FIRST GAMMA-RAYS FROM GALAXY CLUSTERS

SERGIO COLAFRANCESCO
INAF - Osservatorio Astronomico di Roma,
Via Frascati, 33 - I00040 Monteporzio, Italy

We present the evidence for the association of galaxy clusters with unidentified EGRET sources at high galactic latitude. Even though preliminary, these are the first evidence for γ-rays from galaxy clusters and may lead to a deeper understanding of their structure and evolution.

1 Prologue

The large part (170 out of 271) of the γ-ray sources detected with the EGRET instrument on board the CGRO satellite have not yet been identified with secure counterparts at other wavelenghts because of the poor spatial resolution of the EGRET instrument[12]. Most of the unidentified γ-ray sources are found at low galactic latitudes, $|b| \lesssim 20$ deg, and are likely to belong to our Galaxy[10]. Fifty of these sources are found at high galactic latitudes, $|b| \gtrsim 20$ deg, and there are several hints that they are of extra-galactic nature[11]. Among the identified extra-galactic γ-ray sources observed with EGRET, most of them are AGNs[12] but there are no firm evidence that the remaining unidentified EGRET sources can be associated with another population of active galaxies. In fact, most of the unidentified EGRET sources have a rather low flux variability while AGNs usually show a strong flux variability in the γ-rays.
Galaxy clusters are bright sources of X-rays produced through bremsstrahlung emission from a hot (temperature $T \sim 10^7 - 10^8$ K), optically thin (number density $n \sim 10^{-3}$ cm^{-3}), highly ionized intracluster (IC) gas (mainly consisting of a population of thermal electrons and protons) in nearly hydrostatic equilibrium with the overall gravitational potential of the structure. Many galaxy clusters also show the presence of non-thermal emission phenomena like extended radio halos, likely produced by synchrotron emission of relativistic electrons either accelerated in the intracluster medium (ICM) by merging shocks or produced in the decay of dark matter

annihilation products [4]. Many clusters also host bright radio (or active) galaxies living in their environment that can inject relativistic particles into the ICM. The presence of relativistic particles in the ICM has been also suggested to explain the emission excesses observed in some clusters in the EUV[14,2] and in the hard X-rays [8,9,15,13]. However, there is no evidence for a detection of γ-ray emission in the direction of a few selected clusters like Coma[17] and Virgo. There are, nonetheless, several theoretical motivations to expect that galaxy clusters can indeed be extended sources of γ-rays emitted in the decay of neutral pions, produced either in the interaction of cosmic ray protons with the ICM protons ($pp \to X + \pi^0 \to \gamma + \gamma$ [6]) or in the annihilation of dark matter particles ($\chi\chi \to X + \pi^0 \to \gamma + \gamma$ [7]). The secondary electrons produced in the previous mechanisms[1,7] can also produce additional γ-ray emission through both bremsstrahlung and Inverse Compton Scattering (ICS) against the CMB photons. Also primary cosmic ray electrons can produce a diffuse flux of γ-rays due to non-thermal bremsstrahlung and ICS of the CMB photons[4]. On top of such diffuse emission, the γ-ray emission from individual 'normal' and 'active' galaxies living in the cluster is also expected, [5].

2 The association of galaxy clusters with EGRET unidentified sources

We report, following Colafrancesco[5], the results of a detailed spatial and spectral analysis of the unidentified EGRET sources at high galactic latitude and the preliminary evidence for a correlation between galaxy clusters and unidentified EGRET sources at $|b| > 20$ deg.

Spatial association We found that the coordinates of the optical centers of 52 Abell clusters fall within the contour containing the 95% confidence level error region for the positions of 39 unidentified EGRET sources in the Third EGRET catalog [12]. Based on our simulations, we found that, on average, 26 EGRET sources can be randomly associated with simulated cluster positions. Based on a Kolmogorov-Smirnov test, the probability that all of the remaining 13 EGRET unidentified sources are still randomly associated with galaxy clusters is $\lesssim 1\%$. However, since a substantial fraction of the sky observed by EGRET has a low sensitivity (where it would be difficult to observe any faint source), the previous estimate of the significance level of the correlation can be safely considered as a lower limit of the true one[5].

To select out of the full association list the more probable associations of galaxy clusters with the unidentified EGRET sources, we superposed the optical cluster positions and their X-ray images onto the maps containing the probability distribution for the spatial position of the EGRET sources found in our spatial correlation analysis (see Fig.1 for the case of the cluster A1758). We exclude those sources associated with galaxy clusters that have also AGNs (with confirmed identification), Gamma Ray Burst and SN remnants whose position fall within the 95% confidence level position error contours of the EGRET source. We also excluded 12 EGRET sources with a possible, but not confirmed, AGN contamination. Eventually, we found in our conservative analysis that 24 galaxy clusters are associated to 18 unidentified EGRET sources with $|b| > 20$ deg for which there is no firmly established counterpart at other wavelengths, neither extragalactic (AGN or "active" galaxy) or galactic (Supernova remnant, pulsar, neutron star). According to our selection procedure, the significance level of such a spatial association is $\approx 2.55\sigma$ which corresponds to a probability $\lesssim 1\%$ for the null hypothesis that the two source populations are randomly associated. However, the point is still to determine how many of these spatial associations are due to random projection effects and which are the most probable physical associations. A rough estimate of the probability to have still random associations in the sample here selected and to be not contaminated by either extra-galactic or galactic γ-ray sources, yields that about 2/3 of the 18 selected EGRET sources are still random associations. This rough estimate would yield 6 most probable cluster–EGRET source associations with a confidence level of 1.73σ. Note, however, that this is again a lower limit to the true statistical confidence of the correlation since the effect of the non-uniform EGRET sky coverage would tend to increase the statistical significance level of the most probable association. If we correct for the number of correlations expected in the fraction of the EGRET sky ($\sim$ 30% of the full sky) which has a flux limit below $F(>$ 100 MeV$) \leq 6 \cdot 10^{-8} cm^{-2} s^{-1}$, we obtain that the expected confidence level of the most probable associations raises from 1.73σ to 2.12σ.

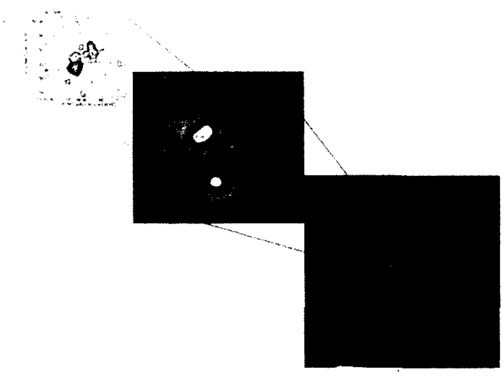

Figure 1: One of the most probable associations between galaxy clusters and EGRET unidentified γ-ray sources: A1758. This cluster has a radio halo/relic inhabiting the cluster and a number of identified radio galaxies in the ICM. Shown are the EGRET image with the cluster X-ray brightness contours superposed (right), the ROSAT-HRI X-ray image of the cluster (center) with the NVSS radio sources in the field (red circles) and the radio halo/relic image observed with the VLA at 1.4 GHz (left).

Flux and spectral analysis In addition to the spatial information contained in the Third EGRET catalog and in the Abell cluster survey, we used more physical criteria to determine the number of spurious correlations in our selected sample. Specifically, we analyzed the flux level, the flux variability and the spectral indices of the 18 selected EGRET sources compared to the same quantities of other γ-ray sources more definitely identified in the Third EGRET catalogue (mainly AGN and Pulsars). The flux variability for the probable 18 cluster-EGRET source associations is, on average, $\lesssim 20\%$ and only in a few cases (3EG J1825-7926, 3EG J1212+2304, 3EG J0616-3310, 3EG J2248+1745) is $\gtrsim 30\%$ in some specific Viewing Period [5]. The correspondingly associated clusters are poorly studied, do not have X-ray information and do not have any identified bright radio galaxy or radio halo/relic emission. Hence, we also consider these cases as suspiciously due to projection effects. The upper limits of the analyzed EGRET sources do not strongly affect our conclusions on their overall flux variability due to their low statistical significance.

The EGRET sources correlated with clusters are not found to be brighter than $F(> 100\mathrm{MeV}) \sim 2 \cdot 10^{-7}$ counts cm$^{-2} s^{-1}$ and show spectral indices in a large range $\sim 2-3.5$ (see Fig.2) which are consistent with those expected from the viable mechanisms for γ-ray emission in clusters. With a remarkable difference, the EGRET sources identified with known AGNs span over a much higher γ-ray flux range and have a much smaller range of spectral index values ($\gamma \sim 2-2.5$) especially at very bright flux levels $F(>$ 100 MeV$) > 5 \cdot 10^{-7}$ counts cm$^{-2} s^{-1}$. Pulsars also show very flat spectral indices $\gamma \lesssim 2$ and very high γ-ray flux which cannot be compared with those of the EGRET sources associated with clusters. Simulations of the flux variabil-

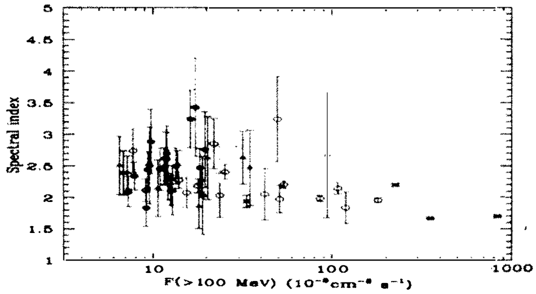

Figure 2: The γ-ray spectral index is plotted vs. the flux $F(> 100\text{MeV})$ of the EGRET sources spatially associated with galaxy clusters. We compare the spectral indices for the EGRET sources which are more probably associated with clusters (filled circles) with the EGRET sources correlated with clusters and in which an identified AGN is also found (open circles). The data for the EGRET sources contaminated by possible AGNs (gray triangles), GRB (open, light-gray triangle), SNR (open black triangle) and Pulsars (stars) are also shown for comparison.

ity of the 18 EGRET sources here selected show that we should expect 4 EGRET sources with $\Delta F/F \lesssim 0.2$, while the remaining 14 EGRET sources possibly associated with galaxy clusters should have $0.2 \lesssim \Delta F/F \lesssim 1$. The actual data show that there are about 11 EGRET sources with $\Delta F/F \leq 0.2$ and only 7 sources with $0.2 \lesssim \Delta F/F \lesssim 1$. This indicates that the low flux variability shown by the EGRET sources found in association with clusters cannot be recovered by a simple random distribution at more than 5σ confidence level.

Based on these results, we expect that about 10 EGRET sources, out of the 18 listed by Colafrancesco[5], are probable EGRET-cluster associations having $\Delta F/F \lesssim 0.2$, $F(> 100\text{ MeV}) < (1-2) \cdot 10^{-7} cm^{-2} s^{-1}$ and $\gamma \sim 2 - 3.2$. A detailed analysis of the spatial and spectral features of each EGRET source as well as a detailed analysis of their cluster counterparts[5] revealed also the nature of the physical association between EGRET sources and galaxy clusters.

Luminosity correlations In fact, the 12 galaxy clusters more likely associated to the 9 EGRET sources previously found are quite peculiar since all of them have bright NVSS radio sources in their environment and six of them have also bright radio galaxies. Three of the clusters (A1758, A1914 and A85) also show the presence of extended radio halos or relics. Hence, such galaxy clusters which have strong radio emission (either diffuse or associated with member galaxies) show the direct presence of a population of relativistic electrons which are injected in their ICM. Such relativistic electrons can be injected by radio galaxies, which are mainly found in the central regions of the clusters, and may produce $\sim$ GeV γ-ray emission which can be observed by EGRET. Such particles can also diffuse in the magnetized ICM and interact with the IC gas (mainly electrons and protons) to produce diffuse radio emission, heating of the ICM itself and secondarily produced γ-ray emission [4]. In addition, particles in the ICM could be efficiently accelerated at the accretion shocks located at the cluster periphery as well as at the ICM shocks produced by subcluster mergings and/or by fast galaxy motions. The subsequent interaction of the accelerated particles with the surrounding hot, magnetized ICM can again produce diffuse radio halo/relic emission[1,16] and diffuse γ-ray emission at $E > 100$ MeV[6]. On top of these acceleration mechanisms, it has been recently shown that dark matter particle (neutralinos) annihilation may produce both diffuse radio halo emission and diffuse γ-ray emission [7]. The presence of such relativistic particles into the ICM strongly suggests, in conclusion, that themselves and/or their parent population (e.g., relativistic protons, dark matter particles) can be responsible for a substantial γ-ray flux at the EGRET energies ($E > 100$ MeV) as well as non-thermal radio emission through different mechanisms. In fact, we also found

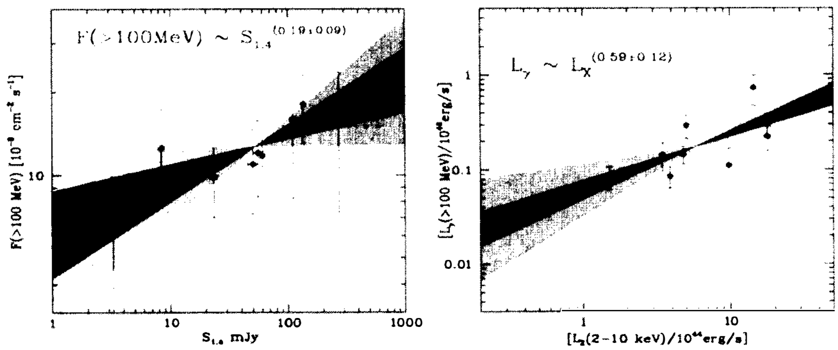

Figure 3: **Left** The correlation between the γ-ray flux, $F(>100$ MeV), and the radio flux at 1.4 GHx, $S_{1.4}$, shown by the most probable EGRET source – cluster associations. The best fit curve $F(>100 \text{ MeV}) \sim S_{1.4}^{0.19}$ is shown (solid) together with the 1σ (green/dark gray) and 2σ (yellow/pale gray) confidence level regions of the fit. **Right** The $L_\gamma - L_X$ correlation shown by the clusters most probably associated with EGRET sources. The best fit curve (solid line) is shown together with the 1σ (green/dark-gray area) and 3σ (yellow/pale-gray area) confidence level region for the fitting parameters.

a correlation $F(>100 \text{ MeV}) = AS_{1.4}^{B}$ with $A = 6.053^{+2.637}_{-1.836}$ and $B = 0.187 \pm 0.091$ (1σ errors) between the radio flux at 1.4 GHz, $S_{1.4}$, of the brightest radio source in the cluster and the EGRET source flux, $F(>100$ MeV) (see Fig.3). Even though the uncertainties in the EGRET source fluxes do not allow to draw any strong conclusion for the universality of such correlation, our results indicate that there is a connection between the activity of the ICM, and of its active galaxy content, and the overall γ-ray behaviour of these large scale structures, an indication that can be definitely confirmed by the next generation γ-ray telescopes.
Moreover, the same EGRET-cluster associations (with the exception of the source 3EGJ0159-3603 associated with the clusters A219 and A2963 because no reliable redshift is available for these clusters) also show a correlation $L_\gamma = CL_X^D$ (with best fit values $C = 0.06 \pm 0.01$ and $D = 0.593 \pm 0.122$, 1σ errors) between their γ-ray luminosity L_γ and their X-ray luminosity L_X (see Fig.3). Such a $L_\gamma - L_X$ correlation also indicates a connection between the physical status of the cluster ICM, and of its galaxy content, and the overall γ-ray emissivity of the cluster: such a connection is indeed expected in the viable model for the γ-ray emission of galaxy clusters[5].

3 Preliminary conclusions and future outline

We found that there are several converging evidence (even though still preliminary) of an association between unidentified EGRET sources at high galactic latitude ($|b| > 20$ deg) and galaxy clusters which show an enhanced radio activity in their ICM as triggered by radio (or active) galaxies or by non-thermal phenomena giving rise also to radio halos and relics[5]. Such evidence are found at several levels, from the geometrical spatial association with a minimal statistical confidence level of $\sim 2.5\sigma$, to the γ-ray flux and luminosity correlations with the radio and X-ray data of the associated clusters with a statistical confidence level of $\sim 2.1\sigma$ and $\sim 4.9\sigma$, respectively. Even though the cluster sample we derived here is far from being an *a priori* flux limited sample, the correlation we found with unidentified EGRET γ-ray sources can be considered as the first evidence of the expected distribution of the γ-ray luminosity of "active" galaxy clusters. While at the moment we have the first, preliminary evidence for the first γ-rays coming from galaxy clusters, their detailed study will have a full bloom with the next gener-

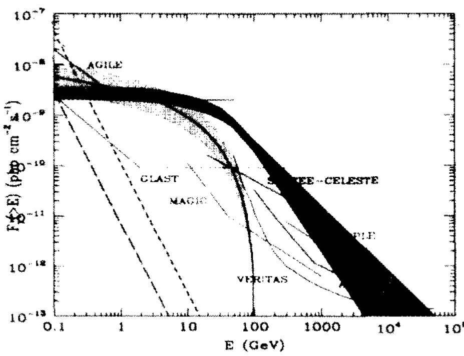

Figure 4: The γ-ray flux $F_\gamma(> 100$ MeV) predicted for a Coma-like cluster are shown as a function of the γ-ray energy and are compared with the sensitivity of the next generation γ-ray experiments: non-thermal electron bremsstrahlung for two choices of the IC magnetic field ($B = 0.3\mu$G: short-dashed curve and $B = 1\mu$G: long-dashed curve); decay of π^0 produced in *pp* collisions (blue curve and the associated theoretical uncertainties given in the cyan region); decay of π^0 produced in the annihilation of dark matter neutralinos (black solid curve and the associated theoretical uncertainties given in the yellow region). Due to the very different spatial resolution of the various experiments reported, we show here the case of their sensitivity for point-like sources.

ation space-borne (AGILE, GLAST, MEGA) and ground-based (VERITAS, ARGO, MAGIC) γ-ray instruments. The next generation γ-ray telescopes, and especially the GLAST mission, will have the spatial and spectral capabilities to confirm the preliminary result here presented and to disentangle between the diffuse and concentrated nature of the cluster γ-ray emission. Gamma-ray observations of galaxy clusters in the range $\sim 0.01 - 10^4$ GeV (see Fig.4) can probe directly the existence of different populations of relativistic particles (e.g., electrons, protons, dark matter particles) in the ICM through their distinctive γ-ray spectral features and will open a new window on the astrophysical studies of large scale structures in the universe.

References

1. Blasi, P. & Colafrancesco, S. 1999, Astroparticle Physics, 12, 169
2. Bowyer, S., 2000, Proc. of the *American Astronomical Society, HEAD Meeting*, 32, 1707
3. Carilli, C.L. & Taylor, G.B. 2001, ARAA, in press (astro-ph/0110655)
4. Colafrancesco S., 2002, in *Multifrequency Behaviour of High-Energy Cosmic Sources*, Ed. F.Giovannelli, in press
5. Colafrancesco, S. 2002, A&A, in press (astro-ph/0203443)
6. Colafrancesco S. & Blasi P., 1998, Astroparticle Physics, 9, 227
7. Colafranesco S. & Mele B., 2001, ApJ, 562, 24
8. Fusco-Femiano R. et al., 1999, ApJ, 513, L21
9. Fusco-Femiano R. et al., 2000, ApJ, 534, L7
10. Gehrels, N. et al. 2000, Nature, 404, 363
11. Grenier, I.A., 2002, these Proceedings
12. Hartman, R.C. et al., 1999, ApJS, 123, 79
13. Kaastra J. et al., 1999, Ap.J, 519, L119
14. Lieu R. et al., 1999, ApJ, 510, L25
15. Rephaeli, Y., Gruber, W. & Blanco, P., 1999, ApJ, 511, L21
16. Sarazin, C.L. 2001, preprint astro-ph/0105418
17. Sreekumar, P. et al., 1996, ApJ, 464, 628