Compton X-ray and Gamma-ray Emission from “Extended” Radio Sources
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W50/SS433 Complex at 20cm (Dubner et al.)

Fornax A at 20cm (orange) and Optical (Fomalont et al. Image by J. Uson, NRAO)

One Degree

50 arcmin

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Conventional Wisdom

Blazars will dominate the (extragalactic) gamma-ray sky.

G-ray sources are predominantly “non-thermal”. Radio (to X-ray) observations traces the relativistic particles through their synchrotron emission.

See previous GLAST talks: Carson, Coppi, Sikora, Healey, etc.
Why “Extended” Radio Sources?

Radio Galaxies (‘misaligned’ blazars) are dominated by emission from extended components.

Cygnus A
Spitzer & VLA

Radio Lobes

Galaxy

VLA red (Perley et al. NRAO)
Spitzer blue (Harris, Stawarz, Ostrowski, Cheung)

50 kiloparsecs
Relevant question: What are relative contributions of a radio source to integrated g-ray signal detected by GLAST?

Blazar = jet axis pointed toward Earth; the central region is dominant

Complication: (unresolved) Compton scattered g-rays have contributions from accretion disk, clouds, jet (SSC), starlight (galactic scales), etc.
Anatomy 101

Relevant question: What are relative contributions of a radio source to integrated gamma-ray signal detected by GLAST?

What about contribution from extended components? (classified as “radio-galaxies”)

Dominant seed photon source for Compton process on 10’s-100’s kpc scale is 3K background
Inverse Compton Scattering of 3K Background is an Obligatory Process in Cosmic Synchrotron Sources

On This Rock...
Evidence for Extended IC/CMB

Fornax A = NGC 1316
D=19 Mpc (z=0.006)
Top 5 brightest radio source in sky

10 arcmin (54 kpc)

East Lobe
XMM (Isobe et al. 2006)

x: ROSAT point sources

ASCA color (Kaneda et al. 1995)
see also ROSAT detection by Feigelson et al. 1995

Figures from N. Isobe talk
Evidence for Extended IC/CMB

XMM power-law spectrum of east lobe minus (thermal?) point sources

Spectral Energy Distribution

MOSのスペクトル
\( a \chi = 0.62 \pm 0.15 \)

\( \varnothing S_{1\text{keV}} = 86 \pm 9 \text{ nJy} \)

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Figures from N. Isobe talk
Lobe B-Field & Energetics

Future Radio spectral mapping is a long overlooked method to constrain B-field!

Cheung et al. 2005

IC/CMB vs. equipartition constraints on B-field.

TABLE 1

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>$\phi$ (rad)</th>
<th>$\nu_1$ (GHz)</th>
<th>$k$</th>
<th>$B_{ME}$ ($\mu$G)</th>
<th>$B_{IC}$ ($\mu$G)</th>
<th>$B_{ME}/B_{IC}$</th>
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<td>1</td>
<td>11.0</td>
<td>1.7</td>
<td>6.4</td>
</tr>
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</table>

Note.—The calculation is based on the following: $\alpha_r = -0.8$, $S_r = 74$ Jy at $\nu_r = 1.4$ GHz, $\theta = 1020'$, and $s = 74$ kpc are derived from low-frequency synchrotron observations (Ekers et al. 1983). Fitting a $\alpha_r = -0.8$ power-law model with Galactic foreground $N_H = 2 \times 10^{20}$ cm$^{-2}$ to the west lobe excess gives $S_x = 1.7 \times 10^{-30}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ at $E_x = 1$ keV. The upper synchrotron cutoff is taken to be $\nu_2 = 100$ GHz.

where $k$ is the ratio of the energy in heavy particles to the energy in electrons, $\eta$ is the filling factor of the synchrotron emitting region, $\theta$ is the lobe diameter in arcseconds, $s$ is the path length through the source in kiloparsecs, $\phi$ is the angle between the (assumed uniform) magnetic field and the line of sight, and $\nu_1$ and $\nu_2$ (GHz) are the upper and lower cutoff frequencies for the radio synchrotron spectrum. While $B_{ME}$ depends on several factors that are not well constrained by observation, the dependence is relatively weak.

from Feigelson et al. 1995
IC/CMB G-rays from Fornax A?

Does the IC/CMB spectrum extend into the GLAST band?

GLAST 1-yr (5 sigma)

Spectrum from N. Isobe talk
Relevant Lorentz Factors

- Electrons that produce synchrotron (radio) emission at frequency \( \nu \) have energies \( \gamma_s \sim 2 \times 10^4 \left( \nu \frac{1+z}{dB} \right)^{1/2} \).
- Electrons that Compton scatter CMB photons to energy \( E_c \) have energies \( \gamma_c \sim 10^3 \left( \frac{E_c}{dG} \right)^{1/2} \).
- Electrons with \( \gamma < \gamma_{KN} = 2 \times 10^8 / (G \ 1+z) \) Compton scatter CMB photons in the Thomson regime. (see Dermer & Atoyan 2002)

Legend

\( \gamma \) = electron Lorentz factor, \( E = \gamma mc^2 \)
\( \nu \) in GHz; \( E_c \) in keV
\( d \) = Doppler beaming factor
\( G \) = jet bulk Lorentz factor
\( B \) = magnetic field in microGauss
In Fornax A Lobes...

$$\gamma_s \approx 2 \times 10^4 \left( \nu \frac{1+z}{d} B \right)^{1/2} = 2 \times 10^4 \left( \nu \right)^{1/2}$$
$$\gamma_c \approx 10^3 \left( \frac{E_c}{d G} \right)^{1/2} = 10^3 \left( E_c \right)^{1/2}$$

$$\gamma \ll \gamma_{KN} = 2 \times 10^8$$

1 keV X-ray emission from $\gamma_c \sim 10^3$ electrons which emit synch. rad. at $\sim 2$ MHz.

Emission in GLAST bands ($\sim 10^{1-3}$ MeV $= 10^{4-6}$ keV) require $\gamma_c \sim 10^{5-6}$; these electrons emit synch. rad. at $\nu \sim 20-2000$ GHz

Legend
- $\gamma = \text{electron Lorentz factor}$, $E = \gamma mc^2$
- $\nu$ in GHz; $E_c$ in keV
- $d = \text{Doppler beaming factor} = 1$
- $G = \text{jet bulk Lorentz factor} = 1$  \hspace{1cm} (z~0)
- $B = \text{magnetic field in microGauss} = 1.5 +/- 0.5$ (Isobe et al. 2006)
Fornax A Detectable by GLAST!

GLAST 1-yr (5 sigma)

Same electrons

Synchrotron

Compton

Spectrum from N. Isobe talk

GLAST Image?
Other Extended Radio Galaxies?

Centaurus A = 3EG J1324-4313

Steinle et al. 1998

http://outreach.atnf.csiro.au/about/history/doverheights/
Expectations with Redshift

- Monochromatic Compton to synchrotron flux ratio (alpha=1):
  \[ \frac{f_c}{f_s} = \frac{u_{\text{cmb}}}{u_B} = aT^4 \left( \frac{B^2}{8\pi} \right) = 4 \times 10^{-13} (1+z)^4 \left( \frac{B^2}{8\pi} \right) = 4 \times 10^{-13} (1+z)^4 \left( \frac{B_{\mu G}}{8\pi} \right)^2 \]
  \[ \frac{f_c}{f_s} = 10 (1+z)^4 \left( \frac{B_{\mu G}}{8\pi} \right)^2 \]

\( \frac{f_c}{f_s} \) will increase:
1. in low B-field regions
   \( B(\text{lobes}) \sim \text{few } \mu \text{G} \);
   \( B(\text{jet}) \sim 10' \text{ s } \mu \text{G} - \text{ mG} \);
   \( B(\text{blazar}) \sim 100' \text{ s } \text{ mG} \)

2. at higher-redshifts
   \( u_{\text{cmb}}(z=4) \sim 10 \, u_{\text{cmb}}(z=0.8) \)
   \( \sim 100 \, u_{\text{cmb}}(z=0) \), so...

\[ \frac{f_c}{f_s} \sim 10 (1+z)^4 \left( \frac{B_{\mu G}}{8\pi} \right)^2 \]
The Highest-Redshift Radio Galaxies

17 $z>3.5$ Radio Galaxies

alpha~1, so:

$$\frac{fc}{fs} \sim 10 (1+z)^4 / \mu G^2$$

GLAST/Chandra Predictions

Chandra corresponds to 1-10 MHz ($B=1 \mu G$) and 10-100 MHz ($B=10 \mu G$) radio
GLAST corresponds to 20-2000 GHz ($B=1 \mu G$) and $2 e 11-2 e 13$ Hz ($B=10 \mu G$)
IC/CMB (Jet) Detections at High-z

GB1508+5714 z=4.3

1745+624 z=3.9

VLA contours, Cheung 2004
X-ray color, Siemiginowska et al. (2003), Yuan et al. (2003)

Cheung, Stawarz, & Siemiginowska 2006

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IC/CMB Jets at High-Redshift

GB1508+5714 $z=4.3$

$\alpha_{\text{radio}}=1.4 \pm 0.2$

1745+624 $z=3.9$

$f\chi/f_r$ large at very high-$z$ as expected in IC/CMB origin

Cheung (2004)  
Cheung, Stawarz, Siemiginowska (2006)
IC/CMB Jets at High-Redshift

$f_X/f_R$ for jets depends also on beaming in addition to other parameters (e.g., $B$).

Advantage Radio Galaxy: emission is negligibly/ not beamed; spectral shapes, dimensions better measured than jets (to constrain B-field)
Recall that radio-loud sources are a *special* subset of AGN/Quasars (~10%) and Blazars are special subset of these radio-loud sources...

I considered radio-galaxies (i.e. “misaligned” blazars) but...

What about the other 90% of the general (radio-quiet, but not radio-silent) AGN population? e.g. Seyferts

**Perspective:** Radio-loudness may be linked with black hole mass (see e.g., McLure & Jarvis 2004)? BH Spin (e.g., Wilson & Colbert 1995), Accretion (e.g., Rawlings & Saunders 1991)?
Issues of Wider Interest

Perspective: Radio-loudness may be linked with black hole mass (see e.g., McLure & Jarvis 2004)? BH Spin (e.g., Wilson & Colbert 1995), Accretion (e.g., Rawlings & Saunders 1991)?

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This process is relevant to any synchrotron radiating system

Other galaxies (particularly with larger SN rates) should emit X to g-rays via IC/CMB channel

Starburst galaxy NGC253 (D~2.6 Mpc)
Optical DSS (white contours)
HEGRA TeV 40, 65, 80% conf. levels (Itoh+ 02)
HESS collab (Aharonian et al. 2005)

A. Kappes webpage

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Summary

• I considered g-rays from radio galaxies through IC/CMB process (thermal extended and point source contribution negligible; cf. issues in X-ray studies)
• GLAST images of nearby large angular size RGs (e.g. Fornax A)
• GLAST may detect high-z RGs; as radio galaxies outnumber blazars; what is their contribution to a (soft) g-ray background?
• High-z RGs as “standard lamps” (radio data define e- distribution); are g-rays absorbed at high-z?
• TO DO: Identify more “Fornax A type” and high-z radio galaxies
  • obtain relevant radio data (define synchrotron spectrum from 10’s MHz - 100’s GHz)
  • obtain relevant X-ray data (XMM, Chandra): determines extended/point source thermal contribution
• Other extended sources with relativistic particles (synchrotron emitters): SNRs, Cluster halos (hard X-ray sources)