A Survey of Hidden Molecular Clouds in the Milky Way

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Star formation, a critical process within galaxies, occurs in the coldest, densest interstellar clouds, whose gas and dust content are observed primarily at radio and infrared wavelengths. The formation of molecular hydrogen is an essential early step in the condensation of these clouds from the ambient interstellar medium, but H_2 molecules are difficult to observe directly. Proxy detectors like carbon monoxide (CO) are often used for H_2 detection, but this method is not perfect. Through a comparative study, we find substantial dark molecular hydrogen that is not detected in CO emission. We use far-infrared dust emission measurements from the *IRAS* and *Planck* satellites for two independent measures of total gas column density. We trace visible gas column density using radio 21-cm hydrogen emission from Arecibo and 2.6-mm CO data from multiple surveys. Without dark gas, the dust and visible gas column densities should be equivalent, but instead we find considerable excess column in a number of cold clouds, indicating the presence of dark molecular hydrogen overlooked by standard observations.

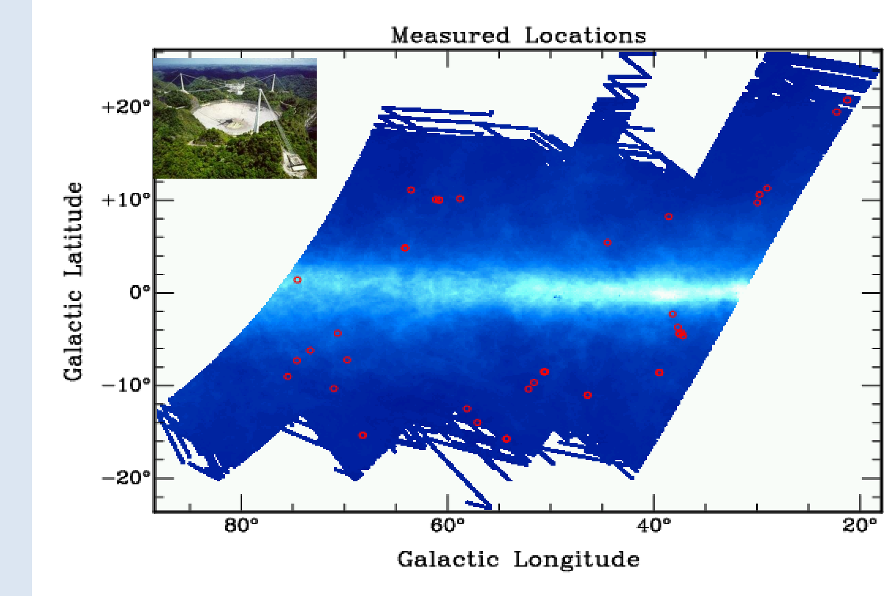

Figure 1: We identified over 40 cold clouds in the Arecibo I-GALFA survey with narrow HI emission lines (Fig. 3).

1. Identify cold atomic hydrogen emission clouds
2. Measure clouds in multiple wavelengths
3. Convert measurements to column densities
4. Compare column densities to find hidden gas
5. Model HI line shape to constrain atomic component

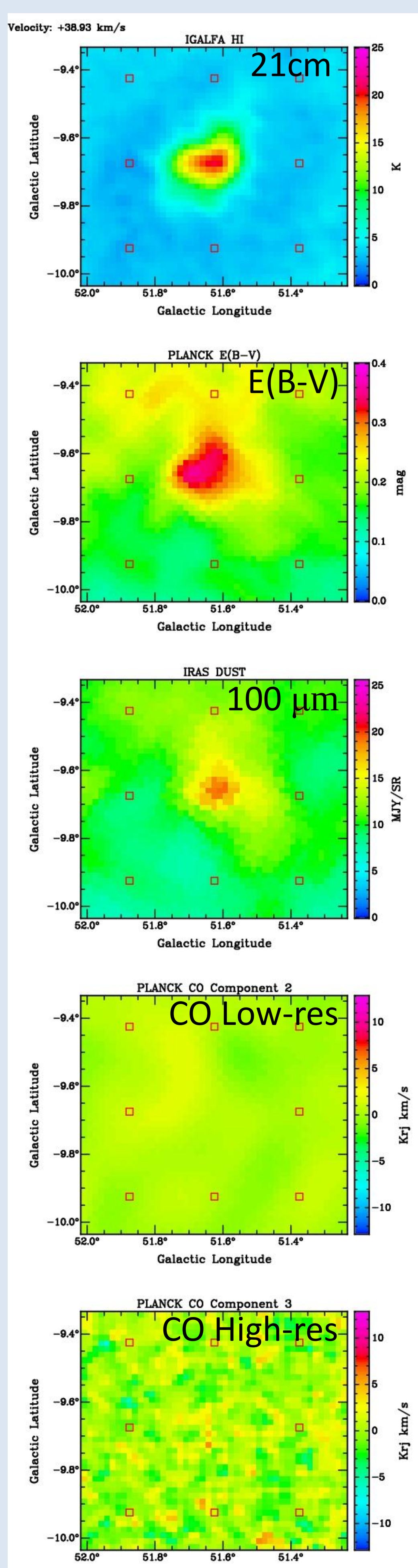

Figure 2 (from top to bottom):
Red boxes are off locations; images scaled to column densities of 2.3x10^{21} cm^{-2}

- Arecibo 21-cm IGALFA survey channel map of neutral atomic hydrogen
- *Planck* 850µm dust optical depth rescaled to *E(B-V)* reddening units
- *IRAS* 100µm map of dust emission as proxy for total gas column density
- *Planck* CO line integral maps of differing resolution and sensitivity as proxies for molecular hydrogen, which is not detected

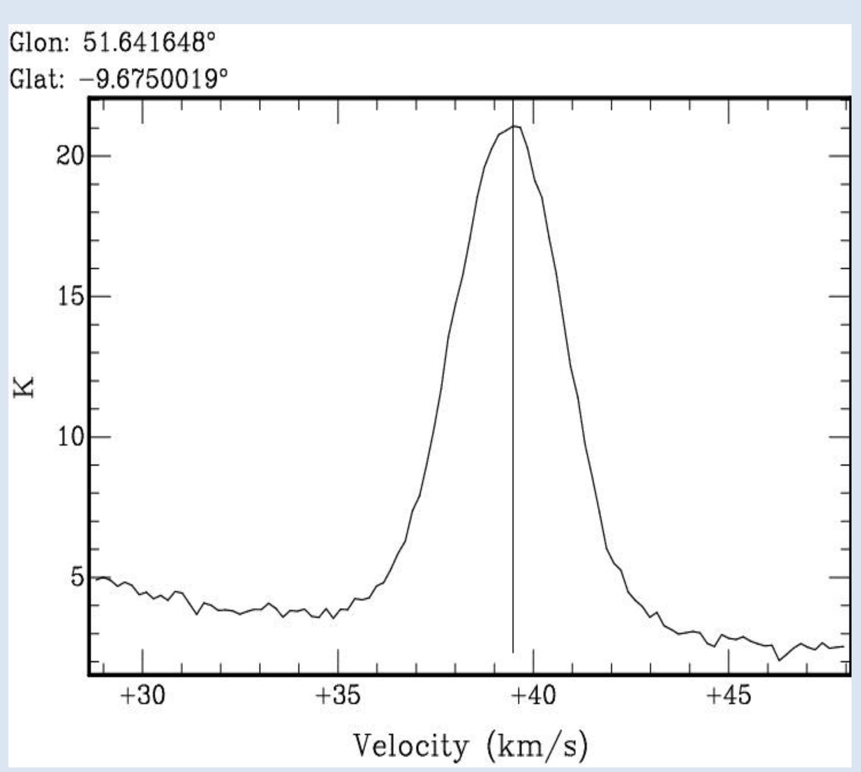

Figure 3: A narrow emission line, implying a cold temperature (less than 350 K), taken from the center of the feature mapped in Figure 2

$$T_K \leq \left(\frac{FWHM}{0.215\ \mathrm{km/s}}\right)^2$$

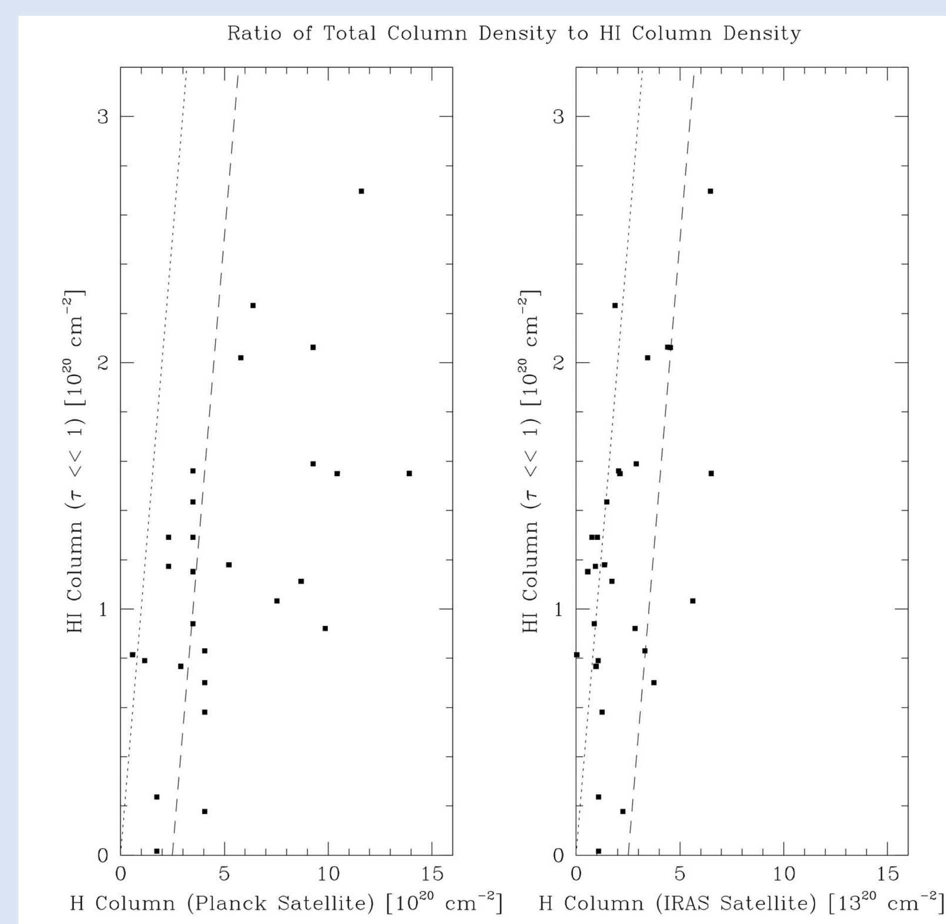

Figure 4: The features included in this graph have negligible CO content implying little to no molecular hydrogen as commonly measured. If so, the total gas column density traced by dust should equal that of the atomic hydrogen as shown on the dashed line. To account for noise, a dotted line at one standard deviation in CO measurements was included. Features to the right of these lines have dark gas (either molecular or optically thick HI).

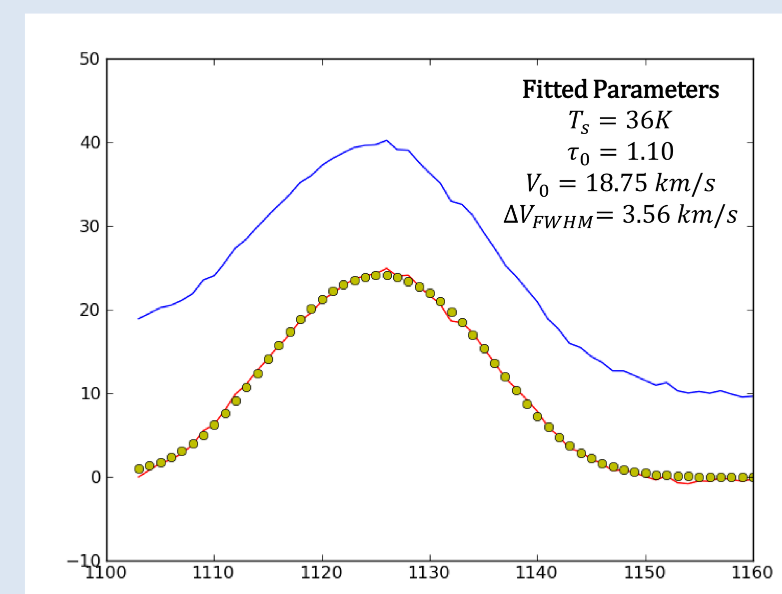

Figure 5: Modeling the feature. The x-axis is the velocity channel. The y-axis is the brightness temperature in kelvins. The blue line represents the observed line profile. The red line is the data with the background emission removed. The yellow dots are the resulting fit, which is not consistent with a large optical depth.

Equations Relating Observations to Column Densities

- $N_H \cong N_{HI} + 2\left(N_{H_2,CO} + N_{H_2,dark}\right)$
- $N_{HI,\tau\ll 0} = C_0 \int T_B(v)dv \leq N_{HI,all}\,;\ C_0 = 1.823 \times 10^{18}\,\frac{\mathrm{cm}^{-2}}{\mathrm{K\,km/s}}$
  - Dickey and Lockman(1990)
- $N_H = X_{EBV}E_{B-V};\ X_{EBV} = 5.8 \times 10^{21}\mathrm{cm}^{-2}\mathrm{mag}^{-1}$
  - Bohlin et al.(1978)
- $N_H = X_{I_{100}}I_{100};\ X_{I_{100}} = 0.9 \times 10^{20}\mathrm{cm}^{-2}(\mathrm{MJy/sr})^{-1}$
  - Reach et al.(1994)
- $N_{H_2,CO} = X_{^{12}CO} \int T_{B,^{12}CO}(v)dv\,;\ X_{^{12}CO} = 1.8 \times 10^{20}\mathrm{cm}^{-2}(\mathrm{K\,km/s})^{-1}$
  - Dame et al.(2001)

Results:

There is clear evidence that some cold clouds contain dark gas. Preliminary 21cm line fits (Fig. 5) imply that most of this dark gas is hidden H_2 because the HI line shapes do not appear greatly saturated.

Future and Current Work:

The modeling is not yet complete. We are investigating potential biases in the column conversion methods and line fitting algorithms to improve the confidence in our results.

References:

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