Diffuse Gamma-Rays seen by Fermi-LAT and Cosmic-Ray Distributions

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Short History of Gamma-ray Astronomy

• Prediction of Gamma-rays
  ➢ Feenberg & Primakoff (1948): inverse Compton scattering (photon & CR electron)
  ➢ Hayakawa (1952): $\pi^0$-decay (matter & CR nucleon)
  ➢ Hutchinson (1952): bremsstrahlung (matter & CR electron)
  ➢ Morrison (1958)

• Early Observations
  ➢ OSO-3 (1967-1968): First detection of gamma-rays from Gal. plane
  ➢ SAS-2 (1972-1973) map of the Gal. plane
  ➢ COS-B (1975-1982) study CR and matter distribution

• Diffuse gamma-rays has been one of main topics of gamma-ray astronomy since the beginning of its history

A powerful probe to study cosmic-rays (CRs) and the interstellar medium
• 1991-2000, 30 MeV-30 GeV
  ➢ resolved 271 gamma-ray sources (Hartman et al. 1999)
  ➢ detailed study of Galactic diffuse emission (Hunter et al. 1997) and extragalactic diffuse emission (Sreekumar et al. 1998)
The LAT 3 Month All-Sky Map

LAT all-sky $E>200$ MeV

Diffuse emission $\sim80\%$ total gamma-ray flux

- The Fermi-LAT has already surpassed the EGRET in many aspects
  - More than 3 dozen pulsars (6 by EGRET)
  - 205 bright sources and 444 above 5 $\sigma$ (271 by EGRET) arXiv:0902.1340
  - Exciting results on individual targets
    CTA1, GRB080916C, Vela Pulsar, etc.
Performance of the Fermi LAT

- Primary observing mode is Sky Survey
  - Full sky every 2 orbits (3 hours)
  - Uniform exposure, with each region viewed for ~30 minutes every 2 orbits
  - Best serves majority of science, facilitates multiwavelength observation planning
  - Exposure intervals commensurate with typical instrument integration times for sources
  - EGRET sensitivity reached in days

- Large Field of View (2.4 sr)
- Large Effective Area (>=8000 cm² in 1-10 GeV)
- Good Angular Resolution (3.5 deg@100 MeV and 0.6 deg@1 GeV; 68% contaminant radii, best event class)

Large FOV and uniform exposure: ideal for the study of diffuse gamma-rays
Plan of this Talk

1. Models to study diffuse gamma-rays
2. Mid-latitude region (GeV-excess)
3. Mid/high-latitude region (local CR flux and spectrum)
4. LMC (local group galaxy)
Models to Study Diffuse Gamma-rays: CR Propagation, Maps of Gas and ISRF
CR Interactions with the Interstellar Medium

We need models of CR injection, CR propagation, ISRF, gas distribution and gamma-ray production
CR Injection/Propagation by GALPROP

• The cosmic-rays have to be accelerated
  ➢ What are the accelerator?
    ✓ SNR, pulsars, … ?
    ✓ Affects the spatial distribution and spectra

• Propagation through the galaxy
  ➢ Diffusion coefficients, secondary production, energy losses, …
    ✓ Determined from local observations of cosmic-rays

Predict CR distribution w/ constraints by local measurements
Model Gas Maps

- Gas distribution determined from radio surveys
  - velocity => distance through a rotation curve

HI density from LAB survey
  - Opacity correction needed especially close to Gal. plane

Clements (1985)
(R_0, v_0) = (8.5 kpc, 220 km/s)


H_2 density from 2.6 mm CO line
  - assumptions on X_co = N(H_2)/W_{CO}

Target for producing gamma-rays through π^0-decay and electron bremsstrahlung
InterStellar Radiation Field

- CR $e^+/e^-$ need targets to create g-rays
  - Interstellar radiation field determined from a realistic model taking into account stellar and dust distribution
    - Starlight ($\sim 0.1 \, \mu m – 10 \, \mu m$)
    - Dust ($\sim 10 \, \mu m – 300 \, \mu m$)
    - CMB ($>300 \, \mu m$)

There are uncertainties associated with gas and ISRF

Porter et al. 2008
Fermi-LAT Diffuse Analysis

**Distribution of ISM**
- HI/CO surveys, ISRF model
- + spatial mapping of ISM
- + conversion to HI/H$_2$ column density

**Galactic gamma-ray emissivities**
- • from GALPROP cosmic-ray propagation
- • derived from data for special regions

Line-of-sight integration (by GALPROP) to create gamma-ray flux map for individual

- • emission processes
- • ISM components
- • galactocentric annuli

$\gamma$-ray model map has been used for point source and diffuse analyses
- • already provided lots of exciting results on individual targets
- • possible uncertainties (or improvement)
  - CR source distribution, CR propagation
  - optical depth correction (HI), Xco (H$_2$), ISRF
  - dark gas (Grenier et al. 2005)

Deviations from input model used to iteratively improve the diffuse model
Mid-Latitude Region ($|b| = 10^\circ$-$20^\circ$): GeV Excess?
EGRET GeV Excess (1)

• EGRET observations showed excess emission > 1 GeV when compared with cosmic-ray propagation models based on local cosmic-ray nuclei and electron spectra
• Variety of possible explanations
  ➢ Variations in cosmic-ray spectra over Galaxy
  ➢ Unresolved sources (pulsars, SNRs, …)
  ➢ Dark matter
  ➢ Instrumental

\[ b = 6^\circ - 10^\circ \]

\[ b = 2^\circ - 6^\circ \]

\[ b \leq 2^\circ \]

\[ \sim 100\% \text{ difference above } 1 \text{ GeV} \]

Hunter et al. 1997
Above 1 GeV, EGRET data are above the GALPROP prediction everywhere in the sky.

LAT statistics are already good enough to confirm/refute all-sky nature of this excess.

The Fermi LAT View (1)

- Spectra shown for mid-latitude range => GeV excess in this region of the sky is not confirmed.
- Sources are not subtracted but are a minor component.
- LAT errors are dominated by systematic uncertainties and are currently estimated to be ~10% -> this is preliminary
- EGRET data is prepared as in Strong, et al. 2004 with a 15% systematic error assumed to dominate (Esposito, et al. 1999)
- EG+instrumental is assumed to be isotropic and determined from fitting the data at at $|b| > 10^\circ$. 

Preliminary
Intermediate latitude gamma-ray spectra can be explained by cosmic-ray propagation model consistent with locally measured cosmic-ray nuclei and electron spectra. The EGRET GeV excess is not seen in this region of the sky (|b|=10°-20°) with the LAT.

LAT spectrum of Vela (Abdo et al. arXiv:0812.2960) also suggests that the EGRET GeV excess is instrumental.
Mid/High-Latitude Region (|b|=22°-60° in Third Quadrant): Local CR Flux and the Spectrum
Study of Local CRs using HI

Observed Wco (Dame, et al. 2001)

Galactic Center (significant contribution from IC)

- Away from the Galactic Center and the Plane:
  - Small contribution from IC and point sources
  - Less affected by H₂ (uncertainty of Wco)
  - Small optical depth correction
  - Most of HI gas is close to solar system

Measurement of HI emissivity constrains the local CR flux and the spectrum
Count maps in E>=200 MeV, accumulated from Aug. 4 to Oct. 30

**Preliminary**

- The Fermi-LAT has already tripled the number of known gamma-ray sources (29 by LAT three month catalog and 9 in EGRET 3rd catalog).
  - The diffuse spectrum by Fermi-LAT is less affected by unresolved sources than early missions.
Column Density of Atomic Hydrogen

Column density maps of HI gas (w/ optical depth correction)

- \( N(\text{HI}) \) is small, less than \( 18 \times 10^{20} \text{ cm}^{-2} \) throughout the region
  - Small uncertainty of the optical depth correction
- We see a correlation between diffuse gamma-ray counts and \( N(\text{HI}) \)
Correlation with the HI Column Density

- Point sources are masked (1° radius). IC and residual point source contributions are subtracted. Error bars are statistical only.
- Correlation from 200 MeV to 10 GeV. The slope gives the $\gamma$-ray emissivity of HI gas.
Emissivity of Local Atomic Hydrogen

• Similar to previous works but with much better statistics especially above 1 GeV.
• Agree with the model prediction from the local interstellar spectrum consistent with measurements at Earth.

Local CR nucleon spectrum is close to that directly measured at Earth

Calibration below 200 MeV is underway and will allow us to discuss CR electron spectrum

(30% sys error is assumed below 1 GeV)

(assumed spectra are not identical)
Large Magellanic Cloud (Local Group Galaxy)
Local Group Galaxies

EGRET Observation Summary:

• LMC detection: CR density is similar to MW
• SMC non-detection: CR density is smaller than in the MW
• First direct evidence: CRs are galactic and not universal

• M31 non-detection: has to have smaller CR density than the MW (size M31>MW)

<table>
<thead>
<tr>
<th>Source</th>
<th>$F(&gt;100 \text{ MeV}), \text{ cm}^{-2} \text{ s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC</td>
<td>$(1.9\pm0.4)\times10^{-7}$</td>
</tr>
<tr>
<td>SMC</td>
<td>$&lt;0.5\times10^{-7}$</td>
</tr>
<tr>
<td>M31</td>
<td>$&lt;0.8\times10^{-7}$</td>
</tr>
</tbody>
</table>

Sreekumar et al.(1992-94)
Why Study the Large Magellanic Clouds?

LMC is
- seen ~ face-on ($i \approx 27^\circ$)
- nearby (~ 50 kpc)
- active (many massive star forming regions)

30 Doradus

NASA/JPL-Caltech/M. Meixner (STScI) & the SAGE Legacy Team

ATCA+Parkes H I (Kim et al. 2003)
EGRET View of the LMC

EGRET maps and profiles of LMC

Sreekumar et al. (1992)

EGRET achievements

• first detection of LMC
• morphology consistent with radio data (yet no real spatial resolution of the emission)
• flux >100 MeV: (1.9 ± 0.4) \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}
• flux consistent with either:
  - dynamic balance model
  - uniform CR density equal to that in solar neighborhood
EGRET vs. Fermi-LAT View of LMC

PRELIMINARY

adaptively smoothed counts map (s.n.r. = 5)
Fermi-LAT Image of the LMC

PRELIMINARY

161 days of survey data
~ 1300 events above 100 MeV
Location (assuming point source):
\( a = 84.6 \pm 0.2 \) (95%)
\( d = -69.1 \pm 0.1 \) (95%)

Consistent with 30 Doradus / R136 location (\( a=84.67, \ d=-69.10 \))

adaptively smoothed 100 MeV - 10 GeV counts map (s.n.r. = 5)
• Fermi-LAT is a superb instrument for diffuse emission studies
  ➢ uniform and deep coverage of the sky

• CR propagation model and gas/ISRF maps have been developed
  ➢ already provided many exciting results of individual sources

• First results on mid latitude Galactic emission show no evidence for EGRET feature > 1 GeV seen in the same region of the sky
• Mid-high latitude observation indicates the local CR nucleon spectrum is close to that measured at Earth
  ➢ Work to analyze and understand diffuse emission over the entire sky is in progress.

• Easily detected diffuse emission from LMC
  ➢ Emission resolved => 30-Doradus, host galaxy
  ➢ More results very soon
And More to Come

Contributions to ICRC 2009 (http://icrc2009.uni.lodz.pl/)

- GeV-non-excess
- Large-scale diffuse
- The Galactic-Center
- Extragalactic gamma-ray background
- Orion/Monoceros molecular clouds
- LMC
- Diffuse gamma-rays from Cassiopeia region

Stay tuned for further results on diffuse gamma-ray emission by Fermi-LAT