EGRET UPPER LIMITS ON THE HIGH-ENERGY GAMMA-RAY EMISSION OF GALAXY CLUSTERS

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ABSTRACT

We report EGRET upper limits on the high-energy gamma-ray emission from clusters of galaxies. EGRET observations between 1991 and 2000 were analyzed at positions of 58 individual clusters from a flux-limited sample of nearby X-ray–bright galaxy clusters. Subsequently, a co-added image from individual galaxy clusters has been analyzed using an adequately adapted diffuse gamma-ray foreground model. The resulting upper 2 σ limit for the average cluster is \( \sim 6 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ for } E > 100 \text{ MeV} \). Implications of the nondetection of prominent individual clusters and of the general inability to detect the X-ray–brightest galaxy clusters as a class of gamma-ray emitters are discussed. We compare our results with model predictions on the high-energy gamma-ray emission from galaxy clusters as well as with recent claims of an association between unidentified or unresolved gamma-ray sources and Abell clusters of galaxies and find these contradictory.

Subject headings: galaxies: clusters: general — gamma rays: observations — X-rays: galaxies: clusters

On-line material: color figures

1. INTRODUCTION

Clusters of galaxies are excellent representatives for the formation and the evolution of structure in the universe. They have been studied extensively at radio, optical, and X-ray wavelengths. Within the last decade, radio, extreme-ultraviolet (EUV) and hard X-ray observations have revealed the following emission features that led to the prediction that galaxy clusters might be emitters of high-energy gamma rays.

1. The existence of diffuse radio halos (Giovannini et al. 1993; Giovannini, Tordi, & Feretti 1999; Giovannini & Feretti 2000; Kemper & Sarazin 2001).

2. The rather controversially discussed observations of EUV excess emission in galaxy clusters such as A1795, A2199, and the Coma Cluster (Bowyer, Berghöfer, & Korpela 1999), A2199 (Lieu et al. 1999), A1367 and A1656 (Coma), A1795 and A2199 (Arabadjis & Bregman 1999), Virgo (Berghöfer et al. 2000), Virgo and A1795 (Bonamente, Lieu, & Mittaz 2001), the Fornax Cluster (Bowyer, Korpela, & Berghöfer 2001), A2199 and A1795 (Berghöfer & Bowyer 2002), A1795, A2199, A4059, Coma and Virgo (Durret et al. 2002).

3. The observational hint of a distinct nonthermal emission component at hard X-ray wavelengths in the case of the Coma Cluster (Fusco-Femiano et al. 1999; Rephaeli, Gruber, & Blanco 1999), Abell 2199 (Kaastra et al. 1999), Abell 2256 (Fusco-Femiano et al. 2000), and perhaps A754, A119 (Fusco-Femiano et al. 2003).

Various scenarios were suggested to connect and explain the links between these observations and, consequently, to predict a high-energy emission component at gamma-ray wavelengths. Whereas the diffuse radio emission is clearly synchrotron radiation by highly relativistic electrons, the EUV excess emission was first attributed to a second but cooler thermal component. Now a more plausible explanation is inverse Compton scattering of cosmic microwave background radiation by a nonthermal electron population (Ensslin & Biermann 1998; Blasi & Colafrancesco 1999). The hard X-ray excess can be produced by inverse Compton scattering of the same electron distribution generating the nonthermal radio emission (Giovannini et al. 1993). To avoid the problem of the rather low magnetic field strength in such a scenario, nonthermal bremsstrahlung has been proposed as an alternative emission process (Ensslin, Lieu, & Biermann 1999). As pointed out by Petrosian (2001), the nonthermal bremsstrahlung cannot be persistently produced on account of the low radiation efficiency of electrons in the 100 keV range. Hadronic particle populations were considered to produce gamma rays via p-p-interactions of high-energy cosmic rays with the intracluster medium (ICM) or as the origin of a secondary population of relativistic electrons (Berezinsky, Blasi, & Ptuskin 1997; Atoyan & Völk 2000). Cluster merger systems might offer sufficient cosmic-ray injection rates in conjunction with a mechanism for heating the ICM to the observed temperatures (Blasi 2001; Fujita & Sarazin 2002).

Gamma-ray radiation from galaxy clusters is also expected as a result of large-scale cosmological structure formation scenarios (Dar & Shaviv 1995, 1996; Colafrancesco & Blasi 1998; Völk & Atoyan 1999; Loeb & Waxman 2000; Waxman & Loeb 2000; Totani & Kitayama 2000; Kawasaki & Totani 2002; Miniati 2002). However, apart from the general prediction of its existence, quantitative estimates range between the "dominant part of the already observed extragalactic diffuse background by EGRET" to "magnitudes below the detection threshold of the current gamma-ray instrumentation" — a range of predictions substantially more uncertain than that for the contribution of unresolved active galactic nuclei.
(AGNs) to the extragalactic diffuse gamma-ray background (see, e.g., Mücke & Pohl 2000 and references therein). The benefit of dealing with a class of astronomical objects already detected at gamma-ray wavelengths, as, for example, AGNs, is not granted for the galaxy clusters. In contrast to the blazar population well observed by EGRET, no galaxy cluster has been unambiguously identified at gamma-ray wavelengths to date. Nevertheless, for several individual clusters, model predictions exist that place their gamma-ray fluxes close to or even below the instrumental sensitivity threshold of the EGRET telescope at $E > 100$ MeV (Dar & Shaviv 1995; Ensslin et al. 1997; Blasi & Colafrancesco 1999). Until now, galaxy clusters in gamma rays have been analyzed using only early EGRET data and preliminary analysis techniques, resulting in nondetections of the Coma Cluster (Sreekumar et al. 1996) and several Abell clusters (McGlynn, Vestrand, & Jennings 1994). Therefore, galaxy clusters have not been considered as likely counterparts of EGRET sources in the 3EG source catalog (Hartman et al. 1999).

Just recently, claims of an association between galaxy clusters from the Abell catalog and unidentified gamma-ray point sources from the 3EG catalog have been made by Colafrancesco (2001) and Kawasaki & Totani (2002). Likewise, Abell clusters were proposed to be connected with unresolved gamma-ray excesses (Scharf & Mukherjee 2002). All these detection claims have a statistical significance for association at the $3\sigma$ level in common.

Here in order to provide an up-to-date and comprehensive view of the high-energy gamma-ray emission from galaxy clusters, we have expanded a preliminary analysis by Reimer (1999) by considering all relevant EGRET observations between 1991 and 2000. Using the finalized EGRET data, which incorporate the latest instrumental efficiency normalizations, we analyzed individual, nearby X-ray–bright galaxy clusters with the likelihood technique. Subsequently, the gamma-ray data from individual galaxy clusters have been co-added in cluster-centered coordinates (Reimer & Sreekumar 2001). The co-added images were again analyzed using the likelihood technique, however, in conjunction with an adequately adapted diffuse gamma-ray foreground model. We also reexamined the statistical associations between unidentified EGRET sources and Abell clusters as a population (Colafrancesco 2002). For that purpose, we measured the cluster autocorrelation and thus derived the correct chance probabilities for the null hypothesis of no correlation between EGRET sources and Abell clusters. Finally, we compare our results, which benefit from the application of the likelihood analysis technique, with the result by Scharf & Mukherjee (2002).

2. THE FLUX-LIMITED, X-RAY–BRIGHT GALAXY CLUSTER SAMPLE

For observationally probing the gamma-ray emission of galaxy clusters, a sample of X-ray–emitting clusters of galaxies has been chosen. This sample consists of the X-ray flux-limited cluster catalogs from $\textit{Einstein}$ (Edge et al. 1990), $\textit{EXOSAT}$ (Edge & Steward 1991), and $\textit{ROSAT}$ surveys (XBACs: Ebeling et al. 1996; BCS North: Ebeling et al. 1998; BCS South: De Grandi et al. 1999). Cluster selections based on X-ray catalogs currently provide the best way to obtain completeness without introducing biases (i.e., projection effects). Although appearing as extended sources with typical radii of several arcminutes in X-rays, the width of the point-spread function of the EGRET instrument [$\theta = 5.85(E_{\gamma}/100 \text{ MeV})^{-0.534}$ and $\theta$ the energy-dependent radius for a 68% flux enclosure] does not permit a similar handling of galaxy clusters as extended sources in gamma rays. Thus, the attempt to analyze clusters of galaxies as pointlike excesses at energies above 100 MeV is justified. Here a total of 58 individual X-ray–bright galaxy clusters within $z < 0.14$ were chosen to represent a reasonable candidate sample for the subsequent analysis at high-energy gamma-ray wavelengths. Although further but similar cluster surveys are on the way or have been completed recently (in particular, HIFLUGCS and REFLEX), this sample adequately represents the high-flux end of the log $N$–log $S$ distribution of X-ray–bright galaxy clusters. Almost all clusters that are extensively discussed in the literature for evidence of nonthermal X-ray emission, EUV-excess features, and/or characteristic diffuse radio halos are included in this sample. The number of galaxy clusters has been restricted primarily to achieve a manageable amount of analysis work in the gamma rays but also because a simple measure such as cluster mass ($M$) over distance squared ($d^2$), as explained in the discussion, already should be a major constraint for the detectability of galaxy clusters in gamma rays. Thus, only nearby clusters ($z < 0.14$) were considered. This choice reflects the expectation that the nearest, most massive galaxy clusters are most likely the ones to be detected as individual sources of gamma-ray emission, whatever their flux. Figure 1 shows the spatial arrangement of the galaxy cluster sample (crosses) and cataloged high-energy gamma-ray sources (Hartman et al. 1999) in Galactic coordinates.

3. ANALYSIS OF GALAXY CLUSTERS AT HIGH-ENERGY GAMMA RAYS

3.1. The Study of Individual Galaxy Clusters

Until recently, no positional coincidences between an individual galaxy cluster and gamma-ray point sources in existing EGRET source catalogs have been reported. For the Coma Cluster, the result of an EGRET analysis has been published on the basis of observations from $\textit{Compton Gamma Ray Observatory}$ ($\textit{CGRO}$) cycles 1 and 2 (Sreekumar et al. 1996). In the analysis described here, EGRET data of individual viewing periods from $\textit{CGRO}$ observation cycles 1–9 were used for the analysis of 58 individual clusters. The latest and presumably final improvements in the efficiency corrections for the instrumental response of the EGRET spark chamber telescope have been fully implemented. Each galaxy cluster has been individually analyzed by means of standard EGRET data reduction techniques (likelihood source finding algorithm and subsequent flux determination at the position of the center of the X-ray emission). This analysis goes beyond the preliminary study presented by Reimer (1999) in which 4 yr of EGRET observations were analyzed in strict congruence with the 4 yr of EGRET observations used for the 3EG catalog of gamma-ray point sources. Co-added images of individual viewing periods, where a cluster has been observed at less than $30^\circ$ off the pointing axis of the EGRET instrument (standard field-of-view observations) or less than $19^\circ$ (narrow field-of-view observations), have been searched for gamma-ray excesses after modeling cataloged (and therefore well known) identified gamma-ray point sources by using the maximum-likelihood technique as described in...
Mattox et al. (1996). Gamma-ray source fluxes have been determined at the coordinates of the cluster center position known from X-ray observations. Applying the same detection criteria as used and described in the EGRET source catalogs, none of the 58 galaxy clusters are detected in the EGRET data. Special care has been exercised when already cataloged gamma-ray point sources are near the position of an Abell cluster (see Table 1 note). Three of these sources are unambiguously identified blazar-class AGNs: 1633+382 = 3EG J1635+3818 near A2199, 3C 279 = 3EG J1255−0549 near A1651, and 1604+159 = 3EG J1605+1553 near A2147. In these cases, the particular AGN has been modeled at its known radio position and simultaneously taken into account in the determination of the gamma-ray flux at the position of the Abell cluster in question. Only one of the remaining three catalog sources shows considerable overlap at the position of an analyzed cluster (A85 with the unidentified source 3EG J0038−0949). Keeping in mind the width of the point-spread function of the EGRET telescope, the total number of unidentified gamma-ray sources, and the size of our galaxy cluster sample, this occurrence is perfectly in agreement with chance coincidence. The probability of at least one coincidence between one of the 170 unidentified EGRET sources and one of the 58 considered galaxy clusters at a distance of 0.81 as in the case of 3EG J0038−0949 and A85 is 48.1%. Here a gamma-ray flux has been obtained at the cluster position without explicitly modeling the known but unidentified gamma-ray source.

Exemplary for the detailed results given in Table 1, the intensity and test statistics map of three prominent galaxy clusters (Perseus, Virgo, and Coma) are shown in Figure 2.

The most significant gamma-ray excess for any individual cluster has been found for A3532, corresponding to a detection significance of 1.6 $\sigma$. This is well below the detection threshold for being seriously considered as a source by standards of the EGRET data analysis, which is more than 4 $\sigma$ at high Galactic latitudes. Furthermore, the achieved detection significance is less than expected from statistical fluctuations at 58 trials alone. Therefore, for each galaxy cluster, a 2 $\sigma$ upper limit at the position of the cluster center has been determined and is given in Table 1.

### 3.2. The Study of the Cluster Population

Having established that individual clusters are not found in the EGRET data, a further analysis has been performed to study whether or not these galaxy clusters radiate in gamma rays as a population. For this purpose, the counts, exposure, and intensity maps of the individual galaxy clusters have been used. Each individual map has been transformed into a cluster-centered coordinate system under conservation of the original pixilation. Subsequently, the individual images have been co-added. Three sets of images have been produced in order to assure that the center region of the stacked image is not dominated by already-identified point sources or the Galactic plane:

1. A superposition of all 58 galaxy clusters in the sample;
2. A superposition of 54 galaxy clusters, excluding those with unambiguously identified dominant EGRET sources in the central map bins (A2199: 1633+382, A1650, A1651, and A1689: 3C 279); and
3. A superposition of 50 galaxy clusters, excluding those with unambiguously identified and dominant EGRET sources (see above) or the Galactic plane in the map center (the Oph and Cyg A clusters, 3C 129, and 3A 0745−191).

Each of the three sets has been analyzed; however, here we report only from the least-contaminated set (3). Due to the wealth of accumulated instrumental exposure, the results do not differ dramatically between these selections. The
| Number | Name                     | $l$  | $b$  | Flux (>100 MeV) | Viewing Periods | Notes |
|--------|--------------------------|------|------|-----------------|-----------------|-------|
| 1      | A426 (Per Cluster)       | 150.58 | -13.26 | 0.0184          | <3.72           |       |
| 2      | Oph Cluster              | 0.56  | 9.27  | 0.028           | <5.00           |       |
| 3      | VIR Cluster              | 282.08 | 75.20  | 0.0038          | <2.18           |       |
| 4      | Coma Cluster             | 58.13  | 88.01  | 0.0238          | <3.81           |       |
| 5      | A2319                    | 75.68  | 13.50  | 0.056           | <3.79           |       |
| 6      | A371                     | 316.31 | 28.54  | 0.04            | <6.34           |       |
| 7      | A3526 (Cen Cluster)      | 302.40 | 21.55  | 0.0109          | <5.31           |       |
| 8      | Tra Cluster              | 324.36 | -11.38 | 0.051           | <8.13           |       |
| 9      | 3C 129(3A 0446+449)      | 160.39 | 0.13  | 0.0223          | <5.29           |       |
| 10     | AWM7 (2A 0251+413)       | 146.34 | -15.63 | 0.018           | <3.47           |       |
| 11     | A754                     | 239.20 | 24.71  | 0.054           | <8.18           |       |
| 12     | A2029                    | 6.49   | 50.55  | 0.0768          | <7.49           |       |
| 13     | A2142                    | 44.23  | 48.69  | 0.0899          | <4.97           |       |
| 14     | A2199                    | 62.93  | 43.69  | 0.0299          | <9.27           |       |
| 15     | A3667                    | 340.88 | -33.39 | 0.055           | <3.82           |       |
| 16     | A478                     | 182.43 | -28.29 | 0.09            | <5.14           |       |
| 17     | A85                      | 115.04 | -72.06 | 0.055           | <6.32           |       |
| 18     | A3266                    | 272.14 | -40.16 | 0.0545          | <4.42           |       |
| 19     | A401                     | 164.18 | -38.87 | 0.075           | <9.28           |       |
| 20     | 3A 0745–191              | 236.42 | 2.99   | 0.01028         | <7.08           |       |
| 21     | A496                     | 209.57 | -36.48 | 0.0327          | <7.11           |       |
| 22     | A1795                    | 33.81  | 77.18  | 0.063           | <3.98           |       |
| 23     | A2256                    | 111.10 | 31.74  | 0.056           | <4.28           |       |
| 24     | Cyg A Cluster            | 76.19  | 5.76   | 0.057           | <4.46           |       |
| 25     | 2A 0335+096              | 176.25 | -35.08 | 0.0349          | <8.11           |       |
| 26     | A1060                    | 269.63 | 26.50  | 0.0114          | <14.85          |       |
| 27     | A3558                    | 312.00 | 30.72  | 0.048           | <3.58           |       |
| 28     | A644                     | 229.93 | 15.29  | 0.0704          | <9.71           |       |
| 29     | A1651                    | 306.73 | 58.63  | 0.086           | <3.75           |       |
| 30     | A3562                    | 313.30 | 30.35  | 0.0499          | <3.62           |       |
| 31     | A1367                    | 234.80 | 73.03  | 0.0215          | <2.72           |       |
| 32     | A399                     | 164.36 | -39.46 | 0.072           | <4.92           |       |
| 33     | A2147                    | 28.80  | 44.49  | 0.0356          | <7.45           |       |
| 34     | A119                     | 125.74 | -64.11 | 0.044           | <4.51           |       |
| 35     | A3158                    | 264.68 | -48.76 | 0.0575          | <2.52           |       |
| Number | Name            | $l$  | $b$  | $z$  | Flux (>100 MeV) | Viewing Periods | Notes          |
|--------|-----------------|------|------|------|----------------|-----------------|----------------|
|       |                 | deg | deg | deg | (10^{-8} cm^2 s^{-1}) |                 |                |
| 36    | Hyd A Cluster   | 242.93 | 25.09 | 0.0538 | <7.24 | 0300, 0330, 0410, 0440 |                |
| 37    | A2065           | 42.86 | 56.56 | 0.06 | <5.51 | 0092, 0240, 0245, 0250, 0250 |                |
| 38    | A2052           | 9.42  | 50.12 | 0.0348 | <6.24 | 0240, 0245, 0250, 3390, 4060, 4070 |                |
| 39    | A2063           | 12.82 | 49.69 | 0.036 | <5.52 | 0240, 0245, 0250, 3390, 4060, 4070 |                |
| 40    | A1644           | 304.89 | 45.44 | 0.0456 | <2.89 | 0300, 0310, 0320, 0340, 0340, 0360, 0360, 0370, 0380, 0380, 3040, 3050, 3060, 3070, 3120, 3120, 3140, 4050, 4060, 4070, 4080, 4240, 5110, 5115, 6060, 6070, 6080, 6090, 6100, 6105, 6111, 6215, 8065, 8067, 9100 |                |
| 41    | Klem 44 (A4038) | 25.08 | -75.90 | 0.0283 | <3.60 | 0091, 0132, 4040, 4280 |                |
| 42    | A262            | 136.58 | -25.09 | 0.0161 | <6.00 | 0150, 0260, 0280, 2110, 3170, 3250, 4250, 4270, 7287, 7289 |                |
| 43    | A2204           | 21.09 | 33.25 | 0.153 | <7.99 | 0160, 0240, 0245, 0250, 3240, 3390, 4290 |                |
| 44    | A2597           | 65.36 | -64.84 | 0.0824 | <8.19 | 0091, 0132, 0190, 3200, 3220, 3270, 4040 |                |
| 45    | A1650           | 306.72 | 61.06 | 0.084 | <3.07 | 0030, 0110, 2040, 2050, 2060, 2070, 3040, 3050, 3060, 3070, 3080, 3086, 3110, 3116, 4050, 4060, 4070, 4080, 5110, 5115, 6060, 6070, 6080, 6090, 6100, 6105, 6111, 6215, 8065, 8067, 9100, 9111 |                |
| 46    | A3112           | 252.95 | -56.09 | 0.0746 | <4.86 | 0100, 0290, 3290, 3350, 3355, 4090, 4280, 5170, 8010, 8020, 8339 |                |
| 47    | A3532           | 304.44 | 32.48 | 0.0537 | <7.42 | 0120, 0320, 2050, 2070, 2080, 2150, 2170, 3160, 4050, 4080, 4240 |                |
| 48    | A4059           | 356.84 | -76.06 | 0.0748 | <2.86 | 0091, 0132, 4040, 4250 |                |
| 49    | A3395           | 263.18 | -25.13 | 0.0498 | <3.28 | 0007, 0060, 0080, 0170, 2300, 3010, 3290, 3350, 3355, 3385, 4090, 4150, 5210 |                |
| 50    | MKW 3s         | 11.38 | 49.45 | 0.0434 | <5.31 | 0240, 0245, 0250, 3390, 4060, 4070 |                |
| 51    | A1689           | 313.38 | 61.10 | 0.1832 | <4.00 | 0030, 0110, 0240, 0245, 2040, 2050, 2060, 2070, 3040, 3050, 3060, 3070, 3080, 3086, 3110, 3116, 5115, 6060, 6070, 6080, 6090, 6100, 6105, 6111, 6215, 8065, 8067, 9100, 9111 |                |
| 52    | A576            | 161.42 | 26.24 | 0.038 | <3.47 | 0006, 0180, 0310, 2160, 2270, 2280, 3190, 3195, 4111, 4115, 5185 |                |
| 53    | A2244           | 58.81  | 36.31 | 0.097 | <4.29 | 0092, 0210, 2020, 3034, 4030, 5165, 5190, 6178, 7210, 7225 |                |
| 54    | A2255           | 93.95  | 34.93 | 0.0808 | <5.43 | 0092, 0220, 2010, 2020, 2120, 3020, 3032, 3034, 3037, 4030, 7100, 7110 |                |
| 55    | A1736           | 312.55 | 35.10 | 0.0431 | <3.48 | 0120, 0320, 2040, 2050, 2060, 2070, 2080, 2150, 2170, 3160, 4050, 4080, 4240, 5115 |                |
| 56    | A400            | 170.24 | -44.94 | 0.0238 | <6.51 | 0210, 3170, 4250, 6311, 9175 |                |
| 57    | A2657           | 96.65  | -50.30 | 0.0414 | <7.43 | 0190, 0260, 0280, 3200, 3270, 3360, 4100, 4250, 5070, 5075 |                |
| 58    | A1775           | 31.99  | 78.73 | 0.0722 | <3.47 | 0030, 0040, 0110, 0240, 0245, 2180, 2220, 3040, 3070, 3080, 3086, 3110, 3116, 3120, 3130, 4060, 4070, 5150 |                |

**Notes.**—(a) ~1.9 of 3EG J1635+3813. (b) ~0.8 of 3EG J0038+0949. (c) ~3.3 of 3EG J1347+2932. (d) ~1.4 of 3EG J0812−0646. (e) ~1.8 of 3EG J1255−0549. (f) ~0.7 of 3EG J1605+1553.
interpretation, however, simplifies considerably since we are not urged to discuss identified and dominant point sources or foreground emission features at or close to the image center anymore. The total exposure in the center region, averaged over the four central \(0.5 \times 0.5\) map bins, is \(3.4 \times 10^{10}\) cm\(^2\) s \((E > 100\) MeV\) for the 50 cluster selection, the lowest values at the edge of the \(40\arcmin \times 40\arcmin\) images are about \(1.4 \times 10^{10}\) cm\(^2\) s. Figure 3 (upper part) shows the co-added counts, exposure, and intensity map for the 50 cluster sample.

We have analyzed these images using the maximum-likelihood technique as already described. Here, however, we have to provide a customized diffuse galactic gamma-ray foreground model adapted for the application of our superpositioned cluster sample in the cluster-centered coordinate system. This was achieved by adopting the standard diffuse galactic emission model (GALDIF; Hunter et al. 1997) used for EGRET likelihood analysis, given on a \(0.5 \times 0.5\) grid, into a specific diffuse foreground model for the galaxy clusters in cluster-centered coordinates. Corresponding in image size and coordinates with the counts, exposure, and intensity map of the individual clusters, the appropriate diffuse maps have been taken directly from the GALDIF model. These maps were subsequently transformed into the cluster-centered coordinate system.

In each individual cluster observation, we expect the diffuse foreground emission to contribute a certain number of counts \((c_i)\) that can be calculated as the product of the respective exposure map \((\varepsilon_i)\) and the intensity of the diffuse emission \((DF_i)\). The appropriate diffuse foreground intensity for the co-added data, \(DF_{tot}\), is then derived by

\[
DF_{tot} = \frac{1}{\varepsilon_{tot}} \sum_i c_i = \frac{1}{\varepsilon_{tot}} \sum_i \varepsilon_i DF_i , \quad \varepsilon_{tot} = \sum_i \varepsilon_i .
\]

By applying the maximum-likelihood procedure in conjunction with the appropriately adapted diffuse model, the \(40\arcmin \times 40\arcmin\) images were searched for excesses. Of interest here is only the map center corresponding to the emission maximum of the considered galaxy clusters in X-rays. No significant gamma-ray emission excess has been found within a radius of \(5\) of the origin in the cluster-centered image. With a cumulative exposure of \(3.4 \times 10^{10}\) cm\(^2\) s \((E > 100\) MeV\), the corresponding upper limit is \(5.9 \times 10^{-9}\) cm\(^2\) s\(^{-1}\) (averaged over the four central \(0.5 \times 0.5\) map bins) for the so-constructed average galaxy cluster. Figure 3 (lower part) shows the customized diffuse model and the resulting likelihood test statistics maps. Easily seen in the test statistics image is 3C 279, located at \(\sim 13\) from the map center and thus far too distant to cause any conflict with the determined upper limit.

4. DISCUSSION

4.1. Cases of Individual Galaxy Clusters

The negative results from both an analysis of the gamma-ray data from the EGRET instrument at positions of 58 individual galaxy clusters as well as from a superposition of 50 galaxy clusters needs to be discussed critically with respect to underlying systematics. Categorically, the question of an appropriately chosen selection of galaxy clusters might arise. The assumption has been made that the brightest and nearest clusters detected at X-ray wavelengths should be the most likely candidates to emit observable gamma rays, supported by various models explaining the multifrequency emission properties and the general understanding of confinement and interaction of cosmic rays in the ICM of a galaxy clusters (Berezinsky et al. 1997; Völk,
Aharonian, & Breitschwerdt 1996). Because almost all clusters exhibiting unusual multifrequency emission characteristics (EUV-excess emission, nonthermal X-ray emission, and/or a diffuse radio halo) are naturally included here, the above assumption is certainly not artificial. In Table 2, we compare our results with two different scenarios of gamma-ray emission from cosmic-ray interactions in the ICM, quantitatively predicting gamma-ray emission for some individual galaxy clusters.

Our upper limits are consistently below the predictions as given by Ensslin et al. (1997) and especially Dar & Shaviv (1995). Thus, the suggested scenarios are ruled out in the given parameter space. Concerns about the results of Dar & Shaviv (1995) already have been pointed out by Stecker & Salamon (1996) on account of the spectra of the diffuse galactic and extragalactic gamma-ray background. With the apparent conflict between these model predictions and the observational upper limits for the individual galaxy

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clustering, we clearly disfavor these models against models that predict gamma-ray emission below the sensitivity of the instruments of the CGRO-era-like inverse Compton scenarios from cosmic-ray electrons accelerated at accretion shocks by Colafrancesco & Blasi (1998), Miniati et al. (2001), and Miniati (2002).

At present, with quantitative predictions about the gamma-ray emission made only in cases of the most prominent galaxy clusters and with measured upper limits and predicted fluxes not orders of magnitudes apart, only a moderate, conservative interpretation is tenable. The degree of freedom in the parameters in the models is in conflict with our measurements, especially if predicting a diffuse extragalactic background component without a single positive detection of the object class in question does not allow us to discriminate between the suggested scenarios solely on the basis of the presented gamma-ray data. Not until the next generation of gamma-ray telescopes are available will there be good prospects for the detection of individual galaxy clusters as well as the chance to observationally constrain the constituents of the extragalactic diffuse background. The sensitive measurements to discriminate between the various scenarios for gamma-ray emission from galaxy clusters must originate at other wavelengths. Here three wavebands are of particular interest: the new generation of low-threshold, ground-based Cerenkov telescopes presently being built or just starting their observations will provide very sensitive measurements at energies above 100 GeV, thus providing the necessary information to constrain the inverse Compton component at the highest energies. More and better hard X-ray measurements may discriminate clearly between thermal and nonthermal emission components and therefore help to identify the nature of the originating particle population, in particular, deciding on the preference of inverse Compton or nonthermal bremsstrahlung scenarios. Finally, more sensitive radio halo measurements may be performed, especially at the high-frequency end of the synchrotron emission component, where currently only the radio halo of the Coma Cluster has been sufficiently investigated (Schlickeiser, Sievers, & Thiemann 1987; Thierbach, Klein, & Wielebinski 2003). High-frequency radio measurements from diffuse cluster halos will directly constrain the shape and intensity of the resulting inverse Compton component at high energies.

4.2. The Case of Galaxy Clusters as a Population

We now discuss the result for the average cluster from our analysis of 50 galaxy clusters population. At the achieved sensitivity, there is still no indication of gamma-ray emission from galaxy clusters. The 2σ upper limit for the flux of the average cluster is $5.9 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$. This may help to resolve the stark inconsistency between studies performing direct EGRET data analysis on galaxy clusters (e.g., McGlynn et al. 1994; Sreekumar et al. 1996; and this work) and the recently published detection claims originating from information on gamma-ray point sources from the 3EG catalog in conjunction with statistical assessments by Colafrancesco (2001, 2002) and Kawasaki & Totani (2002). Here we would like to give a reassessment of these detection claims on a firm spatial-statistical foundation. The cluster sample studied by Colafrancesco consists of the entire Abell cluster catalog (Abell, Corwin, & Olowin 1989) at Galactic latitudes $|b| > 20°$. The corresponding Poissonian probability distribution for spatial association between the cluster sample and gamma-ray point sources from the EGRET catalog is easy to determine and given in Figure 4a. The two-point

| Cluster     | $F_{\gamma}^{a}$ | $F_{\gamma}^{b}$ | $F_{\gamma}^{c}$ |
|-------------|------------------|------------------|------------------|
| A426 (Perseus) | $<3.7 \times 10^{-8}$ | $12 \times 10^{-8}$ | $10 \times 10^{-8}$ |
| Ophiuchus     | $<5 \times 10^{-8}$  | $9 \times 10^{-8}$  | ...              |
| A1656 (Coma)  | $<3.8 \times 10^{-8}$ | $6 \times 10^{-8}$  | $5 \times 10^{-8}$  |
| M87 (Virgo)   | $<2.2 \times 10^{-8}$ | $3 \times 10^{-8}$  | $22 \times 10^{-8}$ |

Note.—$F_{\gamma}$ in units of photons cm$^{-2}$ s$^{-1}$.

a This measurement.
b From Ensslin et al. 1997.
c From Dar & Shaviv 1995.
autocorrelation function, $\omega_{ab}$, for the population of Abell clusters has been intensively studied previously (Hauser & Peebles 1973; Postman, Geller, & Huchra 1986; Olivier et al. 1990; Akylas, Georgantopoulos, & Plionis 2000), but its impact on the correlation analysis can be calculated rigorously for only a very large sample of objects. Here we are concerned with only 170 unidentified EGRET sources, 59 of which are located at $|b| > 20^\circ$. Therefore, we have directly determined the chance probability for an association between an arbitrary source and one of the Abell clusters as a function of the radius of interest (roi), i.e., the maximum separation of sources considered as associated. Colafrancesco (2002) reports an association of 50 EGRET sources (respectively, 18 unidentified EGRET sources) and 70 Abell clusters (respectively, 24 Abell clusters) based on an initial sample of 3979 Abell clusters and 128 EGRET sources (respectively, 59 unidentified EGRET sources) at $|b| > 20^\circ$.

Pure Poissonian statistics predict a total of 34.4 (17.2) single, 8.6 (2.0) double, and 1.3 (0.2) triple associations between EGRET sources and Abell associations at 1$^\circ$ roi (respectively, 0.81 as the average $\Theta_{95}$). Using the modified chance probabilities (Fig. 4b) to account for the autocorrelation of the Abell clusters, one expects a total of 28.0 (10.6) single, 8.9 (2.5) double, and 2.6 (0.5) triple associations by chance. Autocorrelation among the unidentified EGRET sources at $\leq 1^\circ$ scale per se is excluded due to the moderate angular resolution of the EGRET telescope and its relative inability to discriminate neighboring sources adequately (source confusion). Hence, the expected chance associations amount to 40.7 EGRET sources and 56.6 Abell clusters for 128 EGRET sources at 1$^\circ$ roi and 13.7 EGRET sources and 17.5 Abell clusters for 59 unidentified EGRET sources at $\Theta_{95}$, respectively. In terms of the cumulative Poisson probability, the significance of the correlation claim by Colafrancesco needs to be reassessed to only 1.36 $\sigma$ in case of the 128 EGRET sources (which is meaningless anyway because of the contamination with already-identified EGRET sources, the blazars) or 1.03 $\sigma$ in case of the 59 unidentified EGRET sources, rigorously indicating the statistical insignificance of the correlation claim.

Furthermore, the explicitly suggested Abell cluster/unidentified EGRET source associations by Colafrancesco (2002) do not contain the most likely and prominent galaxy clusters predicted to be the clusters with the best chance to be detected in high-energy gamma rays (Fig. 5). Actually, only one of the 18 listed unidentified EGRET sources indeed has a truly X-ray–bright Abell cluster counterpart: the remaining 23 clusters are not even included in the most recent and carefully compiled sample of a flux-limited, X-ray–bright galaxy cluster population (Reiprich & Böhringer 2000). Thus, the identification sequence as suggested by Colafrancesco (radio halo/host radio galaxies $\rightarrow$ X-ray brightness $\rightarrow$ counterpart in unidentified gamma-ray source) simply does not work this way, either globally or just in a few of the referenced cases. Similarly, the predictive power of the $L_{\gamma}-L_{\text{radio}}$ and $L_{\gamma}-L_X$ correlation as given in Colafrancesco (2002) must be seriously questioned.

A further suggestion of possibly merging clusters as counterparts of unidentified gamma-ray sources by Kawasaki & Totani (2002) is based on only seven individual gamma-ray sources, all of which belong to the sample of steady unidentified EGRET sources classified as such by Gehrels et al. (2000). However, more specific variability studies of EGRET sources as performed by Tompkins (1999) and

![Image](image-url)
flux of $4.7 \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1}$, which is marginally inconsistent with our findings. Considering a 2° aperture by inclusion of the second innermost bin of $\sim 1.2 \times 10^{-6} \text{ photons} \text{ cm}^{-2} \text{s}^{-1}$ from Scharf & Mukherjee (2002), the corresponding mean cluster flux will increase to $9.6 \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1}$, which is clearly inconsistent with our upper limit for the average cluster from the sample of nearby X-ray–bright galaxy clusters. Since it is not within the scope of this paper to perform an in-depth study of possible systematic effects, we state only that the results presented by Scharf & Mukherjee (2002), although at a comparable sensitivity level, are apparently inconsistent with ours.

In conclusion, we still have to await the first observational evidence for the high-energy gamma-ray emission of galaxy clusters. The last generation of gamma-ray telescopes on board CGRO was not able to resolve an individual galaxy cluster nor the nearby X-ray–brightest clusters of galaxies as a population. Until the next generation of gamma-ray instruments challenges this important scientific topic, progress is expected at other wavelengths: from GHz frequency radio observations of radio halos, from studies of soft and hard X-ray excess features with sufficient statistical significance, and from measurements of the new generation of imaging atmospheric Cerenkov telescopes.

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