Study of the ISM and CRs in the MBM 53-55 Clouds and the Pegasus Loop

Mar. 18th, 2017@JPS meeting in Osaka

T. Mizuno (Hiroshima Univ.) on behalf of the Fermi-LAT Collaboration

フェルミ衛星によるMBM53-55分子雲・Pegasus Loop領域における星間ガスと宇宙線の研究

Mar. 18th, 2017 @大阪大学 (日本物理学会)

水野恒史 (広島大学) on behalf of the Fermi-LAT Collaboration

Motivation: ISM as a tracer of CRs

Deconvolved $\gamma$-ray image of W44 w/ Spitzer 4.5 $\mu$m contours (tracer of shocked H$_2$)

$\gamma$-ray spectrum shows a low-energy cutoff (signature of $\pi^0$-decay)

$\nu = \nu_0$ for CR hadronic interactions

An accurate estimate of the interstellar medium (ISM) densities is crucial to study Galactic cosmic rays (CRs), since $I_\gamma \propto N(H_{\text{tot}})U_{\text{CR}}$

<table>
<thead>
<tr>
<th>$W_{\text{SN}}$</th>
<th>$5 \times 10^{51}$ erg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{\text{CR}}$</td>
<td>$4 \times 10^{49} (n/100\text{cm}^{-3})^{-1}$ erg</td>
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</table>
Fermi revealed a component of ISM not measurable by standard tracers (HI 21 cm, CO 2.6 mm), confirming an earlier claim by EGRET (Grenier+05).
Uncertainty of ISM: Dark Gas

- Fermi revealed a component of ISM not measurable by standard tracers (HI 21 cm, CO 2.6 mm), confirming an earlier claim by EGRET (Grenier+05)
- Mass of “dark gas” is comparable to or greater than that of H$_2$ traced by W$_{CO}$

<table>
<thead>
<tr>
<th>Molecular cloud</th>
<th>H$<em>2$ mass traced by W$</em>{CO}$ ($M_{\text{sol}}$)</th>
<th>“dark gas” ($M_{\text{sol}}$)</th>
<th>$M_{DG}/M_{H2,CO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamaeleon</td>
<td>~5x10$^3$</td>
<td>~2.0x10$^4$</td>
<td>~4</td>
</tr>
<tr>
<td>R CrA</td>
<td>~10$^3$</td>
<td>~10$^3$</td>
<td>~1</td>
</tr>
<tr>
<td>Cepheus &amp; Polaris</td>
<td>~3.3x10$^4$</td>
<td>~1.3x10$^4$</td>
<td>~0.4</td>
</tr>
<tr>
<td>Orion A</td>
<td>~5.5x10$^4$</td>
<td>~2.8x10$^4$</td>
<td>~0.5</td>
</tr>
</tbody>
</table>

See also Planck Collaboration 2015, A&A 582, 31 (CA: Grenier)
Study of ISM and CRs using Fermi-LAT

• Study of ISM and CRs in high-latitude clouds using Fermi-LAT data has advanced significantly
  – We can assume that CR flux is uniform
  – We now have Planck dust thermal emission model which is useful to trace total gas column density (N(H_{tot})) in detail
  – (Procedure to convert dust distribution into N(H_{tot}) has not been established yet)

• Here we will present the study of MBM53-55 and Pegasus Loop region and implications for the ISM and CRs using Fermi-LAT
W_{HI}-Dust Relation (1)

- Dust is mixed with gas and has been used as a tracer of N(H_{tot})
  - But what kind of quantity should we use?

- We examined correlations btw. W_{HI} and two dust tracers (radiance (R) and opacity at 353 GHz (τ_{353})) (see also Fukui+14,15, Planck Collab. 2014)
  - Two tracers show different, dust-temperature (T_d) dependent correlations with W_{HI}

(Areas with W_{co}>1.1 K km/s are masked)

Lines show best-fit linear relations in T_d>21.5K
**$W_{\text{HI}}$-Dust Relation (2)**

- Dust is mixed with gas and has been used as a tracer of $N(H_{\text{tot}})$
  - But what kind of quantity should we use?
- We examined correlations btw. $W_{\text{HI}}$ and two dust tracers (radiance (R) and opacity at 353 GHz ($\tau_{353}$)) (see also Fukui+14,15, Planck Collab. 2014)
  - Two tracers show different and $T_d$-dependent correlations with $W_{\text{HI}}$
  - We tested two tracers against $\gamma$-ray data. We also examined $T_d$ dependence and found that $N(H_{\text{tot},\gamma})/R$ (or $\tau_{353}$) depends on $T_d$. (likely artificial)
  
  $=>$ use $\gamma$-ray data to compensate for the dependence ($I_\gamma \propto N(H_{\text{tot}})U_{\text{CR}}$)

$N(H_{\text{tot}})$ template ($\propto R$) ($10^{20}$ cm$^{-2}$)  

$N(H_{\text{tot}})$ template ($\propto \tau_{353}$) ($10^{20}$ cm$^{-2}$)
We started with R-based N(H$_{tot}$) map and applied a correction on N(H$_{tot}$) by using an empirical function as below (modeling the increase of N(H$_{tot}$) in areas with low Td):

$$N(H_{tot,mod}) = \begin{cases} N(H_{tot,R}) & (T_d > T_{bk}) \\ (1 + 0.05 \cdot C \cdot \frac{T_{bk}-T_d}{1K}) \cdot N(H_{tot,R}) & (T_d \leq T_{bk}) \end{cases}, \quad (T_{bk}=20.5 \text{ K})$$

Then we scanned coefficient C which best represents $\gamma$-ray data
- Idea is to use $\gamma$-ray data as a robust tracer of N(H$_{tot}$) ($I_{\gamma} \propto N(H_{tot})U_{CR}$)
- $T_{bk}=20.5 \text{ K}$ and C=2 (10% required increase in N(H$_{tot}$) by 1K) provides highest fit likelihood. It gives $M_{DG}/M_{H_2,CO} \leq 5$. 

N(H$_{tot}$) inferred by $\gamma$-ray data ($10^{20} \text{ cm}^{-2}$)
HI emissivity spectrum is compared with model curves based on the local interstellar spectrum (LIS) and results by relevant LAT studies employing a conventional template-fitting method.

Our spectrum agrees with the model for LIS with $\varepsilon_m$ (nuclear enhancement factor)=1.45, while previous LAT studies favor $\varepsilon_m=1.84$.

Most of difference can be understood due to the different N(H$_{tot}$) inferred in low T$_d$ area (where our method has more flexibility to adjust N(H$_{tot}$)).

Systematic study of other high-latitude regions is necessary to better understand the ISM and CRs.
Summary

- An accurate estimate of ISM densities is crucial to study CRs
- Diffuse GeV $\gamma$ rays are a powerful probe to study the ISM and CRs
- We present a joint Planck & Fermi-LAT study of MBM 53-55 clouds and the Pegasus Loop for the first time
  - We propose to use $\gamma$ rays as a robust tracer of $N(H_{\text{tot}})$, and obtained the ISM (and CR) properties
  - We obtained physical quantities on ISM and CRs (e.g., mass of dark gas, HI emissivity)
  - Systematic study of other high-latitude regions is necessary to better understand the ISM and CRs

Thank you for your Attention
References (Fermi-LAT Studies of Diffuse Emission in MW)

- Abdo+09, PRL 103, 251101 (CA: Johanneson, Porter, Strong)
- Abdo+10, PRL 104, 101101 (CA: Ackermann, Porter, Sellerholm)
- Ackermann+12, A&A 538, 71 (CA: Grenier, Tibaldo)
- Planck Collaboration 2015, A&A 582, 31 (CA: Grenier)
- Remy+17, A&A accepted (CA: Grenier, Remy)
References (others)

- Dame+01, ApJ 547, 792
- Grenier+05, Science 307, 1292
- Kalberla+05, A&A 440, 775
- Kiss+04, A&A 418, 131
- Ysard+15, A&A 577, 110
Backup Slides
All-Sky Map in $\gamma$ Rays

- Interstellar Medium (ISM) plays an important role in physical processes in the Milky Way
- **Diffuse GeV $\gamma$ rays** are a powerful probe to study the ISM gas [tracer of the total gas column density, $N(H_{\text{tot}})$]

Fermi-LAT 4 year all-sky map = point sources + **diffuse $\gamma$ rays**

$\sim$80% of $\gamma$ rays
All-Sky Map in Submillimeter

- Planck submillimeter map (30-857 GHz)
  = Dust thermal emission = ISM gas in the Milky Way (MW)

Nearby molecular clouds at high latitude
All-Sky Map in γ Rays

- Diffuse GeV γ-rays ~ Cosmic Rays (CRs) x ISM

Detailed studies of individual clouds (+ISM in galactic plane) published/submitted

Processes to Produce $\gamma$ rays (1)

$\gamma$ rays = CRs x ISM gas (or ISRF)

- Known ISM distribution => CR properties
- Those “measured” CRs => ISM distribution

A powerful probe to study ISM and CRs
(\textit{$\gamma$ rays directly trace gas in all phases})
Processes to Produce $\gamma$ rays (2)

$\gamma$ rays = CRs x ISM gas (or ISRF)

$\gamma$-ray data and model (mid-lat. region)
Abdo+09, PRL 103, 251101 (CA: Porter, Johanneson, Strong)

We can distinguish gas-related $\gamma$ rays from others based on the spectrum (right plot) and morphology (see the following slides)

**a powerful probe to study ISM and CRs**

*Pro:* optically-thin, “direct” tracer of all gas phases
*Con:* low-statistics, contamination (isotropic, IC), depend on CR density

$\pi^0$ decay, $\Gamma \sim 2.7$ above a few GeV
(Isotropic)

Inverse Compton, $\Gamma \sim 2.1$
To test this SNR paradigm of CRs, we need to observe

- CRs accelerated at SNRs and star-forming regions
- CR distribution in Milky Way (MW)

\[ u_{CR} \approx 1 \text{ eV/cm}^3 \text{ at the solar system} \]
\[ V_{gal} = 10^{67-68} \text{ cm}^3, \tau_{esc} \approx 10^7 \text{ yr} \]

\[ P_{CR} \approx 10^{41} \text{ erg/s} \]

\[ E_{SN} \approx 10^{51} \text{ erg}, F_{SN} \approx 1/30 \text{ yr} \]

If \( \eta \approx 0.1 \)

\[ P_{inj} \approx 10^{41} \text{ erg/s} \]
For local CR, the $\gamma$-ray emissivity is

$$Q_{\gamma}(>100\text{MeV}) \sim 1.6 \times 10^{-26} \text{ ph/s/sr/H-atom}$$
$$\sim 1.5 \times 10^{-28} \text{ erg/s/H-atom}$$

Then, the $\gamma$-ray luminosity is

$$L_{\gamma}(>100\text{MeV}) \sim (M_{\text{gas}}/m_p) \times Q_{\gamma}$$
$$\sim 10^{39} \text{ erg/s}$$

(compatible to Galactic Ridge X-ray Emission)

MW is bright in $\gamma$ rays

A probe to study CR origin & propagation, ISM distribution
Molecular Gas

- Scale height ~70 pc. Site of star formation
- Usually traced by CO lines in radio
  - not an “all-sky” map, uncertainty of $X_{\text{CO}} = N(\text{H}_2)/W_{\text{CO}}$

CO 2.6 mm map (Dame+01)

Typically

$X_{\text{CO}} \sim 2 \times 10^{20} \text{ cm}^{-2}/(\text{K km/s})$
Atomic Gas

- Scale height ~200 pc. Main component of ISM
- Usually traced by 21 cm line
  - uncertainty due to the assumption of the spin temperature (T_s)

Galactic plane
Atomic Gas

- Scale height ~200 pc. Main component of ISM
- Usually traced by 21 cm line
  - uncertainty due to the assumption of the spin temperature (Ts)

Galactic plane

\( \Delta V = 10 \text{km/s} \)

- \( \Delta T_b \) vs. Log(HI column density) [\(/\text{cm}^2\)]
- \( T_S = 100 \text{ K} \) vs. \( T_S = 40 \text{ K} \)

Kalberla+05

T. Mizuno et al.
Dark Gas

- Usually ISM gas has been traced by radio surveys (HI by 21 cm, H$_2$ by 2.6 mm CO)
- Grenier+05 claimed considerable amount of “dark gas” surrounding nearby CO clouds
  - Cold HI or CO-dark H$_2$? M$_{DG}$?
  - It can be inferred from the distribution of dust, but what kind of dust property should we use?

Grenier+05

center@l=70deg

E(B-V)$_{excess}$ (residual gas inferred by dust) and W$_{co}$

“dark gas” inferred by $\gamma$ rays (EGRET)
Modeling of $\gamma$-ray Data

- Under the assumption of a uniform CR density in the region studied, diffuse $\gamma$ rays can be modeled by a linear combination of template maps.

$$\propto I_{CR}$$

$$\propto (I_{CR} \times X_{CO})$$

$$\propto (I_{CR} \times X_{DG})$$

$$\propto q_{HI} \times N(\text{HI})$$

$$\propto q_{CO} \times W_{CO}$$

$$\propto q_{DG} \times \text{dust}_{res}$$

$$\propto \text{Inverse Compton (e.g., galprop)}$$

(2008-)

Source of uncertainties:
- HI is usually estimated by assuming a uniform spin temperature ($T_s$).
- $W_{CO}$ is not an all-sky map, may miss some fraction of $H_2$.
- It is not clear what kind of dust property we should use to trace dark gas.
Fermi-LAT Performance (Pass8)

- Launch in 2008, nearly uniform survey of the $\gamma$-ray sky
- Performance of Fermi-LAT was improved significantly with Pass8
  - large effective area ($\sim 1$ m$^2$) and field-of-view ($\geq 2$ sr)
Fermi-LAT Performance (Pass8)

- Launch in 2008, nearly uniform survey of γ-ray sky
- Performance of Fermi-LAT was improved significantly with Pass8
  - large effective area (~1 m²) and field-of-view (~2 sr)
Uncertainty of ISM: $X_{\text{CO}}$

- Usually $H_2$ gas is traced by CO 2.6 mm line observations. A canonical value of $X_{\text{CO}} (\equiv N(H_2)/W_{\text{CO}})$ is $\sim 2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$
- $\gamma$ rays are a useful probe to study $X_{\text{CO}}$
  - CRs penetrate to the core of $H_2$ clouds
  - CR density can be estimated from nearby HI clouds
  - $X_{\text{CO},\gamma}$ does not depend on assumptions on the dynamical state of the gas
- Even in nearby clouds/local arm, uncertainty is by a factor of $\sim 2$

![Graph showing radiative transfer of $^{12}$CO and $^{13}$CO and dust-derived values](chart.png)

- Fermi-LAT
- Cep-Pol
- RCrA
- Ori
- Cha
- Cygnus
- 2Q Local Arm
- 3Q Local Arm
- Inter arm
- 1Q Per arm
- 2Q Per arm
- 3Q Per arm

Grenier+15, ARAA 53, 199 (see also Remy+17, A&A accepted)
Fermi-LAT Results (3): Local Emissivity ($I_{CR}$)

- “local” CR densities among regions agree by a factor of 1.5, within systematic uncertainty
- Uncertainties are shown by inserts and are mostly due to the assumption of $T_s$

![Graph showing log($E_{ej}$) vs. log($E_{ej}$) with different regions and energy levels.]

- Average of high lat.
- Individual clouds
- Arms in Galactic plane

See Grenier+15, ARAA 53, 199 and reference therein.
Nearby, high-latitude clouds suitable to study the ISM and cosmic rays (CRs) in the solar neighborhood (Welty+89, Kiss+04, Yamamoto+03,06)

– $d \sim 150$ and 100 pc for MBM 53-55 and Pegasus Loop, respectively

– Most of HI in the region is local (from HI velocities in appendix)
Initial Modeling with a Single $N(H_{\text{tot}})$ Map

- We assumed $N(H_{\text{tot}}) \propto R$ (or $\tau_{353}$) and constructed $N(H_{\text{tot}})$ maps
  - Coefficients were determined by assuming that HI is optically thin and well represents $N(H_{\text{tot}})$ in $T_d > 21.5$ K (dotted lines in slide #15)
- We used 7 years P8R2 data and modeled $\gamma$-ray intensity as below
  - $q_\gamma$ is the emissivity model adopted. Subscript $i$ is for separating $N(H_{\text{tot}})$. Single map is used in initial analysis
    \[ I_\gamma(l, b, E) = \sum c_{1,i}(E) \cdot q_\gamma(E) \cdot N(H_{\text{tot}})_i(l, b) + c_2(E) \cdot I_{IC}(l, b, E) + I_{iso}(E) + \sum PS_j(l, b, E) \]
  - We found R-based $N(H_{\text{tot}})$ better represents $\gamma$-ray data in terms of lnL

\[ N(H_{\text{tot}}) \text{ template } (\propto R) \left( 10^{20} \text{ cm}^{-2} \right) \]
\[ N(H_{\text{tot}}) \text{ template } (\propto \tau_{353}) \left( 10^{20} \text{ cm}^{-2} \right) \]
• Even though R-based $N(H_{tot})$ is preferred by $\gamma$-ray data, true $N(H_{tot})$ could be appreciably different.

• Therefore we split $N(H_{tot})$ template map into four based on $T_d$ and fit $\gamma$-ray data with scaling factors freely varying individually.
  – Scaling factors should not depend on $T_d$ if $N(H_{tot}) \propto D$ (R or $\tau_{353}$).

• Fit improves significantly and shows clear $T_d$ dependence of scaling factors.
  – The trend is robust against various tests of systematic uncertainty.

We propose to use $\gamma$-ray data to compensate for the dependence.
We found, from $\gamma$-ray data analysis, neither the radiance nor $\tau_{353}$ are good tracers of $N(H_{\text{tot}})$

- Even though the interstellar radiation field (ISRF) is uniform in the vicinity of the solar system, the radiance (per H) could decrease as the gas (and dust) density increases, because the ISRF is more strongly absorbed by dust. This will cause a correlated decrease in the $T_d$ and the radiance (per H).

Ysard+15, Fig.2
(Radiance per H vs. $T_d$ for several choices of ISRF hardness. Both radiance and $T_d$ decrease as the ISRF is absorbed)
Possible Explanation of $T_d$ Dependence (2)

- We found, from $\gamma$-ray data analysis, neither the radiance nor $\tau_{353}$ are good tracers of $N(H_{\text{tot}})$
  - In the optically-thin limit, $I_\nu = \tau_\nu B_\nu(T_d) = \sigma_\nu N(H_{\text{tot}}) B_\nu(T_d)$, where $\tau_\nu$ and $\sigma_\nu$ are the optical depth and the dust opacity (cross section) per H, respectively. $\sigma_\nu$ depends on the frequency and is often describes as a power law, giving $I_\nu = \tau_{\nu_0} (\nu/\nu_0)^\beta B_\nu(T_d)$ (modified blackbody, $\beta \sim 1.5 - 2$).
  - Therefore, IF the dust cross section is uniform, $\tau_\nu \propto N(H_{\text{tot}})$ and we can measure the total gas column density by measuring the dust optical depth at any frequency (e.g., $\tau_{353}$).
  - However, dust opacity is not uniform but rather anti-correlates with $T_d$ as reported by Planck Collaboration (2014).
We started with R-based $N(H_{tot})$ map and employed an empirical function as below [modeling the increase of $N(H_{tot})$ in areas with low $T_d$]

$$N(H_{tot, mod}) = \begin{cases} N(H_{tot, R}) \ (T_d > T_{bk}) , \\ (1 + 0.05 \cdot C \cdot \frac{T_{bk} - T_d}{1K}) \cdot N(H_{tot, R}) \ (T_d \leq T_{bk}) , \end{cases}$$

$T_{bk} = 20.5$ K and $C = 2$ [10% required increase in $N(H_{tot})$ by 1K] gives highest fit likelihood, and obtained $N(H_{tot, mod})$ and the spectrum are shown below.
Obtained data count map (left) and model count map (right) in E > 300 MeV

Data

Model

3C 454.3 (AGN)

MBM 53-55

Pegasus Loop
Discussion (ISM)

- The correlation between $W_{\text{HI}}$ and the “corrected” $N(H_{\text{tot}})$ map
  - Scatter due to dark gas (DG)
The correlation between $W_{HI}$ and the "corrected" $N(H_{tot})$ map

- Scatter due to dark gas (DG). $T_s < 100$ K is inferred in the scenario that optically thick HI dominates.
Discussion (ISM)

- Integral of gas column density ($\propto M_{\text{gas}}$) as a function of $T_d$ for $N(H_{\text{tot}})$, $N(H_{\text{I thin}})$, $N(H_{\text{tot}})-N(H_{\text{I thin}})$ ($\sim N(H)$ for dark gas) and $2N(H_2,CO)$
  - $M_{\text{DG}}$ is $\sim 25\%$ of $M_{H_{\text{I thin}}}$ and $\sim 5 \times M_{H_2,CO}$ (the factor of 5 is large compared to those in other regions)
  - $M_{\text{DG}}$ differs by a factor of $\sim 4$ if we use only $R$ (or $\tau_{353}$); The correction based on $\gamma$-ray data is crucial

$$M(DG,\gamma) = \sim 4 \times M(DG, R)$$

$$\sim 1/4 \times M(DG, \tau_{353})$$

$10^{22}$ cm$^{-2}$ deg$^2$ corresponds to $\sim 740$ M$_{\text{sun}}$ for $d=150$ pc
We also employed a conventional template-fitting method

- Fit gamma-ray data with $N(\text{HI}_{\text{thin}})$ map, $W_{\text{CO}}$ map, $R_{\text{res}}$ map (template of dark gas) with isotropic, Inverse Compton and point sources
- $M_{\text{DG}}$ (shown by red dotted histogram) is $\sim 50\%$ smaller than that we obtained through $T_d$-corrected modeling

$10^{22} \text{ cm}^{-2} \text{ deg}^2$ corresponds to $\sim 740 \, M_{\odot}$ for $d=150$ pc
ISM Maps of the Region Studied

- $N(\text{HI}_{\text{thin}})$ in $10^{20}$ cm$^{-2}$
- $W_{\text{co}}$ in K km/s
- $T_d$ in K
Intermediate Velocity Clouds

- We are studying high-latitude region, therefore most of gas is in local. Still, there are some clouds with different velocities [intermediate velocity clouds (IVCs)]
- (Left) WHI of local clouds. (Right) WHI of IVCs
  - Contribution of IVCs is at the ~5% level

\[-30 < V_{lsr} (\text{km/s}) < 20\quad \text{(K km/s)}\quad -80 < V_{lsr}(\text{km/s}) -30\]