OH as an Alternate Tracer for Molecular Gas: A Study in the W5 Star-forming Region

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History: Millstone Hill Observatory, 1963

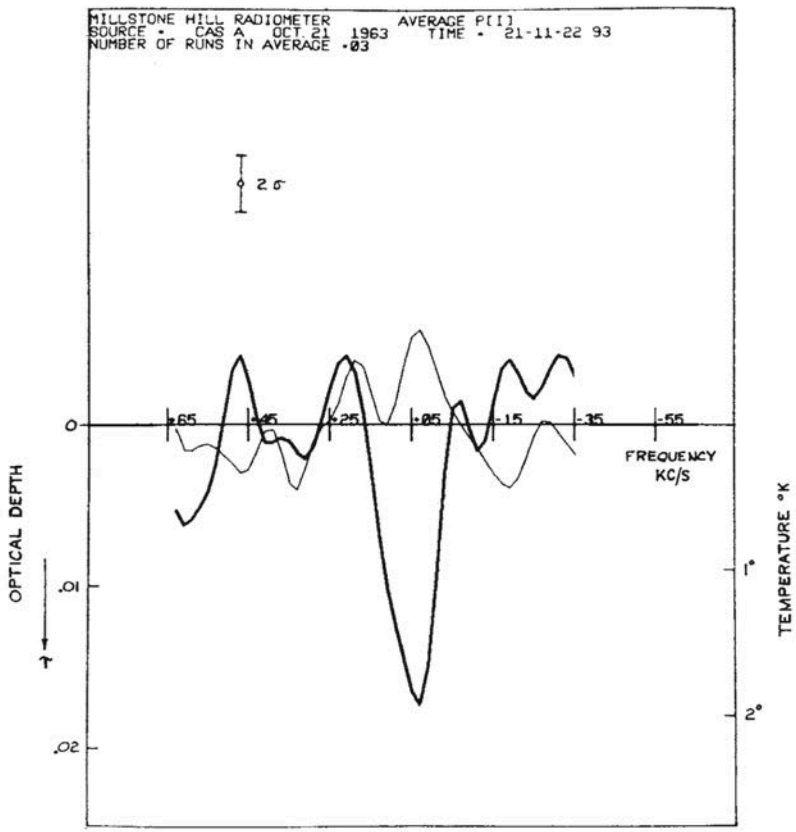


Fig. 1. Observed 1,667 Mc/s OH absorption spectrum in Cassiopeia *A*. The heavy line shows 8,000 sec of data taken with the antenna beam directed at Cassiopeia *A*, and the light line shows 6,000 sec of data taken with the beam displaced slightly from Cassiopeia *A*. The frequency scale is specified in kc/s with respect to the local standard of rest assuming the line rest frequency to be 1,667,357 kc/s

First radio detection of an interstellar molecule: OH 18-cm

Weinreb et al. (1963) *Nature* 200, 829

Right here, in Westford, Massachusetts!

Today, we'll revisit OH as an alternate molecular gas tracer

Tracing Molecular Gas

To find molecular gas, we need a tracer: a molecule mixed with the H_2 in smaller quantities

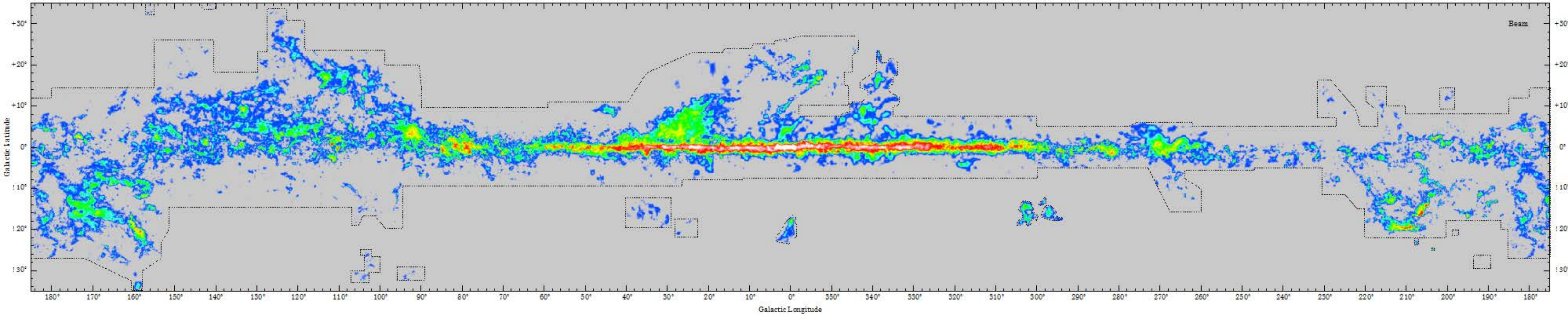
Typically, we use CO(1-0), which has a strong emission signal

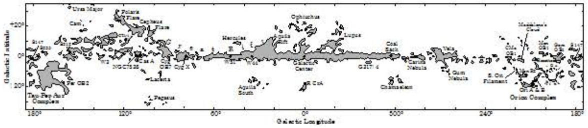
CO X-factor method to estimate column densities from profile integrals (because line is optically thick)

X-factor is determined by: velocity dispersion of a CO cloud → mass of CO cloud by virial theorem

Also can be estimated using IR from dust, as well as gamma rays from cosmic ray interactions with hydrogen

CO as a Tracer for Molecular Gas





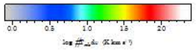


FIG. 2.—Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

From Dame et al. (2001)

Limitations of CO as a Molecular Tracer

CO(1-0) is optically thick, so cannot calculate column densities directly, requires X-factor assumptions

CO(1-0) may not trace the less dense parts of the ISM: critical density ~ (10^3 cm^{-3})/τ

Might there be significant amounts of diffuse molecular gas not dense enough to be traced by CO?

Wolfire et al. (2010): There could also be chemical reasons for no CO in some molecular gas

“Dark” Gas in ISM

Meanwhile, a mystery…

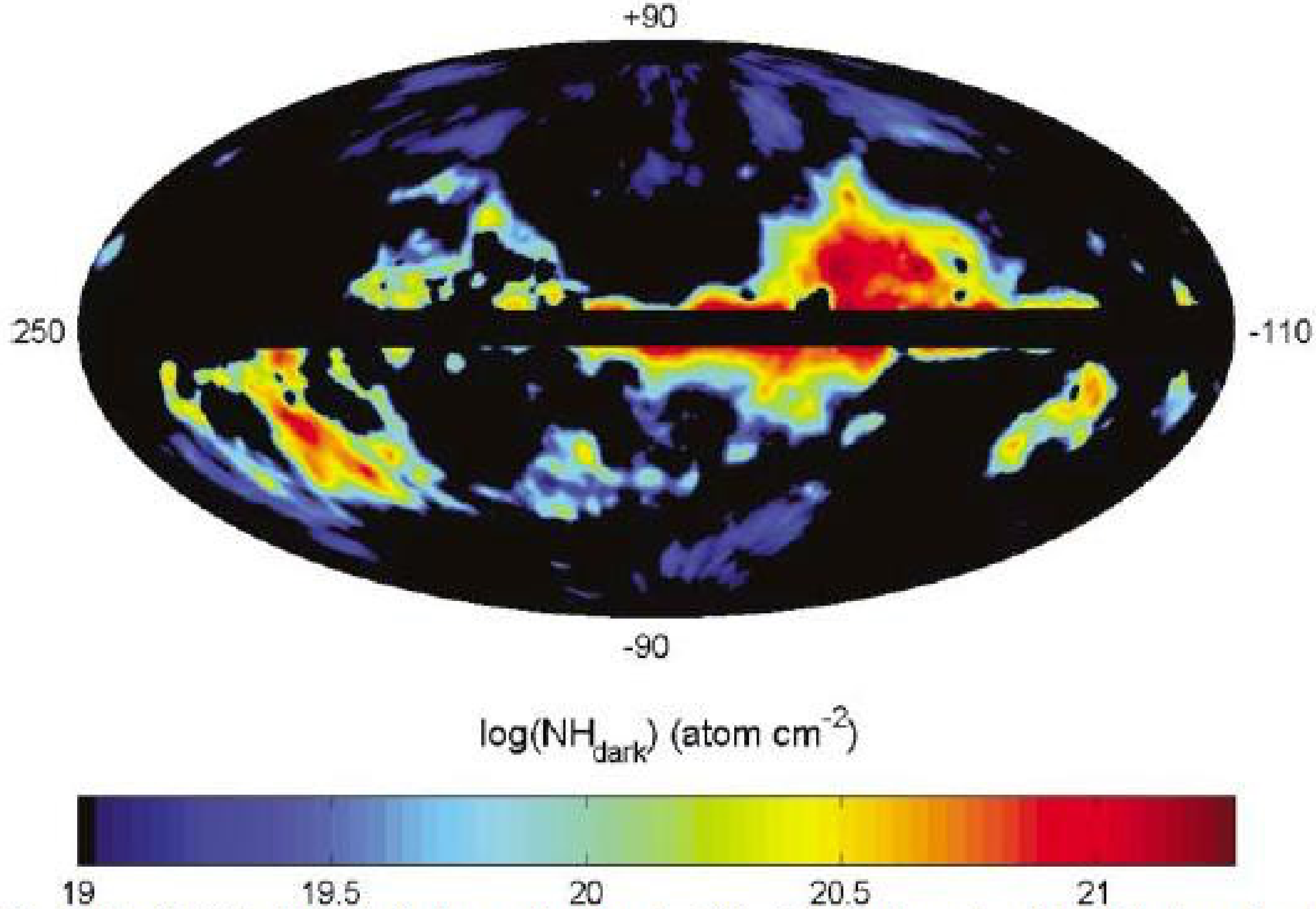
Grenier et al. (2005), Tibaldo et al. (2015): there is “dark” gas in the ISM that we are not seeing

1) Far-IR Emission: evidence of dust in regions without CO emission
2) X-Ray and Gamma-Ray Emission: evidence of cosmic ray collisions with hydrogen nuclei in regions without CO emission

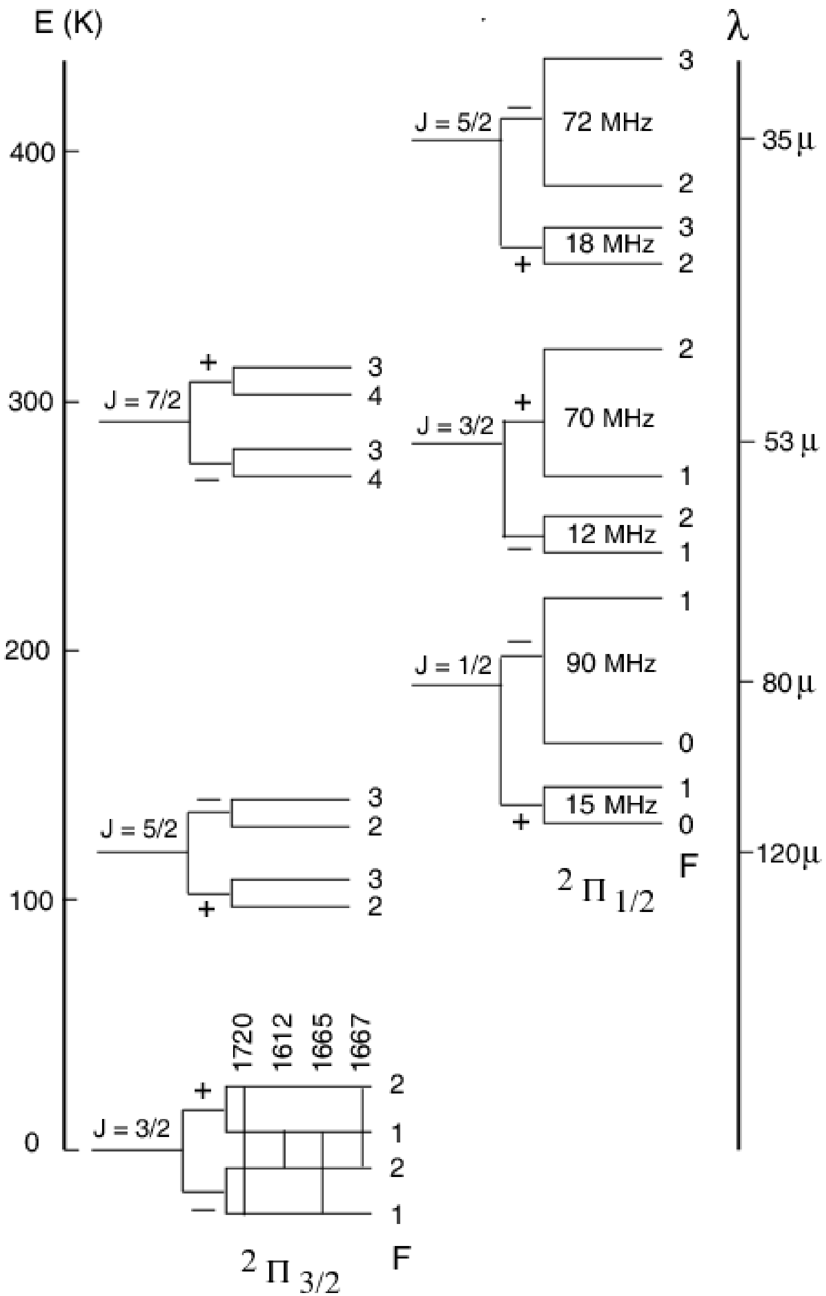
Also, C+ emission is enhanced, implying higher collision rates due to dark gas (Langer et al. 2014, Wiesenfeld & Goldsmith 2015)

Could this “dark” gas be diffuse molecular gas not dense enough to be traced by CO?

“Dark” Gas Distribution as Traced by Gamma Rays



From Grenier et al. (2005)



OH Energy Levels

Using Einstein coefficients, Boltzmann distribution partition function, ratio is

1:5:9:1 for 1612, 1665, 1667, 1720 MHz

Excitation Temperature Definition

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{\frac{-h\nu}{k_B T_{ex}}}$$

From Lockett and Elitzur (2008)

OH as a Molecular Gas Tracer: Benefits over CO

Historically, OH emission was infeasible as a molecular tracer because it was too faint, but now we can detect it.

And OH emission has some benefits over CO emission as a tracer:

Optically thin—this means we can calculate column densities directly.

Critical density is lower:

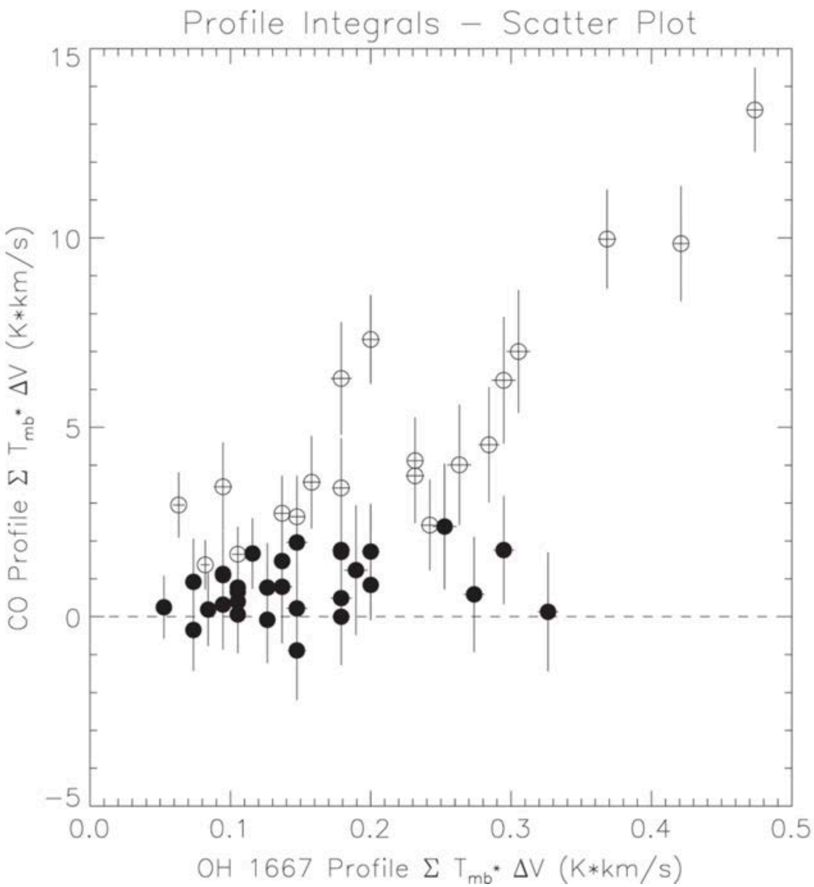
OH critical density ~ 10 cm^{-3}

as compared to CO's critical density ~ (10^3 cm^{-3})/τ

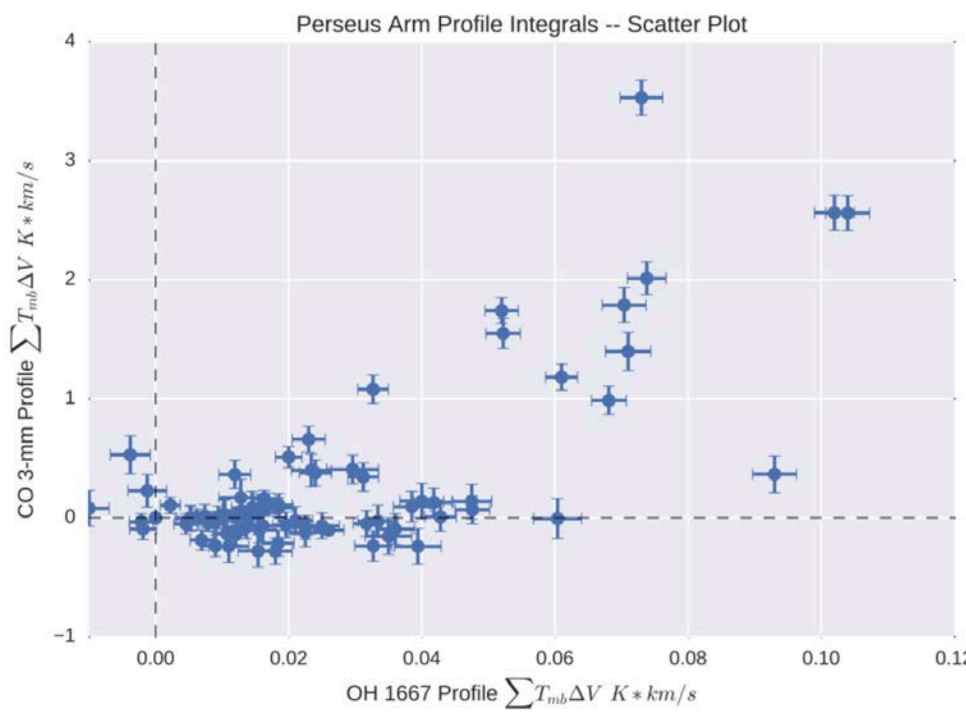
This means OH might help us find out if the "dark" gas is just "CO-dark" molecular gas!

OH 18-cm Surveys to Trace Molecular Gas towards the Outer Galaxy

Allen et al. (2015):



Busch et al. (in prep)



What about Star-forming Regions?

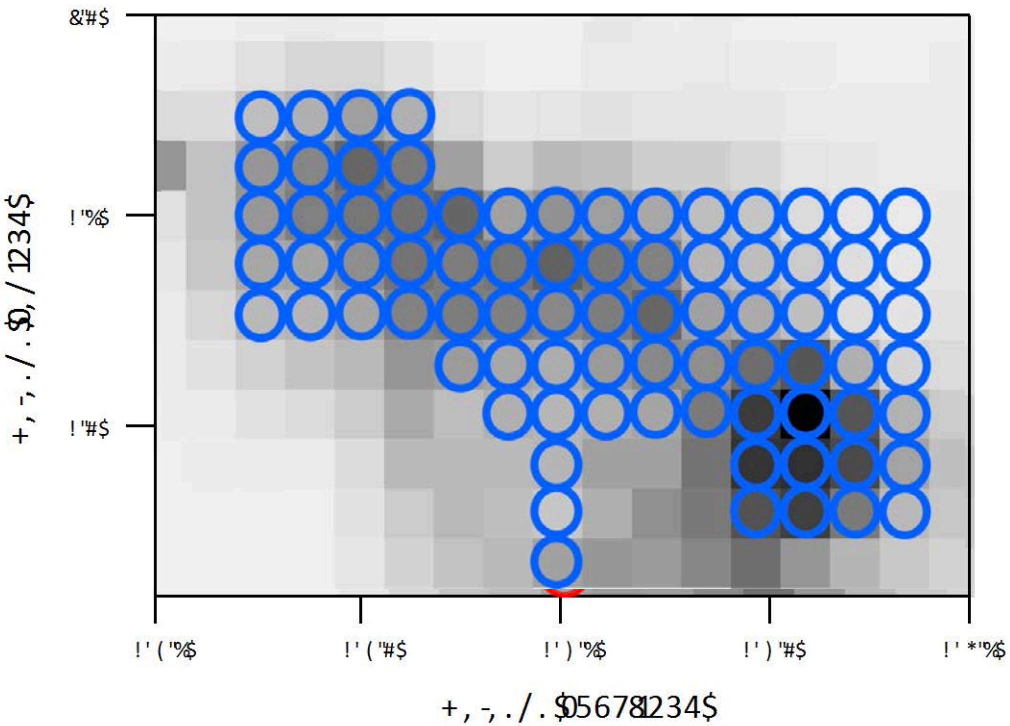
How do molecular clouds in star-forming regions compare to molecular clouds in quiescent regions?

CO tells us one story

- More molecular gas in star-forming regions, and this higher abundance is believed to cause the star formation

What kind of “second opinion” does OH give us?

W5 OH Survey Map



Pointings for GBT OH survey over W5.

Background is smoothed version of 1420 MHz continuum from Taylor et al. (2003)

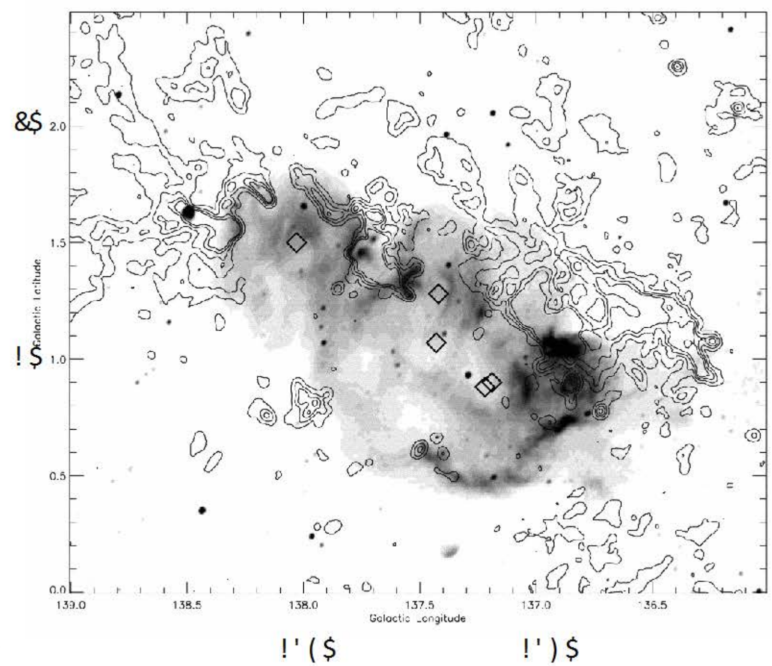


Fig. 2 from Karr & Martin (2003), showing W5.

-Grayscale is 1420 MHz continuum,
-Contours are CO(1-0) between -31 and -49 km/s,
-Diamonds are O and B stars.

Green Bank Telescope (GBT)

100 m radio telescope located in National Radio Quiet Zone in West Virginia

FWHM ~ 7.6’

Used Gregorian Receiver, 1.15-1.73 GHz L-band

Frequency Switching to remove instrumental signature

2 hours per pointing

Calculating OH Column Densities

$$N(OH) = 2.3 \times 10^{14} \frac{T_{ex}}{T_{ex} - T_C} \int \phi(v)\,dv$$ Emission

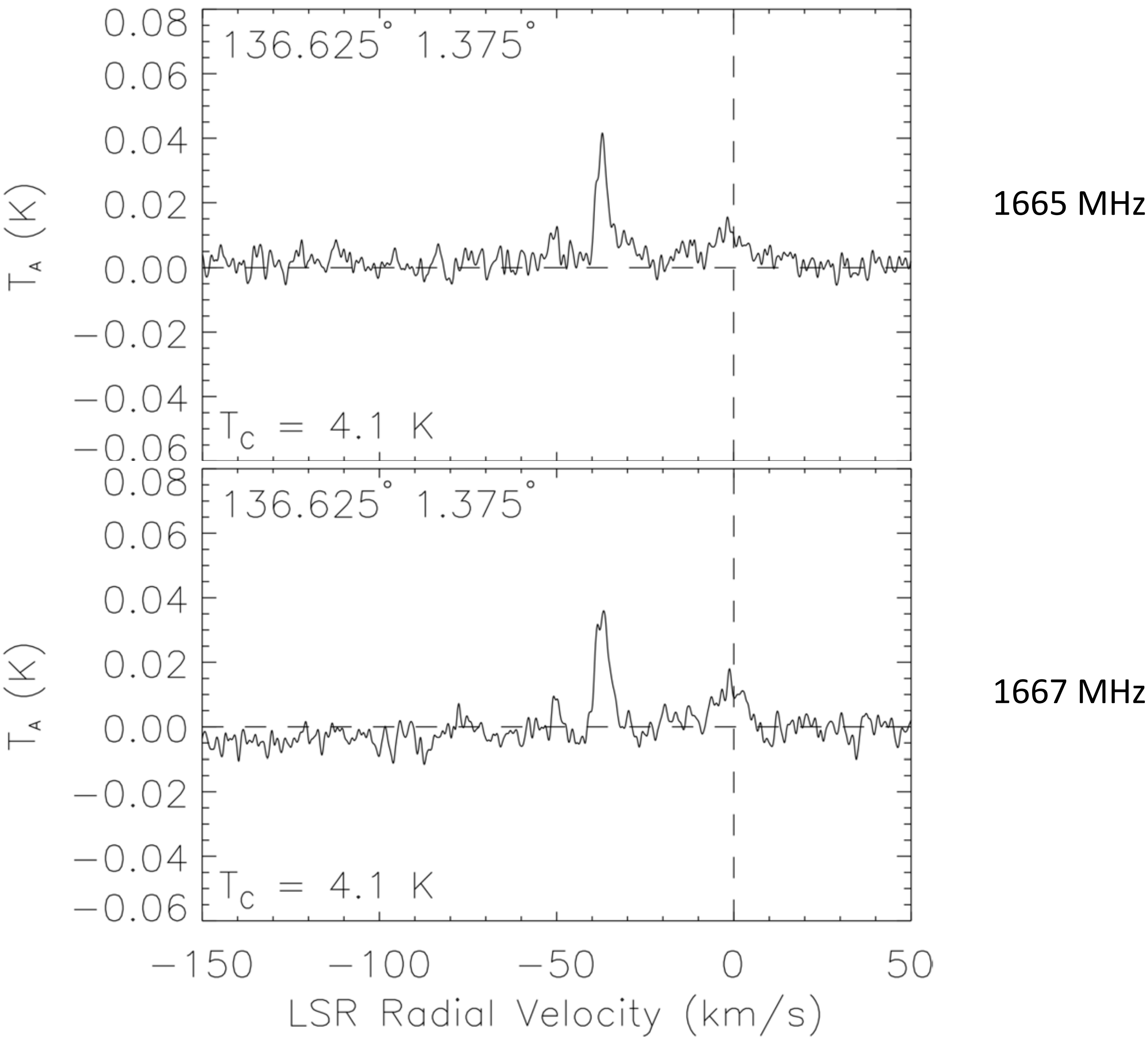
$$N(OH) = 2.3 \times 10^{14} T_{ex} \int \tau(v)\,dv$$ Absorption

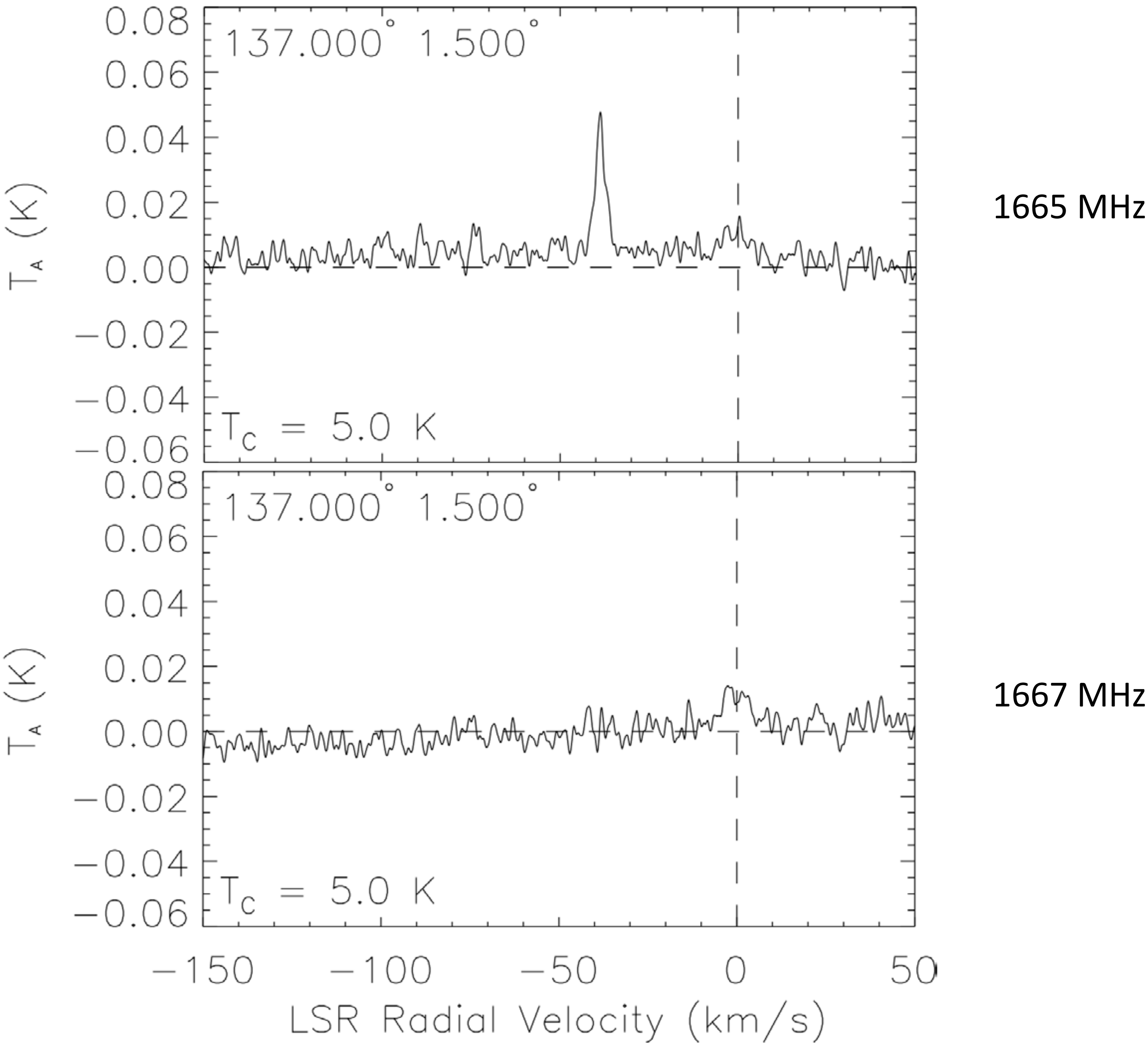
We need to know:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{\frac{-h\nu}{k_B T_{ex}}}$$

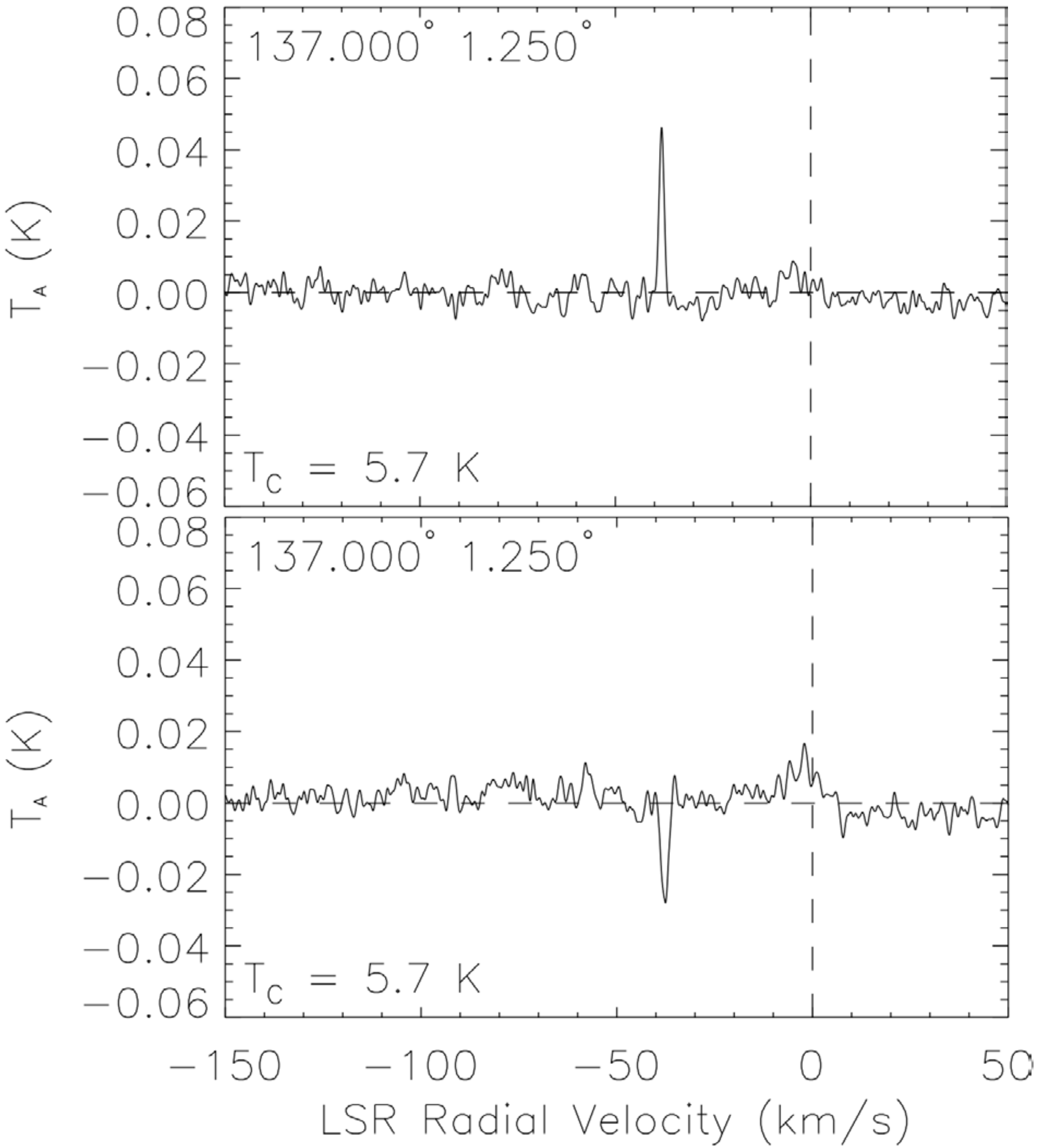
1) Integral under spectral lines
2) Continuum temperature
3) Excitation temperature

From OH column densities, we can estimate total molecular column densities using $N(H_2)/N(OH)$ ratio of 10^7 from UV absorption data (Weselak et al 2010)


136.625° 1.375°
T_C = 4.1 K
136.625° 1.375°
T_C = 4.1 K
T_A (K)
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−150
−100
−50
0
50
LSR Radial Velocity (km/s)
1665 MHz
1667 MHz

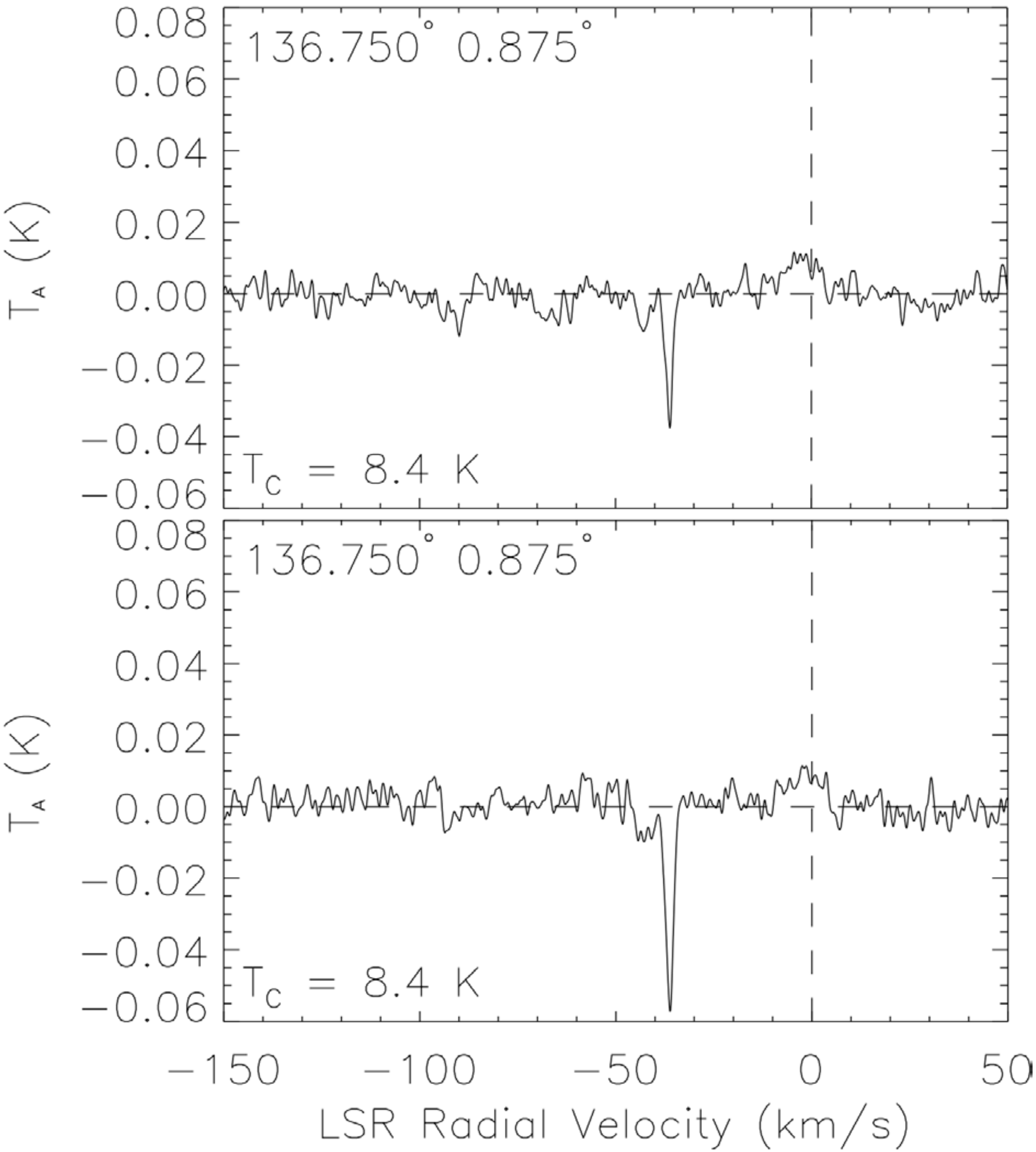


137.000° 1.500°
T_A (K)
T_C = 5.0 K
1665 MHz
137.000° 1.500°
T_A (K)
T_C = 5.0 K
1667 MHz
LSR Radial Velocity (km/s)



1665 MHz

1667 MHz



1665 MHz

1667 MHz

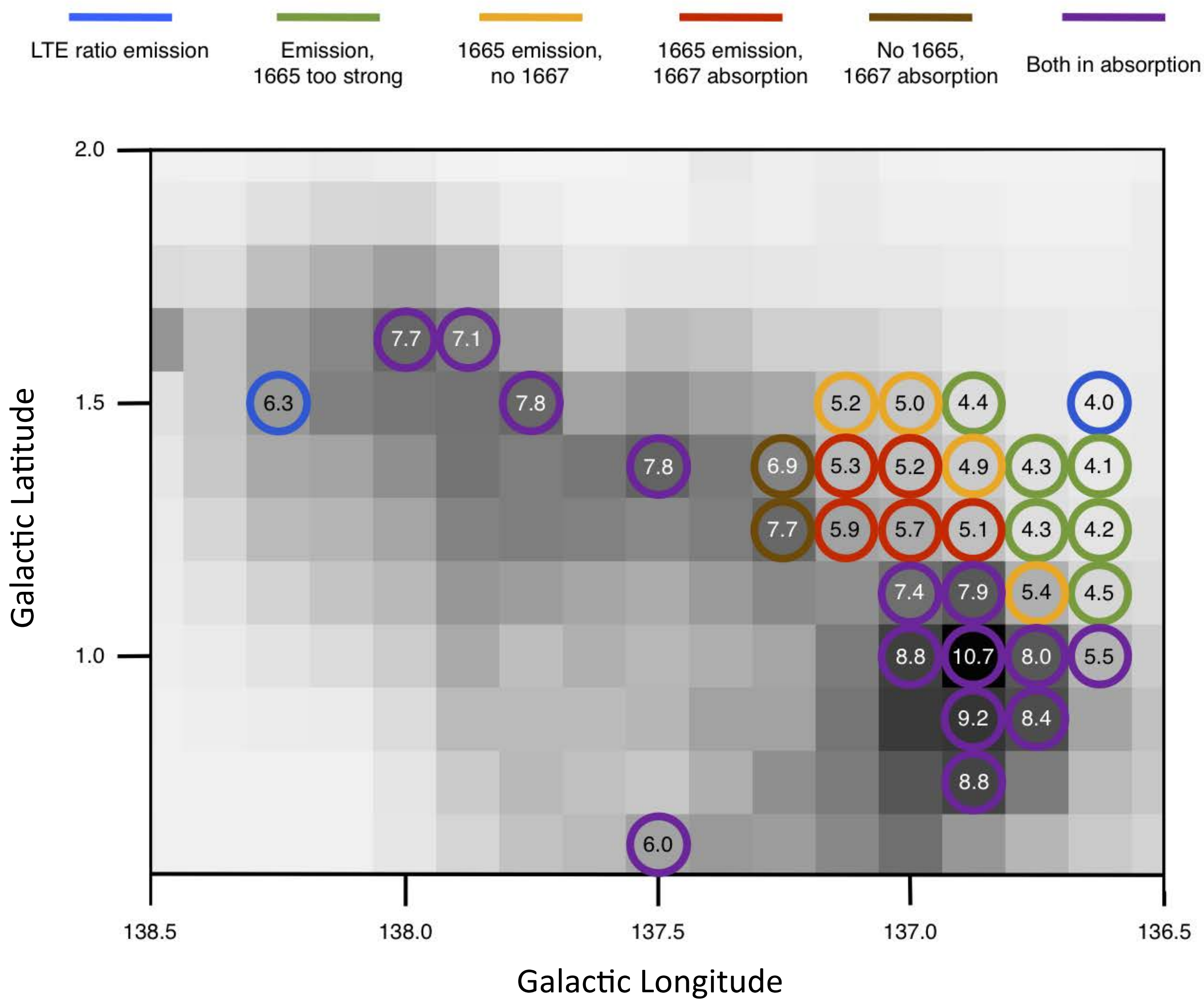
Main Line Excitation Temperature Difference

Seven-sigma result that $T_{ex\_1665} > T_{ex\_1667}$

Consistent with findings in the literature (e.g. Crutcher (1979, Tang et al. 2017) but there had been a lack of consensus on this.

Our new result confirms this definitively.

OH Detections in W5



Excitation Temperatures Summary

The Continuum Background Method and Expected Profile Methods were both tried

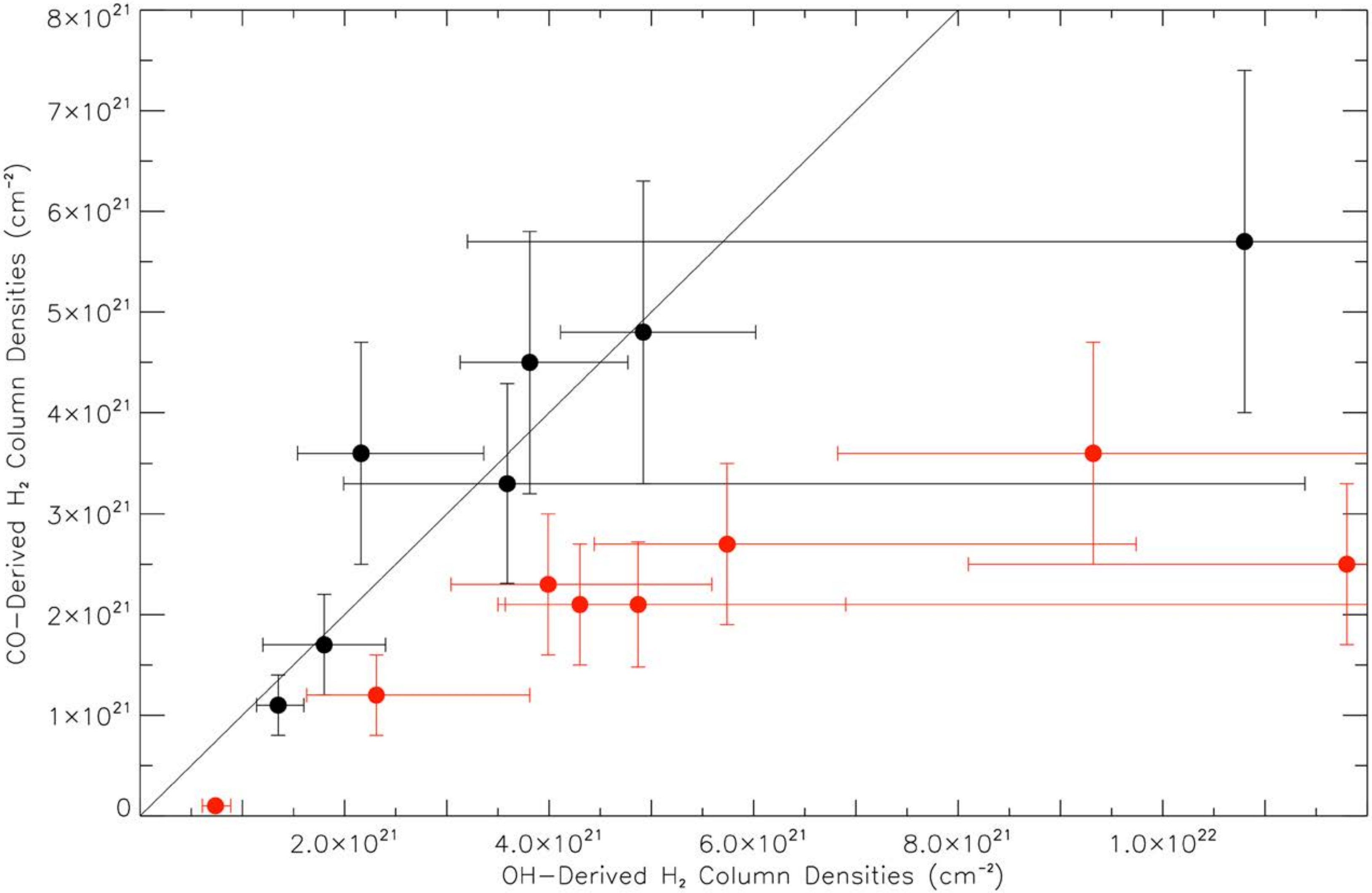
The Continuum Background Method provided more precise results, and demonstrated unequivocally that $T_{ex\_65} > T_{ex\_67}$

Further Constraints can be made by analyzing filling factor effects

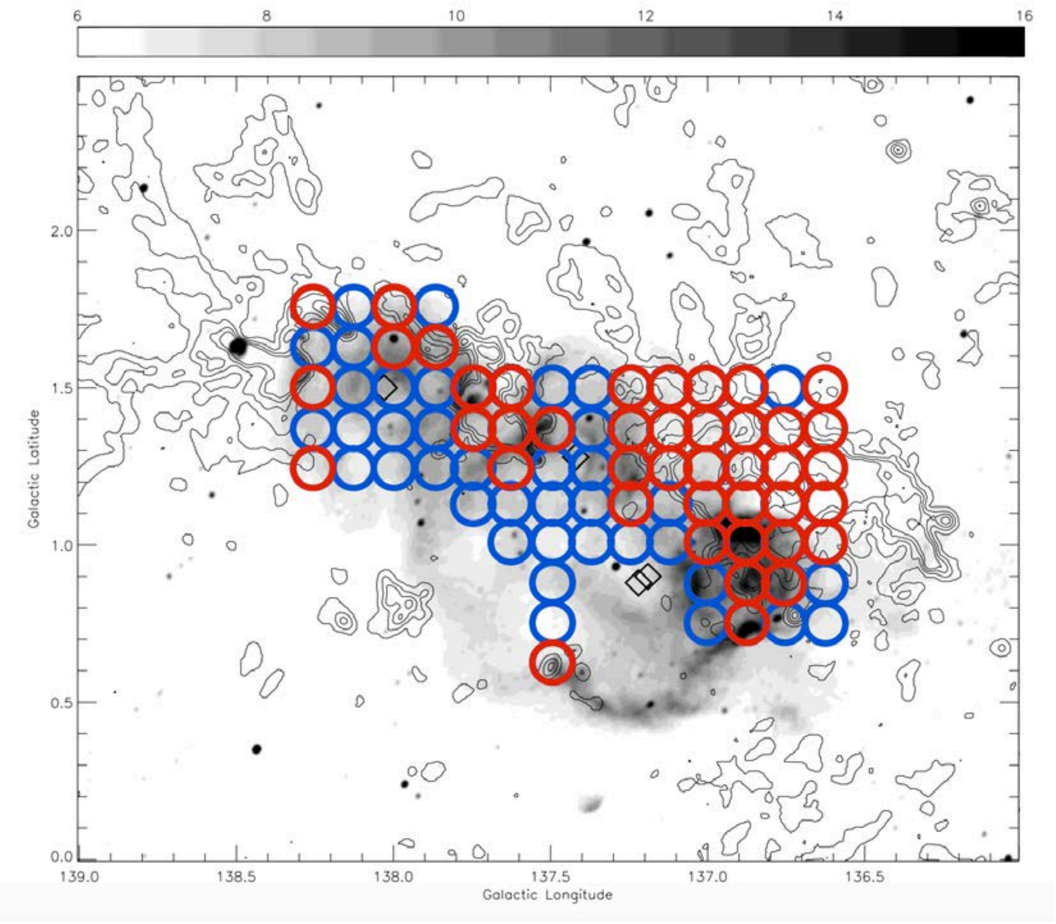
T_{ex_1665} = 5.87 + 0.43 or - 0.37 K
T_{ex_1667} = 5.13 + 0.17 or - 0.23 K

Why? Most likely from differences in collisional cross sections. Modeling using molpopCEP08-TD code (Asensio Ramos & Elitzur 2018) are able to reproduce the finding

Comparison of Molecular Gas Column Densities: All Features Containing OH Emission in Some Form



OH Detections in the W5 Survey superimposed on Karr and Martin (2003) Figure 2



Blue Circle: GBT observation, no OH detection

Red Circle: GBT observation, OH detection

Grayscale: 1420 MHz continuum

Contours: CO(1-0) profile integral within -49 and -31 km/s

Problems with using Absorption Data

The difference in T_{ex} between the main lines gives us a convenient test of absorption line reliability:

Five pointings contain emission at 1665 MHz, but absorption at 1667 MHz

These are the same coordinates and same field of view, so N(OH) should be equal for both

Result: absorption lines systematically give N(OH) values 1-2 ORDERS OF MAGNITUDE less than corresponding emission lines

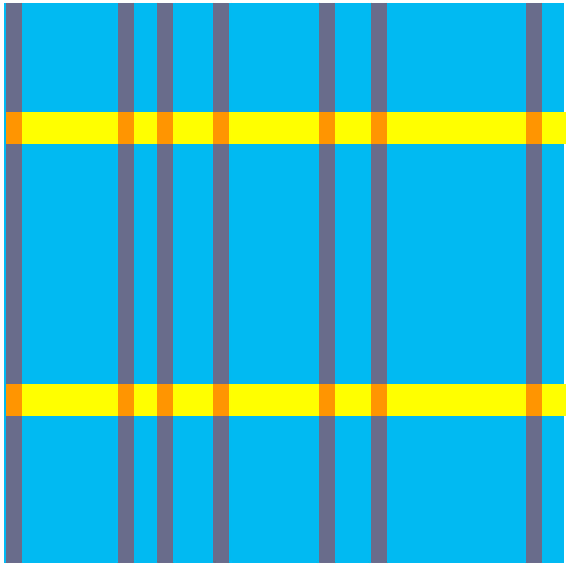
Absorption Filling Factor Model

Can this discrepancy be explained by filling factor effects?

Create a model - simulate a field of view

-Stripes of two values of T_C (High: $T_C > T_{ex}$, and Low: $T_C < T_{ex}$)

-Independent set of stripes of two values of N(OH)



Blue = Low T_C and low N(OH)

Red = High T_C

Yellow = High N(OH)

Absorption occurs at the red/yellow overlap (orange)

Absorption Filling Factor Model

Two major reasons why absorption under-predicts N(OH):

1) For a given OH distribution, only the portions that overlap with elevated T_C appear in absorption, and clouds can have ”fractal”-like morphologies

2) Within a field of view, there may be a mixture of emission (where T_C is low) and absorption (where T_C is high). The beam averaged T_C may be above T_{ex} and the beam-averaged profile may be in absorption, but the emission included in the beam average will reduce the strength of the beam-averaged absorption profile

The model can also help us measure a rough estimate of the filling factor that yields the appropriate results,
Roughly a few to 10%

OH as a Second Opinion on W5 Molecular Gas Content

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

- This is different from our quiescent region surveys, where OH is often detected without a corresponding CO detection

What is the molecular gas content of W5? Considering the region within our survey,

Ignoring pointings 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 $M_\odot$

This means that OH traces **roughly twice** the amount of molecular gas that CO does in W5, using the standard CO X-factor.

The total mass is greater, of course, because half the OH detections were in absorption at both main lines, and were not used for column densities

Conclusions

1) Precise OH 18-cm Excitation Temperatures Measured in W5 using Continuum Background Method

2) $T_{ex\_1665} > T_{ex\_1667}$ with 7-sigma confidence in W5

3) OH Traces Greater Column Density of Molecular Gas than does CO in 8 out of 15 cases containing OH emission in W5

4) OH and CO Morphologies are Nearly Identical.

5) OH Traces 1.7 (+ 0.6 or – 0.2) x 10^4 $M_\odot$ of H_2 while CO traces 9.9 (+/- 0.7) x 10^3 $M_\odot$ of H_2

6) OH Absorption Underestimates Column Densities by 1-2 Orders of Magnitude in this survey, model explains it as resulting from filling factor effects. Filling factor of OH appears to be ~ a few to 10 %

Thank You

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Excitation Temperatures: Expected Profile Method

Traditional method to estimate excitation temperatures in front of extragalactic continuum sources (see Lucas and Liszt 1996)

$$T_{ex} \approx \frac{T_L}{\tau} + T_C$$

Check results from the continuum background method

Want to see OH absorption in front of extragalactic continuum sources, and emission in surrounding region

Chose compact background sources in W5 field from NVSS catalogue

Expected Profile Method: VLA Component

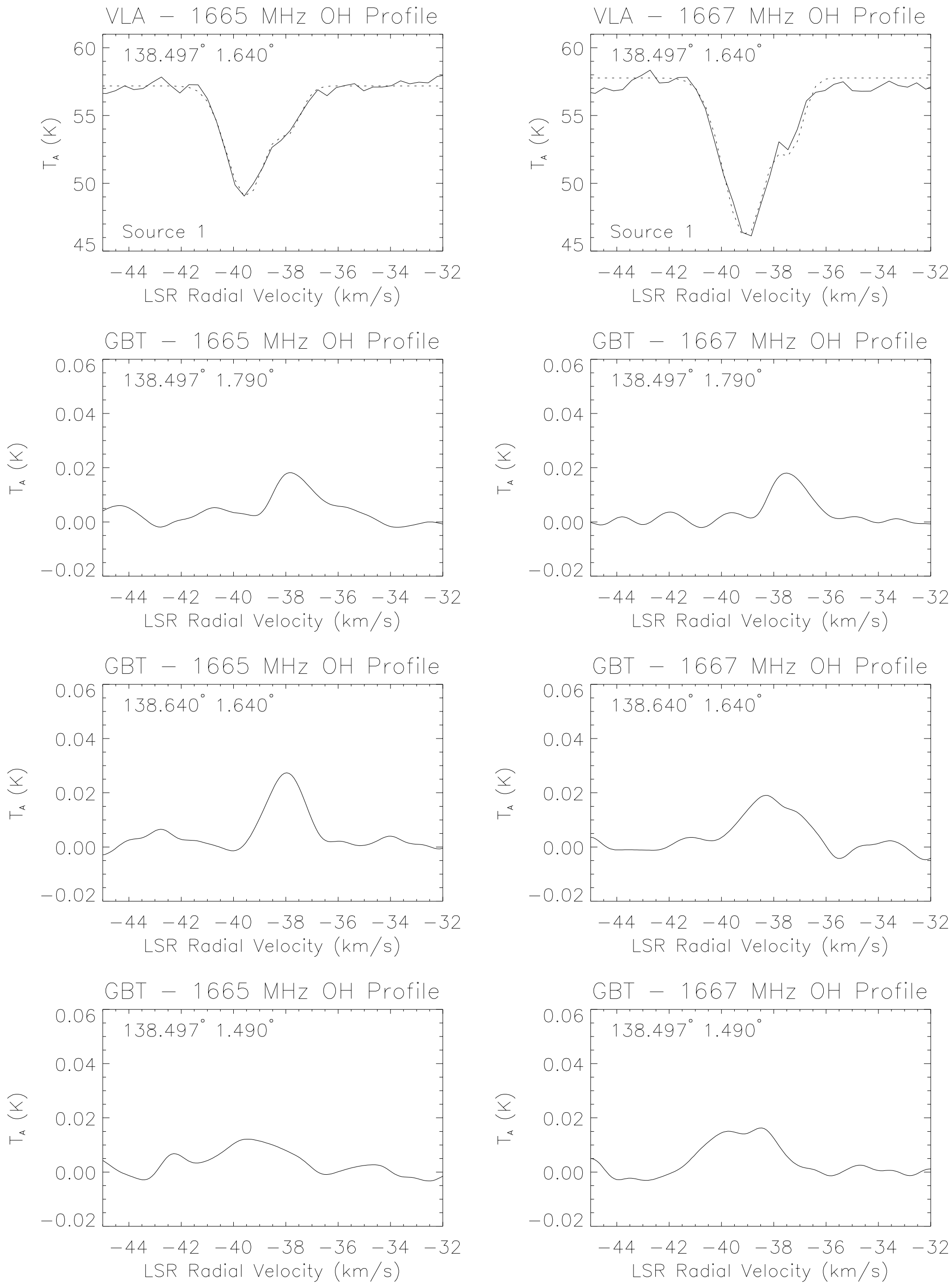
The Very Large Array (VLA) in New Mexico can observe OH absorption in front of extragalactic sources

Used D array configuration

46 arcsecond resolution

(0.77 arcminutes)

Also D=>C hybrid configuration



Expected Profile Method Results

Higher uncertainty than Continuum Background Method

Results:

$4K < T_{ex\_1665} < 6.4$ K
$4K < T_{ex\_1667} < 6.2$ K

Consistent with Continuum Background Method Results, but less conclusive

Emission-Emission Cases: OH Column Densities as Calculated from 1667 MHz Emission and from Corresponding 1665 MHz Emission