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

Jul. 19th, 2017@ICRC2017 in Busan, South Korea

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

(T. Mizuno, S. Abdollahi, Y. Fukui, K. Hayashi, A. Okumura, H. Tajima, and H. Yamamoto)
Motivation: ISM as a Tracer of CRs

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

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

ISM: Interstellar medium   CR: cosmic ray

Abdo+10, Science 327, 1103 (CA: Tajima, Tanaka, Uchiyama)

Ackermann+13, Science 339, 807 (CA: Funk, Tanaka, Uchiyama)
Motivation: ISM as a Tracer of CRs(2)

The γ-ray spectrum shows a low-energy cutoff (signature of π⁰-decay).

### Parameters of the source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{SN}$</td>
<td>$5 \times 10^{51}$ erg</td>
</tr>
<tr>
<td>$W_{CR}$</td>
<td>$4 \times 10^{49} (n/100 \text{cm}^{-3})^{-1}$ erg</td>
</tr>
</tbody>
</table>

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

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)

Acknowledgments

(CA: Hayashi, TM)
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$_{\text{CO}}$.

<table>
<thead>
<tr>
<th>Molecular cloud</th>
<th>H$<em>2$ mass traced by W$</em>{\text{CO}}$ (M$_{\text{solar}}$)</th>
<th>“dark gas” mass (M$_{\text{solar}}$)</th>
<th>M$<em>{\text{DG}}$/M$</em>{\text{H2,CO}}$</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 to trace total gas column density \(N(H_{tot})\) distribution in a fine resolution
  - Yet, a procedure to convert dust distribution into \(N(H_{tot})\) has not been established
- Here we will present the study of MBM53-55 and Pegasus loop
**$W_{\text{HI}}$-Dust Relation (1)**

- 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, dust-temperature ($T_d$) dependent correlations

Lines show best-fit linear relations in $T_d$>21.5K to convert $R$ (or $\tau_{353}$) into $N(H_{\text{tot}})$ for all $T_d$ (initial analysis)

(Areas with $W_{\text{CO}}$>1.1 K km/s are masked)
**W_{HI}-Dust Relation (2)**

- We examined correlations btw. $W_{HI}$ 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
  - Two template maps ($\propto R$ or $\tau_{353}$) not well correlate with $\gamma$-ray data; both $I_{\gamma,\text{gas}}/R$ and $I_{\gamma,\text{gas}}/\tau_{353}$ depend on $T_d$. (likely due to dust properties)

=> use $\gamma$-ray data to compensate for the dependence ($I_{\gamma} \propto N(H_{\text{tot}})U_{\text{CR}}$)
**Td-Corrected Modeling**

- We can correct dust-based $N(H_{tot})$ map to match with $\gamma$-ray data (robust tracer of $N(H_{tot})$)
  - start with R-based template and increase $N(H_{tot})$ in low $T_d$ area
    
    \[
    N(H_{tot,mod}) = \begin{cases} 
    N(H_{tot,R}) \ (T_d > T_{bk}) \
    (1 + 0.05 \cdot C \cdot \frac{T_{bk}-T_d}{1 \text{ K}}) \cdot N(H_{tot,R}) \ (T_d \leq T_{bk}) 
    \end{cases}
    \]

- $T_{bk}=20.5 \text{ K}$ and $C=2$ (10% 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 from $\gamma$-ray data ($10^{20} \text{ cm}^{-2}$)**
We compare HI emissivity spectrum 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)~1.5, while previous LAT studies favor $\varepsilon_m$~1.8. Most of the difference comes from different $N(H_{tot})$ in low $T_d$ area (where our method has more flexibility to adjust $N(H_{tot})$).

Systematic study of high-lat. 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
    • \( M_{\text{DG}}/M_{\text{H}_2,\text{CO}} \leq 5 \),
    • HI emissivity consistent with LIS & \( \varepsilon_m \sim 1.5 \) favored
  – Systematic study of 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 601, 78 (CA: Grenier, Remy)
References (others)

- Bolatto+03, ARAA 51, 207
- Bell+06, MNRAS 371, 1865
- Dame+01, ApJ 547, 792
- Grenier+05, Science 307, 1292
- Grenier+15, ARAA 53, 199
- Kalberla+05, A&A 440, 775
- Kiss+04, A&A 418, 131
- Ysard+15, A&A 577, 110
Backup Slides
Uncertainty of ISM: $X_{\text{CO}(1)}$

- Usually CO 2.6 mm line observations have been used to estimate $H_2$ gas mass (and CR density).
- A canonical value of $X_{\text{CO}}(\equiv N(H_2)/W_{\text{CO}})$ is $\sim 2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$
- Uncertainty is uncomfortably large (factor of $\geq 3$)

### TABLE 1

<table>
<thead>
<tr>
<th>Method</th>
<th>$X_{\text{CO}}/10^{20}$ cm$^{-2}(\text{K km s}^{-1})^{-1}$</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>Virial</td>
<td>2.1</td>
<td>Solomon et al. (1987)</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>Scoville et al. (1987)</td>
</tr>
<tr>
<td>Isotopologues</td>
<td>1.8</td>
<td>Goldsmith et al. (2008)</td>
</tr>
<tr>
<td>Extinction</td>
<td>1.8</td>
<td>Frerking, Langer &amp; Wilson (1982)</td>
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<td></td>
<td>2.9 – 4.2</td>
<td>Lombardi, Alves &amp; Lada (2006)</td>
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<tr>
<td></td>
<td>0.9 – 3.0</td>
<td>Pineda, Caselli &amp; Goodman (2008)</td>
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<td>2.1</td>
<td>Pineda et al. (2010)</td>
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<td>1.7 – 2.3</td>
<td>Paradis et al. (2012)</td>
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<td>Dust Emission</td>
<td>1.8</td>
<td>Dame, Hartmann &amp; Thaddeus (2001)</td>
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<td></td>
<td>1.9</td>
<td>Planck Collaboration et al. (2011a)</td>
</tr>
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<td>$\gamma$-rays</td>
<td>1.7</td>
<td>Strong &amp; Matteix (1996)</td>
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<td></td>
<td>0.9 – 1.9 *</td>
<td>Grenier, Casandjian &amp; Terrier (2005)</td>
</tr>
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<td></td>
<td>1.9 – 2.1 *</td>
<td>Abdo et al. (2010d)</td>
</tr>
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<td></td>
<td>0.7 – 1.0 *</td>
<td>Ackermann et al. (2011, 2012d)</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>Ackermann et al. (2012b,c)</td>
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</tbody>
</table>

Bolatto+03, ARAA 51, 207
Uncertainty of ISM: $X_{\text{CO}}(2)$

- A canonical value of $X_{\text{CO}}(\equiv N(\text{H}_2)/W_{\text{CO}})$ is $\sim 2 \times 10^{20} \text{ cm}^{-2} \left(\text{K km s}^{-1}\right)^{-1}$
- $\gamma$ rays are a useful probe to study $X_{\text{CO}}$
  - CRs penetrate to the core of $\text{H}_2$ 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, uncertainty is by a factor of $\geq 2$

![Graph showing Fermi-LAT data and uncertainty of $X_{\text{CO}}$ in nearby clouds and the radiative transfer of $^{12}\text{CO}$ and $^{13}\text{CO}$, with dust-derived values and nearby clouds highlighted.](image)
X_{CO} in Small and Large Scales

- The study confirms (sometimes overlooked) discrepancy of X_{CO,\gamma} between measurements at nearby clouds and large Galactic scales
- This may be due to determination biases induced by difficulty at large distance to separate HI clouds and dark gas envelopes from CO-bright H$_2$ cloud

<table>
<thead>
<tr>
<th>$\gamma$-ray telescope</th>
<th>Location</th>
<th>X_{CO} factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large Galactic scales</strong></td>
<td></td>
<td></td>
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<tr>
<td>COS-B</td>
<td>1st quadrant</td>
<td>2.5$^e$</td>
<td>Lebrun et al. (1983)</td>
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<tr>
<td>COS-B</td>
<td>Galactic disc</td>
<td>2.3$^e$</td>
<td>Bloemen et al. (1986)</td>
</tr>
<tr>
<td>COS-B</td>
<td>Galactic disc</td>
<td>2.3 ± 0.3</td>
<td>Strong et al. (1988)</td>
</tr>
<tr>
<td>EGRET</td>
<td>Galactic disc</td>
<td>1.9 ± 0.2</td>
<td>Strong &amp; Mattok (1996)</td>
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<td>EGRET</td>
<td>Galactic disc</td>
<td>1.56 ± 0.05</td>
<td>Hunter et al. (1997)</td>
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<tr>
<td>EGRET</td>
<td>5$^\circ$ &lt; $</td>
<td>\theta</td>
<td>$ &lt; 80$^\circ$</td>
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<td>EGRET</td>
<td>Local arm 3rd quadrant</td>
<td>1.64 ± 0.31</td>
<td>Digel et al. (2001)</td>
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<tr>
<td>Fermi-LAT</td>
<td>Local arm 2nd quadrant</td>
<td>1.59 ± 0.17</td>
<td>Abd et al. (2010)</td>
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<td>Fermi-LAT</td>
<td>Local arm Cygnus</td>
<td>1.68 ± 0.05</td>
<td>Ackermann et al. (2012d)</td>
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<td>Fermi-LAT</td>
<td>Local arm 3rd quadrant</td>
<td>2.08 ± 0.11</td>
<td>Ackermann et al. (2011)</td>
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<tr>
<td>Fermi-LAT</td>
<td>between the Local and Perseus arms</td>
<td>1.93 ± 0.16</td>
<td>Ackermann et al. (2011)</td>
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<td>Fermi-LAT</td>
<td>Perseus arm</td>
<td>1.9 ± 0.2</td>
<td>Abd et al. (2010)</td>
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<tr>
<td><strong>Nearby clouds</strong></td>
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<tr>
<td>COS-B</td>
<td>Oph-Sag</td>
<td>0.9 ± 0.4$^d$</td>
<td>Lebrun &amp; Huang (1984)</td>
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<tr>
<td>COS-B</td>
<td>Orion</td>
<td>2.1 ± 1.0$^b$</td>
<td>Bloemen et al. (1984)</td>
</tr>
<tr>
<td>EGRET</td>
<td>Oph</td>
<td>1.1 ± 0.2</td>
<td>Hunter et al. (1994)</td>
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<td>Orion</td>
<td>1.35 ± 0.15</td>
<td>Digel et al. (1999)</td>
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<td>Cepheus</td>
<td>0.92 ± 0.14</td>
<td>Digel et al. (1996)</td>
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<td>EGRET</td>
<td>Taurus</td>
<td>1.08 ± 0.10</td>
<td>Digel &amp; Grenier (2001)</td>
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<td>Fermi-LAT</td>
<td>Orion</td>
<td>1.21 ± 0.02</td>
<td>Ackermann et al. (2012b)</td>
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<td>Fermi-LAT</td>
<td>Cepheus &amp; Cassiopeia</td>
<td>0.87 ± 0.05</td>
<td>Abd et al. (2010)</td>
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<td>Fermi-LAT</td>
<td>Cepheus &amp; Polaris</td>
<td>0.63 ± 0.02</td>
<td>Ackermann et al. (2012c)</td>
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<td>Fermi-LAT</td>
<td>RCrA</td>
<td>0.99 ± 0.08</td>
<td>Ackermann et al. (2012c)</td>
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<td>Fermi-LAT</td>
<td>Chamaeleon</td>
<td>0.69 ± 0.02</td>
<td>Planck Collaboration Int. XXVIII (2015)</td>
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<td>10$^\circ$ &lt; $</td>
<td>\theta</td>
<td>$ &lt; 70$^\circ$</td>
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</table>

X_{CO}=1.5-2.5
(1.5-2.0 by EGRET and Fermi)

X_{CO}=0.6-2.1
(0.6-1.4 by EGRET and Fermi)
**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 $\gamma$ Rays

- Diffuse GeV $\gamma$-rays $\sim$ Cosmic Rays (CRs) x ISM

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


(See also references)
Processes to Produce $\gamma$ rays (1)

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

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

Fermi-LAT (2008-)

A powerful probe to study ISM and CRs
($\gamma$ 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
$\Rightarrow$ need to be complemented with other gas tracers

$\pi^0$ decay, $\Gamma \approx 2.7$
above a few GeV
(Isotropic)
Inverse Compton, $\Gamma \approx 2.1$
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)

\[ u_{\text{CR}} \approx 1 \text{ eV/cm}^3 \text{ at the solar system} \]
\[ V_{\text{gal}} = 10^{67-68} \text{ cm}^3, \tau_{\text{esc}} \approx 10^7 \text{ yr} \]
\[ P_{\text{CR}} \approx 10^{41} \text{ erg/s} \]
\[ E_{\text{SN}} \approx 10^{51} \text{ erg}, F_{\text{SN}} \approx 1/30 \text{ yr} \]
\[ \text{If } \eta \approx 0.1 \]
\[ P_{\text{inj}} \approx 10^{41} \text{ erg/s} \]
GeV $\gamma$ ray as a tracer of CRs and ISM

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

(compatible to Galactic Ridge X-ray Emission)

MW is bright in $\gamma$ rays

A probe to study CR origin & propagation, ISM distribution
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)
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

$\Delta V = 10 \text{ km/s}$

$T_S = 100 \text{ K}$

$T_S = 40 \text{ K}$

$\Delta T_b$

Log(HI column density) [cm$^{-2}$]

$\tau$

$\tau = 0.01$

$\tau = 0.1$

$\tau = 1$

$\tau = 10$

$\tau = 100$

$\Delta T_b$

$T_S = 100 \text{ K}$

$T_S = 40 \text{ K}$

Kalberla+05
Molecular Gas

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

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

Galactic plane

CO 2.6 mm map (Dame+01)
**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?

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:

\[
\alpha I_{CR} \propto (l_{CR} \times X_{CO}) + (l_{CR} \times X_{DG})
\]

Source of uncertainties:
- $\text{HI}$ is usually estimated by assuming a uniform spin temperature ($T_s$)
- $W_{\text{CO}}$ 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 ($\sim 1 \text{ m}^2$) and field-of-view ($\geq 2 \text{ sr}$)
Fermi-LAT Performance (Pass8)

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

See Grenier+15, ARAA 53, 199 and reference therein
MBM 53,54,55 & Pegasus Loop

- 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$_{tot}$) Map

- We assumed N(H$_{tot}$) $\propto$ R (or $\tau_{353}$) and constructed N(H$_{tot}$) maps
  - Coefficients were determined by assuming that HI is optically thin and well represents N(H$_{tot}$) in $T_d > 21.5$ K
- 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$_{tot}$). Single map is used in initial analysis
  
  \[ I_\gamma(l, b, E) = \sum_i c_{1,i}(E) \cdot q_\gamma(E) \cdot N(H_{tot})_i(l, b) + c_2(E) \cdot I_{IC}(l, b, E) + I_{iso}(E) + \sum PS_j(l, b, E) \]
  - We found R-based N(H$_{tot}$) better represents $\gamma$-ray data in terms of lnL

![N(H$_{tot}$) template ($\propto$ R) (10$^{20}$ cm$^{-2}$)](image1)

![N(H$_{tot}$) template ($\propto$ $\tau_{353}$) (10$^{20}$ cm$^{-2}$)](image2)
Td-Sorted Modeling

- 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 $N(H_{tot}) \propto D (R \text{ or } \tau_{353})$.
- 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.
Possible Explanation of $T_d$ Dependence (1)

- We found, from $\gamma$-ray data analysis, neither the radiance nor $\tau_{353}$ are good tracers of $N(H_{tot})$
  - 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 $I_\nu = \tau_{\nu0} (\nu/\nu_0)^\beta B_\nu(T_d)$ (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 $N(H_{\text{tot}})$ map and employed an empirical function as below [modeling the increase of $N(H_{\text{tot}})$ in areas with low $T_d$]

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

- $T_{bk}=20.5$ K and $C=2$ [10% required increase in $N(H_{\text{tot}})$ by 1K] gives highest fit likelihood, and obtained $N(H_{\text{tot,mod}})$ and the spectrum are shown below
T_d-Corrected Modeling (3)

- Obtained data count map (left) and model count map (right) in E > 300 MeV
Discussion (ISM)

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

- 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 $2N(H_{2,\text{CO}})$
  - $M_{\text{DG}}$ is $\sim 25\%$ of $M_{H_{\text{I,thin}}}$ and $\sim 5 \times M_{H_{2,\text{CO}}}$ (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

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

$10^{22} \text{ cm}^{-2} \text{ deg}^2$ corresponds to $\sim 740 M_{\text{Sun}}$ for $d=150$ pc
Based on $N(H_{\text{tot}})$ inferred by $\gamma$–ray data, they obtained integral of gas column density ($\propto M_{\text{gas}}$) as a function of $T_d$ for each gas phase:

- $M_{\text{DG}}$ is $\sim 25\%$ of $M_{\text{HI,thin}}$ and $\sim 5 \times M_{\text{H_2,CO}}$ (the factor of 5 is large compared to those in other regions)

(Not clear yet if the linear relation is applicable to other regions)

$10^{22}$ cm$^{-2}$ deg$^2$ corresponds to $\sim 740 M_{\text{sun}}$ for $d=150$ pc
Results by a Conventional Template-Fitting Method

- We also employed a conventional template-fitting method
  - Fit gamma-ray data with $N(H_{\text{thin}})$ 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 $d=150 \, \text{ pc}$
ISM Maps of the Region Studied

- $N(\text{H}_1\text{thin})$ in $10^{20} \text{ cm}^{-2}$
- $W_{\text{co}}$ in K km/s
- $T_d$ in K

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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) $W_{\text{HI}}$ of local clouds. (Right) $W_{\text{HI}}$ of IVCs
- Contribution of IVCs is at the ~5% level

-30 < $V_{\text{lsr}}$ (km/s) < 20

-80 < $V_{\text{lsr}}$ (km/s) -30

![Local Clouds](image1)

![IVCs](image2)