Interstellar gamma rays

New insights from Fermi

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on behalf of Fermi-LAT collaboration

COSPAR Scientific Assembly, Bremen, July 2010

Session E110:
' The next generation of ground-based Cerenkov Telescopes'
see also talk by Eric Charles on Fermi results,
Where do most of these gamma rays come from?
cosmic-ray sources: p, He .. Ni, e

Secondary: 10Be, 10,11B ... Fe..

gamma-rays

synchrotron

energy loss
decay

reacceleration

HALO

intergalactic space

B-field

gas

bremsstrahlung
inverse Compton

ISRF

bremsstrahlung
inverse Compton

gamma-rays
EARLY CONCLUSIONS from Fermi-LAT

Fermi does not confirm EGRET GeV excess.

Abdo et al (2009)  PRL 103, 251101

so back to the drawing board for models based on GeV excess!
LATEST DIFFUSE EMISSION RESULTS FROM FERMI-LAT

New:

>1 year of data

low background event class (developed for extragalactic background study)

Fermi-measured electron spectrum

Improved gas tracer: dust emission
The **goal**: use *all* types of data in self-consistent way to test models of cosmic-ray propagation.

Observed *directly, near Sun*:
- primary spectra (p, He ... Fe; e⁻)
- secondary/primary (B/C etc)
- secondary e⁺, antiprotons...

Observed *from whole Galaxy*:
- γ - rays
- synchrotron
Modelling the gamma-ray sky

Main ingredients of GALPROP model

cosmic-ray spectra p, He, e-, e+ (including secondaries)
  (including *Fermi*-measured electrons)
cosmic-ray source distribution follow e.g. SNR/pulsars

secondary/primary (B/C etc) for propagation parameters
halo height = 4 - 10 kpc (from radioactive cosmic-ray nuclei)

Interstellar radiation field (-> inverse Compton)
HI, CO, dust surveys
CO-to-H$_2$ conversion a function of position in Galaxy
Fermi 1$^{st}$ Year Source Catalogue
First use a model based on *locally-measured* cosmic rays.

PROTONS

\[ \text{galdef ID 54_5gXvarh7S} \]

- \( E^2 I(E), \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV} \)
- \( E = \text{energy, MeV} \)
- Data points for different electric fields (F#)

ELECTRONS

\[ \text{galdef ID 54_71Xvarh7S} \]

- \( E^2 I(E), \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV} \)
- \( E = \text{energy, MeV} \)
- Data points for different electric fields (F#)

\( \bullet = \text{Fermi} \)
Electron spectrum measured by Fermi-LAT extended down to 7 GeV

Abdo et al 2009 PRL.102, 181101, Grasso et al 2009 Astropart.Ph. 32, 140
NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky
NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky
INTERMEDIATE LATITUDES
+10 < b < +20

Preliminary Fermi inverse Compton brems.

π sources total diffuse sources isotropic
inverse Compton brems.

galdef ID 54_z04G4c5PS

E² x Intensity, cm² sr⁻¹ MeV

0.25° < l < 179.75°, 180.25° < l < 359.75°
10.25° < b < 19.75°, 10.25° < b < 19.75°

good agreement with basic model

PRELIMINARY
Remarkable agreement. Confirms that dust is a better tracer of local gas than HI+CO (Grenier, Casandjian: found this in EGRET data)

PRELIMINARY
Dust emission is a better tracer of local gas than HI+CO!
Inner Galaxy
$330^\circ < l < 30^\circ, |b|<5^\circ$

PRELIMINARY

![Graph showing various energy distributions: $\pi^0$, Fermi, Catalogue sources, Inverse Compton, isotropic, bremsstrahlung.](galdef ID 54_z04G4c5PS)
Inner Galaxy
$330^\circ < l < 30^\circ$, $|b|<5^\circ$

- **Fermi**
- **Inverse Compton**
- **bremsstrahlung**

Catalogue sources

$\pi^0$ isotropic

PRELIMINARY excess : unresolved sources?
Agrees within 15% over 2 decades of dynamic range
The observed flux is the sum of many components:
importance of modelling them all!

PRELIMINARY
Evidence for large cosmic-ray halo

4 kpc halo height

10 kpc halo height

Inverse Compton at high latitudes suggests a large cosmic-ray halo

Preliminary
Gamma-ray distribution in outer Galaxy

Gamma-ray emissivity falls off \textit{slower than expected} for SNR source origin

Large halo will flatten it .... more evidence for large halo

2\textsuperscript{nd} Galactic quadrant

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    height=0.8\textwidth,
    xlabel={$R$ (kpc)},
    ylabel={$\Gamma_{11}$ (cm$^{-3}$ s$^{-1}$ s$^{-1}$)},
    xmin=0, xmax=20,
    ymin=0, ymax=25 \times 10^{-27},
    xtick={0,2,4,6,8,10,12,14,16,18,20},
    ytick={0,5,10,15,20,25 \times 10^{-27}},
    legend pos=north east,
    grid=major,
]

\addplot[blue, thick, mark=none] table [x=R, y=Gamma_11] {data.csv};
\addlegendentry{SNR/pulsars}

\addplot[green, thick, mark=triangle*] coordinates {(10, 10 \times 10^{-27})};
\addlegendentry{Fermi}

\end{axis}
\end{tikzpicture}
\end{center}

more cosmic rays than expected!
Gamma-ray emissivity distribution in outer Galaxy

3rd Galactic Quadrant

varying the halo size

- Flat for $R > 10$ kpc
- Flat for $R > 15$ kpc

varying the source distribution

- LAT data

$E_{\gamma} \geq 100$ MeV
$E_{\gamma} \geq 100$ MeV

$z_h = 4$ kpc, $D_0 = 5.8 \times 10^{26}$ cm$^2$ s$^{-1}$


NEW: PRELIMINARY
Fermi measures molecular gas content of the outer Galaxy by comparing gamma-ray emissivities of molecular and atomic hydrogen.

Scaling factor $X_{\text{CO}}$ from $^{12}\text{CO}$ to $\text{H}_2$

Local and Outer Galaxy (2$^{\text{nd}}$ quadrant)

Confirms increase from inner to outer Galaxy

Local HI gamma-ray emissivity

Agrees well with pion-decay calculation!

Facit

Large Scale Diffuse Gamma Ray Emission:

The diffuse emission model reproduces the Fermi data remarkably well.

The remaining residuals have many possible origins: this is where the current action and interest is focussed.
OR PARTLY UNRESOLVED SOURCES?
Source contribution from luminous (pulsars etc) sources

Due to Fermi sensitivity, unresolved source flux will finally be at percent level

A. Strong, 2009 Fermi Symposium
Source contribution from possible low-luminosity sources

Many more dim sources can hide. Just limits can be set on their contribution.

A. Strong, 2009 Fermi Symposium
INTEGRAL / SPI
spectrum of inner Galaxy

NEW
Bouchet et al 2010, in preparation
this conference: E18 Poster #65
Gamma-rays, inner Galaxy

inverse Compton from primary electrons, secondary electrons + positrons

These processes are very relevant down to hard X-rays!

power-law continuum measured by INTEGRAL / SPI

large fraction of the inverse Compton power comes out in hard X-rays!
a glimpse of things to come....
and towards the highest energies...

Diffuse Galactic Emission


This model was adapted to EGRET GeV-excess, gave a good fit to MILAGRO but now with Fermi situation will change!
Milky Way Galaxy is a special target for multi-wavelength studies because ... 

We know much more about our Galaxy than external galaxies:

* cosmic rays directly measured 
* gamma rays mapped in detail 
* synchrotron mapped in detail 
* magnetic fields measured 

so study of the Galaxy allows a better understanding of the detailed inner workings to clarify the overall picture including e.g. cosmic-ray CALORIMETRY
Galactic center region

Radio surveys

WMAP

Galactic center region

GALPROP model

SYNCHROTRON

|b| < 1.75

|l| < 60

408 MHz

405 MHz

-60.75°<l<0.25°, 0.25°<l<60.75°

-10.75°<b<0.25°, 0.25°<b<10.75°

Northern Sky

WMAP

|b| < 1.75

408 MHz

-1.75°<b<0.25°, 0.25°<b<1.75°
Since we live inside the Galaxy, global properties e.g. luminosity are not easy to deduce.
how does it look from out there?
Since we live inside the Galaxy, global properties e.g. luminosity are not easy to deduce.

Model-dependent.

Need 3D models.
Galaxy luminosity over 20 decades of energy

Strong et al., 2010 submitted to ApJL
Galaxy luminosity over 20 decades of energy

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Galaxy luminosity over 20 decades of energy

Strong et al., 2010 submitted to ApJL
Galaxy luminosity over 20 decades of energy

Strong et al., 2010 submitted to ApJL
Galaxy luminosities

based on GALPROP model
Fermi gamma rays and electrons

<table>
<thead>
<tr>
<th>Source</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic-ray nuclei</td>
<td>$10^{41}$</td>
</tr>
<tr>
<td>Cosmic-ray electrons</td>
<td>$1.6 \times 10^{39}$</td>
</tr>
<tr>
<td>Gamma rays &gt; 100 MeV</td>
<td>$1.2 \times 10^{39}$</td>
</tr>
<tr>
<td>$\pi^0$-decay</td>
<td>$7 \times 10^{38}$</td>
</tr>
<tr>
<td>bremsstrahlung</td>
<td>$1 \times 10^{38}$</td>
</tr>
<tr>
<td>inverse Compton</td>
<td>$4 \times 10^{38}$</td>
</tr>
<tr>
<td>Synchrotron</td>
<td>$4 \times 10^{38}$</td>
</tr>
<tr>
<td>Optical + IR</td>
<td>$10^{44}$</td>
</tr>
</tbody>
</table>

$1\%$ of nuclei energy converts to gamma rays
$75\%$ of electron energy converts to inverse Compton gamma rays
$25\%$ of electron energy converts to synchrotron radiation
Galaxy is electron calorimeter! - but only if inverse Compton is included, not just synchrotron

Strong et al., 2010 submitted to ApJL
FIR/radio correlation IRAS Galaxies

Yun et al. 2001 ApJ 554, 803

Graph showing the correlation between $L_{1.4\text{GHz}}$ (in W Hz$^{-1}$) and $L_{60\mu\text{m}}$ ($L_\odot$) with $N = 1809$.
FIR/radio correlation IRAS Galaxies

N = 1809

$L_{1.4\text{GHz}}$ (W Hz$^{-1}$)

$L_{60\mu m}(L_\odot)$

Milky Way

(a)
Outlook

Fermi operational, 2 years so far. Diffuse emission results appearing. The fine data challenges the models.

Essential to exploit synergy between cosmic-rays - gammas – microwave - radio