Galactic Cosmic-Rays Observed by Fermi-LAT (and GRBs)

Tsunefumi Mizuno
Hiroshima Univ.
on behalf of the Fermi-LAT Collaboration

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Plan of the Talk

1. Cosmic-ray overview and Fermi Gamma-ray Space Telescope
2. Cosmic-ray electrons seen by Fermi-LAT (nearby CR sources)
3. Galactic CRs revealed by diffuse $\gamma$-ray emission observed by Fermi-LAT (CRs in distant location)
Introduction:
Cosmic-Rays and the Fermi Gamma-ray Space Telescope
Cosmic-Rays Overview

- Discovered by V. Hess in 1912
- Globally power-law spectrum with some structures (knee and ankle)
  - Hint of the origin
  - $E < E_{\text{knee}}$ are (probably) Galactic origin
- Composition:
  - $e^- \sim (1/100 - 1/1000) \times p$, $e^+ \sim (1/10) \times e^-$
- Large energy density: $\sim 1$ eV cm$^{-3}$
  - Comparable to $U_B$ and $U_{\text{rad}}$
- Studied by direct and indirect measurements
- GRBs are the possible origin of ultra high-energy CRs. May also affect the Galactic CRs. (e.g., Wick et al. 2004)

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Introduction (1):
What Can We Learn from HE $e^-/e^+$ (and $p/\bar{p}$) ?

- Inclusive spectra: $e^- + e^+$
  - Electrons, unlike protons, lose energy rapidly by Synchrotron and Inverse Compton: at very high energy they probe the nearby sources

- Charge composition: $e^+/(e^- + e^+)$ and $\bar{p}/(\bar{p} + p)$ ratios
  - $e^+$ and $\bar{p}$ are produced by the interactions of high-energy cosmic rays with the interstellar matter (secondary production)
  - There might be signals from additional (astrophysical or exotic) sources

- Different measurements provide complementary information of the origin, acceleration and propagation of cosmic rays
  - All available data must be interpreted in a coherent scenario

Study nearby sources (astrophysical or exotic)
HE $\gamma$-rays are produced via interactions between Galactic cosmic-rays (CRs) and the interstellar medium (or interstellar radiation field).

A powerful probe to study CRs (mostly protons) 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

Fermi-LAT consists of three subsystems
- **ACD**: segmented plastic scintillators
  - BG rejection
- **Tracker**: Si-strip detectors & W converters
  - ~1.5 R.L. (vertical)
  - Identification and direction measurement of γ-rays
- **Calorimeter**: hodoscopic CsI scintillators
  - ~8.5 R.L. (vertical)
  - Energy measurement
  - Also serves as an Imaging Calorimeter

Ideal for the direct and indirect (through γ-ray obs.) measurement of CRs

直接測定(e⁻ + e⁺)、間接測定(diffuse γ)

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Fermi-LAT Results (1): CR Electrons
-- Nearby CR Sources? --
Quick Review of Positron and Antiproton Fraction: 2008-09

PAMELA positron and antiproton fraction consistent with secondary production.

Anomalous rise in the positron fraction above 10 GeV.

Several different viable interpretations (>200 papers over the last year).

See also Nature 456, 362 (2008) and PRL 101, 261104 (2008) for pre-Fermi CRE spectrum by ATIC and HESS.

*e+ fraction excessは2ndary 起源とは相いれない*
FOM for CRE Measurement

Exposure factor (effectively) determines the # of counts

\[ E_f(E) = G_f(E) \times T_{\text{obs}} \]

• The exposure factor determines the statistics
• Imaging calorimeters (vs. spectrometers) feature larger Gf
• Space (vs. balloon) experiments feature longer T_{\text{obs}}

Fermi-LAT gives the largest Ef and highest statistics
Fermi-LAT Capability for CR Electrons

- Validate the MC against the beam test up to 280 GeV

- Finite energy resolution is taken into account in the spectrum.

- Compare the flight histogram with the simulated ones, and account for the differences in systematic errors.

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Fermi-LAT Electron Spectrum

- statistics for 6 month data
  - >4 million electrons above 20 GeV
  - >400 electrons in the last energy bin
  - Harder spectrum (spectral index: -3.04) than previously thought

- Pre-Fermi reference model (GALPROP conventional model): ---------
  - conventional source distribution (uniformly distributed distant sources)
  - source PL index: $\gamma_0 = 2.54$
  - diffusion coefficient index: $\delta = 0.33$

- no ATIC excess
- hard spectrum ($\Gamma \sim 3$)
Implication from Fermi-LAT CRE (1)

- Fermi CRE spectrum can be reproduced by the “conventional” model with harder injection spectral index (-2.42) than in a pre-Fermi conventional model (-2.54), within our current uncertainties both statistical and systematic.

- for detail, see D. Grasso et al. 2009 (Astroparticle Physics, 32, 140)

- New “conventional” model
  ✓ $\gamma_0=2.42$ ($\delta=0.33$, w/ reacceleration)
  ✓ $\gamma_0=2.33$ ($\delta=0.6$, plain diffusion)

- re-Fermi “conventional” CRE Model
  $\gamma_0=2.54$

New “conventional” CRE models
  $\gamma_0=2.42$  $\gamma_0=2.33$

新しいカメラをちょっといじればOK
Implication from Fermi-LAT CRE (2)

• Now include recent PAMELA result on positron fraction

\[ \frac{e^+}{e^- + e^+} \sim E^{(-\gamma_P + \gamma_0)}; \gamma_P \sim 2.7 \text{ (proton spectral index), } \gamma_0 \sim 2.4 \]

The hard $e^+ + e^-$ spectrum found by Fermi-LAT sharpens the anomaly
Implication from Fermi-LAT CRE (3)

• It is becoming clear that we are dealing with at least 3 distinct origins of HE e⁻/e⁺
  ➢ Uniformly distributed distant sources, likely SNRs.
  ➢ Unavoidable e⁺e⁻ production by CRs and the ISM “conventional” sources
  ➢ And those that create positron excess at high energies.
    ➢ Nearby (d<1 kpc) and Mature (10⁴ - 10⁶ yr) pulsars (e.g., Grasso+ 09)
    ➢ Nearby GRB (or GRB-like event) (Ioka 09)
    ➢ Nearby SNR in dense cloud (e.g., Fujita+ 09)
    ➢ Dark matter (many including Grasso+ 09)
    ➢ Klein-Nishina effect (Stawarz+ 09, Schlickeiser+ 09)

• Fermi data requires an e⁻/e⁺ injection spectrum significantly harder than generally expected for shell-type SNRs
Pulsar Scenario

- An example of the fit to both Fermi and PAMELA data with Monogem and Geminga with a nominal choice for the e+/e- injection parameter (blue lines).

This particular model assumes:
- 40% e-/e+ conversion efficiency
- $\Gamma = 1.7$
- $E_{\text{cut}} = 1$ TeV
- Delay = 60 kyr

$(E_{\text{max}} = 1/\beta t, \beta = 1.4 \times 10^{-16}$ GeV$^{-1}$ s$^{-1}$)

(Discrepancy in positron fraction at low energies can be understood as the charge-sign effect of solar modulation)
GRB Scenario?

Ioka 2009 (arXiv: 0812.4851)

• model (a) fits to the Fermi and PAMELA data well:
  \( t_{\text{age}} = 2 \times 10^5 \) yr
  \( E_{e^+} = 0.9 \times 10^{50} \) erg
  \( \alpha = 2.5, \) up to 10 TeV
  \( b = 10^{-16} \text{ GeV}^{-1} \text{ s}^{-1} \)

• ATIC data can also be explained by a somewhat harder and older GRB-like event
• Chance probability of having such a GRB: \( \sim 0.6-6 \% \)

近場のGRBでも(Pulsarと同様に)OK
Summary of CRE

• Real breakthrough during last 1-1.5 years in CR electrons: ATIC, HESS, PAMELA and finally Fermi-LAT
• The hard $e^-$/$e^+$ spectrum by Fermi contradicts with PAMELA’s positron fraction.
• We may be coming close to the first detection of cosmic-ray sources
• Source nature (astrophysical or exotic) is still unclear but strongly constrained by the data of Fermi-LAT (+ others)
• More results from Fermi-LAT are coming. Extending energy range to 5 GeV – 2 TeV and searching for the CRE anisotropy at a level of ~1%.

近場の宇宙線源をとらえた？異方性がでれば決め手になりうる

Ioka 09
Fermi-LAT Result (2):
Diffuse Gamma-ray Emission and Galactic CRs
Probing CRs using Gamma-rays

- HE $\gamma$s are generated through pi0-decay (p and ISM), bremsstrahlung ($e^+e^-$ and ISM) and IC ($e^+e^-$ and IRF)
- CR spectrum can be deduced from the gamma-ray data and the ISM distribution

$$\gamma = \text{ISM} \times \text{宇宙線}$$

Mid/high latitude region & Galactic plane:
Study of the local CRs and CR gradient in the outer Galaxy

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From Wikipedia
Outstanding Question: EGRET GeV Excess

- EGRET showed excess emission > 1 GeV everywhere in the sky over the model based on directly measured CRs. (Γ~2.7 PLで落ちてくれない)
- A variety of explanations including large CR variation and DM annihilation

- $|b| = 10^\circ - 20^\circ$: Avoid Gal. plane but still have high statistics
- LAT spectrum is significantly softer and does not confirm the EGRET GeV excess
Accurate Measurements of the Local CRs

Mid-high lat. region in 3rd quadrant:
- small contamination of IC and molecular gas
- correlate $\gamma$-ray intensity and HI gas column density

Abdo et al. 2009 (contact: TM)

- Best quality $\gamma$-ray emissivity spectrum (per H-atom) in 100 MeV-10 GeV ($T_p = 1$-100 GeV)

- Directly measured CR spectrum (LIS) is representative of the local CR spectrum

- Not easy to detect the additional $e^-/e^+$ signal through $\gamma$s. (no hadron rejection)
CR Distribution in Galaxy

- CR distribution is a key to understand their origin and propagation
- Distribution of SNRs not well measured
- Previous Gamma-ray data suggests a flatter distribution than SNR/pulsar distributions (e.g., Strong et al. 2004)

- Fermi-LAT is able to map out CR distributions in the Galaxy with unprecedented accuracy

- Preliminary analysis of the 3\textsuperscript{rd} quadrant (outer Galaxy) will be discussed.

銀河面拡散γ線: 宇宙線の空間分布
Fermi-LAT View of the 3rd Quadrant

- One of the best studied regions in $\gamma$-rays
  - Vela, Geminga, Crab and Orion A/B
- Galactic plane between Vela and Geminga (green square) is ideal to study diffuse $\gamma$-rays and CRs.
  - small point source contamination, kinematically well-separated arms (local arm and Perseus arm)
Construction of the Model

- Fit gamma-ray data with a linear combination of model maps
  \[ I(E, l, b) = \sum A(E) \cdot H(l, b) + \sum B(E) \cdot Wco(l, b) + \sum \text{others} + \sum \text{point sources} \]
- Coefficients give the gamma-ray (CR) spectral distribution of outer Galaxy

拡散γ線 = \sum \text{ISM} \cdot \text{宇宙線} + \alpha

+ others (ISM, IC and point sources)
HI Emissivity (CR) Spectra

• Emissivity spectrum of local arm (R=8.5-10 kpc) is slightly smaller than the model for LIS
• Decreasing emissivity (local arm => interarm => Perseus arm) are interpreted to be due to the decreasing CR density across the Galaxy
• Similar CR spectral shape up to R=16 kpc
• Can constrain the CR source distribution and propagation parameters
  ➢ study in progress

Point sources with Ts>=100 are included in the fitting

銀河宇宙線の分布が明らかになりつつある
Summary

• Fermi-LAT is a powerful instrument to measure CRs either directly or indirectly.

• Fermi-LAT revealed that high-energy $e^- + e^+$ spectrum is harder than previously assumed.
  - this finding + PAMELA positron fraction require local sources (astrophysical or exotic)
  - nearby GRB is one of possible origins
  - Source nature is still unclear but strongly constrained.

• CRs in distant locations can be “measured” by diffuse $\gamma$-rays.
  - EGRET GeV-excess not confirmed.
  - Fermi proves that local CR nuclei spectra are close to those of LIS.
  - CR density distribution in outer Galaxy is being studied.

Thank you for your attention!