High-Energy Interstellar Emission

Gulli Johannesson
University of Iceland & NORDITA
gudlaugu@hi.is

XSCRC2017: Cross sections for Cosmic Rays,
March 31, 2017
The Fermi–LAT

General Background Information on High-Energy Interstellar Emission
   The Interstellar Gas
   The Interstellar Radiation Field
   Cosmic Rays

Example Results
   Local Emissivity
   CR Distribution in the Galaxy
   Properties of the ISM

Moving Towards Three Dimensional Modeling

Conclusions
**The Fermi–LAT**

**Fermi–LAT on top of rocket**

**Basic information**

- Pair conversion telescope sensitive to $\gamma$-rays in the energy range from $\sim 30$ MeV to $\gtrsim 1$ TeV.
- $\sim 60^\circ$ field of view and covers the entire sky every $\sim 3$ hours.
- Nearly 1 m$^2$ effective area above 1 GeV.
  - Effective area falls quickly below 1 GeV
- PSF around $0^\circ .1$ above 10 GeV, increasing to $\sim 10^\circ$ at $\sim 30$ MeV.
- International collaboration
  - Nearly 180 (60) institutes in 26 (10) countries
  - 550 (150) members (full)
- For more information please use web search and look at the official web pages.
High-energy interstellar emission arises from interactions between cosmic-rays (CRs) and the interstellar medium (gas and radiation).

- CR nuclei
  - $\pi^0$ decay from interactions with gas
- CR electrons ($e^+$ and $e^-$)
  - Bremsstrahlung from interactions with gas
  - Inverse Compton (IC) from interactions with radiation.

Interstellar emission is typically defined as the result of these processes.
What is high-energy interstellar emission?

Emission processes

- Interstellar emission arises from interactions between cosmic-rays (CRs) and the interstellar medium (gas and radiation).
- CR nuclei
  - $\pi^0$–decay from interactions with gas
- CR electrons ($e^+$ and $e^-$)
  - Bremsstrahlung from interactions with gas
  - Inverse Compton (IC) from interactions with radiation.

Very simple and useful

- Only need to know the distribution of CRs and the interstellar medium along with the interaction processes.
- Can also be used to study one of the three if we can measure the emission and know the other two.
Interstellar Matter

Overview

- Accounts for \( \sim 10\% \) of the mass of the Galactic disk.
- Split into dust and gas phase with a gas-to-dust ratio of \( \sim 100 \).
- The gas phase consist of mostly hydrogen and helium and is split into components depending on temperature and ionization (Ferriere 2001)

### Components by mass

- Gas (99%)
- Dust (1%)
- Metals (1.5%)
- H (70%)
- He (28%)

### Component Table

<table>
<thead>
<tr>
<th>Component</th>
<th>( T ) [K]</th>
<th>( n ) [cm(^3)]</th>
<th>( M ) ( [10^9 \text{M}_\odot] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold molecular</td>
<td>10–20</td>
<td>( 10^2–10^6 )</td>
<td>( 1.3 – 2.5 )</td>
</tr>
<tr>
<td>Cold atomic</td>
<td>50–100</td>
<td>20–50</td>
<td></td>
</tr>
<tr>
<td>Warm atomic</td>
<td>6000–10000</td>
<td>( 0.2–0.5 )</td>
<td>( {6.0 )</td>
</tr>
<tr>
<td>Warm ionized</td>
<td>( \sim 8000 )</td>
<td>( 0.2–0.5 )</td>
<td>( 1.6 )</td>
</tr>
<tr>
<td>Hot ionized</td>
<td>( \sim 10^6 )</td>
<td>( \sim 0.006 )</td>
<td></td>
</tr>
</tbody>
</table>
Hydrogen observed in three phases:
- **Atomic (H\textsubscript{I}):** The most massive phase with a large filling factor. Scale height approximately 200 pc.
- **Molecular (H\textsubscript{2}):** The densest phase, very clumpy. Scale height approximately 100 pc.
- **Ionized (H\textsubscript{II}):** The least significant component with a large scale height. Scale height approximately 1 kpc.

Helium assumed to have the same distribution as hydrogen.

Rest of the interstellar medium is not interesting as targets for CRs, but it can provide important information on the distribution of Hydrogen.

21 cm line

- Hyperfine splitting of the lowest energy state because of interactions between the magnetic moment of the proton and electron.
  - Emits radiation at 21 cm that can be used to estimate its column density.
- Not optically thin along the plane so we need to correct for optical depth
  - Usually done using the approximation of a homogeneous line of sight

\[
N_{\text{H}_1}(v) = -\log \left( 1 - \frac{T(v)}{T_S(v) - T_{\text{bg}}} \right) T_S(v)C
\]

where \( v \) is the observed Doppler velocity, \( T_S(v) \) is the spin temperature, \( T(v) \) is the brightness of the emission expressed as temperature, \( T_{bg} \approx 2.7 \) K, and \( C \) is a constant.
- Need to know \( T_S(v) \) for all lines of sight but usually assume a single value for the entire sky.
21 cm line

- Hyperfine splitting of the lowest energy state because of interactions between the magnetic moment of the proton and electron.
  - Emits radiation at 21 cm that can be used to estimate its column density.
- Not optically thin along the plane so we need to correct for optical depth
  - Usually done using the approximation of a homogeneous line of sight

\[
N_{\text{H}_1}(\nu) = -\log \left( 1 - \frac{T(\nu)}{T_S(\nu) - T_{bg}} \right) T_S(\nu)C
\]

where \( \nu \) is the observed Doppler velocity, \( T_S(\nu) \) is the spin temperature, \( T(\nu) \) is the brightness of the emission expressed as temperature, \( T_{bg} \approx 2.7 \text{ K} \), and \( C \) is a constant.

- Need to know \( T_S(\nu) \) for all lines of sight but usually assume a single value for the entire sky.

This is the “easy” component!

- Works very well at high latitudes where optical depth is small.
- Significant issues in the plane where optical depth is larger, especially the inner Galaxy.
Molecular Hydrogen

**CO line**

- No line emission from cold H\(_2\) – Need to use a surrogate tracer.
  - The most common tracer is the CO molecule that forms under similar conditions as H\(_2\).
  - The CO line emission is collisionally excited by H\(_2\).
  - The column density of H\(_2\) is found observationally to be roughly linearly dependent on the integrated line intensity of the \(^{12}\)CO \(J = 1 - 0\) line emission \(N_{H_2}(v) = X_{CO} W_{CO}(v)\).
  - \(X_{CO}\) has been shown to vary throughout the Galaxy and even in the local (\(< 1 \) kpc) medium.

- CO is not a perfect tracer of H\(_2\)
  - The \(^{12}\)CO \(J = 1 - 0\) line is optically thick
  - The line width of the emission from a molecular cloud is correlated with its size and hence the mass.
  - This has to do with interstellar turbulence (Bolatto, Wolfire & Leroy, 2013, ARA&A 51).
  - There can be large variations in \(X_{CO}\) if velocity dispersion is large (e.g. tidal disruption near the GC).
  - C depletion into CO depends on density on the periphery of clouds because of photo dissociation.
  - Need other tracers such as dust emission to get a complete picture.
Molecular Hydrogen

CO line

- No line emission from cold H\(_2\) – Need to use a surrogate tracer.
  - The most common tracer is the CO molecule that forms under similar conditions as H\(_2\).
  - The CO line emission is collisionally excited by H\(_2\).
  - The column density of H\(_2\) is found observationally to be roughly linearly dependent on the integrated line intensity of the \(^{12}\text{CO} \ J = 1 \rightarrow 0\) line emission \(N_{\text{H}_2}(\nu) = X_{\text{CO}} W_{\text{CO}}(\nu)\).
  - \(X_{\text{CO}}\) has been shown to vary throughout the Galaxy and even in the local (\(<\sim 1\text{ kpc}\)) medium.

CO is not a perfect tracer of H\(_2\)

- The \(^{12}\text{CO} \ J = 1 \rightarrow 0\) line is optically thick
  - The line width of the emission from a molecular cloud is correlated with its size and hence the mass.
  - This has to do with interstellar turbulence (Bolatto, Wolfire & Leroy, 2013, ARA&A 51).
  - There can be large variations in \(X_{\text{CO}}\) if velocity dispersion is large (e.g. tidal disruption near the GC).
- C depletion into CO depends on density on the periphery of clouds because of photo dissociation.
  - Need other tracers such as dust emission to get a complete picture.
Dust emission

- Defined as gas not traced by HI and CO emission line surveys
  - Was revealed for the first time using $\gamma$-rays and dust in analysis of EGRET data (Grenier et al. 2005, Science 307).
  - Has since then been confirmed in many analysis combining Fermi–LAT data and dust emission.
- This gas is likely low density $H_2$ that is not traced properly by CO emission because of photo dissociation.
- Interstellar dust is mixed with interstellar gas and their column density is roughly linearly related.
  - Can be used as an alternative tracer of interstellar gas to probe the dark neutral medium.

Dust comes with its own set of issues

- No distance information in dust emission, need absorption measures for distance estimates.
- Dust emission is strongly temperature dependent that can be difficult to correct for near star-forming regions.
- The dust to gas ratio is not constant throughout the Galaxy and the column density of dust is not linearly related to that of gas.
The Dark Neutral Medium

Dust emission

- Defined as gas not traced by HI and CO emission line surveys
  - Was revealed for the first time using γ-rays and dust in analysis of EGRET data (Grenier et al. 2005, Science 307).
  - Has since then been confirmed in many analysis combining Fermi–LAT data and dust emission.
- This gas is likely low density H₂ that is not traced properly by CO emission because of photo dissociation.
- Interstellar dust is mixed with interstellar gas and their column density is roughly linearly related.
  - Can be used as an alternative tracer of interstellar gas to probe the dark neutral medium.

Dust comes with its own set of issues

- No distance information in dust emission, need absorption measures for distance estimates.
- Dust emission is strongly temperature dependent that can be difficult to correct for near star-forming regions.
- The dust to gas ratio is not constant throughout the Galaxy and the column density of dust is not linearly related to that of gas.
Comparison To Gas

HI4PI + Dame CO using $X_{CO} = 2 \cdot 10^{20} \text{ cm}^{-2} \text{ (K km/s)}^{-1}$
By subtracting gas from dust in a linear fit we get an estimate of the distribution of the dark neutral medium.
**Velocity model**

- Doppler shift of emission lines used to place gas given a model for its velocity field in the Galaxy.
- Cylindrical rotation is a good approximation for the gas motion.

\[ V_{\text{LSR}} = \sin l \cos b \left[ \frac{R_\odot}{R} \Theta(R) - \Theta(R_\odot) \right] \]
Kinematic Distances and Rotation Curves

**Velocity model**

- Doppler shift of emission lines used to place gas given a model for its velocity field in the Galaxy.
- Cylindrical rotation is a good approximation for the gas motion.

\[ V_{LSR} = \sin l \cos b \left[ \frac{R_{\odot}}{R} \Theta(R) - \Theta(R_{\odot}) \right] \]

**Some known issues**

- Near–far ambiguity in the inner Galaxy.
- Does not work for directions near dotted line.
- Limited distance resolution because of thermal and turbulent motion.
- Non–circular motion.
- Difficult to measure rotation curve, especially in the outer Galaxy.
**Method**

- Using the rotation curve of Clemens 1985 the LAB HI survey (Kalberla 2005) can be turned into annular maps.
- The egg shape is from our constraint that the gas height above the plane be less than 1 kpc.
- Interpolation used in regions near the Galactic center and anti-center.
- The width of the annuli in the inner Galaxy is between 500 and 1000 pc (1–12) while those in the outer Galaxy are wider (14–17).
The Interstellar Radiation Field (ISRF)

Stars and dust

- Three main components:
  - Stellar light.
  - Dust re-emission of stellar light.
  - The cosmic microwave background.

- Only directly observable from our position ⇒ Need modeling codes to predict its distribution.
  - Stellar distribution and properties.
  - Dust distribution and properties.
  - Radiative transport.

- Inverse Compton (IC) cross section is angle dependent so we need angular dependent SEDs throughout the Galaxy.
  - A skymap of SEDs at each grid point.

- Current models are axisymmetric but three dimensional models are in the pipeline.
- Significant freedom in model properties, especially in the inner Galaxy.

CR Distribution

Trivia

- Only directly observable from our position.
- No directional information in observations.
- Source properties and propagation badly constrained.

Example CR source distributions


http://www.wolaver.org/Space/milky_way_illustration.htm
### Trivia
- Only directly observable from our position.
- No directional information in observations.
- Source properties and propagation badly constrained.

### Template method
- Uses templates for the target properties and determines the CR distribution from a fit to $\gamma$-ray data.
- Does not depend on source properties and propagation.
- Fast method, no need to solve complex propagation equations.
- Generally gives a better representation of data.

### Propagation method
- Assumes CR source properties and propagation parameters to determine the CR distribution solving the propagation equation.
- Not biased by unmodeled components.
- Smoothly varying CR distribution.
- Self-consistent IC emission.
CR Distribution

Fermi–LAT is crucial for CR physics

▶ γ-rays are the best way we have to probe the distribution of CRs in the Galaxy and learn about their origin and propagation.

▶ Fermi–LAT data have been invaluable in learning about CR properties in:

Local region:
▶ Ackermann, M. et al. 2011, Science, 334
▶ Ade P. A. R et al. 2015, A&A, 582

Outer Galaxy:

Inner Galaxy:

Galactic halo:

External galaxies:
The local CRs

- Emission with \( |b| > 10^\circ \) is contained mostly within \( \sim 1 \) kpc because of small gas scale height.
- Template modeling using gas, IC, point sources, isotropic, Loop I, Fermi–bubbles, earth limb and more.
### Results from Casandjian 2015, ApJ, 806

- **Conclusions**
  - Measurement are very precise and have the potential to help constrain models for $\gamma$-ray production and heliospheric modulation.
  - Good agreement between local CR observations and local emissivity.

- **Caveats**
  - Considerable modeling is required to extract the emissivity, estimated modeling systematics is included in error bars.
  - Component separation becomes more difficult at lowest energies because statistics decrease and PSF increases.
Measuring CR density distribution

- Similar likelihood template fit can be used in the outer Galaxy.
- More CR measured than predicted by standard CR propagation models with isotropic and homogeneous diffusion and CR sources concentrated in the inner Galaxy.

CRs in the outer Galaxy (collection of results from a few papers)
Towards the Inner Galaxy

Some issues

- Already mentioned near–far ambiguity.
- Optical depth correction in HI more important.
- Line of sight includes both inner and outer Galaxy.
- IC emission more important and also more uncertain.
- Density of other γ-ray emitters increases and their separation becomes more difficult.
- Larger flux from unresolved point sources both because they are more numerous and the sensitivity depends on background.

**Notable results**

- More CRs in the inner Galaxy than outer Galaxy.
- Hardening of CRs towards the inner Galaxy.

**Caveats**

- Error bars are statistical only. Very little attempt to study systematics as the goal was to create a model for point source analysis.
- Gas placement and column density estimates impose considerable uncertainty on the radial profile.
**Analysis method**

- Focus of the analysis to study the excess observed in the direction of the Galactic center in the *Fermi*-LAT data.

- Created fore-/background models using GALPROP models as baseline
  
  - Two source distributions studied, one based on OB-stars and the other on pulsars.

- Models adjusted by scaling the intensity of different annuli in a maximum likelihood fit.

- Worked from outside in, first fitting and fixing the outer Galaxy rings in regions where they dominate
  
  - Spectral adjustment allowed in the inner Galaxy as well.

**Caveats**

- Analysis not focused on finding CR distribution in inner Galaxy.

- Minimal freedom allowed in the tuning of the model, results should be taken as indicative for distribution of CR flux.
  
  - This was by design

Table 5
Scaling Coefficients with Respect to the Baseline IEM

<table>
<thead>
<tr>
<th>Model</th>
<th>Process</th>
<th>Annulus 2</th>
<th>Annulus 3</th>
<th>Annulus 4</th>
<th>Annulus 5</th>
<th>Annulus 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intensity-scaled</td>
<td>IC</td>
<td>1.3</td>
<td>1.3</td>
<td>1.6</td>
<td>1.49</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>$\pi^0$-decay H$_1$</td>
<td>1</td>
<td>1</td>
<td>1.62</td>
<td>1.21</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>1</td>
<td>1</td>
<td>1.42</td>
<td>1.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Pulsars</td>
<td>index-scaled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IC</td>
<td>1.71</td>
<td>1.71</td>
<td>1.6</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>$\pi^0$-decay H$_1$</td>
<td>(0.5, 0.29, 0.14)</td>
<td>(0.5, 0.29, 0.14)</td>
<td>(0.32, 0.29, 0.14)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>(0.22, 0.30, 0.30)</td>
<td>(0.22, 0.30, 0.30)</td>
<td>(0.37, 0.30, 0.30)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>OBstars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intensity-scaled</td>
<td>IC</td>
<td>4.15</td>
<td>4.15</td>
<td>1.48</td>
<td>1.13</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$\pi^0$-decay H$_1$</td>
<td>3.7</td>
<td>3.7</td>
<td>1.2</td>
<td>1.19</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>1.2</td>
<td>0.8</td>
<td>1.3</td>
<td>1.37</td>
<td>0.69</td>
</tr>
<tr>
<td>OBstars</td>
<td>index-scaled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IC</td>
<td>2.21</td>
<td>2.21</td>
<td>1.48</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>$\pi^0$-decay H$_1$</td>
<td>(1, 0.17, 0.17)</td>
<td>(1, 0.4, 0.4)</td>
<td>(0.67, 0.17, 0.17)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>1</td>
<td>1</td>
<td>(0.17, 0.41, 0.06)</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Main results

- Increased flux in outer Galaxy, hardening in inner Galaxy.
- IC brighter in the inner Galaxy than predicted by GALPROP.
Radial Distribution of $X_{CO}$

Collection of results from *Fermi–LAT*

**Explanation**

- Using HI to find the CR flux one can estimate the $X_{CO}$–factor from $\gamma$ rays.
  - Assumes uniform penetration and no variations in CR flux.
  - Other $H_2$ column density estimators suffer from other more severe assumptions.
- Black points in same radial range come from analysis in different regions of the sky.
  - Clearly not just a simple radial dependence.
### Model Grid

- Four CR source distributions from the literature
  - All based on massive star origin
- Different CR confinement volumes (halos)
  - Vertical: 4, 6, 8, and 10 kpc.
  - Radial: 20 and 30 kpc.
- Two values for spin temperature $T_S$.
- Two values for high extinction cut on dust correction map.
- Compared to 21 months of *Fermi*-LAT data fitting $X_{CO}$ and ISRF scaling.
- Iterate $X_{CO}$ values back to propagation parameter determination.
- Used as a basis to estimate uncertainties on source parameters in most recent *Fermi*-LAT analysis.

**Main point**

- Propagation parameters determined from a fit to CR data (B/C from HEAO3)
- \(X_{CO}\) feedback from \(\gamma\)-ray fit very important, propagation parameters depend on the details of the ISM and CR source distribution.
The Galaxy is not a simple uniform disk

The spiral structure

- This is with a constant radial profile.

A simple spiral model

- Create a 3D model with spiral arms but keep radial distribution identical.
- Use spiral arm distribution from NE2001.
- Test the effect of modifying CRs and the interstellar GAS.

Attention

- This is for illustration only and should not be considered a good model of the ISM.
- Shows that getting the ISM correct is important for correct interpretation of the high precision data from AMS.
Effect on B/C

Spectral and spatial variations (Johannesson et al. ICRC 2013)

- Primary nuclei tuned to observations at 8.5 kpc
- Only minor (~5%) changes in spectra at low energies
- Secondary nuclei affected strongly by gas model at all energies
- Depends on the local structure of gas

Some implications

- Secondary production no longer uniform within the disk.
- Easy to imagine more complex models.
  - Diffusion unlikely to be uniform and B/C may not probe the same propagation as $\bar{p}$
Electromagnetic signal is the key to solving this problem.

Probing CR flux with the IEM

- γ-rays can travel nearly unhindered through the entire Galaxy.
  - They are the best probe we have for the distribution of CR flux in the Galaxy.
- Requires careful modeling of the distribution of targets and other γ-ray emitters.
- Synchrotron radiation can also help in constraining the CR electrons.
Spiral arms and a bar

- Adding spiral arm structure and a bar to the ISRF model can significantly improve the agreement with observations.
  - Should not come as a surprise because we know our Galaxy is a spiral arm galaxy and more degrees of freedom usually improve the fit quality.
- This does not come for free, the increase size in the parameter space makes it more difficult to find the best model.
- The resulting ISRF model also takes an order of magnitude more space than the equivalent axisymmetric model.
- The 3D ISRF model is preliminary, we are still scanning the parameter space for a better model.
  - The 2D model showed here is not the “Standard” model distributed with GALPROP but rather the axisymmetric version of the 3D model.
Three Dimensional ISRF and IC emission

IC with 2D ISRF at 200 MeV
IC with 3D ISRF at 200 MeV
Three Dimensional ISRF and IC emission

Difference between 3D ISRF and 2D ISRF at 200 MeV (3D - 2D)
Three Dimensional ISRF and IC emission

Comparison with extra emission component from P7REP IEM

- When creating the P7REP IEM we included a filtered residual component in the model to account for structures in the model that did not have a proper template (Casandjian et al. arXiv:1502.07210).
- The differences between the 2D and 3D model are of the same order of magnitude as the extra emission template
  - Some of the structures might be related to 3D structures in the ISRF
  - The sign is incorrect, but fitting other components in a template method may create the positive structure in the residual component. This has not yet been tested.
Three Dimensional CRs

- We can also try to put some of the CR sources into a spiral arm structure.
- Following figures from a toy model containing spiral arms with density three times higher than that of the disk.
  - These have not been tuned to $\gamma$-ray data; They are for illustration only
  - The models shown below have either a 2D or 3D ISRF as indicated.
We can also try to put some of the CR sources into a spiral arm structure. Following figures from a toy model containing spiral arms with density three times higher than that of the disk.

- These have not been tuned to $\gamma$-ray data; They are for illustration only
- The models shown below have either a 2D or 3D ISRF as indicated.
Modeling the interstellar emission is a non-trivial task.
  • Many components, all of which have uncertainties to various degrees.
  • Important to simultaneously determine the emission from all known components in the sky if one performs a maximum likelihood fit.

Electromagnetic radiation can help considerably in determining the properties of CR sources and propagation.
  • We need accurate $\gamma$-ray production cross sections but they are not the most limiting factor.

New and interesting modeling capabilities required to explain the high quality data the Fermi–LAT has been accumulating over the years.
  • Getting the propagation and source properties correct can help better understand and utilize local observations of CRs.