Galactic diffuse gamma-rays

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GeV gamma-ray sky by EGRET

Compton Gamma-ray Observatory (1991-2000)

Diffuse emission: ~80% of total gamma-ray flux!
Gamma-ray detection

- **Photoelectric effect**
  - Gamma-ray
  - Nucleus
  - Photoelectron

- **Pair creation**
  - Gamma-ray
  - Nucleus
  - Positron
  - Electron

- **Compton scattering**
  - Gamma-ray
  - Scattered electron
  - Recoil electron

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Evans 1955
Gamma-ray detector

EGRET (Energetic Gamma Ray Experiment Telescope)
SAS-2 & COS-B Profile

SAS-2  (Thompson et al. 1976)

COS-B  (Mayer-Hasselwander et al. 1982)
SAS-2 & COS-B Spectrum

Fig. 4. Local differential production spectra for major diffuse production processes and the pulsar component as discussed in the text (left hand scale). The right hand scale and data points are from the COS-B and SAS-2 data in the longitude range around the galactic center and are shown in comparison to the predicted shape of the total spectrum.
EGRET Intensity Map

Galactic center

Cygnus region

Vela pulsar

Geminga

Crab

Galactic latitude

Galactic longitude
Point sources = Observed intensity – Diffuse model

EGRET observed intensity

Diffuse model

Intensity – model

Depends on diffuse model!
Likelihood analysis

Maximize $L$ to get best fit:

The likelihood is the probability of the observed EGRET data for a specific model of high-energy $\gamma$-ray emission. It is the product of the probability for each pixel:

$$L = \prod_{ij} p_{ij},$$  \hspace{1cm} (3)

where

$$p_{ij} = \frac{\theta_{ij} e^{-\theta_{ij}}}{n_{ij}!}$$  \hspace{1cm} (4)

is the Poisson probability of observing $n_{ij}$ counts in pixel $ij$ when the number of counts predicted by the model is $\theta_{ij}$. The logarithm of the likelihood is more conveniently calculated

$$\ln L = \sum_{ij} n_{ij} \ln (\theta_{ij}) - \sum_{ij} \theta_{ij} - \sum \ln (n_{ij}!) .$$  \hspace{1cm} (5)

Because the last term is model independent, it is not useful for estimation or for the likelihood ratio test. Neglecting the last term,

$$\ln L = \sum_{ij} n_{ij} \ln (\theta_{ij}) - \sum_{ij} \theta_{ij} .$$  \hspace{1cm} (6)

Model = $K_1 \times$ (diffuse model) 
+ $K_2 \times$ (isotropic) 
+ $\Sigma_i F_i \times$ (PSF)$_i$

Adjust $K_1$ & $K_2$ and seek for best fit with $F_i$
Diffuse Emission Model

- Three main components:
  - Bremsstrahlung: electron + matter $\rightarrow \gamma + X$
  - Inverse Compton: electron + photons $\rightarrow \gamma + X$
  - Nuclear interaction: proton(nuclei) + matter $\Rightarrow \pi^0 \rightarrow 2\gamma$

Matter = HI + HII + H$_2$
Photon = 2.7K BB + FIR + NIR + Optical + UV
Two approaches

- **GALDIF (Hunter et al.)**

EGRET/GLAST Diffuse Emission Model

- **Inputs to model:**
  - Gamma-ray production processes in the ISM
    - Pion production, Bremsstrahlung, inverse Compton scattering
  - Tracers of the ISM (matter and radiation)
    - Galactic rotation curve $\rightarrow$ 3-D ISM distribution
      - H1 (21 cm), H$_2$ (115 GHz CO), HII (pulsar dispersion), low-energy photon density
  - Physical parameters:
    - N(HI)/W$_{H_2}$ conversion factor, CR spectrum, $e/p$ ratio, interaction cross-sections, Galactic rotation curve, etc.
  - Model assumptions:
    - Assume the CRs are in dynamic balance with ISM
  - There are only two adjustable parameters in this calculation!
    - Molecular mass ratio, $X=N(H_2)/W_{CO}$, CR coupling scale
  - Discrepancies between model and observation are directly interpretable in terms of model inputs and parameters.

- **GALPROP (Strong et al.)**

Mainly for cosmic-ray propagation

Transport Equation

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p)$$ sources (SNR, nuclear reactions...)

- Diffusion $+ \vec{D} \cdot \nabla \psi - \nabla \cdot \vec{D} \psi$
- Convection
- Diffusive reacceleration
  $$\frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \frac{\partial \psi}{\partial p^2} \right]$$
- E-loss
  $$- \frac{\partial}{\partial p} \left[ \frac{\partial \psi}{\partial t} - \frac{1}{3} p \nabla \cdot \vec{v} \psi \right]$$
  convection
- Fragmentation
  $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

$\psi(\vec{r}, p, t)$ – density per total momentum
Galactic Matter Distribution (GALDIF)

- **HI**: 21cm surveys
  Weaver & Williams (1973)
  Maryland-Parkes (1986)
  Leiden-Green Bank (1985)
- **H$_2$**: $N(H_2) = X W_{\text{CO}}$
  CO: Columbia CO survey at 2.6mm (1987)
- **HII**: Taylor & Cordes (1993)
  (pulsar dispersion / interstellar scattering measure)
- **Interstellar radiation field**: 2.7K BB + FIR + NIR + Optical + UV
- **Local Electron spectrum**: Skibo (1993) [$E^{-2.42}$ injection]
- **Local Proton spectrum**: Stecker (1970) [$E^{-2.7}$]
- **Cosmic-ray enhancement factor**: $\rho \propto N(\text{HI})+N(H_2)+N(\text{HII})$
  Gaussian along the Galactic axis (scaling parameter $r_0$

*Only two parameters in this model:*

$X = (1.5\pm0.2) \times 10^{20}$ H-mol cm$^{-2}$(K km s$^{-1}$)$^{-1}$

$r_0 = (2.0\pm0.5)$ kpc
Cosmic-ray Enhancement Factor (GALDIF)

Fig. 9.—(a) The cosmic-ray enhancement factor $c(\rho, l)$ derived by convolving the sum of the H I, H$_2$, and H II surface densities from Fig. 8 with a Gaussian with FWHM equal to the best-fit value of $r_0 = 1.76$ kpc (see § 5). The enhancement factor is normalized to unity at the position of the Sun, indicated by the cross. (b) The azimuthal average of the cosmic-ray enhancement factor for each Galactocentric quadrant indicated in (a). The azimuthally symmetric gamma-ray emissivity, which is proportional to the cosmic-ray enhancement factor, determined by Strong et al. (1988, 150–300 MeV, their case 3, scaled to $R_0 = 8.5$ kpc, and normalized to unity in the 8–10 kpc ring) is indicated by the dotted line.
GALDIF: Longitudinal Profile

100-300 MeV

GALDIF: Latitude Profile

100-300 MeV

Fig. 4.—Average diffuse gamma-ray spectrum of the inner Galaxy region, $300^\circ < l < 60^\circ$, $|b| \leq 10^\circ$ (0.73 sr). The contributions from point sources detected with more than $5\sigma$ significance have been removed. The data are plotted as crosses where the horizontal line indicates the width of the energy interval and the vertical line the $\pm 1\sigma$ statistical error. The intensity and error for the four lowest energy intervals include corrections to the EGRET effective area derived using observations of the Crab pulsar (Thompson et al. 1993b). The best-fit model calculation (see § 5) plus the isotropic diffuse emission is shown as the solid line. The individual components of this calculation, nucleon-nucleon (NN), electron bremsstrahlung (EB), and inverse Compton (IC), are shown as dashed lines. The isotropic diffuse emission (ID, Sreekumar et al. 1997) is shown as a dash-dotted line.
GALDIF: Contribution of each component

Observation by EGRET

○ $|b| \leq 10^\circ$, 38 point sources ($>5\sigma$) removed

◎ 30MeV - 50GeV with excellent statistics (cf. COS B)

◎ General agreement with model predictions in spatial profile

● 40-60% excess against model predictions above 1 GeV

⇒ Possible solutions:
  • Instrumental calibration error?
  • Unresolved sources?
  • Nuclear interaction model?
  • Cosmic-ray spectrum?
Interstellar radiation field (GALPROP)

Interstellar Radiation Field

- Stellar
- Dust
- CMB
Molecular hydrogen $H_2$ is traced using $J=1-0$ transition of $^{12}CO$, concentrated mostly in the plane ($z\sim 70$ pc, $R<10$ kpc)

Atomic hydrogen $H\ I$ has a wider distribution ($z\sim 1$ kpc, $R\sim 30$ kpc)

Ionized hydrogen $H\ II$ - small proportion, but exists even in halo ($z\sim 1$ kpc)
GALPROP: injection spectrum

Particle Injection Spectra and Normalizations

<table>
<thead>
<tr>
<th>Model</th>
<th>ID</th>
<th>Injection Index$^a$</th>
<th>Break Rigidity (GV)</th>
<th>Normalization at 100 GeV$^b$</th>
<th>Injection Index$^a$</th>
<th>Break Rigidity (GV)</th>
<th>Normalization at 32.6 GeV$^b$</th>
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</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>44_500180</td>
<td>1.98/2.42</td>
<td>9</td>
<td>$5.0 \times 10^{-2}$</td>
<td>1.60/2.54</td>
<td>4</td>
<td>$4.86 \times 10^{-3}$</td>
</tr>
<tr>
<td>Hard electron</td>
<td>44_500181</td>
<td>1.98/2.42</td>
<td>9</td>
<td>$5.0 \times 10^{-2}$</td>
<td>1.90</td>
<td>...</td>
<td>$1.23 \times 10^{-2}$</td>
</tr>
<tr>
<td>Optimized</td>
<td>44_500190</td>
<td>1.50/2.42</td>
<td>10</td>
<td>$9.0 \times 10^{-2}$</td>
<td>1.50/2.42</td>
<td>20</td>
<td>$2.39 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Note.—The GALPROP model IDs are given for future reference; the corresponding parameter files contain a complete specification of the models.

$^a$ Below/above the break rigidity.

$^b$ Normalization of the local spectrum (propagated). Values are in units of m$^{-2}$ sr$^{-1}$ s$^{-1}$ GeV$^{-1}$.

Fig. 2.—Proton spectra as calculated in conventional (solid lines) and optimized (dotted lines) models compared with the data (upper curve, LIS; lower curve, modulated to 630 MV). Thin dotted line shows the LIS spectrum best fitted to the data above 20 GeV (Moskalenko et al. 2002). Data: AMS (Alcaraz et al. 2000b), BESS 98 (Sanuki et al. 2000), CAPRICE 94 (Boezio et al. 1999), IMAX 92 (Meun et al. 2000), and LEAP 87 (Seo et al. 1991).

Fig. 3.—Electron spectra for conventional (solid lines), hard electron (dashed lines), and optimized models (dotted lines), compared with the data (upper curve, LIS; lower curve, modulated to 600 MV). Data: AMS (Alcaraz et al. 2000a), CAPRICE 94 (Boezio et al. 2000), HEAT 94-95 (DuVernois et al. 2001), MASS 91 (Grimani et al. 2002), and Sanriku (Kobayashi et al. 1999).
GALPROP: Longitude profile

\(\pi^0\)-decay (dots, red), IC (dashes, green), bremsstrahlung (dash-dot, cyan), EGRB (thin solid, black), total (thick solid, blue)
GALPROP: Latitude profile

$\pi^0$-decay (dots, red), IC (dashes, green), bremsstrahlung (dash-dot, cyan), EGRB (thin solid, black), total (thick solid, blue)
Fig. 13. — $\gamma$-ray spectrum of optimized model with (thick lines) and without (thin lines) primary electrons, to show the contribution of secondary electrons and positrons. $Br_{\text{tot}}$ and $Br_2$ labels denote the total bremsstrahlung and the separate contribution from secondary leptons, correspondingly. Similarly, $IC_{\text{tot}}$, $IC_2$ indicate the total IC and the contribution from secondaries.
Flatter Proton Spectrum?  -1

Mori 1997

Standard:

$E^{-2.7}$

↓

$E^{-2.45}$  ?
Flatter Proton Spectrum?  -2

Völk 2000

Source: $E^{-2}$

Transport effect

**FIGURE 1.** The differential diffuse $\gamma$-ray energy flux vs $\gamma$-ray energy above 4.4 GeV (cf. Berezhko & Völk, 1999). The heavy symbols are the EGRET measurements, and the dash-dot line is the model prediction of Hunter et al. (1987a). The full curve corresponds to our acceleration model with $\gamma_{SCR} = 2$, whereas the dashed curve corresponds to the Leaky Box model. Both theoretical curves incorporate energy-dependent loss from the acceleration region.
Figure 6. Average gamma-ray spectra for the inner Galaxy (−60° < l < 60° and |b| < 20°) for an injection spectrum of (a) $E^{-2.4}$ and (b) $E^{-2.2}$. The individual contributions to the diffuse gamma-ray spectrum are indicated: IC by the broken curve; bremsstrahlung by the dotted curve; synchrotron by the chain curve; $\pi^0$-decay by the double chain curve. The full curve is the sum of all contributions. Data are from various satellite telescopes: blocked data: EGRET [22], horizontally hatched boxes: COS-B [18], vertically hatched boxes: COMPTEL [12], and data points: OSSE [12] (original data from [20]).

Figure 7. Diffuse gamma-ray spectra in the direction $l = 0°$, $b = 0°$. Heavy full curves show the IC spectrum for an $E^{-2.4}$ injection spectrum of electrons; light full curves show the IC spectrum for $E^{-2.2}$. For each injection spectrum, the lowest branch is for a cut-off at 100 TeV, the next higher branch a cut-off at 1 PeV, and the next higher no cut-off in the injection spectrum; each of these curves includes attenuation on the CMBR. The dotted curve shows the IC spectrum for an $E^{-2.2}$ spectrum with no cut-off and no attenuation on the CMBR. The chain curve shows the predicted spectrum for $\pi^0$-decay (including attenuation on the CMBR) calculated by Ingelman and Thunman [63]; the broken curve shows the predicted $\pi^0$-decay spectrum (including attenuation on the CMBR) calculated by Berezinsky et al [62].
Fig. 5.—Gamma-ray intensity in the direction of the inner Galaxy. The data points are taken from Hunter et al. (1997). The error bars include an estimate for the systematic error of 8%, which accounts for the uncertainty in the energy-dependent correction of the spark chamber efficiency (Esposito et al. 1998). The data are compared with bremsstrahlung (“ebr”) and Inverse Compton (“ic”) spectra from our model, on the basis of sources with injection indexes following a normal distribution of mean 2.0 and dispersion 0.2 and the spatial distribution of SNRs in spiral arms. The \( \pi^0 \)-component is a template and not a model.
Energy calibration?

(a) Plot of integral (E > 1 GeV), all-sky diffuse model flux vs. EGRET observed flux for $335^\circ < l < 45^\circ$, $|b|< 90^\circ$. (b) A similar plot with a renormalization factor of $(1.6)^{-1}$ applied to the observed flux.

GeV anomaly exists uniformly over the whole sky and extends from high to low intensity galactic flux emission.

→Most likely traceable to the detector itself!

Fig. 2. Required inverse renormalization factor for different energy bins, given as the ratio of observed-to-predicted flux vs. energy.

Fig. 4 Diffuse gamma rays from the Outer Galaxy. The plotted points are COS-B data (Paul et al. 1978); (Δ): 91° ≤ l ≤ 125°, | b| ≤ 10°; (+): 116° ≤ l ≤ 136°, | b| ≤ 10°. Present data (Tibet) is given by the limit at 10 TeV for 140° ≤ l ≤ 225°. The ground based data are shown by W (Whipple, Reynolds et al. 1993) and HEGRA (Klecker et al. 1995) are data for sky regions apart from the galactic disc. The theoretical curves are assigned by B (Fukazawa et al. 1999) for \( e^+ \rightarrow 2\gamma \) decay, P&P (Porter & Protheroe 1986) for the inverse Compton by electrons with injection spectral indices -8.0 and -8.4, respectively. The curves of P&P are the case of energy at 100 TeV for the shock acceleration.

Fig. 5 Diffuse gamma rays from the inner Galaxy. The plotted points are COS-B data (Paul et al. 1978); (Δ): 16° ≤ l ≤ 36°, | b| ≤ 10°; (+): 31° ≤ l ≤ 36°, | b| ≤ 10°, and EGRET data (Hunter et al. 1997); (●): 300° ≤ l ≤ 60°, | b| ≤ 10°. Present data (Tibet) is given by the upper limit at 10 TeV for 30° ≤ l ≤ 55°, | b| ≤ 5°. In addition to the theoretical curves B and P&P in Fig. 4, I&T (Ingelman & Thunman 1996) for \( e^+ \rightarrow 2\gamma \) decay is shown by a dot-dot-dashed curve.
Ground-based observations

- CASA-MIA (Borione et al. 1998)
  $50^\circ < l < 200^\circ$, $-5^\circ < b < 5^\circ$; 310 TeV
  mu-poor showers $\Rightarrow I_{\gamma}/I_{CR} < 2.4 \times 10^{-5}$

- Tibet (Amenomori et al. 1997)
  $-5^\circ < b < 5^\circ$, 10 TeV, excess counts $\Rightarrow$
  $140^\circ < l < 225^\circ$: $< 2 \times 10^{-10}$ cm$^{-2}$s$^{-1}$sr$^{-1}$
  $20^\circ < l < 55^\circ$: $< 4 \times 10^{-10}$ cm$^{-2}$s$^{-1}$sr$^{-1}$

- EAS-TOP (Aglietta et al. 1996); 1 PeV
  mu-poor showers $\Rightarrow I_{\gamma}/I_{CR} < 7.3 \times 10^{-5}$

- HEGRA (Karle et al. 1995); 80 TeV
  $N_e/\text{Ch cut} \Rightarrow I_{\gamma}/I_{CR} < 7.8 \times 10^{-3}$

- MILAGRO (Abdo et al. 2008); 15 TeV
  $8.6 \sigma$ excess in Cygnus region: $2 \times 10^{-13}$ TeV$^{-1}$cm$^{-2}$s$^{-1}$sr$^{-1}$
Whipple observation

- 4.8° FOV camera, Center: (l,b)=(40,0)
- 1998: 7 on/off pairs (28min. Each), >700GeV
  1999: 10 on/off pairs, >500GeV
- Sensitivity correction across the field
Whipple results

1998: $1.84 \pm 0.57/\text{min}$ (3.2$\sigma$!)
1999: $0.42 \pm 0.43/\text{min}$
HEGRA observations

- 4-telescope setup, total 105hr (1997/98)
- No source candidate above 1/4 Crab
- Artificial Neural Network analysis for gamma/hadron separation in progress

Pühlhofer et al. 1999
Lampeitl et al. 1999

\(E = 2.29 \pm 0.07 \pm 0.02\)
CANGAROO-III results

(a) $\ell = -19^\circ.5$

(b) $\ell = +13^\circ.0$

Figure 8. Measurement of the Galactic diffuse emission > 50 GeV with the Whipple telescope [29] extrapolated to the EGRET energy range on the assumption of single power-law spectral indices of 2.0, 2.2, 2.4, and 2.6. The spectral index must be ≤2.4 to be consistent with the EGRET observations, shown as ±1σ data points. The unpointed balloon results from Nishimura et al. [28] and the JACEE experiment [27], taken at 4 gm/cm² and 5.5 gm/cm², shown as triangles and diamonds, respectively, should be treated as upper limits. The JACEE results corrected for the atmospheric contribution are shown as upper limits.
Fig. 1.— Galactic longitude profile of the $\gamma$-ray emission around 15 TeV in the Galactic plane as measured by Milagro. Top: Before subtraction of source contributions (red data points with dashed error bars) and after subtraction of source contributions (black data points). Bottom: Source-subtracted profile overlaid with prediction of the optimized GALPROP model. The red line represents the pion contribution, the green line represents the IC contribution, and the blue line represents the total flux prediction between Galactic latitude $\pm 2^\circ$. There are no data points in the region of longitude $l \in [-144^\circ, 2^\circ]$, because it is below the Milagro horizon. The region $l \in [111^\circ, 135^\circ]$ is excluded, because the analysis method is insensitive here (see text for details).

### Gamma-Ray Emission from the Galactic Plane around 15 TeV

| Region for $|b| < 2^\circ$ | Statistical Significance $\sigma$ | Milagro$^a$ | Optimized | Conventional |
|--------------------------|-----------------------------------|-------------|-----------|--------------|
| ($l$, deg)               |                                   |             |           |              |
| 30–65                    | 5.1                               | $23.1 \pm 4.5^{+2.6}_{-0.6}$ | 20.0       | 4.9          |
| 65–85                    | 8.6                               | $21.8 \pm 2.5^{+2.2}_{-1.5}$ | 10.2       | 2.7          |
| 85–110                   | 1.3                               | $<7.1$ (95% CL) | 5.8       | 1.3          |
| 136–216                  | 0.8                               | $<5.7$ (95% CL) | 3.1       | 0.9          |

$^a$ The first error represents the statistical, the second, the systematic, uncertainty. See text for details.
Fig. 3.—Source-subtracted Galactic latitude profile of the $\gamma$-ray emission around 15 TeV in the inner Galaxy (left), in the Cygnus region (middle), and in the region above Cygnus (right) as measured by Milagro (points with errors) and predicted by the optimized GALPROP model. The blue curve shows the total $\gamma$-ray flux, the red curve shows the pion contribution, and the green curve shows the IC contribution.
Fig. 2.—Gamma-ray spectra of the diffuse emission as predicted by the optimized GALPROP model for the Galactic plane. Left: Inner Galaxy ($l \in [30^\circ, 65^\circ]$). Right: Cygnus region ($l \in [65^\circ, 85^\circ]$). The red bars represent EGRET data, and the black bar represents the Milagro measurement, where the length of the bar represents the statistical uncertainty only. The dark blue line represents the total diffuse flux predicted by the optimized GALPROP model, the dark gray line represents the extragalactic background, and the light blue line represents the bremsstrahlung component. The two contributions at Milagro energies are shown as the red line, the pion contribution, and the green line, the total IC contribution. The green dashed line shows the dominant IC contribution from scattering of electrons off the cosmic microwave background, which amounts to about 60%–70% of the IC component at Milagro energies. Other IC contributions, which are less important, such as infrared and optical, are not shown separately.
Cherenkov2005 poster

Dark gas contribution!

3EG catalog

“Extended” catalog
Unveiling Extensive Clouds of Dark Gas in the Solar Neighborhood

Fig. 3. Longitude (top) and latitude (bottom) profiles of the observed γ-ray intensity in the Aquila-Ophiuchus-Libra region versus the N(HI) + W(CO) gas model (blue) and the N(HI) + W(CO) + E(B-V) model (red). The dashed and dotted curves (bottom) outline the IC and extragalactic background intensities, respectively. Error bars show mean ± SD.

Fig. 4. Map, in Galactic coordinates centered on l = 70°, of the column densities of dark gas found in the dust halos, as measured from their γ-ray intensity with the reddening map. This gas complements that visible in HI and CO. The two dust tracers [E(B-V) and 94-GHz emission] yield consistent values within 30% over most regions.
Skymap of 3EG and revised catalog

Casandjian & Grenier, I. A.AA 489, 849 (2008)


This work
Superimposed...

Black: 3EG
Red: EGR
Two approaches for cosmic-ray density gradient

- **Ring model**
  - Gas column-densities in 6 rings (boundary 3.5/7.5/9.5/11.5/13.5kpc) + IC intensity map (from GALPROP) + isotropic

\[
N_{\text{pred}}(l, b) = \left[ \sum_{i=\text{rings}} q_{\text{HI},i} N_{\text{HI}}(r_i, l, b) + \sum_{\text{rings}} q_{\text{CO},i} W_{\text{CO}}(r_i, l, b) + q_{\text{dark}} N_{\text{H}_{\text{dark}}}(l, b) + q_{\text{IC}} I_{\text{IC}}(l, b) + I_{\text{iso}} \right] \times \epsilon(l, b) + \sum_{j=\text{sources}} \epsilon(l_j, b_j) f_j \text{PSF}(l_j, b_j)
\]

- **GALPROP model**
  - Strong et al. 2007
  - Optimized CR spectrum to fit the GeV excess

\[
N_{\text{pred}}(l, b) = \left[ q_{\gamma^0} I_{\gamma^0}(l, b) + q_{\text{brem}} I_{\text{brem}}(l, b) + q_{\text{dark}} N_{\text{H}_{\text{dark}}}(l, b) + q_{\text{IC}} I_{\text{IC}}(l, b) + I_{\text{iso}} \right] \times \epsilon(l, b) + \sum_{j=\text{sources}} \epsilon(l_j, b_j) f_j \text{PSF}(l_j, b_j)
\]

Dark gas: associated with cold and anomalous dust at the transition between the atomic and molecular phases (Grenier et al. 2005)
Fig. 1. The top figure is the longitudinal profile of all photon counts observed by EGRET above 100 MeV at all latitudes (black error bars), compared with the diffuse counts predicted by the 3EG model (blue curve) and the Ring model (red curve). The bottom figure is the residual expressed in number of standard deviation, colors are the same as above, we added the Galprop residuals in purple. Counts from bright sources have been added to the diffuse component. For more visibility the plot are presented with a binning of 4°.
Map of the residuals

Fig. 2. Map in Galactic coordinates of the residuals (expressed in $\sigma = \sqrt{N_{\text{pred}}}$ values) between the $E > 100$ MeV photon counts (in 0.5° bin) and the best fit with the Ring model using Equation (1)
Source detection

- 3 maps: >100MeV, 0.3-1GeV, >1GeV
- 0.5°×0.5° bin both in Galactic and equatorial coordinates
- Iterative detection from high \(T_S\) to low \(T_S\), adding detected sources to the background model until no excess (\(\sqrt{T_S} > 3\)) was left

Fig. 3. An example of the iterative source detection with the 2D binned likelihood around Geminga at energies above 100 MeV. 4 consecutive \(T_S\) maps are shown. Sources are detected, then are included in the background for the next step until no significant one is left. The colourbar gives \(T_S\).
Fermi Gamma-ray Space Telescope

Launched in June 2008

<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>
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<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>
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<tr>
<td><strong>Fermi LAT</strong></td>
<td><strong>2008–</strong></td>
<td><strong>3.5°</strong></td>
<td><strong>0.1°</strong></td>
<td><strong>0.02–300</strong></td>
<td><strong>25,000</strong></td>
<td><strong>1 \times 10^6$/yr</strong></td>
</tr>
</tbody>
</table>

- LAT has already 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: first 3 months

NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky

Credit: NASA/DOE/Fermi LAT Collaboration
3EG / EGR / 0FGL sources
No good consistency around the Galactic center...
• Spectra shown for mid-latitude range $\rightarrow$ GeV excess in this region of the sky is **not** confirmed.
• Sources are **not** subtracted but are a minor component.
• LAT errors are dominated by systematic uncertainties and are currently estimated to be $\sim 10\% \rightarrow$ this is **preliminary**.
• EGRET data are prepared as in Strong, et al. 2004 with a 15% systematic error assumed to dominate (Esposito, et al. 1996).
• **EG + instrumental** is assumed to be isotropic and determined from fitting the data at $|b| > 30^\circ$. 
LAT: Galactic “mid-latitude” diffuse

Fermi LAT mid-latitude close up

$0^\circ \leq \theta \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$

PEGRENT

LAT

Model ($\pi^0 + IC + Brem$) + EG + instr

$E_\gamma$ (MeV)

$E_\gamma^2 J_\gamma (E_\gamma)$ (MeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)

PRELIMINARY!
Figure 1 | VHE $\gamma$-ray images of the Galactic Centre region. a, $\gamma$-ray count map; b, the same map after subtraction of the two dominant point sources.

Active accelerators in the last $10^4$ years? Sgr A East (SNR) or Sgr A*?
Calculation of diffuse gamma-rays

- Input parameters:
  - Proton/electron injection spectrum
    - Local interstellar spectrum ↔ Galactic spectrum?
  - Cosmic-ray composition in the Galaxy
  - Interaction cross section for protons/nucleus
  - Matter and radiation distribution in the Galaxy (3D)
  - Gas distribution
  - Atomic abundance
    \[ \text{H:He:CNO:NeMgSiS:Fe} = 1 : 0.096 : 1.38 \times 10^{-3} : 2.11 \times 10^{-4} : 3.25 \times 10^{-5} \]
    following the compilation by Meyer (1985)

Honda et al. 2004
pp→π^0 cross section

Gammas from neutral pion decay pp→π^0

- New parameterization (Kamae+ 2005, 2006) is based on Pythia Monte Carlo event generator and includes diffraction dissociation
- New parameterization shows some improvement over the old formalism employed in GALPROP
- Galprop now has a parameter to choose a formalism

Pion decay γ-ray spectra for different regions on the sky

Moskalenko et al., GLAST symposium, Feb. 2007
Nuclear enhancement factor

\[ e_M = 1 + \sum_i m_{ip} \frac{\phi_i(T)}{\phi_p(T)} + \sum_i m_{i\alpha} \frac{\phi_i(T)}{\phi_p(T)} \times \frac{r}{1-r} = 1.52 \]

### Table 1

Multiplication factor at \( T = 10 \) GeV/nucleon. G&S is quoted from Ref. [9].

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>( m_{ip} )</th>
<th>( m_{i\alpha} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DPMJET-3</td>
<td>G&amp;S</td>
</tr>
<tr>
<td>H (( A = 1 ))</td>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>He (( A = 4 ))</td>
<td>3.68</td>
<td>3.57</td>
</tr>
<tr>
<td>CNO (( A = 14 ))</td>
<td>11.7</td>
<td>11.4 (N)</td>
</tr>
<tr>
<td>Mg–Si (( A = 25 ))</td>
<td>20.3</td>
<td>20 (Al)</td>
</tr>
<tr>
<td>Fe (( A = 56 ))</td>
<td>38.8</td>
<td>40</td>
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</tbody>
</table>
Nuclear enhancement factor

Table 4
Nuclear enhancement factor decomposed to each component at 10 GeV/nucleon.

<table>
<thead>
<tr>
<th>Target</th>
<th>H</th>
<th>He</th>
<th>CNO</th>
<th>NeMgSiS</th>
<th>Fe</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>0.405</td>
<td>0.0177</td>
<td>0.0047</td>
<td>0.0006</td>
<td>1.428</td>
</tr>
<tr>
<td>He</td>
<td>0.203</td>
<td>0.083</td>
<td>0.0036</td>
<td>0.0035</td>
<td>0.0004</td>
<td>0.293</td>
</tr>
<tr>
<td>CNO</td>
<td>0.038</td>
<td>0.015</td>
<td>0.0006</td>
<td>0.0018</td>
<td>0.0002</td>
<td>0.055</td>
</tr>
<tr>
<td>MgSi</td>
<td>0.033</td>
<td>0.013</td>
<td>0.0005</td>
<td>0.0026</td>
<td>0.0003</td>
<td>0.049</td>
</tr>
<tr>
<td>Fe</td>
<td>0.014</td>
<td>0.006</td>
<td>0.0002</td>
<td>0.0021</td>
<td>0.0002</td>
<td>0.022</td>
</tr>
<tr>
<td>Sum</td>
<td>1.288</td>
<td>0.520</td>
<td>0.023</td>
<td>0.0147</td>
<td>0.0017</td>
<td>1.845</td>
</tr>
</tbody>
</table>
Energy dependence

Fig. 2. Energy dependence of nuclear enhancement factor contributions from each ISM component.
Fermi diffuse model

Fermi

EGRET

Wait for details!
Fermi diffuse model

Fermi

EGRET
Summary

- Galactic diffuse gamma-rays are the most abundant class of gamma-rays in the GeV sky, and are the background for point source detection.
- Diffuse gamma-rays above 1 GeV observed by EGRET showed a flatter spectrum than expected.
- Fermi observations (mid-lat. range) can be accounted assuming “normal” cosmic ray spectrum. (But be patient for their results on the plane!)
- Observation of the Galactic Plane in the TeV region is difficult, but there are some indications near the Galactic center and along the plane.
Vela pulsar by Fermi

Spectral mismatch between EGRET and Fermi!