Fermi Results: Particle Physics

Igor V. Moskalenko (stanford/kipac)

for the LAT collaboration
GLAST - Fermi

- Two instruments: Large Area Telescope (LAT), 20 MeV - >300 GeV
  - Surveys the whole sky every 2 orbits
- Gamma-ray Burst Monitor (GBM), 10 keV - 25 MeV
  - $4\pi$
Fermi Gamma-Ray Space Telescope (*Fermi*)

DoE - NASA - international partnership

GLAST renamed *Fermi* by NASA on August 26, 2008

http://fermi.gsfc.nasa.gov/

“Enrico Fermi (1901-1954) was an Italian physicist who immigrated to the United States. He was the first to suggest a viable mechanism for astrophysical particle acceleration. This work is the foundation for our understanding of many types of sources to be studied by the Fermi Gamma-ray Space Telescope, formerly known as GLAST.”
The Large Area Telescope (LAT)

LAT images the sky one photon at a time: γ-ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon.

GBM
The LAT

- Modular design
- 4x4 array of identical towers
- Anti-coincidence detector (ACD)

Tracker
- Silicon strip detectors (16 planes), 80 m² of silicone
- Tungsten conversion foils
- 1M readout channels

ACD
- Segmented (89 tiles) to minimize self-veto
- 0.9997 average detection efficiency

Calorimeter
- Hodoscopic tower of 1536 CsI(Tl) crystals
- 8.6 radiation lengths on-axis
- 3D shower profile reconstruction
- Leakage correction & hadron rejection
LAT as a Gamma-Ray Telescope

<table>
<thead>
<tr>
<th></th>
<th>Years</th>
<th>Ang. Res. (100 MeV)</th>
<th>Ang. Res. (10 GeV)</th>
<th>Eng. Rng. (GeV)</th>
<th>$A_{\text{eff}} \Omega$ (cm$^2$ sr)</th>
<th># $\gamma$-rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGRET</td>
<td>1991–00</td>
<td>5.8°</td>
<td>0.5°</td>
<td>0.03–10</td>
<td>750</td>
<td>$1.4 \times 10^6$/yr</td>
</tr>
<tr>
<td>AGILE</td>
<td>2007–</td>
<td>4.7°</td>
<td>0.2°</td>
<td>0.03–50</td>
<td>1,500</td>
<td>$4 \times 10^6$/yr</td>
</tr>
<tr>
<td><em>Fermi</em> / <em>LAT</em></td>
<td>2008–</td>
<td>3.5°</td>
<td>0.1°</td>
<td>0.02–300</td>
<td>25,000</td>
<td>$1 \times 10^8$/yr</td>
</tr>
</tbody>
</table>

- LAT has quickly surpassed EGRET and AGILE celestial gamma-ray totals
- Unlike EGRET and AGILE, LAT is an effective **All-Sky Monitor** whole sky every ~3 hours
Fermi LAT Science

- **> 2000 AGNs**
  - blazars and radiogal = $f(\theta, z)$
  - evolution $z < 5$
  - Sag A*

- **10-50 GRB/year**
  - GeV afterglow spectra to high energy

- **$\gamma$-ray binaries**
  - Pulsar winds
  - $\mu$-quasar jets

- **Possibilities**
  - starburst galaxies
  - galaxy clusters
  - measure EBL unIDs

- **Dark Matter**
  - neutralino lines
  - sub-halo clumps

- **CR electrons**
  - 20 GeV - a few TeV

- **Cosmic rays and clouds**
  - acceleration in Supernova remnants
  - OB associations
  - propagation (Milky Way, M31, LMC, SMC)
  - Interstellar mass tracers in galaxies

- **Pulsars**
  - emission from radio and X-ray pulsars
  - blind searches for new Gemingas
  - magnetospheric physics
  - pulsar wind nebulae
Fermi LAT Collaboration

- **France**
  - IN2P3, CEA/Saclay
- **Italy**
  - INFN, ASI, INAF
- **Japan**
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- **Sweden**
  - Royal Institute of Technology (KTH)
  - Stockholm University
- **United States**
  - Stanford University (SLAC and HEPL/Physics)
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - Ohio State University
  - University of Washington

Principal Investigator:
Peter Michelson (Stanford University)
~270 Members
(~90 Affiliated Scientists, 37 Postdocs, and 48 Graduate Students)

construction managed by
Stanford Linear Accelerator Center (SLAC), Stanford University
GLAST at the launch pad

Kennedy Space Flight Center
Delta II heavy
June 11, 2008
The final check of ignition...
Circular orbit at 565 km
Inclination 25.6°
Lifetime ≥5 years
First 3 Months Skymap (Counts)

The diffuse emission is the brightest source on the sky: \(\sim80\%\) of all photons
First 3 months of LAT data

First movie in gamma rays ever shot!
A Constellation of CR and gamma-ray (also CR!) instruments

- **pbar**
- **anti-d,-He**
- **e^+**
- **e^-**
- **p**
- **He**
- **Z ≤ 8**
- **8 < Z ≤ 28**
- **Z > 28**
- **WIMPs**
- **SUSY**
Some material has been covered in previous talks by:

Neal Weiner, Jan Conrad, Mark Pearce, Eun-Suk Seo
Primary electrons in Cosmic Rays

Journal of Geophysical Research Vol. 70, No. 11 June 1, 1965

Letters

Observation of the Cosmic Ray Electron-Positron Ratio from 100 Mev to 3 bev in 1964

R. C. Hartman and Peter Meyer

Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois

R. H. Hildebrand

Argonne National Laboratory and University of Chicago
Chicago, Illinois

In 1963, DeShong, Hildebrand, and Meyer [1964] reported the results of an experiment designed to measure this ratio in the energy interval from 100 to 1000 Mev. They found an excess of negative electrons which led them to conclude that the electron component consists mainly of directly accelerated particles. Their
Early Measurements of CR Electrons

Early measurements of CR electrons and predictions of possible spectral features associated with local SNR.

\[ E_c = 20 \text{TeV}, \quad \tau = 0 \text{yr} \]
\[ D_0 = 2 \times 10^{29} \text{(cm}^2\text{s}^{-1}) \]

Distant component excluding \( T \leq 1 \times 10^3 \text{yr and } r \leq 1 \text{kpc}\)
CR Electrons “Pre-LAT”

- Combined measurements from balloons and ground
- Most recent: ATIC (3+ flights) and HESS

![Graph showing energy distribution of CR electrons](image-url)
LAT measurements ($e^-+e^+$)

**Graph Details:**
- The graph shows measurements of $E^3 J(E)$ (GeV$^2$ m$^{-2}$ s$^{-1}$ sr$^{-1}$) as a function of $E$ (GeV).
- Data points represent various experiments:
  - AMS (2002)
  - ATIC–1,2 (2008)
  - HESS (2008)
  - FERMI (2009)
  - Kobayashi (1999)
  - HEAT (2001)
  - BETS (2001)
- The graph includes a conventional diffusive model line.
- The error bars indicate uncertainties in the measurements.

**Abdo+’09**

**Equation Reference:**
- The graph is referenced to Abdo+’09.
More HESS electron data

Aharonian+’09

$E^3 \frac{dN}{dE}$ (GeV$^2$ m$^{-2}$ s$^{-1}$ sr$^{-1}$)

$e^+\gamma$

$\Delta E \pm 15\%$

Energy (GeV)

ATIC

PPB-BETS

Kobayashi

H.E.S.S.

H.E.S.S. - low-energy analysis

Systematic error

Systematic error - low-energy analysis

Broken power-law fit

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Interpretation

- The CR electron spectrum appears to be flatter (power-law index ~3) than previously thought
- Has a sharp cut off at ~1 TeV (consistent with expectations)

- The origin of the CR lepton (electrons + positrons) spectrum can’t be understood based on the lepton data alone
- The key is to look at the lepton spectrum in conjunction with data on other CR species and CR propagation models

- This is related to both scenario: astrophysical and “exotic”
CR Propagation: the Milky Way Galaxy

Radio contours: Condon et al. 1998 AJ 115, 1693

NGC891

R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam

"Flat halo" model (Ginzburg & Ptuskin 1976)
CRs in the Interstellar Medium

- **HESS**
- **Chandra**
- **Fermi**

**SNR RX J1713-3946**

42 sigma (2003+2004 data)

**ISM**

- **e^+**
- **e^-**
- **X, Y**
- **P**
- **He**
- **CNO**
- **gas**

**ISRF**

- **B**
- **IC**
- **synchrotron**
- **brems**

**Production of secondaries**

- **diffusion**
- **energy losses**
- **reacceleration**
- **convection**

**CR species:**

- Only 1 location
- modulation
Elemental abundances in CRs and in the Solar System

- CR abundances: ACE
- Solar system abundances

Elemental abundances:
- LiBeB
- CNO
- F
- Cl
- CrMn
- ScTiV
- Si
- Na
- Al
- O
- S
- Fe

"input"

"output"
ISRF: Large Scale Distribution

- Requires extensive modeling:
  - Distribution of stars of different stellar classes in the Galaxy
  - Dust emission
  - Radiative transfer
- The z scale height is large, takes 10s of kpc at R = 0 kpc to get to level of CMB

Optical + IR (no CMB)
Galactic magnetic field

Regular B-field: large-scale structure

- Plane: bisymmetrical field with reversals on arm-interarm boundaries
- Halo: azimuth B-fields with reversed directions below and above the plane
- Random field $\approx$ Regular field
- Consistent with observations of the synchrotron emission
Electron Fluctuations/SNR Stochastic Events

**GeV electrons**

- Energy losses
- Bremsstrahlung
- Ionization
- Coulomb
- IC, synchrotron

**100 TeV electrons**

- Electrons

Electron energy loss timescale:
- 1 TeV: \(~300\) kyr
- 100 TeV: \(~3\) kyr

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Gas distribution in the Milky Way

Molecular hydrogen $H_2$ is traced using $J=1-0$ transition of $^{12}CO$, concentrated mostly in the plane ($z\sim70$ pc, $R<10$ kpc)

Atomic hydrogen $H\ I$ has a wider distribution ($z\sim1$ kpc, $R\sim30$ kpc)

Ionized hydrogen $H\ II$ - small proportion, but exists even in halo ($z\sim1$ kpc)
**Distribution of interstellar gas**

- Neutral interstellar medium - most of the interstellar gas mass
  - 21-cm H I & 2.6-mm CO (surrogate for H$_2$)
  - Differential rotation of the Milky Way - plus random motions, streaming, and internal velocity dispersions - is largely responsible for the spectrum
  - Rotation curve $V(R) \Rightarrow$ unique line-of-sight velocity-Galactocentric distance relationship

- This is the best - but far from perfect - distance measure available

- Column densities: $N(H_2)/W_{CO}$ ratio assumed; a simple approximate correction for optical depth is made for $N$(H I); self-absorption of H I remains
Many different isotopes are produced via spallations of CR nuclei: 
\[ A + (p, \text{He}) \rightarrow B^* + X \]

Secondary, radioactive ~1 Myr & K-capture isotopes

Plus some dozens of more complicated reactions
But many cross sections are not well known…
Effect of Cross Sections: Radioactive Secondaries

Different size from different ratios...

- Errors in CR measurements (HE & LE)
- Errors in production cross sections
- Errors in the lifetime estimates
SNR distribution

Case & Bhattacharya

Milky Way
Transport Equations ~90 (no. of CR species)

\[
\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p) \text{ sources (SNR, nuclear reactions...)} \\
\text{diffusion } + \vec{\nabla} \cdot [D_{xx} \vec{\nabla} \psi - \vec{V} \psi] \\
\text{diffusive reacceleration } + \frac{\partial}{\partial p} \left[ p^2 D \frac{\partial}{\partial p} \frac{\psi}{p^2} \right] \\
\text{E-loss } - \frac{\partial}{\partial p} \left[ \frac{dp}{dt} \psi - \frac{1}{3} p \vec{\nabla} \cdot \vec{V} \psi \right] \\
\text{fragmentation } - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d} \text{ radioactive decay} \]

+ boundary conditions

\psi(\vec{r}, p, t) – density per total momentum
Fixing Propagation Parameters

Using secondary/primary nuclei ratio & flux:

- Diffusion coefficient and its index
- Propagation mode and its parameters (e.g., reacceleration \( V_A \), convection \( V_z \))
- Propagation params are model-dependent
- Make sure that the spectrum is fitted as well

Radioactive isotopes:
Galactic halo size \( Z_h \)

\[
\frac{\text{Be}^{10}}{\text{Be}^9} \\
\text{Carbon}
\]

\[
E_k, \text{MeV/nucleon}
\]

\[
E^2 \text{ Flux}
\]

\[
\text{Interstellar}
\]

\[
0.4 \quad 0.35 \quad 0.3 \quad 0.25 \quad 0.2 \quad 0.15 \quad 0.1 \quad 0.05 \quad 0.01 \quad 0.005 \quad 0.001 \quad 0.0001
\]

\[
10 \quad 100 \quad 1000 \quad 10000 \quad 1e+06
\]

\[
E_k, \text{MeV/nucleon}
\]

\[
\text{Be}^{10}/\text{Be}^9
\]

\[
\text{Carbon}
\]

\[
\text{Be}^{10}/\text{Be}^9
\]

\[
\text{Phil} = 450 \text{ MV}
\]

\[
\text{Data:}
\]

\[
\text{Voyager, Ulysses, ACE}
\]

\[
Z_h \text{ increase}
\]

\[
E_k, \text{MeV/nucleon}
\]

Parameters (model dependent):
\[
D \sim 10^{28} (\rho/1 \text{ GV})^\alpha \text{ cm}^2/\text{s}
\]
\[
\alpha \approx 0.3-0.6
\]
\[
Z_h \sim 4-6 \text{ kpc}
\]
\[
V_A \sim 30 \text{ km/s}
\]
Being tuned to one type of sec/pri ratio (e.g. B/C ratio) the propagation model should be automatically consistent with all sec/pri ratios (sub-Fe/Fe, He³/He⁴, pbar/p...)

B/C ratio in CR is declining >1 GeV/n, not rising!
Pamela: pbar/p ratio

- Pbar/p ratio is consistent with secondary origin

Adriani+’08 (arXiv:0810.4994)
Fermi/LAT: Diffuse emission at mid-latitudes

Conventional GALPROP model is in agreement with the LAT data at mid-latitudes (mostly local emission)
Pamela: positron fraction

- Excess in positron fraction is confirmed and extended to higher energies

Adriani+08
Reasons for the positron fraction to rise

- Main reason - primary positrons are perhaps unavoidable
- There is no deficit in papers explaining the PAMELA positron excess (>300 papers since Oct 2008!)
  - Various species of the dark matter (most of papers)
  - Pulsars
  - SNRs
  - Microquasars
  - a GRB nearby
  - ...
- Perhaps we have to discuss a deficit of positrons, not their excess!
  - Unfortunately, they are >99.7% wrong!
  - Reason - we do not know the positron spectrum, just the ratio...
Scientific Impact (using NASA ADS)

- ATIC electrons: >200 citations (in ~1 yr)
- Fermi LAT electrons: >100 citations (in ~1/2 yr)
- HESS electrons: ~100 citations (in <1 yr)
- PAMELA positron fraction: >300 citations (in ~1 yr)
- PAMELA antiprotons: >150 citations (in <1 yr)
Hypotheses Currently on the Table: Standard CRs

- Currently there is no dominating hypothesis consistent with all sorts of data

- Pros
  - Agrees with spectra and abundances of the CR nuclear component
  - Consistent with the spectrum of the diffuse emission
  - The CR electron spectrum can be easily matched

- Cons
  - Disagreement with CR electron measurements at low energies
  - It is hard to make the positron fraction to rise given the pbars are consistent with secondary origin (the same progenitor, pp -interactions, for both)
Hypotheses Currently on the Table: Astrophysical Source(s)

- An addition to the “standard” CR propagation

**Pros**

- Pulsars are a viable explanation (Aharonian+’95…), they are the sources of primary electrons and positrons

**Cons**

- SNRs accelerate all particles including nucleons, but sec/pri ratio decreases
**Hypotheses Currently on the Table: DM**

- **Pros**
  - WIMPs with leptonic final states
  - The WIMP mass and the "boost factor" can be adjusted

- **Cons**
  - Leptonic final states may lead to a strong gamma-ray signal (not observed)
  - Hard to prove unless a clear spectral feature is discovered
Early Discoveries of New Particles in CRs

1929
Bothe (Nobel Prize 1954) and Kolhorster verified that the cloud chamber tracks were curved. Thus the cosmic radiation was charged particles

1932
a discovery of positron by C. Anderson (Nobel Prize 1936)

1937
a discovery of muon by Neddermeyer & Anderson
and simultaneously by Street & Stevenson

1947
pions predicted by Yukawa (1935, Nobel Prize 1949) to explain the force that binds the nucleus together were discovered (Cecil Powell et al.; Nobel Prize 1950)
kaons were discovered by Rochester & Butler
Morphology of the Diffuse Emission @ 150 GeV

Fig. 9: Sky-map at 150 GeV of the emissions associated to Galactic primary+secondary CRs in the "conventional" model B0. The intensity is shown in logarithmic scale and units [MeV cm^{-2} s^{-1} sr^{-1}]. Left Panel: Inverse Compton radiation. Right Panel: $\pi^0$-decay emission.

Fig. 10: Sky-map at 150 GeV of the emissions induced by WIMP annihilations in the propagation model B0. The intensity is shown in logarithmic scale and units [MeV cm^{-2} s^{-1} sr^{-1}]. Left Panel: Inverse Compton radiation in the DM\epsilon scenario. Right Panel: $\pi^0$-decay emission in the DM\tau scenario.
## 205 Preliminary LAT Bright Sources

### Census of Associations (not Identifications)

<table>
<thead>
<tr>
<th>Class</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio/X-ray pulsar</td>
<td>15</td>
</tr>
<tr>
<td>LAT pulsar</td>
<td>14</td>
</tr>
<tr>
<td>Globular cluster (pulsars?)</td>
<td>1</td>
</tr>
<tr>
<td>HMXB</td>
<td>2</td>
</tr>
<tr>
<td>LMC</td>
<td>1</td>
</tr>
<tr>
<td>Flat Spectrum Radio Quasars</td>
<td>62</td>
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<tr>
<td>BL Lac Objects</td>
<td>46</td>
</tr>
<tr>
<td>Blazar, uncertain type</td>
<td>11</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>2</td>
</tr>
<tr>
<td>Special cases (under study)</td>
<td>14</td>
</tr>
<tr>
<td>Unassociated</td>
<td>37</td>
</tr>
</tbody>
</table>
Fermi Pulsars

33 gamma-ray and radio pulsars (including nine ms psrs)
16 gamma-ray only pulsars

Pulses at 1/10th real rate

• EGRET pulsars
+ young pulsars discovered using radio ephemeris
○ pulsars discovered in blind search
★ millisecond pulsars discovered using radio ephemeris

High-confidence detections through 2/28/2009
Milagro: TeV Observations of Fermi Sources

IC433
SNR
Geminga
MGRO 2019+37
Pulsar (AGILE/Fermi)
Milagro C3
\(\gamma\) Cygni SNR
Fermi Pulsar
MGRO 2019+37
HESS 2032+41
MGRO 2031+41
MAGIC 2032+4130

Radio pulsar
J0631+10
(new TeV source)
Fermi Pulsar
Milagro
MGRO 2031+41
MAGIC 2032+4130

unID
(new TeV source)
Fermi Pulsar
MGRO 1908+06
HESS 1908+063

Credit G. Sinnis
SSI-SLAC, Aug. 11, 2009
:: IVM/Stanford-KIPAC 50
(Some) Important Questions to Answer

- How large is the positron fraction at HE (PAMELA)
  - Identifies the nature of sources of primary positrons
- If SNRs are the sources of primary positrons, this should also affect secondary nuclei...
  - Measure the secondary nuclei (PAMELA, CREAM...)
- How typical for the local Galactic environment is the observed Fermi/LAT spectrum
  - If this is the typical spectrum than the sources of primary positrons are distributed in the Galaxy (could be pulsars, SNRs, or DM)
  - If this spectrum is peculiar than there is a local source or sources of primary positrons
  - The answer is in the diffuse gamma-ray emission (Fermi/LAT)
- Dark matter vs Astrophysical source
  - Distribution of the IC emission at HE (Fermi/LAT)
- WE HAVE ALL NECESSARY INSTRUMENTS IN PLACE (in the orbit) TO ANSWER THESE QUESTIONS
SED of the isotropic diffuse emission (1 keV – 100 GeV)
First 3 months of LAT data

PSR J1836+5925
PKS 1502+106
3C 454.3
The heliosphere is filled with Galactic CR electrons and solar photons

- electrons are isotropic
- photons have a radial angular distribution
The Sun: 5 months of observations

Source Flux (>100 MeV) ~ 4x10^{-7} \text{ cm}^{-2} \text{ s}^{-1} (albedo+IC, preliminary)

Expected IC Flux (>100 MeV) ~ 4.3x10^{-7} \text{ cm}^{-2} \text{ s}^{-1} (near the solar min, IM+’06)
EGRET Flux (>100 MeV) = not found (Thompson+’97)
   = (4.44\pm2.03)x10^{-7} \text{ cm}^{-2} \text{ s}^{-1} (albedo+IC, Orlando&Strong’08)
The ecliptic

Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions.

Gives also independent measurement of the electron spectrum in the heliosphere!
Spectrum of CR electrons in the heliosphere

Looking at different elongation angles one can probe the electron spectrum at different distances from the sun!

Flux_{IC} \sim \frac{1}{r}

\begin{align*}
r_1 \text{ (AU)} &= \sin \alpha, \quad \alpha < 90^\circ \\
r_1 \text{ (AU)} &= 1, \quad \alpha > 90^\circ \\
r_2 &= 10r_1
\end{align*}
Thank you!

You are here