Study of the ISM and CRs of MBM 53, 54, 55 Clouds and the Pegasus Loop

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Fermi衛星LAT検出器によるMBM 53,54,55およびPegasus Loop領域の観測

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on behalf of the Fermi-LAT Collaboration
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 [tracer of the total gas column density, $N(H_{tot})$]

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

~80% of $\gamma$ rays
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 is inferred from the distribution of dust, but what kind of dust property should we use?

Grenier+05

center@l=70deg

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

“dark gas” inferred by $\gamma$ rays (EGRET)
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 of interest (ROI) is local

Planck dust temperature ($T_d$) map

Planck radiance (R) map converted in $N(H_{\text{tot}})$ template map

T. Mizuno et al.
**$W_{\text{HI}}$-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, $T_d$-dependent correlation with $W_{\text{HI}}$

(areas with $W_{\text{CO}}>1.1$ K km/s masked)

lines show best-fit linear relations in $T_d>21.5$K
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, $T_d$-dependent correlation 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 $T_d$.

$\Rightarrow$ use $\gamma$-ray data to compensate for the dependence

T. Mizuno et al. (two tracers show different contrast in $N(H_{\text{tot}})$ template maps)
Td-Corrected Modeling

- 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 Td]

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

- 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$_{tot}$)

- $T_{bk}$=20.5 K and C=2 [10% required increase in N(H$_{tot}$) by 1K] gives best lnL

![Graph showing lnL versus coefficient C]

Preliminary
Discussion (ISM)

• Left: the correlation between $W_{\text{HI}}$ and the “corrected” $N(\text{H}_{\text{tot}})$ map
  – scatter due to dark gas (DG). $T_s < 100$ K is inferred in optically thick HI scenario
• Right: Integral of gas column density ($\propto M_{\text{gas}}$) as a function of $T_d$ for
  $N(\text{H}_{\text{tot}})$, $N(\text{HI}_{\text{thin}})$, $N(\text{H}_{\text{tot}})-N(\text{HI}_{\text{thin}})$ ($\sim N(\text{H})$ for dark gas) and $2N(\text{H}_2, \text{CO})$
  – $M_{\text{DG}}$ is $\sim 25\%$ of $M_{\text{HI}, \text{thin}}$ and $\leq 5 \times M_{\text{H}_2, \text{CO}}$ (the factor of 5 is larger compared to those in other regions)
  – $M_{\text{DG}}$ differs by a factor of $\geq 4$ if we use only $R$ (or $\tau_{353}$); the correction based on $\gamma$ ray data is crucial

10$^{22}$ cm$^{-2}$ deg$^{-2}$ corresponds to $\sim 740$ $M_{\odot}$ for $d = 150$ pc
Summary

• Diffuse GeV $\gamma$ rays are a powerful probe to study the ISM (and CRs)
• We present a joint Planck & Fermi-LAT study of MBM 53,54,55 clouds and the Pegasus Loop for the first time
  – we found neither $R$ nor $\tau_{353}$ inferred from Planck observations were good representations of $N(H_{tot})$
• We propose to use $\gamma$ rays as a robust tracer of $N(H_{tot})$, and obtained the ISM (and CR) properties
  – moderate scatter in $W_{Hi}$-$N(H_{tot})$ relation. $T_s<100$ K is inferred in optically-thick HI scenario
  – $M_{DG}$ is $\sim25\%$ of $M_{Hi,\text{thin}}$ and $\leq 5 \times M_{H_2,CO}$ [in terms of $N(H_{DG})/N(H_2,CO)$, the region is dark-gas-rich]
  – (more details on ISM and CRs in the paper submitted)

Thank you for your Attention
References

- Grenier+05, Science 307, 1292
- Kiss+04, A&A 418, 131
Backup Slides
All-Sky Map in $\gamma$ Rays

- GeV $\gamma$-ray sky = Point sources + Diffuse $\gamma$ rays

Cosmic Rays (CRs) x ISM

Fermi-LAT 4 year all-sky map
All-Sky Map in Microwave

- Planck microwave map (30-857 GHz)

  = dust thermal emission = ISM

Taurus, Cepheus & Polaris, Chamaeleon, MBM 53, 54, 55, Orion, R CrA, nearby gas in high latitude
Molecular Gas

- Scale height ~70 pc. Site star formation
- Usually traced by CO lines in radio
  - not an “all-sky” map, uncertainty of $X_{\text{CO}}=N(H_2)/W_{\text{CO}}$

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

Galactic plane

$\Delta V = 10$ km/s (opt-thin)

$\Delta T_b$ [K]

$T_s = 100$ K
$T_s = 40$ K

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

$\Delta T_b$

$\tau$

$\tau$
ISM Maps of the Region Studied

- $N(HI_{thin})$ in $10^{20}$ cm$^{-2}$
- $W_{co}$ in K km/s
- $T_d$ in K
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 (dotted lines in slide #6)
- 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 $N(H_{tot})$

$$I_\gamma(l, b, E) = \sum_i c_{1,i}(E) \cdot q_\gamma(E) \cdot N(H_{tot})_i(l, b) + c_2(E) \cdot I_{1C}(l, b, E) + I_{iso}(E) + \sum_j PS_j(l, b, E)$$
  - we found R-based $N(H_{tot})$ better represents $\gamma$-ray data in terms of lnL

\begin{align*}
N(H_{tot}) \text{ template (} \propto \tau_{353} \text{)} (10^{20} \text{ cm}^{-2}) \\
N(H_{tot}) \text{ template (} \propto \tau_{353} \text{)} (10^{20} \text{ cm}^{-2})
\end{align*}
Td-Sorted Modeling

- Even though R-based $N(H_{\text{tot}})$ is preferred by $\gamma$-ray data, true $N(H_{\text{tot}})$ could be appreciably different
- Therefore we split $N(H_{\text{tot}})$ 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 $N(H_{\text{tot}}) \propto D (R \text{ or } \tau_{353})$
- Fit improves significantly and shows clear $T_d$ dependence of scaling factors
  - the trend is robust against various tests of systematic uncertainty
We found, from $\gamma$-ray data analysis, neither the radian nor $\tau_{353}$ are good tracers of $N(\text{H}_{\text{tot}})$

- Even though the interstellar radiation field (ISRF) is uniform in the vicinity of the solar system, the radian (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 radian (per H).

Ysard+15, Fig.2
(radiance per H vs. $T_d$ for several choices of ISRF hardness. Both radian 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 $N(\text{H}_{\text{tot}})$
  - In the optically-thin limit, $I_\nu = \tau_\nu B_\nu(T_d) = \sigma_\nu N(\text{H}_{\text{tot}}) B_\nu(T_d)$, 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, $\tau_\nu \propto N(\text{H}_{\text{tot}})$ 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).
**Td-Corrected Modeling (2)**

- 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 Td]

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

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

- Obtained data count map (left) and model count map (right)
Discussion (HI emissivity)

- HI emissivity spectrum is compared with model curves based on the local interstellar spectrum (LIS) and results by relevant LAT studies.
- 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 the 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 $N(H_{tot})$.

![Graph showing comparison of HI emissivity spectra](image)
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) $W_{\text{HI}}$ of local clouds. (right) $W_{\text{HI}}$ of IVCs
  - contribution of IVCs is at the $\sim 5\%$ level

$-30 < V_{\text{lsr}} \text{ (km/s)} < 20$  \hspace{1cm}  $-80 < V_{\text{lsr}} \text{ (km/s)} < -30$