the \( \geq 3 \sigma \) level. We note that had clusters exhibited much more significant emission in the EGRET data, then it is likely that they would have been already directly detected. Our result, therefore, occupies a significance regime inaccessible to anything but statistical analysis.

4. FURTHER ANALYSIS

In order to assess more completely the significance of the shape of the measured \( w_c(\theta) \), we have evaluated the cluster-cluster correlation \( (w_{cc}) \) for the rich \( (R \geq 2) \) subset, with identical sky incompleteness (i.e., the same sky mask as applied to the EGRET data) and using the same annular binning technique. We also convolve \( w_{cc} \) with the EGRET PSF (see below). Here \( w_{cc} \) and \( w_{c} \) should agree at large angular scales (e.g., \( \sim 10^\circ \), if the correct normalization between cluster sky density and gamma-ray emissivity is known). At small angular scales, \( w_{cc} \) should match \( w_{c} \) only in the case of pointlike emission coincident with the clusters. For moderately extended emission (such as that predicted; Keshet et al. 2002), \( w_{c} \) will be suppressed relative to \( w_{cc} \) at small angles—but should still agree at larger scales.

Our measured \( w_{cc} \) agrees reasonably well with previous measurements of the Abell cluster angular autocorrelation (Postman, Geller, & Huchra 1986), which follows an approximate \( w_{cc} \propto \theta^{-1} \) relationship. We have not included any selection bias correction in calculating \( w_{cc} \), in order to
compare directly with $w_{C13}$. We also note that neither $w_{CC}$ (before renormalizing) nor $w_{C13}$ drop to zero by $20^{\circ}$. For this annulus and 447 clusters in $\sim 10^4$ deg$^2$, if the clusters were uniformly distributed, then each data pixel would be sampled several times and $w_{C13}$ should equal zero. However, as $w_{CC}$ illustrates, the clusters are not uniformly distributed. In fact, they tend to trace the super-Galactic plane, which is contiguous across our entire map regions.

In Figure 9, the results for the richest ($R \geq 2$) subset of clusters are plotted together with the renormalized cluster-cluster correlation determined directly from the catalog, before and after smoothing with the energy-weighted EGRET (>100 MeV) PSF (Esposito et al. 1999). We have renormalized $w_{CC}$ to the $10^{\circ}$ annular bin of $w_{C13}$, where we expect agreement. We also plot the greater than 100 MeV EGRET PSF for illustration.

Although the corrected $w_{C13}$ and $w_{CC}$ are broadly similar in shape, there is clear evidence for a flatter slope in $w_{C13}$. In particular, at scales less than $\sim 3^{\circ}$, $w_{C13}$ is significantly lower than $w_{CC}$. At larger scales ($>15^{\circ}$), both functions are less statistically significant. The results summarized in Figure 9 are consistent with nonpointlike cluster gamma-ray emission extending to some $\sim 3^{\circ}$. We discuss this result in the context of theoretical predictions in §6.

5. CONSTRAINTS ON CLUSTERS AND THE EGRB

The basic theoretical predictions for the intergalactic medium (IGM) origin of the EGRB from Loeb & Waxman (2000) are summarized in equations (1) and (2). Approximately 80%–90% of the EGRB is predicted to be due to IGM emission. The remaining fraction can be ascribed to a population of point sources (Chiang & Mukherjee 1998). The more recent work of Keshet et al. (2002) agrees closely with these semianalytic predictions but differs when a numerical cosmological simulation is utilized (see below).

Equation (1) is the predicted spectral intensity of the EGRB (>30 eV) due to upscattered CMB photons from relativistic electrons (Lorentz factors $200 < \gamma < 4 \times 10^7$) produced in IGM shocks. Here

$$E^2 \frac{dJ}{dE} = 1.1 \left( \xi e \frac{\Omega_b h_70^2}{0.05} \right) \left( \frac{f_{sh} k T}{0.04} \right) \text{keV s}^{-1} \text{cm}^{-2} \text{sr}^{-1},$$

where $\xi e$ is the fraction of shock thermal energy transferred to relativistic electrons, $\Omega_b$ is the cosmological baryon density parameter, $h_70$ is the Hubble constant in units of 70 km s$^{-1}$ Mpc$^{-1}$, and $f_{sh}$ is the fraction of baryons shocked to a mass-weighted temperature $T$ (Loeb & Waxman 2000). The value of $\xi e \simeq 0.05$ is obtained from nonrelativistic collisionless shocks in the ISM (supernovae [SNe]) and, as described
in § 1, may actually range from 1% to 10% (Waxman & Loeb 2000; Keshet et al. 2002). From cosmological hydrodynamical simulations, $f_{\text{sh}}(kT/\text{keV}) \sim 1$ (e.g., Cen & Ostriker 1999).

Using a hydrodynamical cosmological simulation, Keshet et al. (2002) find an $E^2 \langle DJ \rangle$ spectrum, which is lower than the above semianalytic Press-Schechter–based prediction. The spectrum has a varying slope with energy, and the amplitude varies from 50 to 160 eV s$^{-1}$ cm$^{-2}$ sr$^{-1}$, in contrast to the 1100 eV in equation (1). Consequently, their prediction is that only $\lesssim 15\%$ of the EGRB is due to the IGM. Keshet et al. (2002) attribute this primarily to a lower present-day gas temperature found in the simulation.

Equation (2) is the predicted nonthermal bolometric luminosity for massive clusters of galaxies, again due to CMB upscatter from the accretion shocks surrounding these systems. For a forming massive cluster (Waxman & Loeb 2000; Keshet et al. 2002),

$$L_\gamma = 1.5 \times 10^{45} \left( \frac{\xi_\gamma}{0.05} \right) \left( \frac{10^9 \text{ yr}}{t_{\text{vir}}} \right) \left( \frac{M_{\text{gas}}}{10^{14} M_\odot} \right) \times \left( \frac{kT_{\text{gas}}}{5 \text{ keV}} \right) \text{ergs s}^{-1},$$

where $t_{\text{vir}}$ is the time taken for gas to cross the cluster virialization shock or, equivalently, a measure of the transience of the gamma-ray emission; $kT_{\text{gas}}$ and $M_{\text{gas}}$ are the thermal gas temperature and mass, respectively, in a cluster. Both equations (1) and (2) assume a cosmology with $\Omega_\Lambda = 0.65$, $\Omega_M = 0.35$, $\Omega_B = 0.05$, and $h = 0.7$. With a slightly different cosmology (Keshet et al. 2002), where $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, $\Omega_B = 0.04$, and $h = 0.67$, very similar amplitudes of 1.5 and $2.2 \times 10^{45}$ are determined for equations (1) and (2), respectively.

We use the excess emission associated with $R \geq 2$ clusters as measured in the innermost (1") bin; $1.19 \times 10^{-6}$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ ($>100 \text{ MeV}$; Fig. 4). This corresponds to the 68% flux enclosure of the EGRET PSF and therefore can be considered as a conservative choice. Relative to our Galactic model–subtracted data, this represents a $\sim 4\%$ fluctuation above the mean diffuse background and corresponds to a mean cluster flux in a 1" radius aperture of $\sim 1.14 \times 10^{-9}$ photons s$^{-1}$ cm$^{-2}$ (100 MeV).

First, we estimate the gamma-ray or nonthermal luminosity implied for a rich cluster of galaxies. Converting our photon count rate into flux (assuming an $E^{-2}$ spectrum), we obtain $f_\gamma = 1.87 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$ ($>100 \text{ MeV}$). To estimate the bolometric gamma-ray flux, we then apply a simple correction term. We assume that the emission spectrum is close to an $E^{-2}$ power law and that the emissivity runs from $\sim 30 \text{ eV}$ to $\sim 1 \text{ TeV}$. The upper limit of the EGRET sensitivity is $\sim 100 \text{ GeV}$; thus, correcting for the missing lower and higher energy flux, we obtain $f_{\text{bolometric}} \equiv f_{30 \text{ eV} \rightarrow 1 \text{ TeV}} = 3.55 \times 10^{-8}$ ergs s$^{-1}$ cm$^{-2}$ (100 MeV).

We note that at $\sim 1 \text{ TeV}$, pair production cascades should effectively cut off the spectrum. Assuming a mean redshift of $z = 0.1$ derived for $R \geq 2$ clusters, and $h = 0.75$, we arrive at an estimated mean luminosity of

$$\bar{L}_\gamma = 1 \times 10^{44} \text{ ergs s}^{-1}. \quad (3)$$

For our purposes, this is fairly robust. Below we discuss the implications of our measured $\bar{L}_\gamma$.

The local ($z \sim 0$) space density of rich clusters is reasonably well known, e.g., De Propris et al. (2002), and for $R \geq 2$ is of the order of $1 \times 10^{-6}$ Mpc$^{-3}$. Consequently, we can simply derive the local gamma-ray volume emissivity of rich clusters. Assuming no evolution in any properties, we can then integrate the expected contribution of rich clusters to the EGRB from a cosmological volume within $z_{\text{max}}$. If $z_{\text{max}} = 1$, then we arrive at the estimated surface brightness (bolometric) contribution,

$$\bar{I}_\gamma = 6.0 \times 10^{-10} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}. \quad (4)$$

Integrating the spectrum defined by equation (1) from 30 eV to 1 TeV, we arrive at a net predicted bolometric IGM surface brightness of $I_{\text{IGM}} = 4.3 \times 10^{-8}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Therefore, the measured EGRET flux of rich clusters implies that $\sim 1\%$ of the predicted diffuse IGM may be due to rich clusters with $z < 1$.

Clearly, this is modulo many parameters and sources of scatter and should be treated with appropriate caution. If we consider the prediction of the Keshet et al. (2002) numerical simulations, then this fraction clearly rises to $\sim 10\%$ of the IGM emission. Similarly, we have assumed zero evolution in all properties and that our estimate of $L_\gamma$ is unbiased.

For comparison, as described in § 1, the 2 $\sigma$ upper limit on emission from the Coma Cluster ($z = 0.0231$) is $4 \times 10^{-8}$ photons s$^{-1}$ cm$^{-2}$ (100 MeV). Following the same procedures, this translates to a bolometric luminosity of $L_{\gamma, \text{Coma}} < 2 \times 10^{44}$ ergs s$^{-1}$. However, the space density of Coma-like clusters ($M_{\text{total}} \sim 10^{15} M_\odot$) is only $3 \times 10^{-9}$ Mpc$^{-3}$. Consequently, only some $\sim 0.01\%$–0.1% of the
EGRB IGM component could be expected to arise from the very richest clusters.

Returning to the prediction of equation (2), what are the other implications of our measurement? If we assume that we are detecting an actively accreting rich cluster population (i.e., within 10^9 yr of shock formation), then based on our knowledge of Abell clusters, the mean thermal gas temperature of the R > 2 population is likely to be ~3 keV, and the typical gas mass is ~10^13 M_⊙ (e.g., White, Jones, & Forman 1993; Petrosian 2001). In this case, our estimated L_ν is a good measure of the typical active nonthermal emission for rich clusters with 0 < z < 1. Special predictions for the population of clusters alone have estimated a contribution to the EGRB of 0.3%–2%, dominated by clusters with z ≤ 0.2 (Colafrancesco & Blasi 1998).

Several caveats are worth noting. First, diffuse Galactic gamma-ray emission is very hard to remove, even with the current best model for its distribution. We believe that we have accounted for the residual effects of this emission by assessing significance via our Monte Carlo simulations, but it still may introduce systematic errors to our results. Second, we cannot, with these data, prove that the excess emission associated with clusters is not due to some population of discrete sources, themselves positively correlated with clusters, although there is no a priori reason to believe this to be the case. Third, estimating the cluster luminosity by measuring the intensity in the innermost 1° bin is likely to be an underestimate, given both the width of the EGRET PSF and the evidence for more extended correlated emission. Finally, several potential sources of random error exist, serving to increase the uncertainty in quoted numbers— which, therefore, should be considered as broad estimates.

It also should be noted that another possible mechanism for producing nonthermal emission in clusters is synchrotron emission in radio galaxies contained in the clusters, which produce relativistic electrons that then upscatter to produce the high-energy gamma rays (e.g., Giovannini et al. 1993; Petrov 2001). In this case, the particles are accelerated in the nuclei of radio galaxies, and this could account for the observed gamma-ray luminosities. In this case, one would expect to see a stronger correlation signal with rich clusters containing radio galaxies. Ledlow & Owen (1995) find that some 79% of R = 2 Abell clusters have evidence of radio-emitting member galaxies (in a statistical subsample of 393 clusters of all richnesses). However, more sophisticated analysis is required owing to the small number of radio-detected clusters, and we will investigate this in an extension to the present work.

As discussed by Colafrancesco & Blasi (1998), Loeb & Waxman (2000), Waxman & Loeb (2000), and Keshet et al. (2002), the appearance of nonthermal emission in IGM/cluster structures is transient, with a timescale of ~10^9 yr. Therefore, the emission disappears almost entirely as soon as there is no strong shocking of gas. If we consider our sample of rich Abell clusters, then we know from other wavelengths that the majority of these low-z systems are probably in a state closely approximating hydrostatic equilibrium (e.g., the presence of X-ray cooling flows, the nearly isothermal gas, etc.). We can consider two extreme states: either only some nonequilibrium clusters are gamma-ray bright, or all clusters are close to equilibrium and we are simply seeing the fading emission of an earlier epoch of accretion activity. In the first case, we can exploit the fact that a system with an EGRET flux of at least ~5 × 10^{-8} photons s^{-1} cm^{-2} (>100 MeV) would be directly detectable in the EGRET map. Given our mean flux of ~1.1 × 10^{-9} (§ 5) and a total of 447 rich clusters, we would obtain an equivalent detection if only ~10 rich clusters had a flux of ~5 × 10^{-8} and the rest were gamma-ray dark. This would then provide a lower limit to the number of actively accreting clusters in the local universe, a 2% fraction by number.

Alternatively, if all clusters are assumed to be close to equilibrium with a mean temperature of kT ~ 3 keV, a mean gas mass ~10^{13} M_⊙, and ξ = 0.05, then they are almost exactly as gamma-ray luminous as predicted by equation (2). This implies that in fact, all clusters should have been actively accreting recently, certainly within z < 0.3–0.4 and possibly at the present time (z = 0).

Even in the low-density simulation of Keshet et al. (2002), it appears to be the case that z = 0 clusters can have active gamma-ray emission. Semianalytic predictions for low-density cosmologies (Ω_m = 0.3, Ω_Λ = 0.7) also suggest that even at z = 0, for massive clusters (10^{15} M_⊙) several 10^{13} M_⊙ in baryons should accrete per 10^9 yr (Lacey & Cole 1993). The shock regions may form some 5–10 Mpc from the cluster core, creating a gamma-ray “ring” of emission (Keshet et al. 2002). The suggestion of a rather more extended emission pattern from our cross-correlation (Fig. 9) supports this scenario. In this case, our estimated L_ν can be considered a good measure of the typical active nonthermal emission for rich clusters. This would then imply that the efficiency of transfer of energy from the shocks to relativistic electrons is similar to the value of 5% inferred from nonrelativistic shocks in the ISM.

The simulations of Keshet et al. (2002) predict that for ξ ≥ 0.03, future high-resolution gamma-ray telescopes with threshold sensitivities greater than ~10^{-10} for energies greater than 10 GeV should be able to resolve some gamma-ray halos associated with large-scale structures. The prospect of direct detection of gamma-ray sources with emission attributed to intergalactic shocks with GLAST, the Very Energetic Radiation Imaging Telescope Array System (VERITAS), the High-Energy Stereoscopic System (HESS) Gamma-Ray Telescope, the Major Atmospheric Gamma-Ray Imaging Cerenkov (MAGIC) Telescope, or other atmospheric Cerenkov telescopes is an exciting one. Such gamma-ray halos could be a new source class of high-energy sources...
sources waiting to be discovered. Their existence would allow an entirely new and direct probe of structure formation processes, leading to an improved understanding of inter- and intracluster gas dynamics, magnetic fields, and energy partitioning. While extrapolations from EGRET data and simulations for future instruments predict at least a dozen or more detectable sources (Keshet et al. 2002), direct determination of gamma-ray sources due to shocks can be used as an independent calibration for $\xi_e$. In fact, if the value of $\xi_e$ were lower than the inferred 5% (see discussion above), this would have an impact on the number of sources resolvable by future telescopes. Keshet et al. (2002) predict that the number drops to $\sim 1$ for $\xi_e \sim 0.2$. GLAST will have the spectral and spatial resolution to confirm whether galaxy clusters can be directly detected in gamma rays.

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