Study of the ISM and CRs in the MBM 53-55 Clouds and the Pegasus Loop (2)

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フェルミ衛星によるMBM 53-55分子雲・Pegasus Loop領域の星間ガスと宇宙線の研究(2)
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Introduction: Dark Gas

- A significant amount of ISM (interstellar medium) gas not traced by standard 21 cm and 2.6 mm radio lines has been recognized recently.

**Chamaeleon Molecular Cloud:**

- $M_{H_2,CO} \sim 5 \times 10^3 \, M_{\text{solar}}$
- $M_{\text{DG}} \sim 2 \times 10^4 \, M_{\text{solar}}$


- These “dark gas” (DG) can be traced by infrared (IR) and $\gamma$-ray observations, but the procedure has not been established yet.

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The procedure to convert dust distribution into \(N(\text{H}_{\text{tot}})\) has not been established yet, giving uncertainty in dark gas distribution. Here we present the study of MBM53-55 and the Pegasus loop by using \(\gamma\)-rays as a robust tracer of \(N(\text{H}_{\text{tot}})\). Under the assumption of uniform cosmic-ray (CR) density, we can trace \(N(\text{H}_{\text{tot}})\) by \(\gamma\)-rays since \(I_{\gamma} \propto N(\text{H}_{\text{tot}})U_{\text{CR}}\).
**$W_{\text{HI}}$-Dust Relation (1)**

- Dust is mixed with gas and has been used as a tracer of $N(\text{H}_{\text{tot}})$
  - 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 $W_{\text{HI}}$

(Areas with $W_{\text{co}}>1.1\, \text{K km/s}$ are masked)
(Lines show best-fit linear relations in $T_d>21.5\, \text{K}$)
W_{HI}-Dust Relation (2)

- 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 (\tau_{353})) (see also Fukui+14,15, Planck Collab. 2014)
  - Two tracers show different and T_d-dependent correlations with W_{HI}
    => Different contrast in N(H_{tot}) template maps (\propto R, \tau_{353}). The map \propto R gives better fit to \gamma-ray data

\[
\begin{align*}
N(H_{tot}) \text{ template (} \propto R \text{) } (10^{20} \text{ cm}^{-2}) \\
N(H_{tot}) \text{ template (} \propto \tau_{353} \text{) } (10^{20} \text{ cm}^{-2})
\end{align*}
\]
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.
  - Scale factors should not depend on \(T_d\) if \(N(H_{\text{tot}}) \propto D (R \text{ or } \tau_{353})\) and \(U_{\text{CR}}\) is uniform.

- Fit improves significantly but scale factors depends on \(T_d\).
  - Negative correlation with \(R\) implies underestimate of \(N(H_{\text{tot}})\) in low \(T_d\).

We propose to use \(\gamma\)-ray data to compensate for the dependence:

\[
N(H_{\text{tot,mod}}) = \left(1 + 0.1 \frac{20.5 K - T_d}{1 K}\right) N(H_{\text{tot,R}})
\]
Discussion of the ISM (1)

- 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 the scenario that optically thick HI dominates
Discussion of the ISM (2)

- Integral of gas column density ($\propto M_{\text{gas}}$) as a function of $T_d$ for $N(H_{\text{tot}})$, $N(H_1\text{thin})$, $N(H_{\text{tot}})-N(H_1\text{thin})$ ($\sim N(H)$ for dark gas) and $2N(H_2,CO)$
  - $M_{\text{DG}}$ is $\sim 25\%$ of $M_{H_1\text{thin}}$ and $\sim 5 \times M_{H_2,CO}$, larger than model predictions of CO-dark $H_2$ scenario (NB: different physical conditions)
  - $M_{\text{DG}}$ 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 $\sim 740 \ M_{\odot}$ for $d=150$ pc
Summary

- An accurate estimate of ISM densities is important
- 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 of the ISM and CRs (e.g., $T_s$ for HI dominant scenario, mass of dark gas)
- Systematic study of other high-latitude regions is important and underway

Thank you for your Attention