Cosmic ray induced gamma–ray emission of the giant elliptical galaxy M 87

Pfrommer & Enßlin 2003
Outline of the Talk

A) Introduction and Motivation
   1.) Acceleration mechanism of CRp
   2.) Hadronic CRp interactions in the ICM

B) CRp induced gamma–ray emission
   1.) Gamma–ray emission of clusters of galaxies
   2.) TeV gamma–ray emission of M 87

C) Conclusions
Main injection mechanisms of CRp into the ICM:

• CRp acceleration at structure formation and accretion shocks:
  - Energy dissipation at the shock front
  - thermal energy
  - CRp acceleration

• Supernova driven galactic winds advect and inject CRp into the ICM

• CRp diffusion away from an AGN/radio galaxy into the ICM

How can we observe CRp in clusters of galaxies?

How many CRp are there?
CRp

magnetic field

radio
+ IC

π
0
π
+
µ
+
γ
γ
ν
µ
ν
_
µ
ν
e
p
CRp

magnetic field
Simulation of CR emission processes in galaxy clusters

Hard X-ray: \( F(> 100 \text{ keV}) \)

Thermal X-ray: \( F(> 100 \text{ MeV}) \)

\( \gamma \)-ray:

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Gamma ray source function

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- CRp population:
  \[ f_p(r, p_p) = \frac{\tilde{n}_{CRp}(r)}{c} \left( \frac{p_p c}{\text{GeV}} \right)^{-\alpha_p} \]

- Pion decay induced differential gamma–ray source function:
  \[ q_\gamma(r, E_\gamma) \simeq \sigma_{pp} c n_N(r) 2^{2-\alpha_\gamma} \frac{\tilde{n}_{CRp}(r)}{\text{GeV}} \times \]
  \[ \frac{4}{3 \alpha_\gamma} \left( \frac{m_{\pi^0} c^2}{\text{GeV}} \right)^{-\alpha_\gamma} \left[ \left( \frac{2 E_\gamma}{m_{\pi^0} c^2} \right)^{\delta_\gamma} + \left( \frac{2 E_\gamma}{m_{\pi^0} c^2} \right)^{-\delta_\gamma} \right]^{-\alpha_\gamma/\delta_\gamma} \]

- Relative deviation of our analytic approach to simulated gamma–ray spectra.
Cooling flow clusters are efficient CRp detectors!

ROSAT observation: Perseus galaxy cluster

Chandra observation: central region of Perseus
Cooling flow cluster model of CRp detection:

\[ \varepsilon_{CRp} = X_{CRp} \varepsilon_{th} \]

Perseus galaxy cluster
Gamma ray flux of Perseus galaxy cluster:

Inverse Compton emission of secondary CRe (B = 0),
pion decay induced gamma ray emission

\[ \frac{d\mathcal{F}_\gamma}{dE_\gamma} \left[ X_{\text{EGRET}} \right] \gamma \text{ cm}^{-2} \text{s}^{-1} \text{ GeV}^{-1} \]

\[
\begin{align*}
\alpha_p &= 2.1 \\
\alpha_p &= 2.3 \\
\alpha_p &= 2.5 \\
\alpha_p &= 2.7
\end{align*}
\]

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Upper limits on $X_{\text{CRp}}$ using EGRET limits:

Cooling flow cluster:

- A85
- Perseus
- A2199
- Centaurus
- Ophiuchus
- Triagulum Australis
- Virgo

Non-cooling flow cluster:

- Coma
- A2256
- A2319
- A3571

$\alpha_p = 2.1$
$\alpha_p = 2.3$
$\alpha_p = 2.7$
$\alpha_p = 2.3$, radio

$B = 10 \mu G$

$X_{\text{CRp}} = \varepsilon_{\text{CRp}}/\varepsilon_{\text{th}}$

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Expected limits on $X_{\text{CRp}}$ using Cerenkov telescopes:

Sensitivity: \[ \mathcal{F}_{\gamma, \text{exp}}(E > E_{\text{thr}}) = 10^{-12} \gamma \text{ cm}^{-2} \text{ s}^{-1} (E_{\text{thr}}/100 \text{ GeV})^{1-\alpha_{\gamma}} \]

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$\alpha_p = 2.1$
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$X_{\text{CRp}} = \varepsilon_{\text{CRp}}/\varepsilon_{\text{th}}$
What is the origin of the M 87 gamma−ray emission?

- Processed radiation of the relativistic outflow (jet):
  e.g. IC upscattering of CMB photons by CRe (jet), SSC scenario

- Dark matter annihilation or decay processes

- Hadronically originating gamma−rays:
  Assuming CRp power−law distribution and a model for the CRp spatial distrib.
  → measurement of the CRp population in ICM/ISM of M 87!
Constraints on the CRp spectral index

- Combining EGRET upper limits ($E > 100 \text{ MeV}$, Reimer et al. 2003) and HEGRA TeV $\gamma$-ray flux ($E > 730 \text{ GeV}$, Aharonian et al. 2003)

  $\Rightarrow$ CRp spectral index: $\alpha < 2.275$
Gamma ray flux profile of M 87 (Virgo):

Top:
- modeled gamma–ray surface flux profile
- normalized to the HEGRA flux (>730 GeV) within the two innermost datapoints

Bottom:
- comparison of detected to simulated gamma–ray flux profiles which are convolved with two different widths of the PSF
Conclusions

 Cosmic ray protons:

\[ X_{\text{CRp}}(r) = \frac{\varepsilon_{\text{CRp}}(r)}{\varepsilon_{\text{th}}(r)} \]

- Cooling flow clusters are efficient CRp detectors
- Limits from \( \gamma \)-rays (EGRET): \( X_{\text{CRp}} < 20\% \)
- M 87 gamma-ray emission is consistent with hadronic scenario!
Simulation of CR emission processes

Secondary emission:
- IC $e^\pm$
- $\pi^0$-decay

Primary emission:
- IC $e^-$

$F(>100 \text{ keV})$

$F(>100 \text{ MeV})$

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