Detection of GeV Emission from Starburst Galaxies with the Fermi LAT

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4 November 2009
Fermi LAT has detected steady, point-like, emission above 200 MeV from two starburst galaxies
- M82 (6.8σ)
- NGC 253 (4.8σ)

Diffuse gamma-ray emission from star-forming galaxies
- Starburst galaxies M82 and NGC 253

Observations and results
- Detection significance maps
- Point-like and steady
- Integral fluxes consistent with galactic diffuse emission

Interpretation
- Correlate star-formation with enhanced cosmic-ray intensity
The most striking feature of the GeV gamma-ray sky is the diffuse emission from our own galaxy.

Cosmic rays interacting with interstellar medium:

- \( \text{CR}_{\text{protons}} \) + gas \( \rightarrow \) neutral pion-decay
- \( \text{CR}_{\text{electrons}} \) + radiation fields \( \rightarrow \) inverse Compton
- \( \text{CR}_{\text{electrons}} \) + ambient protons \( \rightarrow \) bremsstrahlung
Starburst Galaxies

- Starburst galaxies distinguished by regions of rapid star formation, 10-1000 × Milky Way rate
  - Correspondingly high supernovae rates
  - Dense clumps of molecular gas
  - Highly luminous at infrared wavelengths, radio correlation

- M82 and NGC 253
  - Two closest starburst galaxies (~3 Mpc)
  - Edge-on viewing angles
  - Small (~100 pc scale) starburst regions
  - Star formation rate ~10 × Milky Way rate
  - Lack active nuclei
  - Extensively studied in multiple wavebands, detailed modeling/predictions
LAT Observations

• Observation periods
  – 11 months (August 2008 to July 2009)
  – Exclude time periods when Earth limb enters field of view (rocking angle cut at 43°)

• Event selection
  – Energy > 200 MeV
  – Diffuse class (cosmic-ray background contamination < 10 %)
  – Zenith angle < 105°
  – Post launch instrument response functions (P6_V3)

• Model the region
  – 10° radius region of interest
  – Galactic diffuse (template / hybrid / ring) + isotropic component
  – Include all significantly detected LAT sources within region of interest (1st year Catalog)
Detection Significance Maps

Galactic diffuse, isotropic diffuse, and point sources subtracted

Test Statistic (TS) = -2 \log(L_{\text{source}} - L_{\text{no source}})

0.68, 0.95, 0.99 confidence level localization contours

Appear as LAT point sources, starburst regions unresolved

4 November 2009
Fermi Symposium in Washington DC
• Spatial extension upper limits
  – Gaussian model, radius which contains 68 percent of flux ($R_{68}$)

<table>
<thead>
<tr>
<th></th>
<th>$R_{68}$ 95% confidence upper limit</th>
<th>Disk extent (optical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>0.18°</td>
<td>0.19°</td>
</tr>
<tr>
<td>NGC 253</td>
<td>0.30°</td>
<td>0.45°</td>
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• Both sources consistent with constant flux level

Monthly count of the photons in the direction of each source (Aug 08 - Jul 09)

Flux within 1.0° radius of M82

$\chi^2/n_d = 0.72$

$n_d = 10$

Flux within 1.0° radius of NGC253

$\chi^2/n_d = 1.12$

$n_d = 10$
Observed integral fluxes consistent with models of diffuse galactic gamma-ray emission, but data do not yet tightly constrain spectral shapes.

<table>
<thead>
<tr>
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<th>Flux (&gt;100 MeV) (10^{-8} ph cm(^{-2}) s(^{-1}))</th>
<th>Photon Index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M82</strong></td>
<td>1.6 ± 0.5(^{\text{stat}}) ± 0.3(^{\text{sys}})</td>
<td>2.2 ± 0.2(^{\text{stat}}) ± 0.05(^{\text{sys}})</td>
</tr>
<tr>
<td><strong>NGC 253</strong></td>
<td>0.6 ± 0.4(^{\text{stat}}) ± 0.4(^{\text{sys}})</td>
<td>1.95 ± 0.4(^{\text{stat}}) ± 0.05(^{\text{sys}})</td>
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</table>
• Enhanced cosmic-ray intensity required to explain the observed starburst gamma-ray fluxes

• Supernovae trace massive star formation
  – Supernovae remnants are probable source of galactic cosmic rays, although data not yet conclusive

• Beware!
  – Star-formation rate and gas density non-uniform throughout galaxies (Resolved LMC gamma-ray image)
  – Large uncertainty in distance measurements

Compare gamma-ray luminosity and product of supernovae rate and gas mass in each galaxy
• TeV detections summer 2009
  – NGC 253 (H.E.S.S.)
  – M82 (VERITAS)
• Fermi LAT results combined with the TeV data will fill in spectral energy distributions
  – Discern spectral shapes with greater certainty, constrain emission mechanisms
• TeV observations confirm steady sources
• Starbursts unresolved, TeV emission predominantly in central region
• LAT all-sky survey can point out additional candidates for TeV observatories
• Two starburst galaxies, M82 and NGC 253, detected in 1st year of the Fermi mission
  – New class of gamma-ray sources
  – Diffuse emission arising from cosmic-ray interactions
• Searching for the source of galactic cosmic rays
  – Cosmic-ray intensity linked to massive star formation
• Ongoing Fermi LAT all-sky survey will look for additional starbursts and other star-forming galaxies
  – Normal star-forming galaxies are much more common than active galaxies but most often are fainter and unresolved