Galactic CRs: Lessons from diffuse gamma-ray observations

Carmelo Evoli (Gran Sasso Science Institute)

TeVPA - Geneva - 15th of September 2016
Milky Way stars

William Herschel in 1785

GAIA mission yesterday
Milky Way stars

William Herschel in 1785  GAIA mission yesterday

constant luminosity was by far a bad assumption!
Cosmic-ray flux

- Almost a perfect power-law over 12 energy decades.
- Observed at energy higher than terrestrial laboratories!
- Direct measurements versus air-cascade reconstructions.
- Anti-matter component.
- Transition from galactic to extra-galactic?
- Energy density in equipartition with starlight, turbulent gas motions and magnetic fields.

\[ L_{CR} = \frac{\omega_{CR} V_{conf}}{\tau_{esc}} \sim 5 \times 10^{40} \text{ erg/s} \]
The SuperNova paradigm

\[ p p_{\text{ISM}} \rightarrow \pi^0 \rightarrow \gamma\gamma \]

\[ L_{\text{SN}} \sim R_{\text{SN}} E_{\text{kin}} \sim 3 \times 10^{41} \text{ erg/s} \]
The SuperNova paradigm

$$p p_{\text{ISM}} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

Do SNRs accelerate ENOUGH protons?

Do they accelerate protons up to the knee?
Cosmic-ray composition

\[ c\tau_{\text{esc}} = \frac{X(E)}{n_{\text{ISM}} \mu} \sim 10^3 \text{ kpc} \]
Cosmic-ray composition

\[ c \tau_{\text{esc}} = \frac{X(E)}{\bar{n}_{\text{ISM}} \mu} \sim 10^3 \text{ kpc} \]
Cosmic-ray composition

\[ cT_{\text{esc}} = \frac{X(E)}{\bar{n}_{\text{ISM}} \mu} \sim 10^3 \text{ kpc} \]
Cosmic-ray composition

\[
ct_{\text{esc}} = \frac{X(E)}{\overline{n}_{\text{ISM}} \mu} \sim 10^3 \text{ kpc} \quad \gg \text{Galaxy size!}
\]
Fitting local observables

\[
D(E) = D_0 \left( \frac{E}{E_0} \right) ^ \delta
\]

\[
\frac{D_0}{H} \sim 0.75 \, \frac{10^{28} \text{ cm}^2 / \text{s}}{\text{kpc}}
\]

\[
\delta \sim 0.42
\]
~ 70% of all observed photons coming from the diffuse Galactic emission

The extremely accurate gamma ray maps that FERMI is providing are useful to trace the CR distribution throughout all the Galaxy!
Most of the GP $\gamma$ emission is the decay of $\pi^0$ produced in CR/gas collisions.

\[ \int_{\text{los}} dl \ n_p(r) \times \]

\[ + \ n_p(r) \times X_{\text{CO}}(r) \times \]

more details and results in Luigi Tibaldo’s talk.

for a review see I.Grenier, J.Black and A.Strong, ARA&A 2015
Template analysis for the GDE

\[ \Phi_\gamma = \sum_{i} g_{HI}^i N_{HI}(r_i) + \sum_{i} g_{CO}^i W_{CO}(r_i) + \sum_{i} g_{IC}^i I_{IC}(r_i) + I_{iso} \]

from radio observations

\[ \Phi_\gamma \sim \sum_{i} n_p(r_i) N_{HI}(r_i) + \sum_{i} n_p(r_i) X_{CO}(r_i) W_{CO}(r_i) \]

from a propagation model

free parameters

Galactocentric HI rings

FERMI galactic diffuse emission

full sky, without the GP

inner GP

FERMI reference model for the galactic emission

What do we learn about galactic CR?

- standard CR propagation/interaction models adequate for local measurements
- diffuse emissions are reproduced at the expenses of consistent physics (i.e., normalisations “here & then”)  
- FERMI DGE became “a point-source analysis model”!

see Olaf Reimer’s talk at TeVPA2015
Model independent template analysis

\[ \Phi_\gamma = \sum_i g_{\text{HI}}^i N_{\text{HI}}(r_i) + \sum_i g_{\text{CO}}^i W_{\text{CO}}(r_i) + \sum_i g_{\text{IC}}^i I_{\text{IC}}(r_i) + I_{\text{iso}} \]

\[ \Phi_\gamma \sim \sum_i n_p(r_i) N_{\text{HI}}(r_i) + \sum_i n_p(r_i) X_{\text{CO}}(r_i) W_{\text{CO}}(r_i) \]

free parameters

free parameters

Galactocentric HI rings
The radial distribution of the diffuse $\gamma$-ray emissivity in the GP

R. Yang, F. Aharonian, CE, PRD, 2016

$|b| < 5^\circ$

$\eta_p(r) \propto \text{emissivity per H atom (>1GeV/yr)}$ (ph sr$^{-1}$ s$^{-1}$)

Distance to GC (kpc)

\begin{itemize}
\item Templates based:
\begin{itemize}
\item on CO galactic survey of with the CfA 1.2m millimetre-wave Telescope
\item the Leiden/Argentine/Bonn (LAB) Survey on HI gas
\item dust opacity maps from PLANCK for “dark gas”
\end{itemize}
\end{itemize}

Main result: Both the absolute emissivity and the energy spectra of $\gamma$-rays derived in the interval 0.2-100 GeV show significant variations along the galactic plane. 
Comparison with local proton spectrum

R. Yang, F. Aharonian, CE, PRD, 2016

![Graph showing comparison of proton spectra with different radial regions of the Galaxy.](image)
Fermi galactic interstellar emission model (GEIM)

Fig. 8.— Radial distributions across the Galaxy of (a) the \( E^2 \sigma \), emissivity at 2 GeV, per H atom, measured at 2 GeV; (b) the proton flux integrated above 10 GV, with the prediction from the GALPROP model \( S_Y \); (c) the proton spectral index, \( P_{2,\nu} \), with statistical error bars and the prediction for proton rigidities above 1 TV from the same GALPROP model (solid line) and from Gaggero et al. (2015) (dashed line). In all plots, the horizontal bars span the radial widths of the gas annuli used for the measurements. The two data points with smallest Galactocentric radii have large systematic uncertainties (see text). Panel (d) shows the proton flux integrated above 10 GV, normalized to its value at the Sun Galactocentric radius, with the star formation rate traced by supernova remnants, H\( \text{II} \) regions, and pulsars (Stahler & Palla, 2005).

Gaggero et al. (2015)
displacement transport equation:

\[
\begin{align*}
\partial_t N &= 0 \\
&= \nabla \cdot (D \vec{x} \nabla N) - \nabla \cdot (\vec{v}_w N) - \partial_p \left[ p^2 D_p \partial_p \left( \frac{N}{p^2} \right) \right]
\end{align*}
\]

in OneZoneModels these 3 operators are constant in space!
In tension with the SN paradigm?

see Daniele Gaggero’s talk

\[ \delta(r) = A + B \cdot \left( \frac{r}{r_{\odot}} \right) \]
looking for alternative scenarios: sources or propagation?

a single source at the GC active \( \sim 10 \) Myr ago

non-linear effects during propagation
hints of anisotropic diffusion?

\[ \delta_\parallel = 0.33 \text{ and } \delta_\perp = 0.5 \]

\[ \begin{align*}
D_r & \quad \text{diffusion coeff. [cm}^2\text{s}^{-1}] \\
D_z & \quad \text{right panel: } D = 1 \text{ GeV}
\end{align*} \]

\[ \begin{align*}
p = 1 \text{ TeV} \\
\text{profiles of the diffusion coefficients along } r \text{ and } z
\end{align*} \]

\[ \begin{align*}
&\text{left panel: } D = 0.33 \text{ and } D = 0.5 \\
&\text{right panel: } \text{profiles of the normalization coefficients } N \text{ a.u.}
\end{align*} \]

\[ \begin{align*}
&\text{different radial distances from the Galactic Centre.} \\
&\text{An out-of-plane component, directed along the } z \text{-axis is given by the }
\end{align*} \]

\[ \begin{align*}
&\text{GMF has no radial component, while the diffusion along the } z \text{-axis is given by the }
\end{align*} \]

\[ \begin{align*}
&\text{Different components: } \text{a purely azimuthal component, lying on the Galactic disk.}
\end{align*} \]
CRs in the halo

from the gamma-ray emission in high- and intermediate-velocity molecular clouds

CRs at ~GeV originate in the Galactic disk: proved!

but: what is the physical meaning of the halo?
conclusions

- assuming constant properties can be dangerous if one aims at understanding how stars or CRs are distributed in our Galaxy.
- recent model-independent analysis of the gamma-ray emissivity profiles provide strong evidence for inhomogeneous and/or anisotropic diffusion in the different galactic environments.
- propagation models are challenged to reproduce these new exciting results and confirm/rule out the SN paradigm.