High-energy gamma-ray emission from Clusters of Galaxies

Why do we think of gamma-rays in galaxy clusters?
   or: the link from radio & X-rays observations

The present situation in gamma-rays
   or: claims on the way towards an unambiguous detection

Ask the EGRET data once and for all!
   - a sample of individual clusters
   - a collective study

Beyond CGRO?
Hints from radio and X-ray observations

a few galaxy clusters exhibit a diffuse radio halo:

only ~ 5% of the X-ray brightest galaxy clusters show diffuse radio emission ("halos" "relics")
common: high $T$: $kT > 7$ keV & high $Lx > 5 \times 10^{44}$ erg s$^{-1}$ (0.1 - 2.4 keV),
often: presence of merger processes & large core radii & absence of cooling flows
origin: nonthermal electrons interacting with a magnetic field
in-situ acc. during merger processes
diffusion of rel. electrons out of radio galaxies in the cluster
secondary particle production by hadronic interactions of rel. $p$ with ICM
... decay of dark matter annihilation products ...

Olaf Reimer, Ruhr-Universität Bochum
Hints from radio and X-ray observations

**EUV-excess emission**: (not the common phenomenon of diffuse EUV emission) unambiguous evidence only for Virgo and Coma claims vs. anti-claims: A 2199, A1795, A4095, Fornax ...

**hard X-ray emission**: nonthermal = power-law component detected in Coma, A2199, A2256 <-> Virgo!

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**Fig. 1.** Azimuthally averaged radial intensity profile of the EUV emission in the central part of Virgo (centered on M87), shown as a solid line. The dashed line is the vignetting background. There is no EUV emission beyond $r \approx 17'$.

**Figure 1.** RXTE spectrum of the Coma cluster. Data and folded Raymond-Smith ($kT \approx 7.51$ keV), and power-law (index = 2.34) models are shown in the upper frame.

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Consequences from radio and X-ray observations

X-ray emission is *IC scattering* of the *radio producing electrons by the CMB*:
- power-law with index simply related to the index of radio emission
- matching spatial profiles in X-rays and radio images
  (of course, only if this is one and the same electron population)

If electron spectrum extend to energies both below and above the range deduced from the radio measurements: *low energy supra-thermal or trans-relativistic electrons*  
-> nonthermal bremsstrahlung: *also* power-law X-ray emission

Some models require a *second* distinct relativistic electron population!

What about p? (i) if $\pi_0$ decay is *detected* in gamma-rays, YES!  
(ii) if radio & X-ray detected electrons are secondaries from charged pion decays
Now put together the various bits of observational evidence in *multifrequency models* ...

**Fig. 7.** The predicted gamma-ray spectrum of the Coma cluster in the region around 100 MeV. The emission is mainly the result of bremsstrahlung by relativistic electrons and $\pi^0$ decay due to relativistic ions. The electron population was determined by Atoyan & Völk 1999.

**Fig. 1.** The synchrotron and IC fluxes calculated for the magnetic field in Coma cluster $B = 0.12 \mu$G, assuming stationary Atoyan & Völk 1999.
... and constraints from **OSSE** and **EGRET** (Coma):

**Fig. 2.** The bremsstrahlung and IC radiation fluxes calculated in the case of injection of relativistic electrons with $\alpha_{\text{inj}} = 2.3$ during the last $\Delta t_{\text{inj}} = 3 \, \text{Gyr}$ assuming $B = 0.1 \, \mu \text{G}$ (solid curves), and $\alpha_{\text{inj}} = 2.6$, $\Delta t_{\text{inj}} = 1 \, \text{Gyr}$ assuming $B = 0.15 \, \mu \text{G}$ (dashed curves). A mean gas density $n_g = 10^{-8} \, \text{cm}^{-3}$ in the ICM is assumed. In the $\gamma$-ray region, the expected flux sensitivity of the GLAST detector (from Bloom 1996) and the upper flux limit of EGRET (Sreekumar et al 1996) are also shown.

Aloyan & Völk 2000

**Enßlin & Biermann 1999**
Colafrancesco said his analysis shows, for the first time, that galaxy clusters can emit gamma rays [...] 

Colafrancesco said that a large fraction of these unidentified, extragalactic gamma-ray sources are spatially correlated - within one degree - with the position of nearby galaxy clusters. The probability that such a spatial correlation is due to a random effect is less than 0.5%.

Colafrancesco compared the X-ray brightness of a given cluster with the gamma-ray brightness of the spatially associated unidentified gamma-ray source and found further correlation. The existence of such a correlation indicates - with a confidence level greater than 95% - a physical connection between the content of the galaxy cluster and the gamma-ray emission of the associated EGRET source.
High Energy Gamma Ray Emission from Clusters of Galaxies

Abell 85

from Colafrancesco's talk Baltimore 2001

... paper accepted (A&A)

Radio halo/relic map (VLA ~ 327 MHz)

X-ray source (ROSAT PSPC)

EGRET source + SAX contours

NVSS radio sources in the field

50 EGRET sources associated with galaxy clusters within 1 deg radius.

\( P_{\text{random}} < 5 \times 10^{-3} \)

Olaf Reimer, Ruhr-Universität Bochum
High Energy Gamma Ray Emission from Clusters of Galaxies

astro-ph/0108309:

STRONG CORRELATION BETWEEN THE HIGH-LATITUDE STEADY UNIDENTIFIED GAMMA-RAY SOURCES AND POSSIBLY MERGING CLUSTERS OF GALAXIES

WATARU KAWASAKI\textsuperscript{1,2} AND TOMONORI TOTANI\textsuperscript{1,4}

Submitted 2001 Aug 18

ABSTRACT

We report an evidence for the first time that merging clusters of galaxies are a promising candidate for the origin of high galactic latitude, steady unidentified EGRET gamma-ray sources. We made a matched-filter survey of galaxy clusters over $4^\circ \times 4^\circ$ areas around seven steady unidentified EGRET sources at $|b| > 45^\circ$ together with a $100\,\Omega{}$ area near the South Galactic Pole as a control field. In total, 154 Abell-like cluster candidates with $\mu_{\ast} < 0.15$ and 18 close pairs/groups of these clusters, expected to be possibly merging clusters, were identified.

ApJ 2002:

POSITIONAL COINCIDENCE BETWEEN THE HIGH-LATITUDE STEADY UNIDENTIFIED GAMMA-RAY SOURCES AND POSSIBLY MERGING CLUSTERS OF GALAXIES

WATARU KAWASAKI\textsuperscript{1,2,3} AND TOMONORI TOTANI\textsuperscript{4,5}

Olaf Reimer, Ruhr-Universität Bochum
Ask the EGRET data once and for all again!

starting in 1999, a sample of 58 of the X-ray brightest clusters has been analyzed ($z < 0.14$), individually as well as in superposition naturally included: all those *flashy* clusters (EUV excess; hard X-ray emission; most of the radio halo clusters; Perseus, Coma, Virgo)

EGRET Gamma-Ray Sources and X-ray bright Galaxy Clusters

$E > 100 \text{ MeV} \text{ resp. } z < 0.14$

Identified EGRET Sources

Unidentified EGRET Sources

X-ray bright Clusters of Galaxies

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typical procedure for the individual cluster:

- superpositioning of count/exposure files from individual viewing periods (1999: 3EG P1-4, 2001: all available data for r < 25° from cluster center, individually stacked)
- max ln algorithm (discrimination of excesses above diffuse gamma-ray background)
- determination of flux at position centered of X-ray emission maximum

<table>
<thead>
<tr>
<th>#</th>
<th>Name</th>
<th>l</th>
<th>b</th>
<th>r_{VTP} [arcmin]</th>
<th>( \phi )</th>
<th>\text{flux (&gt;100 MeV)} [10^{-8} \text{ cm}^{-2} \text{ s}^{-1}]</th>
<th>viewing periods</th>
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<tbody>
<tr>
<td>1</td>
<td>A496 (PER Cluster)</td>
<td>180.58</td>
<td>-15.36</td>
<td>33.3</td>
<td>0.0184</td>
<td>&lt; 3.72</td>
<td>0155, 0310, 0360, 0390, 3110, 3250, 4370, 7787, 7289</td>
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<tr>
<td>2</td>
<td>OPH Cluster</td>
<td>0.56</td>
<td>9.27</td>
<td>-</td>
<td>0.028</td>
<td>&lt; 5.60</td>
<td>0605, 0960, 0270, 2100, 7140, 2190, 2230, 2260, 2790, 2295, 2320, 3023, 3020, 3240, 3500, 3320, 3340, 3400, 3365, 4310, 4220, 4230, 4235, 4290, 5080, 1295, 6250, 6151</td>
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<tr>
<td>3</td>
<td>VIR Cluster</td>
<td>282.08</td>
<td>75.20</td>
<td>7.5</td>
<td>0.0038</td>
<td>&lt; 2.18</td>
<td>0600, 0040, 0110, 2040, 4050, 2050, 0240, 0340, 3650, 3660, 3070, 3800, 0386, 3110, 3116, 3120, 3130, 4050, 4660, 4079, 4080, 5110, 6015, 6215, 6065, 4667, 9100, 9111</td>
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<tr>
<td>4</td>
<td>COMA Cluster</td>
<td>58.13</td>
<td>88.01</td>
<td>16.5</td>
<td>0.0238</td>
<td>&lt; 3.81</td>
<td>0630, 0040, 0110, 2040, 4050, 0200, 2180, 2210, 3040, 3050, 3070, 3080, 0386, 3110, 3116, 3120, 3130, 4050, 4660, 4079, 4180, 5110, 7155</td>
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<td>5</td>
<td>A2319</td>
<td>70.08</td>
<td>13.50</td>
<td>17.6</td>
<td>0.0560</td>
<td>&lt; 3.70</td>
<td>0920, 0071, 2010, 2020, 2100, 2120, 3020, 3030, 3034, 3037, 3181, 3280, 3310, 3315, 3330, 7190, 7110</td>
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<tr>
<td>6</td>
<td>A3571</td>
<td>316.31</td>
<td>28.54</td>
<td>13.9</td>
<td>0.04</td>
<td>&lt; 6.34</td>
<td>0120, 0230, 0320, 2070, 0890, 2150, 2170, 3160, 4050, 0480, 4240</td>
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<tr>
<td>7</td>
<td>A3526 (CEN Cluster)</td>
<td>362.40</td>
<td>21.35</td>
<td>23.3</td>
<td>0.0109</td>
<td>&lt; 5.31</td>
<td>0120, 0140, 0230, 0320, 2070, 0890, 2150, 2170, 3160, 4050, 3140, 3150, 3160, 4020, 4035, 4240</td>
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<tr>
<td>8</td>
<td>TRA Cluster</td>
<td>324.30</td>
<td>-11.38</td>
<td>-</td>
<td>0.001</td>
<td>&lt; 8.13</td>
<td>0230, 0279, 0350, 0380, 3120, 3140, 3150, 3365, 4020, 4025</td>
</tr>
<tr>
<td>9</td>
<td>SCI20 (A 0466+449)</td>
<td>160.30</td>
<td>0.13</td>
<td>-</td>
<td>0.021</td>
<td>&lt; 5.79</td>
<td>0602, 0005, 0150, 0310, 0360, 0385, 0390, 2130, 2170, 3211, 3215, 3295, 3260, 4120, 4260, 4270</td>
</tr>
</tbody>
</table>
Example: Coma
Comparison with predictions from the literature:

<table>
<thead>
<tr>
<th>Cluster</th>
<th>( E_{\gamma} ) this measurement ( (\text{ph cm}^{-2} \text{s}^{-1}) )</th>
<th>( E_{\gamma} ) from Caffini et al. (1997) ( (\text{ph cm}^{-2} \text{s}^{-1}) )</th>
<th>( E_{\gamma} ) from Dar &amp; Shoviv (1995) ( (\text{ph cm}^{-2} \text{s}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A326 (Perseus)</td>
<td>(&lt; 3.7 \times 10^{-8})</td>
<td>(12 \times 10^{-8})</td>
<td>(1.0 \times 10^{-7})</td>
</tr>
<tr>
<td>Ophiuchus</td>
<td>(&lt; 5 \times 10^{-8})</td>
<td>(9 \times 10^{-8})</td>
<td>(\ldots)</td>
</tr>
<tr>
<td>A1835 (Coma)</td>
<td>(&lt; 3.8 \times 10^{-8})</td>
<td>(6 \times 10^{-8})</td>
<td>(5 \times 10^{-8})</td>
</tr>
<tr>
<td>M87 (Virgo)</td>
<td>(&lt; 2.2 \times 10^{-8})</td>
<td>(3 \times 10^{-8})</td>
<td>(2.2 \times 10^{-8})</td>
</tr>
</tbody>
</table>

but not in conflict with other studies:

Colafrancesco & Blasi 1998:
- A426 \( < 1.1 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \)
- A1656 \( < 0.8 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \)

Miniati 2002:
population study: a highly non-standard approach

-> superpositioning of data of all individually analyzed clusters
   (~ 650 indiv. vp's!! = most data extensive EGRET likelihood analysis ever carried out)
-> determination of appropriate diffuse background model for *this* problem
-> subsequent equalizing to comparable exposures
-> max lh algorithm
-> determination of flux at image center

EGRET Galactic Diffuse Emission Model and Locations of X-ray bright Galaxy Clusters
E > 100 MeV resp. Z < 0.14

stacked images, an exposure weight \( \omega_i \) has been introduced:

\[
\omega_i = \frac{\varepsilon_i}{\sum \varepsilon_i},
\]

where \( \sum \varepsilon_i \) is the total exposure of the galaxy cluster sample and \( \varepsilon \) is the central bins in the individual exposure map in cluster-centered cooridn

\[
\varepsilon = \sum_{j=1}^{4} \frac{\varepsilon_j}{4}
\]

Thus, the corresponding galactic diffuse background model for a cumulat clusters is the sum of the product of the individual diffuse background map \( dgb_i \) and the exposure weight:

\[
dbg = \sum_{\text{cluster}} \omega_i dgb_i
\]

Olaf Reimer, Ruhr-Universität Bochum
High Energy Gamma Ray Emission from Clusters of Galaxies

our results: *still NO* detection!!

combined exposure: $3.5 \times 10^{10}$ cm$^2$ s

upper limit (50 cluster sample): $5.9 \times 10^{-9}$ cm$^{-2}$ s$^{-1}$

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High Energy Gamma Ray Emission from Clusters of Galaxies

What's wrong here?

sample right?

$z < 0.14$ appropriate?

Lx - M - relation right?

Fig. 8. — $\log N(> f_X) - \log f_X$ diagram. Fluxes are measured in the ROSAT energy band ($0.1 - 2.4$ keV). The

Fig. 6. — Gravitational mass–X-ray luminosity relation (solid line) for the extended sample of 106 galaxy clus-

Fig. 9. — X-ray luminosity as a function of redshift. The flux limit is shown as a solid line.
Problems with Colafrancesco's claim and Kawasaki & Totani's result?

YES, unfortunately! ***It's all about number statistics!***

Colafrancesco: \(|b| > 20^\circ\) : 3979 Abell cluster \(\leftrightarrow\) 128 EGRET sources

2.96 \(\sigma\) corr. claim (1°roi): 70 Abell cluster \(\leftrightarrow\) 50 EGRET

33 of it by chance

a) wrong statistics: correct yield: 56.6 Abell \(\leftrightarrow\) 40.7 EGRET by chance

poissonian: 59.3 Abell \(\leftrightarrow\) 47.2 EGRET by chance

b) meaningless comparison, anyway:

identified gamma-ray blazars in sample!!

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High Energy Gamma Ray Emission from Clusters of Galaxies

Problems with Colafrancesco's claim? (Part II)

Colafrancesco: \(|b| > 20^\circ\) : 3979 Abell cluster \(\leftrightarrow\) 59 unid. EGRET sources

\[2.55\sigma\text{ cor. claim} (\Theta_{95}: \sim0.75^\circ)\] : 24 Abell cluster \(\leftrightarrow\) 18 EGRET

12 of it by chance

autocorrelation: \(\omega(\Theta)\) "angular two-point correlation" (\(\rightarrow\) literature)

here: derive exactly for \(|b| > 20^\circ\): \(p(\text{iso/Abell}) \rightarrow p(\text{EGRET/Abell})\)

correctly yield: 15.1 Abell \(\leftrightarrow\) 12.1 EGRET

poissonian: 15.3 Abell \(\leftrightarrow\) 13.5 EGRET
Conflict with Kawasaki & Totani's result?

Not really! Kawasaki & Totani: 7 unidentified EGRET sources studied if one considers one more observable: gamma-ray flux variability

-> 2 highly variable, 2 uncertain (statistical limits)

left: 3 candidates -> sufficient deep optical observation in 3° x 3° field
-> counterparts -> classification ("possible merging clusters" t.b.d.)
-> statistics (no significant result from reduced sample)
-> inappropriate for a population study
High Energy Gamma Ray Emission from Clusters of Galaxies

**Contribution to the extragalactic diffuse gamma-ray background**

![Graph showing photon energy vs. log L_c (erg/s)](image)

**FIG. 1.** Comparison between the predicted (thick line) extragalactic GBR produced by a universal MW-like cosmic ray flux in groups and clusters [Eq. (6)] and the observed high-energy GBR. The dashed, dotted, and full lines are the spectra of the extragalactic GBR derived by Fichtel, Simpson, and Thompson [1] from SAS-2 observations, by Osborne et al. [3] from phase I of EGRET observations on CGRO, and by Digel et al. [5] from EGRET/CGRO observations of the Ophiuchus and Orion region, respectively. The actual data points of the measured GBR by Hunter et al. [4] and by Digel et al. [5] from EGRET/CGRO observations of the Ophiuchus and Orion regions, respectively, are also displayed.

**Dar & Shaviv 1995**

Olaf Reimer, Ruhr-Universität Bochum

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**expected EGDB from Galaxy clusters, considering theoretical uncertainties**

in cluster modelling

Colafrancesco & Blasi 1998

**IC from shock acc. CR electrons**

**$\pi_0$ from p-p inelastic**

**IC secondary electrons**

Miniati 2002
We still have to await the detection of a galaxy cluster in gamma-rays!

But what's next (observationally) on galaxy clusters? Which are the decisive measurements?

**short term:** hard X-ray observations (imaging?), high frequency radio observations resolve/discriminate, spectrum, composition!
Jem-X, but INTEGRAL as a gamma-ray instrument?
coded mask ideally suited best for point sources, arcmin resolution moderate continuum sensitivity pointing strategy, narrow FoV -> exposure on high-latitude sources lines, perhaps?

**long term:** GLAST!
detect individual cluster as (extended?) gamma-ray sources verify estimates of contribution to EGDB a real ACT!
tackle hard X-ray/soft gamma