Fermi-LAT Study of Galactic Cosmic-Rays by Observing Diffuse Gamma-Rays

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HE $\gamma$-rays are produced via interactions between cosmic-rays (CRs) and the interstellar medium (atomic and molecular gas) or interstellar radiation field.

Pioneering theoretical works by Hayakawa (1952), Morrison (1958), etc. Early Observations by OSO-3, COS-B, SAS-2 and EGRET

A powerful probe to study CRs in distant locations
Fermi Gamma-ray Space Telescope

Two instruments:
- Large Area Telescope (LAT)
  20 MeV - >300 GeV
- Gamma-ray Burst Monitor (GBM)
  8 keV - 40 MeV

(launched on June 11, 2008)

- Energy Resolution: ~10%
- Effective Area: >8000 cm² (1-10 GeV)
- PSF (68%) at 100 MeV: ~3.5° (front)
- PSF (68%) at 10 GeV: ~0.1°
- Field Of View: 2.4 sr

Ideal for the study of diffuse gamma-rays and CRs

Atwood et al.
LAT Study of the Galactic Diffuse Emission

- Individual target (GMCs): matter distribution, correlation with mol. gas tracer
- Galactic plane: CR distributions throughout the Galaxy
  (not covered by this talk)

Mid/low-latitude region (EGRET GeV excess) Submitted to PRL
Mid/high-latitude region (local CR flux and spectrum) Submitted to ApJ

Study CRs in the vicinity of the solar system
EGRET GeV Excess

• EGRET observations showed excess emission > 1 GeV everywhere in the sky when compared with models based on directly measured CR nuclei and electron spectra

• Potential explanations
  ➢ Variations in cosmic-ray spectra over Galaxy
  ➢ Dark Matter
  ➢ Unresolved sources (pulsars, SNRs, …)
  ➢ Instrumental

~100% difference above 1 GeV

Hunter et al. 1997
EGRET vs. LAT in $|b|=10^\circ$-$20^\circ$

- Data from mid-August to end of December from $|b|=10^\circ$-$20^\circ$
- EGRET spectrum extracted for the same region
- No source subtraction (minor component)
- LAT spectrum is significantly softer than EGRET -> we do not confirm the EGRET GeV excess

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LAT vs pre-Fermi Model

- Compare with a CR propagation model prediction based on pre-Fermi CR data (Strong et al. 2004, Porter et al. 2008)
  \[ \pi^0\text{-decay, e-Brems, Inverse Compton} \]
- Source and isotropic (w/ residual BG) component come from fitting the data to the sky above 30 deg latitude with model fixed
- Although there is a uniform excess above the model, data is reasonably reproduced by the model

The model is successful considering it is \textit{a priori} pre-Fermi model
Probing Nearby CRs using HI Gas

Correlation with gas column density reveals the CR spectrum
Outside of Galactic plane, most of the gas is local (<=1 kpc)

LAB HI survey

Fermi LAT data

Mid-high latitude region in the 3rd quadrant
Minimize the effect of Inverse Compton and H$_2$
Correlation with the HI Column Density

- Mask point sources (52 total) and subtract the residual point source contributions. Also subtract the IC contributions.
- Correlation from 100 MeV to 10 GeV. The slope gives the $\gamma$-ray emissivity spectrum of local HI gas produced through interactions with CRs.

**Preliminary**
Emissivity of Local Atomic Hydrogen

- Best quality $\gamma$-ray emissivity spectrum in 100 MeV-10 GeV ($T_p = 1$-100 GeV)
- Agree with the model prediction from the local interstellar spectrum (LIS)

- Prove that CR nuclei spectra within 1 kpc from the solar system are close to those directly measured at the Earth
- $E_{\gamma} < 100$ MeV constrain the e- spectrum to be compared with hard X-rays ($> = 100$ keV) from the Galactic Ridge accessible by ASTRO-H SGD
And More to Come

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

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

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

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Summary

• Diffuse gamma-ray emission is a powerful probe to study CRs in distant locations in our Galaxy

• Fermi-LAT is an ideal instrument for studying the diffuse $\gamma$-rays
  ➢ Large effective area and good angular resolution
  ➢ uniform and deep coverage of the sky

• First results on diffuse emission in mid latitude regions
  ➢ No EGRET GeV excess seen at mid-low latitudes. Reasonably reproduced by a priori pre-Fermi model
  ➢ Mid/high latitude data shows the CR nuclei spectra in the vicinity of the solar system is close to those measured at the Earth

Solid basis for future work to study the CR spectra and distributions in our Galaxy
Backup Slides
The LAT 3-month Image

• More than 20 papers published/accepted
• 205 bright sources (>=100 Blazars, ~30 pulsars, 2 HMXBs, Globular cluster, LMC; Abdo et al. ApJS 183)

>=80% photons are from Galactic Diffuse
Assumed CR Spectra

- Use galprop LIS (blue/red solid lines) which reproduces the directly-observed spectra well.
- Uncertainty of the LIS (solar modulation) affects the emissivity spectrum by \( \sim 20\% \) @\( E_\gamma=100 \) MeV and \( \leq 10\% \) above \( E_\gamma>1 \) GeV.
CR protons with $T_p = 1$-100 GeV have similar spectral shape and the flux with those of the LIS.

The contribution of CR protons of various energies to $\gamma$-rays of some specific energies.

$E_\gamma = 10$ GeV

$E_\gamma = 1$ GeV

$E_\gamma = 100$ MeV

$E_\gamma = 10$ MeV

$E_\gamma = 31.6$ MeV

$E_\gamma = 100$ MeV

$E_\gamma = 316$ MeV

$E_\gamma = 1$ GeV

$E_\gamma = 3.16$ GeV

$E_\gamma = 10$ GeV

We adopted the nuclear enhancement factor (effect of heavier nuclei) by Mori (2009) which adopts the recent compilation of abundances in CRs and the ISM. His value (1.84) is ~20% higher than conventional ones (~1.5).