High-Energy Gamma-Rays toward the Galactic Centre

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Diffuse $\gamma$-ray emission produced by cosmic rays interacting with interstellar medium (ISM). Comprises majority of the total $\gamma$-ray flux!
Where to look for gamma-ray signatures of dark matter?

**Galactic Centre:**
good statistics, strong background/foreground + source confusion

**Satellites:**
low background + good source identification, low statistics,

**Spectral lines:**
no astrophysical uncertainties, low statistics

**Galaxy clusters:**
low background, low statistics

**Halo:**
large statistics, diffuse Galactic emission uncertainties

**Extragalactic diffuse:**
large statistics, foreground subtraction + astrophysical source populations
What is Interesting about the GC?

- The region surrounding the GC is complicated containing:
  - Potential signal of particle dark matter
  - Intense emission by cosmic rays interacting with the ISM
  - Many astrophysical sources
- It is the most confused region of the `high-energy' gamma-ray sky
- Numerous groups have analysed the Fermi data and found an `excess' of emission with various explanations being advanced
The Fermi `GeV-excess’

- Not to be confused with the EGRET `GeV-excess’, which was an instrumental issue (see Fermi-LAT collab. PRL 103, 251101 [2009])

- The Fermi GeV-excess is an excess of emission with respect to interstellar emission and point-source models for the region about the GC that are based on knowledge of ISM tracers and cosmic-ray propagation models

- The questions: is this excess explainable by some modelling uncertainty for the components of the existing models, or is a `new’ component definitely required? For the latter, is it in the cosmic ray injector class (accelerators, dark matter), or a collection of weak point sources, or …?

- Conclusive answer of the first question is very difficult
Interpretations

- Dark matter (H&G, Daylan et al.)
- Unresolved sources, e.g., millisecond pulsars (Gordon&Macias, Azerbajian et al.)
- `Normal’ pulsars (O’Leary et al.)
- Other studies have investigated statistically whether the characteristics are consistent with `smooth’ or `point’ (unresolved sources): Lee et al., Bartels et al.
Characterisation of the Emission from 15° x 15° Region About the Galactic Centre


62 Months Data, Front converting CLEAN events > 1 GeV, Pass 7 reprocessed
Disentangling the Many Sources of Gamma-Ray Emission is Challenging ...

The emission toward the inner Galaxy consists of a number of components:
- Outer Galaxy
- Foreground MW
- Region surrounding GC
- Point or small extended sources (over all distances)
- Unresolved sources (over all distances)
- Extragalactic emission
- Isotropic background produced by misclassified cosmic rays (CRs)

Use GALPROP cosmic ray propagation/diffuse emission code

http://galprop.stanford.edu
Cosmic Rays and Interstellar Emission

GALPROP + ISM

X, y

e ±

B synchrotron

diffusion energy losses reacceleration convection etc.

gas

He CNO

P He CNO

CR species:

- Only 1 location modulation

HESS

Chandra

HESS

Fermi

BESS

PAMELA

ACE

helio-modulation

20 GeV/n

The Unraveling of the Sun's Neutron Adventure

Cosmic-Ray Interactions: Neutrino Flashes, Gamma-Ray Bursts, and More

2003+2004 data

HESS SNR RX J1713-3946

42 sigma (2003+2004 data)
Cosmic Ray Source Distributions for Baseline IEMs

Gas distribution in the Milky Way

Molecular hydrogen ($H_2$) traced using CO $J=1\rightarrow0$ transition, concentrated in clouds near Galactic plane ($z_{\text{scale}} \sim 70$ pc)

Atomic hydrogen (HI) \sim smoother and wider distribution out to \sim 30 kpc ($z_{\text{scale}} \sim 0.5$ kpc)

Ionised hydrogen (HII) also contributes with lower density but exists out into halo ($z_{\text{scale}} \sim 1$ 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
- Using rotation curve $V(R)$ and assumption of circular rotation about GC enables a 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
All-sky HI map (Leiden-Argentine-Bonn)
Interstellar Radiation Field

- Detailed modelling required because dust in the ISM is strongly absorbing of starlight
- Need: stellar and dust densities, stellar luminosity model, radiation transfer calculation (typically MC)
- Spectral intensity is strongly dependent on position
Counts

Foreground
Background

Ring extends to "boundary" of Galaxy

-local' ring

Galactocentric ring boundaries.

<table>
<thead>
<tr>
<th>Ring</th>
<th>$R_{\text{min}}$ [kpc]</th>
<th>$R_{\text{max}}$ [kpc]</th>
<th>Longitude (Full)</th>
<th>Longitude (Tangent)</th>
</tr>
</thead>
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<td>1</td>
<td>0.0</td>
<td>1.5</td>
<td>$-10^\circ \leq l \leq 10^\circ$</td>
<td>$10^\circ \leq l \leq 17^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>2.5</td>
<td>$-17^\circ \leq l \leq 17^\circ$</td>
<td>$17^\circ \leq l \leq 24^\circ$</td>
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<tr>
<td>3</td>
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<td>3.5</td>
<td>$-24^\circ \leq l \leq 24^\circ$</td>
<td>$24^\circ \leq l \leq 70^\circ$</td>
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<tr>
<td>4</td>
<td>3.5</td>
<td>8.0</td>
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<td>$70^\circ \leq l \leq 180^\circ$</td>
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<tr>
<td>5</td>
<td>8.0</td>
<td>10.0</td>
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<td>-</td>
</tr>
<tr>
<td>6</td>
<td>10.0</td>
<td>50.0</td>
<td>$-180^\circ \leq l \leq 180^\circ$</td>
<td>-</td>
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</tbody>
</table>
Scaling Procedure Overview

- For each source model generate GALPROP intensity maps separated in Galactocentric rings for $\pi^0$-decay and brem (HI, H$_2$, HIII), and IC $\rightarrow$ brem (all) and $\pi^0$-decay (HII) held constant
- Fit to high latitude data ($|b| > 50^\circ$) to obtain 
  `isotropic' component $\rightarrow$ determines structureless gamma-ray component + background regardless of origin
- Fit the GALPROP ring templates in sky regions where only a single (or couple) of components dominate, e.g., the local gas-related emission and IC are determined using data outside the plane; the in-plane data mainly determines the gas-related emission for all other rings
- Also include a local radio loop template
- Use 3$^{rd}$ Fermi Catalogue (3FGL – 4 years) for point sources in various tuning regions
- Exclude some regions where unmodelled extended components (e.g., Fermi bubbles, Cygnus would bias fit) and (importantly) do not use the 15°x15° region about the GC
Scaled Interstellar Emission Model (IEM) vs. Baseline

- Scaling reduces the under-prediction by the baseline IEM → this is the case for the full energy range that we use (1-100 GeV), even though only the lowest energies are shown above (large green regions are not used for tuning).

- There are 4 IEMs: Pulsars/OBstars intensity tuned, and `index' tuned → the latter variant has additional degrees of freedom for the spectral index of the gas-related interstellar emission inside the solar circle.

- The fractional residuals for each tuned model are very similar, but differ in small details → there is no `best' IEM.
Modelling the 15°x15° RoI

- The emission from the inner RoI is modelled for each IEM
- Point sources candidates are determined using a method employed for the Fermi catalogues to identify seeds and optimise spatial positions
- Each IEM (held constant) + seeds + ring 1 interstellar emission components are fit using max-likelihood
- Procedure iterated (with seed finding) until no significant point-like excesses remain in residuals
- Bremsstrahlung and HII/π0-decay for the inner region are held constant at GALPROP predictions because they are sub-dominant
Components of Model Across $15^\circ \times 15^\circ$ ROI

Fix in $15^\circ \times 15^\circ$ region:
- IC, IEM After tuning
- HI $\pi^0$, IEM After tuning
- $H_2 \pi^0$, IEM After tuning
- Brem+HII $\pi^0$, IEM Predicted

Units: MeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$

PRELIMINARY

Fit in $15^\circ \times 15^\circ$ region:
- IC, Ring I Predicted
- HI $\pi^0$, Ring I Predicted
- $H_2 \pi^0$, Ring I Predicted

IEM refers to foreground/background model

$15^\circ \times 15^\circ$ ROI
E$\geq$1 GeV
~0.23$^\circ$ pixels
Results – Intensity Scaling

- Data-model agreement is ~5-10% averaged over the 15x15 deg region up to ~30 GeV
- The fore/background accounts for most of the emission
Results – Index Scaling

- Agreement better for tuned index IEMs
- For all IEMs the fitted IC for ring 1 is much brighter (7-30x) than predicted – can be due to more intense ISRF or CR $e^\pm$ over the inner region
- Point sources comparable to IC
- HI/H$_2$ $\pi^0$-decay much dimmer than predicted

| Integrated flux in 15\(^\circ\)x15\(^\circ\) ROI, E>1GeV, 10\(^8\) ph cm\(^{-2}\) s\(^{-1}\) |
|-----------------|-----------------|-----------------|-----------------|
| IC, Ring 1 | $\pi^0$, Ring 1 | IC, IEM | $\pi^0$, IEM |
| 41-59 | 1-8 | 24-33 | 151-164 |
Results – Point Sources

We obtain 48 point sources over the RoI with significance $\sim 4\sigma$ or higher (threshold for inclusion in Fermi catalogue) – the 3FGL (4 years, $> 100$ MeV) has approximately 25% more point sources over the same region.

Approximately 60% additional point source candidates that do not satisfy the 4$\sigma$ threshold are also extracted from the region by our analysis → the exact number depends on the IEM.

3 previously unidentified (in $\gamma$-rays) SNRs found in this analysis, but approximately 75% of 1FIG sources without associations.
The unique aspect of this study is that it is the only work that self-consistently derives point sources and interstellar emission. The spatial distribution that we obtain is different to that of the 3FGL. There is a substantial fraction of the 1FIG sources and candidates unassociated and with a good chance being due to mismodelled interstellar emission.
Results – Point Sources

Overlay 1FIG sources, sub-threshold candidates with components of ring 1 interstellar emission

Appears some correlation of sources and candidates with molecular component of ring 1 interstellar emission, but not complete

For the TS < 100 sources there is much larger variability in combined flux over the 4 IEMs used in the study than for larger TS sources
The model with interstellar emission from the fore/background and inner annulus and point sources (1FIG + sub-threshold candidates) accounts for ~99% of the emission.

Some weak residual but requires adoption of a spatial and spectral model and refitting concurrently with the interstellar emission and point sources to determine its flux.
Results – Residual Model Templates

- Test if an additional component centred on GC contributes to data (2D Gaussian, NFW, or gas-like distribution as proxy for unresolved sources)
- The peaked profiles with long tails (NFW, NFW-c) yield the most significant improvements in the data-model agreement but ….
- The resultant model spectrum depends strongly on the fore/background model
Results – Residual Model Template

Without NFW:

1-2 GeV

2-10 GeV

10-100 GeV

Counts in 0.1°x0.1° pixels
0.3° radius gaussian smoothing

With NFW:

1-2 GeV

2-10 GeV

10-100 GeV
Point-source distribution has by-eye correlation with IEM components and residual. Suggests mismodelling of interstellar emission that is still to be understood. Some this can be due to:

- Gas maps not tracing full density distribution (very likely) + artifacts from ring decomposition (likely)
- IC (ISRF – very likely, CRes – likely)
- Other components (additional CR srcs, discrete gamma-ray srcs) + need for 3D modelling
Summary

- The majority of gamma-rays coming from the inner Galaxy are likely described by a combination of the expected emission processes: interstellar emission from cosmic particles and discrete sources.
- There are residuals – positive and negative – across the region remaining even with our current best estimates of these `standard’ emission processes.
- To understand the origin of these we need to invest time in improving how ISM tracers and other components used to construct interstellar emission models are treated.
- This is not an easy task but we have work underway on several fronts that is making progress to address this issue.
- The bottom line is: most likely what is seen in gamma rays toward the inner Galaxy has a prosaic instead of exotic/new physics origin, but to answer this to a high-degree of certainty requires more work.