Interstellar gamma rays and cosmic rays

New insights from Fermi and INTEGRAL and .....
1 year
Where do most of these gamma rays come from?
cosmic-ray sources: p, He .. Ni, e

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

Secondary: e^+  p

cosmic-ray sources: p, He .. Ni, e^-

energy loss
decay

reacceleration

intergalactic space

HALO

γ-rays

synchrotron

bremsstrahlung

inverse Compton

B-field

gas

ISRF

π
EARLY CONCLUSIONS from Fermi-LAT

Fermi does not confirm EGRET GeV excess.

so back to the drawing board for models based on GeV excess!

Abdo et al (2009) PRL 103, 251101
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

See talk by Troy Porter at this conference.

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-$\text{H}_2$ conversion a function of position in Galaxy
- Fermi 1$^{\text{st}}$ Year Source Catalogue
First use a model based on *locally-measured* cosmic rays.
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
$+10 < b < +20$

**Fermi**

Inverse Compton

$\pi^0$

Sources

Total diffuse

Total with sources

Isotropic

Inverse Compton

Bremss.

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
Inner Galaxy
$330^\circ < l < 30^\circ$, $|b|<5^\circ$

Fermi
Inverse Compton
bremsstrahlung
Catalogue sources
\( \pi^0 \)
Isotropic
Excess: unresolved sources?

**PRELIMINARY**
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

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

10 kpc halo height

1 GeV

inverse Compton at high latitudes suggests a large cosmic-ray halo
Gamma-ray distribution in outer Galaxy

Gamma-ray emissivity falls off slower than expected for SNR source origin.

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

\(2^{nd}\) Galactic quadrant

\(\frac{\xi}{E}\) \(\times 10^{-27}\)

SNR/pulsars

Fermi

more cosmic rays than expected!

Gamma-ray emissivity distribution in outer Galaxy

3rd Galactic Quadrant

varying the halo size

\[ E_{\gamma} \geq 100 \text{ MeV} \]

1 kpc halo

20 kpc halo

varying the source distribution

\[ E_{\gamma} \geq 100 \text{ MeV} \]

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

flat for \( R > 15 \text{ kpc} \)

flat for \( R > 10 \text{ kpc} \)


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
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
Bouchet etal 2008, Porter etal 2008

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!


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
Continuum sky surveys

- 22 MHz
- 45 MHz
- 150 MHz
- 23 GHz
- 408 MHz
- 2.3 GHz
- 820 MHz
- 1.4 GHz
Galactic center region

Radio surveys

WMAP

|b| < 1.75

|l| < 60

SYNCHROTRON

GALPROP model

408 MHz

405 MHz

Galactic latitude

Galactic longitude

brightness temperature, T
Since we live inside the Galaxy, global properties e.g. luminosity are not easy to deduce.
how does it look from out here?
Model-dependent.

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

Strong et al., 2010 ApJL 722, L58
Galaxy luminosity over 20 decades of energy
Galaxy luminosity over 20 decades of energy

- Cosmic rays
- Photons
- Inverse Compton
- Electrons

[Diagram showing luminosity distribution across various energy ranges: radio, CMB, IR, optical, X-rays, and gamma-rays.]
Galaxy luminosity over 20 decades of energy

Galactic luminosity, erg Hz⁻¹ s⁻¹

log (Frequency, Hz)

radio  CMB  IR optical  X  γ
**Galaxy luminosities**

based on GALPROP model

Fermi gamma rays and electrons

<table>
<thead>
<tr>
<th>Source</th>
<th>Luminosity (erg s(^{-1}))</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>

\(< 100\) MeV: \(8 \times 10^{38}\)

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
FIR/radio correlation IRAS Galaxies

N = 1809

Yun et al. 2001 ApJ 554, 803
FIR/radio correlation IRAS Galaxies

\[ N = 1809 \]

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

\[ L_{60 \mu m} (L_\odot) \]

Milky Way
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