OH as an Alternate Tracer for Molecular Gas in the Galaxy

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We study OH 18 cm lines as an alternate tracer for molecular gas in the Galactic ISM using the Green Bank Telescope. A major motivation is to trace "CO-dark" molecular gas. OH appears to be a viable tracer for molecular gas including CO-dark gas. We study the molecular gas content of a quiescent region and the W5 star-forming region using OH and compare to CO data. We find that CO-dark gas occurs in lower volume density regions, and that volume density is the primary distinction between CO-bright and CO-dark portions of the ISM.

CO-Dark Gas and OH 18 cm Lines

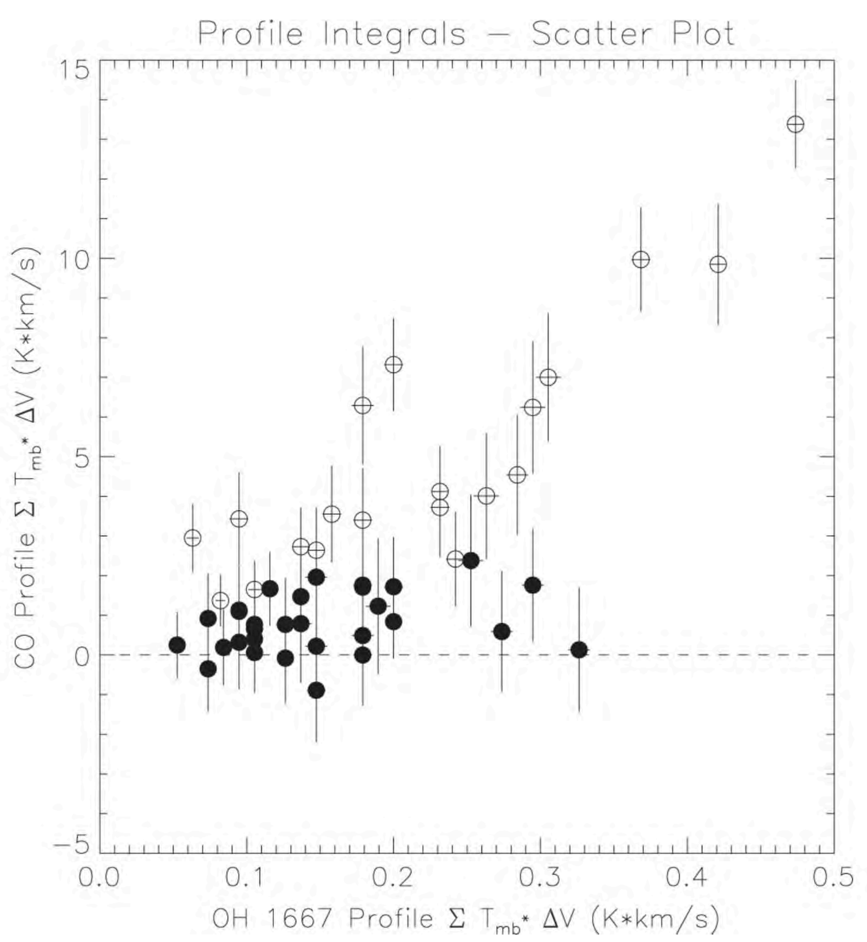
This work is part of a project studying the OH 18-cm transition as an alternate tracer for molecular gas in the Galaxy. Since the majority of the cold, diffuse molecular ISM, H_2, is generally undetectable, we typically use CO(1-0) as a tracer.

Evidence suggests CO-dark molecular gas is present in the ISM (see e.g. Grenier et al. 2005): hidden molecular gas that is not detected in CO surveys

We are trying OH 18 cm lines as an alternate molecular gas tracer, using the Green Bank Telescope with long exposure times.

We have found (see Allen et al. 2015, Busch et al. 2019) that in quiescent regions of the Galaxy towards the outer Galaxy, **OH traces a larger component** of the cold, diffuse molecular ISM than does CO

This indicates a greater mass of molecular gas in the ISM than typically assumed, **roughly doubling the total molecular gas content.**

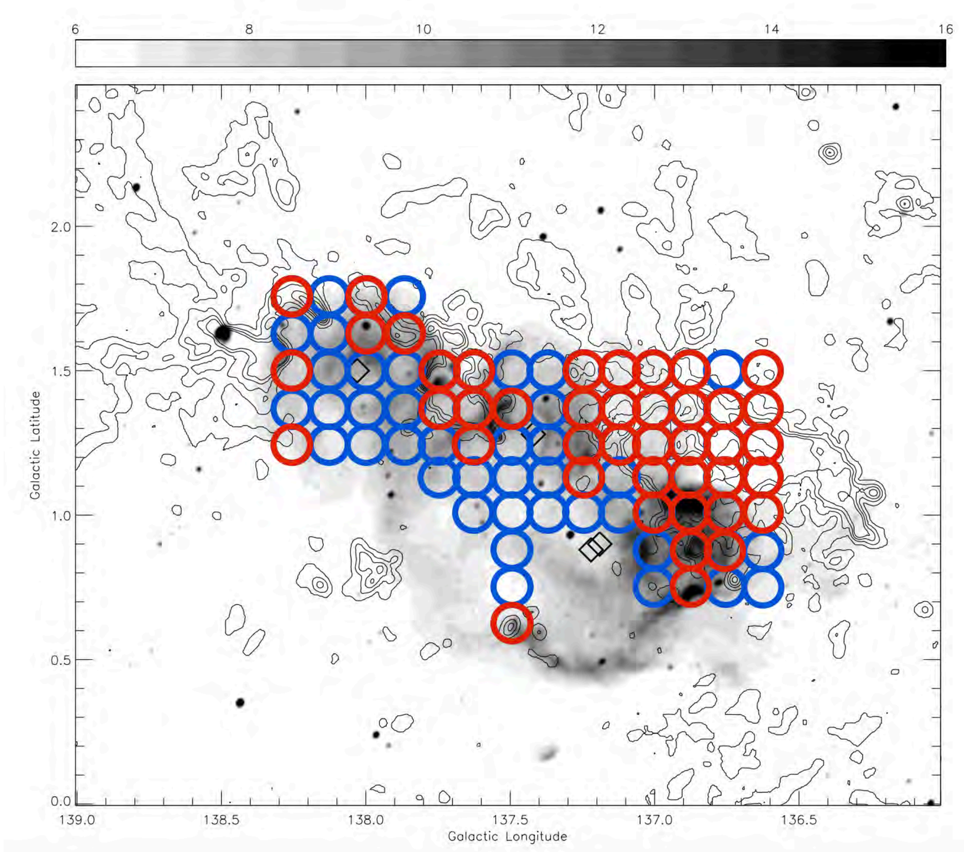


Allen et al. 2015 Figure 10. Scatter plot of OH 1667 MHz emission line strength (X-axis) and the 12CO(1-0) line strength (Y-axis) integrated over the same velocity ranges. The open and filled circles together show all OH features with line strengths in excess of 8σ. Points denoting 12CO(1-0) data for which the CfA CO line strength is within 2σ of the CO zero line are shown as filled circles.

W5 Star-Forming Region Survey

Structure:

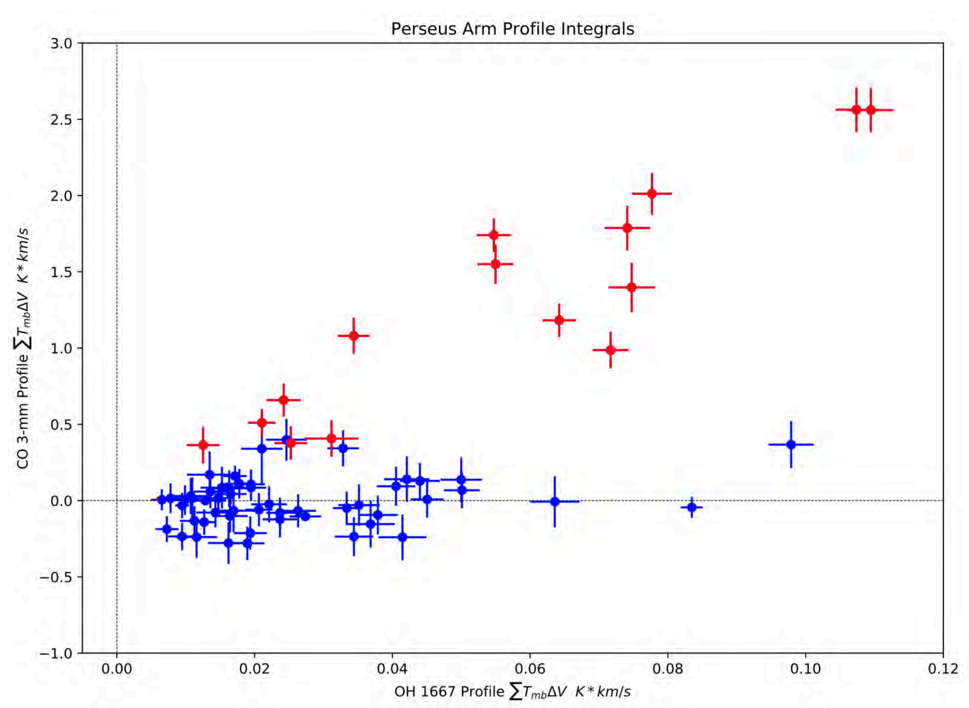
We performed a Green Bank survey of OH in the W5 star-forming region.



Engelke and Allen (2019). Blue circles: GBT observation, no OH detection. Red circles: GBT observation, OH detection. Grayscale: 1420 MHz continuum. Contours: CO(1-0) profile integral at W5 radial velocity range

OH and CO both describe **similar morphology** of molecular gas in W5—pointings containing one molecule contain a detection of the other.

This is **different from our quiescent region** surveys, where OH is often detected without corresponding CO.



Busch et al. (2019) One Square Degree survey results. Note that the CO in this case has lower uncertainties because it comes from the Heyer et al. (1998) survey. The entire range of this plot fits in the bottom left corner of the range of the Allen et al. (2015) plot (note the axis scales), showing that CO-dark gas is detected at smaller scales (left) as well as larger scales (right).

Excitation Temperatures

To calculate column densities from observed emission or absorption lines in W5, we must know excitation temperatures.

We tried two methods to measure excitation temperatures: the traditional "expected profile method" and the "continuum background method" making use of the varying continuum behind the W5 survey. We found that the excitation temperature is different for the two main lines by 0.8 +/- 0.3 K (Engelke and Allen 2018, 2019).

Modeling with line excitation code molpopCEP (Asensio Ramos and Elitzur 2018) indicates that measuring the difference in OH main line excitation temperatures can be a **new way to probe volume density and kinetic temperature** of molecular gas purely from OH observations.

Mass:

For column densities, only emission lines provided useful information. We found that absorption lines underestimate column densities by 1-2 orders of magnitude. We have a model explaining why this happens based on high resolution structure and filling factors within the GBT beam, but future research can test this explanation.

Ignoring coordinates that have OH in absorption at both main lines:

CO says: 9.9 (+/- 0.7) x 10^3 $M_\odot$

OH says: 1.7 (+ 0.6 or – 0.2) x 10^4 $M_\odot$

Total W5 mass estimate for all coordinates: ~ 4 $\pm$ 2 x 10^4 $M_\odot$

Region	Best Estimate Average Molecular Gas Volume Density (cm^{-3})
W5 Star-forming Region	450 $\pm$75
CO-Bright Portion of One Square Degree Detections	170 $\pm$60
CO-Dark Portion of One Square Degree Detections	<100 $\pm$15

This is consistent with a **volume density-based** explanation for the presence or absence of CO-dark gas. CO-dark gas appears to be present in vast reservoirs in the ISM, but in regions of lower density, primarily located outside of star-forming regions.

It also seems that volume density is the primary distinction between the properties of W5 and the quiescent region, more so than mass, which are less distinct.

Volume Densities

We use a diffuse cloud model developed by Neufeld and Wolfire (2016) to model average gas volume densities for the W5 star-forming region, the CO-bright portion of the quiescent region, and the CO-dark portion of the quiescent region.

Average volume density estimates:

W5: 450 $\pm$ 65 cm^{-3}

Quiescent region: ~ 100 $\pm$ 50 cm^{-3}

Rough mass estimates:

W5: ~ 4 $\pm$ 2 x 10^4 $M_\odot$

Comparable size area in quiescent region: ~ 2 $\pm$ 1 x 10^4 $M_\odot$

Conclusions

OH is a viable tracer for molecular gas, including CO-dark molecular gas. CO-dark gas is a significant portion of Galactic baryonic mass content, roughly doubling known molecular gas mass. CO-dark molecular gas can be explained as a low volume density effect. Molecular gas exists in vast reservoirs both inside and outside of star-forming regions, but conditions in star-forming regions and denser parts of the ISM are more amenable to tracing molecular gas using CO(1-0). OH can help us expand our understanding with a fresh perspective.