GeV Observations of Star-forming Galaxies with the Fermi LAT

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Key Science Questions

Origin and transport of cosmic rays (nuclei + electrons/positrons)

“Guaranteed” contribution of unresolved galaxies to extragalactic diffuse gamma-ray background

Hubble view towards the nuclear starburst of M82

Pavlidou & Fields 2002, reviewed by Dermer 2007
Context of Current Work

- **CGRO EGRET era (before 2008)**
  - Large Magellanic Cloud the only external galaxy detected in gamma rays

- **Fermi LAT + Imaging Air-Cherenkov Telescopes**
  - GeV and TeV detection of archetypal starburst galaxies M82 and NGC 253
  - GeV detection of quiescent Local Group galaxies M31, SMC

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**Gamma-ray Luminosity**

\( > 0.1 \text{ GeV} \)

**Best-fit scaling index**

\[ 1.4 \pm 0.3 \] (solid)

**Linear scaling**

(dashed)

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“Population Study”

- Selected for IR brightness and dense molecular gas content
  - Molecular gas as fuel for star formation, traced by HCN \((J=0-1)\) line emission (Gao & Solomon 2004)

- Galaxy sample (69 total)
  - 64 galaxies beyond Local Group
  - Combine with 5 previously studied Local Group galaxies

- *Fermi* LAT observations
  - 36 months
  - 0.1 – 100 GeV
  - 4 significant detections of starburst galaxies

- Identify galaxies hosting AGN as those detected by *Swift* BAT (14 – 195 keV)
SEDs of LAT-detected Starbursts

Preliminary
Comparative SEDs

**Starbursts**
- NGC 1068
- NGC 1068 (H.E.S.S.)
- M82
- M82 (VERITAS)
- NGC 4945
- NGC 253
- NGC 253 (H.E.S.S.)

**Local Group**
- Milky Way Global Model
- M31
- LMC
- SMC

*Preliminary*
Multiwavelength Relations

Gamma-ray vs radio continuum luminosity

Preliminary
Gamma-ray vs radio continuum luminosity ratio

Scaling index $1.10 \pm 0.05$

Scatter = 0.2 dex

(does not significantly change when removing galaxies with AGN)
Multiwavelength Relations

Gamma-ray vs total IR (8-1000μm) luminosity ratio

Ratio of energy output between wavebands

Scaling index $1.16 \pm 0.07$
Scatter = 0.3 dex

Removing galaxies with AGN
Scaling index $1.08 \pm 0.10$
Scatter = 0.3 dex

Not surprising given empirical correlation between IR and radio continuum luminosity
Correlation Significance

- Kendall $\tau$ coefficient (non-parametric, rank correlation test)
  - Generalized to include upper limits
- Compare coefficients of actual data and *observable* permutations
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![Graph showing correlation analysis](image)
Correlation Significance

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Correlation P-values of $< 10^{-5}$ considering all galaxies, $\sim 10^{-3}$ after excluding Swift BAT detected AGN (including NGC 1068 and NGC 4945)

Assume 20% distance uncertainty
Physics of Cosmic Rays

- Gamma-ray luminosity scales almost linearly with photometric estimates of the current SFR (total IR, radio continuum luminosity)
  - Covers at least 3 orders of magnitude ⇒ suggests CR luminosity related to short-lived massive stars

- Normalization of scaling relation provides constraint on product of cosmic-ray luminosity and efficiency of converting cosmic-ray energy to gamma rays
  - Check paradigm that SNRs are primary accelerators of cosmic rays in galaxies (interpreting gamma-rays as mostly hadronic in origin)
We know about the evolving cosmological population of star-forming galaxies thanks to deep multiwavelength surveys.
Consider two spectral models to bracket uncertainty. Shaded bands represent uncertainty in scaling relation parameters. EBL absorption (Franceschini et al. 2008).

Unresolved star-forming galaxies contribute 4-23% of isotropic diffuse component flux 0.1 – 100 GeV.
Anticipated LAT detections

- Scaling relation between gamma-ray and total IR luminosity (including dispersion ⇒ probabilistic)
- Assume point-source, power law spectrum with index 2.2
Anticipated LAT detections

- Scaling relation between gamma-ray and total IR luminosity (including dispersion $\Rightarrow$ probabilistic)
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![Graph showing the detection probability over mission time for various galaxies.](image)
Take-away Points

1. Gamma-ray “population studies” of galaxies now possible

2. Confirm quasilinear scaling relation between gamma-ray luminosity and photometric tracers of SFR

3. Unresolved star-forming galaxies contribute 4-23% of isotropic diffuse component flux 0.1 – 100 GeV

4. Scaling relation would predict roughly 10 external galaxies to be detected during 10-year Fermi mission
Contribution to Isotropic Diffuse

Fraction compared to total contribution $0 < z < 2.5$

Largest contribution from analogs of Milky Way / M31 and startbursts similar to M82 / NGC 253
Contribution to Isotropic Diffuse

Fraction compared to total contribution $0 < z < 2.5$

Contribution from galaxies with $z > 1.5$ rapidly diminishing
Kendall $\tau$ correlation test details

- $\tau$ coefficient is sum of rank values ("$H$") over all pairs of points
  - $\tau=1$ corresponds to monotonically increasing data with no upper limits

Test can be generalized to include upper limits
X-ray selected radio-quiet Seyferts

- NGC 1068 and NGC 4945 are composite systems
  - *Gamma rays from AGN or cosmic rays?*
  - See Lenain et al. 2010

- Parallel *Fermi* LAT analysis of radio-quiet Seyfert galaxies
  - 120 objects selected by *Swift* BAT hard X-ray flux (14-195 keV)
  - Same analysis conditions as for star-forming galaxies
  - Possible association of LAT sources with ESO 323-G077, NGC 6814
  - Could *not* establish as new gamma-ray source class

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*See talk by M. Hayashida*
305.06 in “AGN, QSO, Blazars V”
Wednesday 11 Jan @ 10 am
Pair-Conversion Technique

Fermi Gamma-ray Space Telescope
(*Fermi*)

Large Area Telescope (LAT)
20 MeV to >300 GeV

Gamma-ray Burst Monitor (GBM)
Few keV to 30 MeV
**LAT Detector Subsystems**

**Imaging Calorimeter**
- 8.6 R.L.
- 1536 CsI crystals
- Hodoscopic (12 x 8 layers)

**Precision Converter and Tracker**
- Single sided SSD (40 cm, 228 um) ~ 80 m²
- W foil interleaved (12x3% RL, 4x18% RL)
- 18 xy planes
- 1.5 RL

**Anti-Coincidence Detector**
- 4% RL
- Segmented (89 plastic scintillator tiles, 8 ribbons)
- 0.9997 efficiency

(+ Data Acquisition System)
500 Hz sent to ground
- Launched 11 June 2008
- 3 years of successful operations
- Expected lifetime of 10+ years
Observation Modes

- **Sky-survey mode**
  - Normal operations mode
  - Full-sky every 2 orbits (~3 hrs)

- **Target of Opportunity**
  - Autonomous re-pointing for GRBs
  - Slew to keep target in FoV
  - Proposed pointed observations

**Wide Field of View**

- **LAT**: ~2.4 sr, 20% of sky
- **GBM**: Almost entire sky not occulted by Earth
Effective Area = geometric area × trigger efficiency × selection efficiency

Low Earth Orbit
Cosmic ray flux >10³ gamma ray flux
Fermi LAT Collaboration