Study of the Cosmic Rays and Interstellar Medium in Local HI Clouds using Fermi-LAT Gamma-Ray Observations

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On behalf of the Fermi-LAT collaboration
フェルミ衛星LAT検出器による近傍原子雲領域の星間ガス・宇宙線の研究

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Motivation: Dark Gas

- Significant amount of ISM gas not well traced by standard 21 cm and 2.6 mm lines (Grenier+05)

  Chamaeleon Molecular Cloud:
  \[ M_{\text{H}_2,\text{CO}} \sim 5 \times 10^3 \, M_{\text{solar}} \]
  \[ M_{\text{DG}} \sim 2 \times 10^4 \, M_{\text{solar}} \]

- This “dark gas” (DG) usually traced by dust, but the procedure not established

- Also affect the study of cosmic rays (CRs) because
  \[ I_\gamma \propto N_H U_{\text{CR}} \]
Objectives of the Study

- Accurate estimate of the ISM gas densities is crucial to understand the ISM and Galactic CRs
- Procedure to trace the “dark gas” (gas not properly traced by HI and CO line surveys (Grenier+05)) not established yet => detailed study of nearby clouds

$N_{\text{HI}}^{\text{thin}}$ in $10^{20}$ cm$^{-2}$ and the Region of interest (ROI)

Fermi Data
($>$100 MeV, P8R2_CLEAN_V6)
Fitting Procedure

- Uniform CR density (assumption testable by energy dependence) -> the $\gamma$-ray intensity can be modeled as a linear combination of templates

$$I_{\gamma}(l, b, E) = q_{\gamma}(E) \cdot N_{H}(l, b) + I_{IC}(l, b, E) + I_{iso}(E) + \sum I_{source}(l, b, E) + \cdots$$

$q_{\gamma}(E)$ tells us CR density/spectrum

$$N_{H} = \sum a_i \cdot N(H_i)$$

(e.g., $N(H_I) + 2X_{CO} \cdot W_{CO} + X_{DG} \cdot N(H_{DG})$)

Fit quality tells us which tracer is better

Coefficients ($a_i$) tell us gas properties

We employ “P305” data to reduce residual background toward Ecliptic/Equator while keeping high photon statistics (public data w/ stringent cut also OK)
$W_{\text{HI}}$-Dust Relation (North)

- Correlation btw. $W_{\text{HI}}$ and dust emission $D_{\text{em}}$ ($R$ or $\tau_{353}$)
- Dust temperature ($T_d$) dependence is seen in $W_{\text{HI}}$-$\tau_{353}$ correlation
- Linear curves that follow trends in high $T_d$ area are used to construct $N_H$ model maps assuming $N_H \propto D_{\text{em}}$

$$N_H(\text{cm}^{-2}) = 1.82 \times 10^{18} \times (21.1 \times 10^8 \, R \text{ or } 87.2 \times 10^6 \, \tau_{353})$$
We prepared $N_H$ model maps ($\propto W_{HI}$ or $D_{em}$) and used them in a fit of $\gamma$-ray data -> $R$ gives the best fit.

$N_H$ in $10^{20}$ cm$^{-2}$

$\tau_{353}$

$\Delta \log L = 0$ (ref)

$\Delta \log L = 146.8$

$\Delta \log L = -420.2$
**\(W_{HI}-\text{Dust Relation (South)}\)**

- Correlation between \(W_{HI}\) and \(D_{em}\) (R or \(\tau_{353}\))
- Weak \(T_d\) dependence, non-linear \(W_{HI}-D_{em}\) relations (\(N_H/D_{em}\) and/or \(N_H/N_{HI}\) not uniform)
- Linear curves that follow trends in (high \(T_d\) & low \(W_{HI}\)) area are used to construct \(N_H\) model maps assuming \(N_H \propto D_{em}\)

\[N_H(\text{cm}^{-2}) = 1.82 \times 10^{18} \times (17.6 \times 10^8 \text{ R or } 66.9 \times 10^6 \tau_{353})\]
We prepared $N_H$ model maps ($\propto W_{\text{HI}}$ or $D_{\text{em}}$) and used them in a fit of $\gamma$-ray data -> $R$ gives the best fit.
Summary & Future Prospect

- We have been studying CRs and ISM in mid-latitude region of the 3rd quadrant.
  - Establish the procedure to convert $D_{em}$ to $N_H$, constrain CRs and ISM gas properties
  - Employ P305 data to suppress residual background
- ISM gas tracer investigation ($W_{HI}$-$D_{em}$ relationship):
  - $T_d$ dependence in North, $D_{em}$ dependence in South
- $\gamma$-ray data analysis:
  - $R$ gives best fit (North and South)
- Now evaluating $T_d/D_{em}$ dependence with systematic uncertainties into account to discuss CR/ISM properties

Thank you for your Attention
• Abdo+09, ApJ 703, 1249
• Abdo+10, Science 327, 1103
• Ackermann+13, Science 339, 807
• Grenier+05, Science 307, 1292
• Karberla+05, A&A 440, 775
• HI4PI Collaboration 2016, A&A 594, 116
• Mizuno+16, ApJ 833, 278
• Mori09, Astropart. Phys. 31, 341
• Planck Collaboration 2014, A&A 571, 13 (Planck 2013 Results XIII)