THE MASS AND DISTRIBUTION OF DIFFUSE AND DENSE CO GAS IN THE MILKY WAY

Julia Roman-Duval (STScI)
with Mark Heyer, Chris Brunt, Ralf Klessen, Rahul Shetty

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Density structure of the ISM is a primary driver of star-formation

* SF occurs in high density regions (density threshold for SF?) or regions of high density contrast
* Fraction of dense, star-forming gas varies with environment
Growing evidence that some fraction of molecular gas is fairly diffuse, non-star forming

* In the Taurus molecular cloud (TMC), 50% of the H$_2$ mass is in a diffuse component with $\Sigma < 30$ M$_{\odot}$ pc$^{-2}$ and no detectable $^{13}$CO emission (Goldsmith+2008)

* In M51, 50% of CO luminosity arises from diffuse component on kpc-scale (Pety+2013)
In the Milky Way, we can spatially resolve different gas components.

We use large-scale surveys of $^{12}$CO and $^{13}$CO:
- Galactic Ring Survey (GRS, Jackson +2006) in $^{13}$CO
- University of Massachusetts Stony Brook survey (UMSB) in $^{12}$CO
- EXeter-FCRAO survey (EXFC) in $^{12}$CO and $^{13}$CO (outer Galaxy)
- 45” beam

Follow a statistical method, no cloud decomposition.

See Roman-Duval+2016 for details.
DETECTION

Goal is to detect $^{13}$CO emission with $T_{12}/T_{13}$ up to 10 ($\Sigma_v < 5-10 \, M_\odot \, pc^{-2} (km \, s^{-1})^{-1}$)

1. Amount of gas detected in $^{12}$CO but not $^{13}$CO depends on S/N on each line

   ➞ Smooth data with different kernels to get same S/N for both lines

2. Capturing low S/N diffuse emission ➞ low threshold (e.g., $1\sigma$)

3. Low threshold induces large positive bias by noise

   ➞ Perform erosion/dilation to remove noise peaks
PHYSICAL PROPERTIES OF THE GAS

- Kinematic distances determined using and Clemens+1985 rotation curve
  - In the inner Galaxy, kinematic distance ambiguity
    - Weigh the emission between the near and far distance solutions using a Gaussian PDF with FWHM equal to the scale height of the molecular disk (110 pc)

- \( T_{\text{ex}}, \tau(^{13}\text{CO}), M(\text{H}_2) \) determined in each \((l, b, v)\) position where \(^{13}\text{CO}\) emission is \(>2\sigma\) (Roman-Duval+2010)
  - Conversion factor between \(^{12}\text{CO}\) emission and \(\text{H}_2\) mass (X factor) determined in \(R_{\text{gal}}\) bins of 1 kpc width
  - Same X factor is applied to voxels where \(^{13}\text{CO}\) emission is \(<2\sigma\) to convert \(^{12}\text{CO}\) emission to \(\text{H}_2\) mass

\[
R_{\text{gal}} = 5.6 \text{ kpc} \\
X_{\text{CO}} = 1.9 \times 10^{20} \\
M(\text{H}_2) = 4.0 \text{ L}^{(12}\text{CO})
\]
RADIAL PROFILE OF $^{12}$CO AND $^{13}$CO INTENSITIES

- Knowing distance, “face-on” intensity in each tracer can be computed
  * $I(^{12}$CO)/$I(^{13}$CO) ~ 5-10 inside solar circle
  * $I(^{12}$CO)/$I(^{13}$CO) ~ 10-20 outside solar circle

GRS+UMSB (2.5-8.5 kpc)  EXFC 135-15 (8.5-20 kpc)

Ratio=6
Ratio=10
Ratio=10-20
Dense CO gas detected in $^{12}$CO and $^{13}$CO, $\Sigma_v(H_2) > 5-10 \ M_\odot \ pc^{-2} \ (km \ s^{-1})^{-1}$

Diffuse CO gas detected in $^{12}$CO, not $^{13}$CO, $\Sigma_v(H_2) < 5-10 \ M_\odot \ pc^{-2} \ (km \ s^{-1})^{-1}$

**TOTAL**

**DENSE**

**DIFFUSE**
DIFFUSE AND DENSE GAS IN THE OUTER GALAXY

- Integrated intensity maps of the diffuse and dense CO gas in the Outer Galaxy (135°<l<165° , -4°<b<5°, clouds roughly 3 kpc away).

[Image of diffuse and dense gas in the outer galaxy with red and blue colors, labeled as diffuse and dense respectively.]
The fraction of diffuse gas increases from 10-20% at $R_{gal}=2-6$ kpc, to 50% beyond the Solar Circle.

The diffuse CO gas represents 25% of the total H$_2$ mass ($6.5 \times 10^8$ M$_\odot$).
DENSE GAS FRACTION VS DISK SURFACE DENSITY

- Compute face-on disk surface density on 100 pc scale
- Dense gas fraction increases with surface density as $\Sigma^{0.24}$
- Consistent with results on larger scales from Usero+2015, Bigiel +2016

\[ f_{DG} = 0.02 \Sigma_{gal}^{0.24 \pm 0.01} \]

\[
\Sigma_{gal}^{100pc}(H_2) \ [M_\odot \ kpc^{-2}]
\]

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\text{Dense Gas Fraction}
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\text{Dense Gas Fraction}
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FUTURE WORK: LINK TO STAR FORMATION

- Correlate maps of diffuse, dense CO gas with SFR FIR tracers (Hi-GAL, IRAS, WISE)
DENSE CO GAS VS IRIS 25

- Convolved IRIS 25 mm and CO maps to 100 pc resolution and examined molecular depletion times vs surface density of molecular gas

\[ \tau_{\text{dep}} = \frac{\Sigma(H_2)}{\Sigma_{\text{SFR}}} \]

\[ \Sigma_{\text{SFR}}[M_o yr^{-1} kpc^{-2}] = 2.8 \times 10^{-3} S_{25}[MJy / sr] \]

\[ \tau_{\text{dep}} = 10 \text{ Gyr} \text{ implies inefficient SF in outer galaxy?} \]
CONCLUSION

• We implement an algorithm to robustly detect emission ($^{12}$CO, $^{13}$CO, CS) in large surveys without noise-induced bias and without cloud decomposition.

• We statistically derive the face-on distribution of CO in 1/3 of Milky Way disk.

• Identification of diffuse and dense CO components:
  * Diffuse (dense) CO gas have $T_{12}/T_{13} > (<) 10$ corresponding to $\Sigma < (>) 5 \ M_\odot \ pc^{-2} \ (km \ s^{-1})^{-1}$

• The fraction of diffuse gas increases with radius:
  * 25% of CO gas is diffuse inside Solar Circle, 50% outside.
  * Dense gas fraction increases with disk surface density.

• The efficiency of the SF process may be limited by the availability of dense density structures?