Galactic Cosmic-Rays Observed by Fermi-LAT

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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 (direct measurement of CRs)
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: $\sim 1 \text{ eV cm}^{-3}$
  - comparable to $U_B$ and $U_{\text{rad}}$
- Studied by direct and indirect measurements

![Graph showing the spectrum of cosmic rays with labels for Galactic and Extragalactic regions, as well as knee and ankle energies.](image)
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 in distant locations

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Fermi Launch

- Launched from Cape Canaveral Air Station on June 11, 2008
- Science Operation on Aug 4, 2009
- Orbit: 565 km, 26.5° (low BG)
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
Fermi-LAT Results (1): Direct Measurements of Galactic CR Electrons
Quick Review of Positron and Antiproton Fraction: 2008-09

PAMELA positron and antiproton
Nature 458, 607 (2009)
PRL 102, 051101 (2009)

- 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.
Fermi-LAT Capability for CR Electrons

- Candidate electrons pass through 12.5 $X_0$ on average (Tracker and Calorimeter added together)

- Simulated residual hadron contamination (5-21% increasing with the energy) is deducted from resulting flux of electron candidates

- Effective geometric factor ($G_f$) exceeds $2.5 \text{ [m}^2 \text{sr]}$ for 30 GeV to 200 GeV, and decreases to $\sim1 \text{ [m}^2 \text{sr]}$ at 1 TeV. $G_f$ times live time has already reached several $\times 10^7 \text{ [m}^2 \text{sr s]}$. (very high statistics)

- Full power of all LAT subsystems is in use: Tracker, Calorimeter and ACD act together
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 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: $\delta = 0.33$
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. arXiv:0905.0636 (accepted by Astroparticle Physics)

- New “conventional” model
  - $\gamma_0=2.42$ ($\delta=0.33$, w/ reacceleration)
  - $\gamma_0=2.33$ ($\delta=0.6$, plain diffusion)
Implication from Fermi-LAT CRE (2)

• Now include recent PAMELA result on positron fraction

\[ \frac{e^+}{(e^- + e^+)} \sim E^{(-\gamma_p + \gamma_0)}, \quad \gamma_p \sim 2.7 \] (proton spectral index)

• If the secondary positrons only
  
  \[ \frac{e^+}{(e^- + e^+)} \sim E^{(-\gamma_p + \gamma_0)}, \quad \gamma_p \sim 2.7 \] (proton spectral index)
  
  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? DM?

• Energy source: rotation energy of the NS
• Electron and positrons are re-accelerated at the pulsar wind/shock with a power law spectrum with index Γ~1.5
• e⁻/e⁺ are expected to be confined until T~10-100 kyr after the birth of pulsar. Only mature (10<T<1000 kyr) pulsars are expected to be relevant
• $E_{\text{cut}} \sim 10^3$ TeV for young PWN. It is expected to decrease with the pulsar age ($E_{\text{cut}} \sim 0.1-10$ TeV for mature pulsars)

• 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

(Discrepancy in positron fraction at low energies can be understood as the charge-sign effect of solar modulation)
Like for the case of pulsars, PAMELA and Fermi data tighten the DM constraints

Lepto-philic preferred

Both in the pure $e^+e^-$ and lepto-philic models, a DM interpretation is possible with boost factors of 20-100
Summary of Fermi-LAT CRE

- Real breakthrough during last 1-1.5 years in CR electrons: ATIC, HESS, PAMELA and finally Fermi-LAT
- Fermi-LAT provides precise measurements of CR e⁻/e⁺ spectrum in 20 GeV-1 TeV
- With the new data more puzzles than was before. Fermi-LAT’s hard e⁻/e⁺ spectrum 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 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%.
Fermi-LAT Result (2): Galactic Diffuse Gamma-ray Emission (Indirect Probe of Galactic CRs)
Outstanding Question: EGRET GeV Excess

- We can “measure” the CR spectrum in distant locations by observing diffuse $\gamma$-rays.

- EGRET observations showed excess emission $> 1$ GeV everywhere in the sky when compared with models based on directly measured CR spectra
  - Potential explanations
    - Unexpectedly large variations in cosmic-ray spectra over Galaxy
    - Dark Matter
    - Unresolved sources (pulsars, SNRs, …)
    - Instrumental

- Fermi-LAT is able to confirm or reject this phenomenon

$\sim 100\%$ difference above 1 GeV

Hunter et al. 1997
Intermediate Latitude Region seen by LAT

- $|b|=10°-20°$: avoid Gal. plane but still have high statistics
- EGRET spectrum extracted for the same region

- LAT spectrum is significantly softer and does not confirm the EGRET GeV excess
- Strongly constrains the DM interpretation
Probing CRs using Gamma-rays from ISM

- Correlation with gas column density reveals the CR spectrum
  - Method goes back to SAS-2/COS-B era
- Fermi-LAT’s high performance + CR propagation model (e.g. GALPROP) to predict IC
  - Sensitivity significantly improved

**Gamma-ray intensity**
(Fermi LAT data)

**ISM**
(e.g., LAB HI survey)
(http://www.astro.uni-bonn.de/~webalub/english/tools_labsurvey.php)

Mid/high latitude region:
- Detailed study of local CRs (most of the gas is close to the solar system)

Galactic plane:
- CR gradient in the Galaxy (need to resolve point sources)
Accurate Measurements of Local CRs (1)

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

Accurate Measurement of Local CRs (2)

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

- Prove that local CR nuclei spectra are close to those directly measured at the Earth
- $E_\gamma < 100$ MeV constrain the $e^-$ spectrum
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.
- Large scale analysis in progress. (arXiv:0907.0304)

- Preliminary analysis of the 3rd quadrant (outer Galaxy) will be discussed. See also the relevant study of the 2nd quadrant (arXiv:0907.0312)
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 8 maps + 15 point sources (11 month source list)
• CR spectrum ($\gamma$-ray emissivity) is assumed to be uniform in each Galactocentric ring

- Local arm
  + 1 CO map + excess E(B-V) map (Grenier et al. 2005)
  + IC map (galprop model) + point sources (11 month list)

- Perseus arm
  +2 HI maps (profile fitting technique; arXiv:0907.0312)

Utilize new techniques, understanding of the ISM and power of the LAT.
HI Emissivity (CR) Spectra

HI Emissivity Spectrum of each ring

- Emissivity (CR) spectrum of local arm (R=8.5-10 kpc) is slightly smaller than that of LIS
- Decreasing emissivity (local arm => interarm => Perseus arm) are consistent with decreasing CR density across the Galaxy
- Similar CR spectral shape up to R=16 kpc

Point sources with Ts>=100 are included in the fitting
• Emissivity gradient traces the CR density. Robust against the thresholds for point sources included.
• Significantly flatter than the SNR distributions
  ➢ may indicate more CR sources than previously thought in the outer Galaxy, large halo size, etc.
• Comparison with the model prediction is in progress.
Summary

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

• Fermi-LAT provides largest statistics of high-energy CR $e^-/e^+$ spectrum.
  - Precise and hard CR electron spectrum by Fermi-LAT and PAMELA positron fraction require local sources (astrophysical or exotic)
  - Source nature is still unclear but strongly constrained.

• CRs in distant locations can be “observed” by diffuse $\gamma$-rays.
  - EGRET GeV-excess not confirmed.
  - Fermi proves that local CR nuclei spectra are close to those of LIS.
  - Flat and large CR density in the outer Galaxy is indicated.

Thank you for your attention!