Wide-Area Studies of 18-cm OH Emission: A New View of Galactic Structure as Seen in Low-Density Molecular Gas

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NRAO

Why OH? - I

- **OH is ubiquitous in the Galactic ISM:**
  - The L-band radio lines of OH were initially detected in **absorption** (Weinreb et al 1963), and OH absorption was later found to be widely observable in the Galaxy (e.g. Goss 1968; Turner 1979).
  - OH **emission** with anomalous properties was subsequently found near star-forming regions (Weaver et al 1965) and later identified as a maser phenomenon (see e.g. Reid & Moran 1981 for a review).
  - Steady advances in L-band receiver sensitivity have recently shown that **non-maser OH emission** can also be widely observed in the Galaxy in regions largely devoid of bright radio continuum emission and active star formation (Allen et al 2012, 2013; Dawson et al 2014).
  - This faint, ubiquitous OH emission can be detected at both 1665 and 1667 MHz (Allen et al 2015) and appears to be approximately in LTE, thereby simplifying the interpretation of the observations.

Why OH? - II

- **OH is a molecular tracer:**
  - OH provides a view of the ISM that is complementary to that seen in CO(1-0) emission.
  - With sufficient S/N, OH emission can be seen in regions that are currently faint or even absent in CO emission, hence OH has become a tracer for the "(CO-)Dark Gas" (Allen, Hogg, & Engelke 2015).
- **The L-band OH lines are optically thin.**
  - The usual tracer we use to study the distribution and motions of the ISM in galaxies is HI, but HI is known to be optically thick in the disk of our Galaxy, in several other nearby galaxies (e.g. M31: Braun 2009), and in all other edge-on galaxies so far studied (Peters et al. 2017).
  - CO(1-0) emission is widely known to be optically thick, and its quantitative relation to H_2 is controversial (the "X-factor").
  - The connection to N(OH) and ultimately to N(H_2) is dependent on how well we can understand the physics of OH line formation, a topic that is directly open to theoretical study and to observational confirmation.

GBT OH "First Blind Pilot Survey"

(Allen, Hogg, & Engelke 2015).

3 X 9 grid centered at:
L = 105.0°, B = +1.0°
ΔL = ΔB = 0.5°
(undersampled -
GBT FWHM ≈ 8' @ 18 cm)
1' ≈ 1 pc at Perseus Arm

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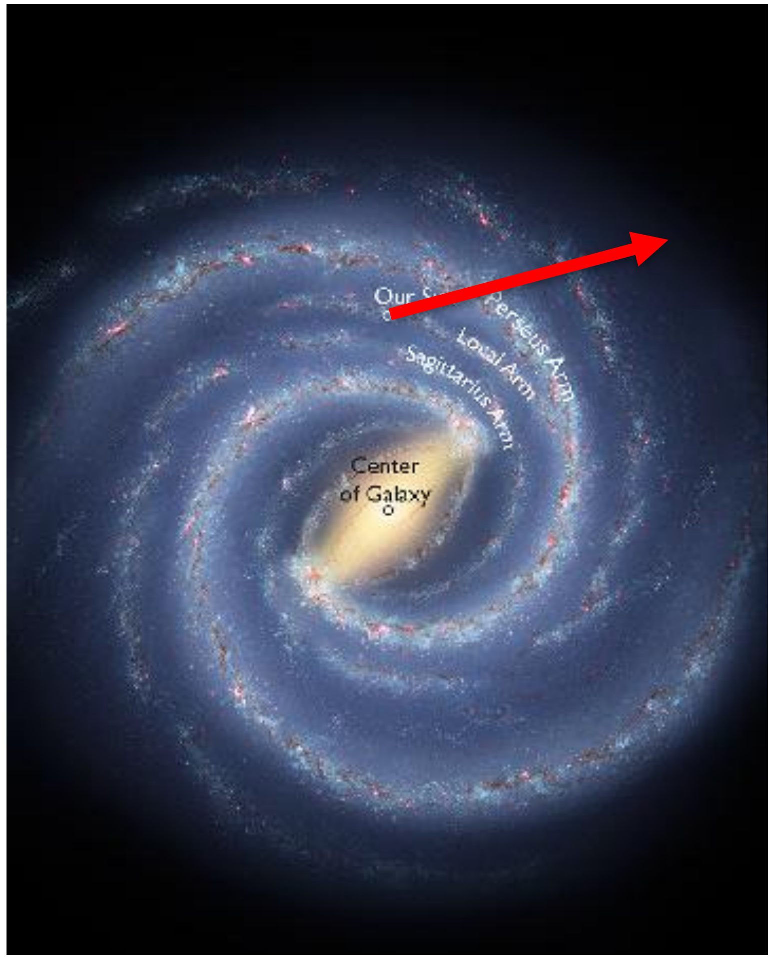
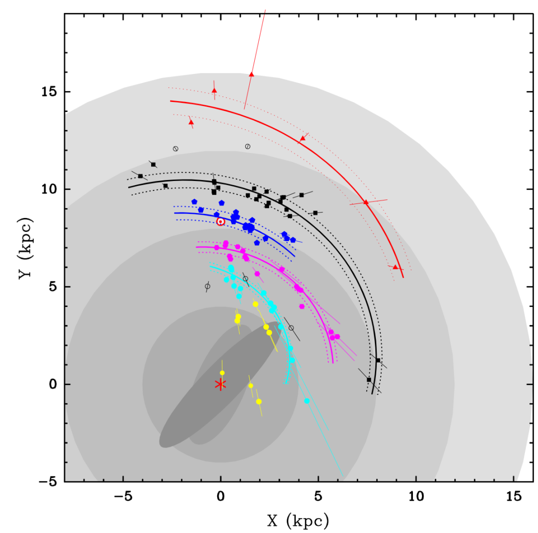
Green Bank Telescope



Galactic rotation separates features in V along the LOS:
- Local gas: $V_{LSR} \approx 0$ km/s
- Perseus: $V_{LSR} \approx -65$ km/s
- Outer: $V_{LSR} \approx -100$ km/s

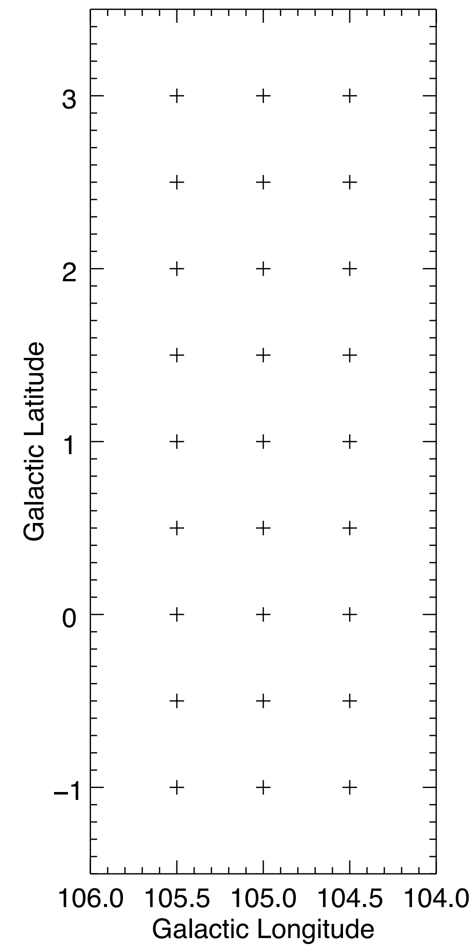
Distances along LOS known in parsec by triangulation:



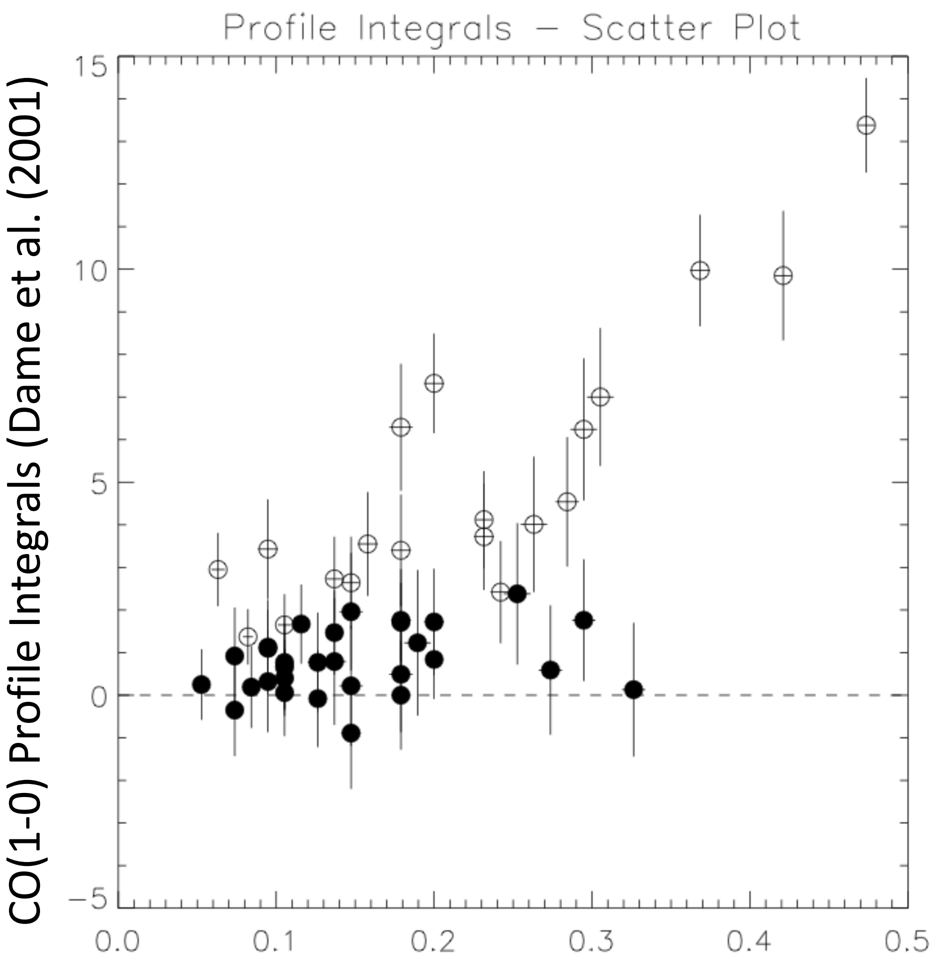
Reid et al 2014, ApJ 783, 130

What did we do?

- 3 X 9 grid of GBT pointings near L=105, B=+1, on 0.5° spacing, straddling the Galactic Plane.
  - 66 hours requested.
  - L-band: 1420/1665/1667/1720 MHz
  - frequency-switching mode
  - 2-hour integrations at OH, final sensitivity ≤ 3.5 mK rms in 0.55 km/s channels
  - 5-min integrations at HI
  - GBT FWHM: 8.9’ at HI, 7.6’ at OH
    - GBT resolution at OH is the same as CfA at CO
- CO data available at 8.4’ FWHM
  - CfA archives – Dame et al. (2001)
  - observe at same pointing positions
  - region chosen to be faint in CO



Comparison of CO and OH Profile Integrals



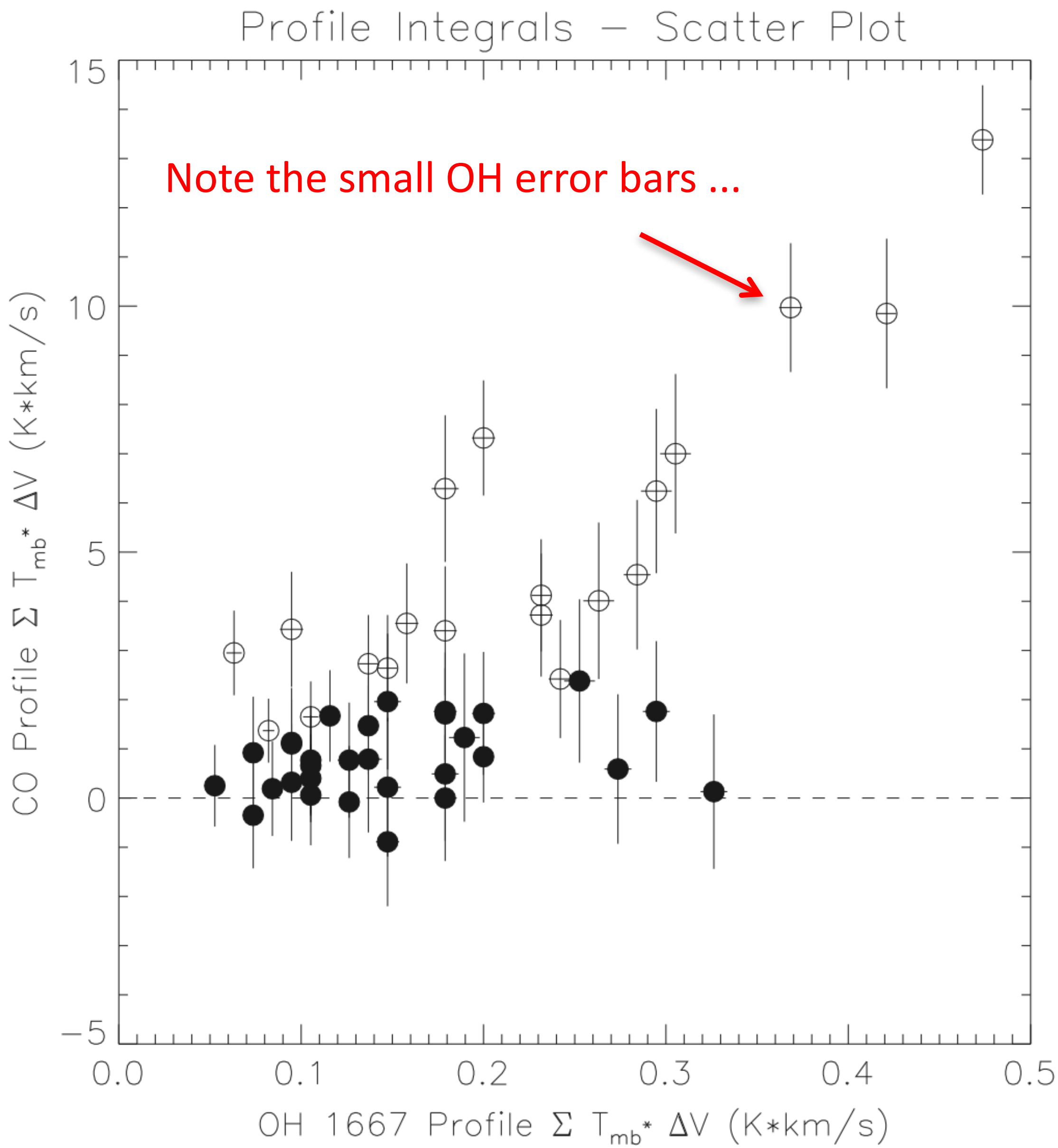
OH 1667 MHz Profile Integrals
from GBT Blind Survey

Out of 27 pointings,

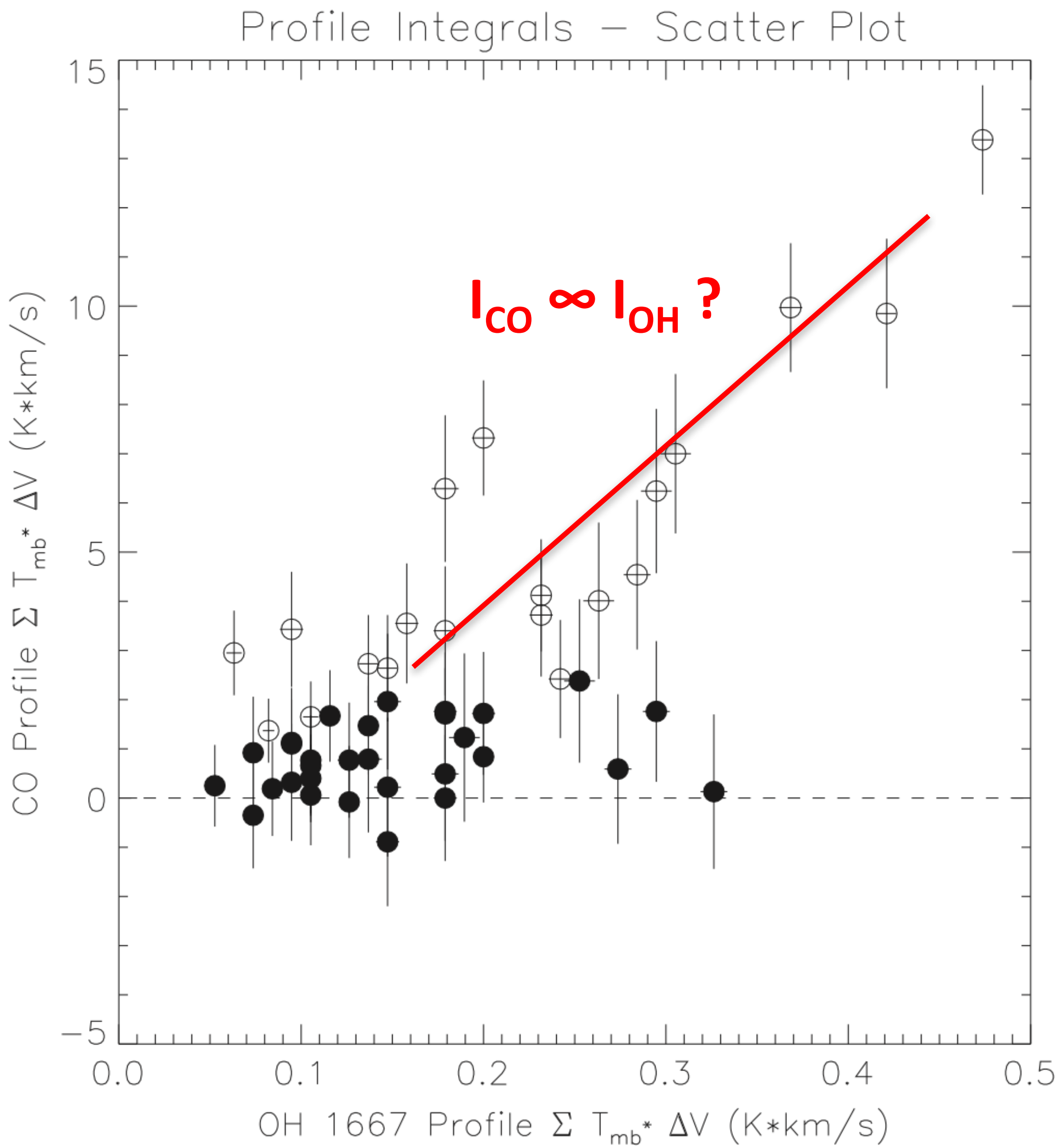
- 78% have OH emission detections
- Many spectra have multiple OH features at different radial velocities
- Out of the detected OH features, less than half have CO counterparts in Dame et al. (2001)
- 27 CO "non-detections" vs. 20 CO detections, 1.35:1 ratio

There is roughly twice as much molecular gas in this region as is usually assumed.

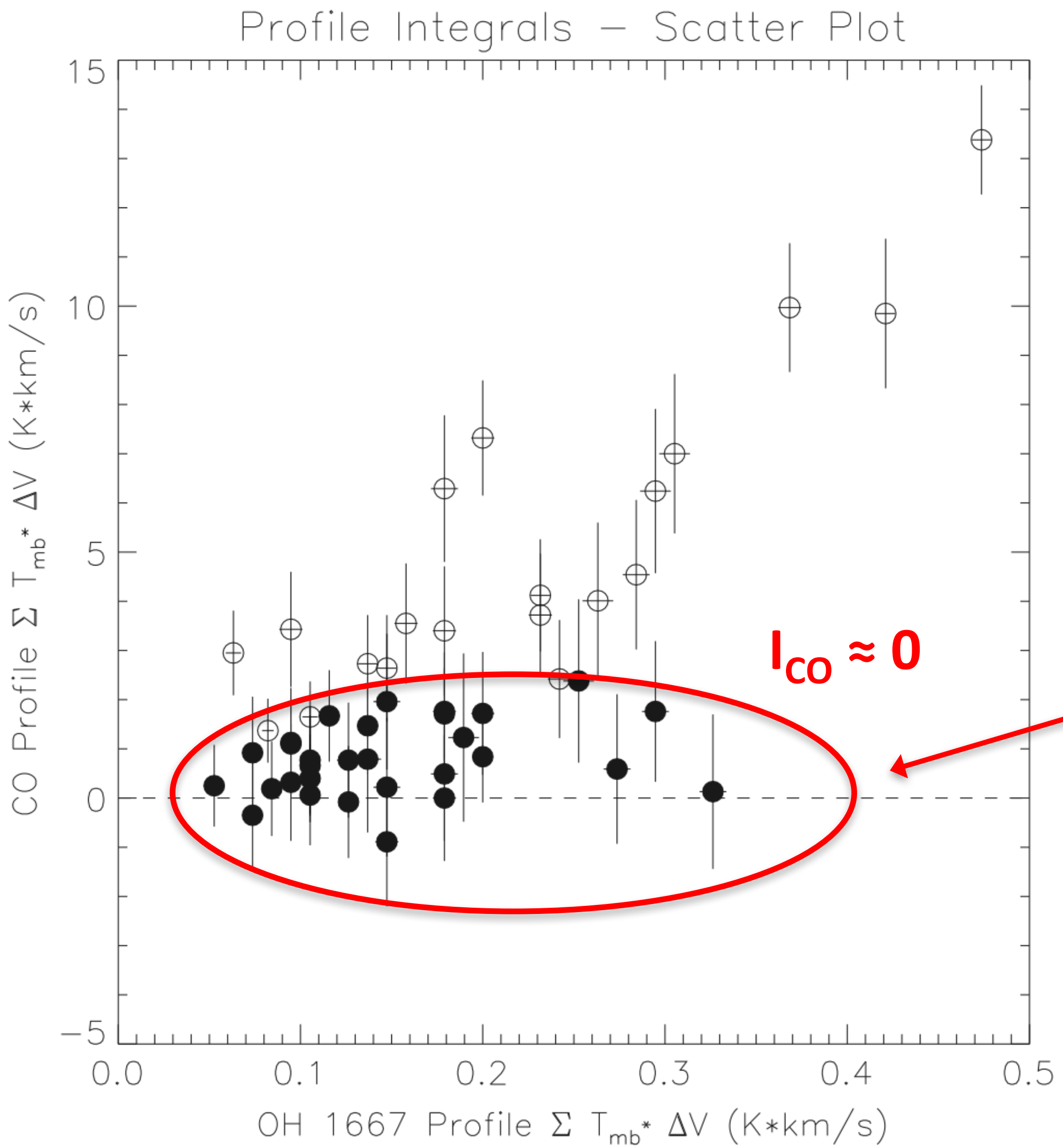
Allen, Hogg, & Engelke (2015)



Allen, Hogg, & Engelke (2015)



Allen, Hogg, & Engelke (2015)



These points have OH S/N ≳ 7, but are statistically = 0 in CO.

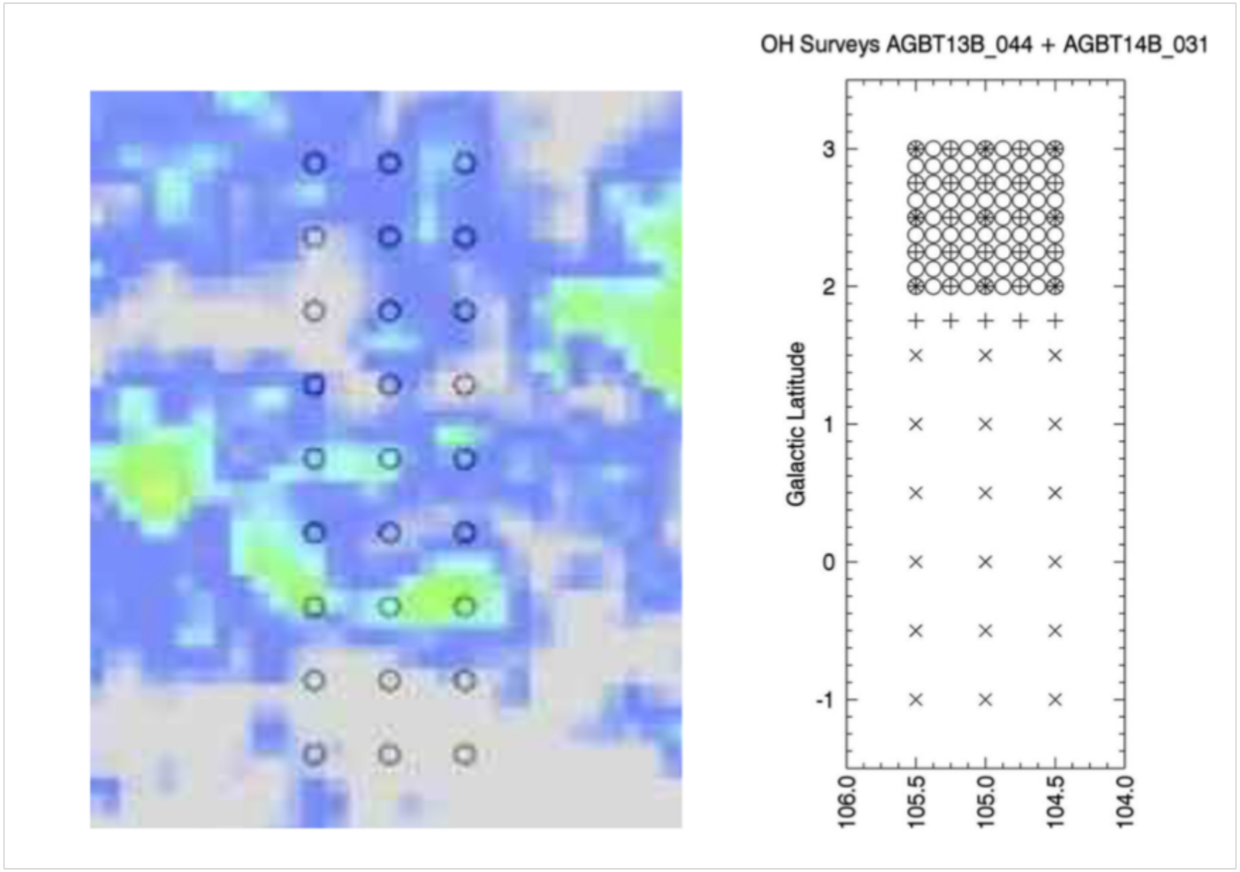
This both confirmed the existence of the "Dark Gas" in the ISM first described by Grenier et al (2005), and suggested that OH is a new tracer for it.

Allen, Hogg, & Engelke (2015)

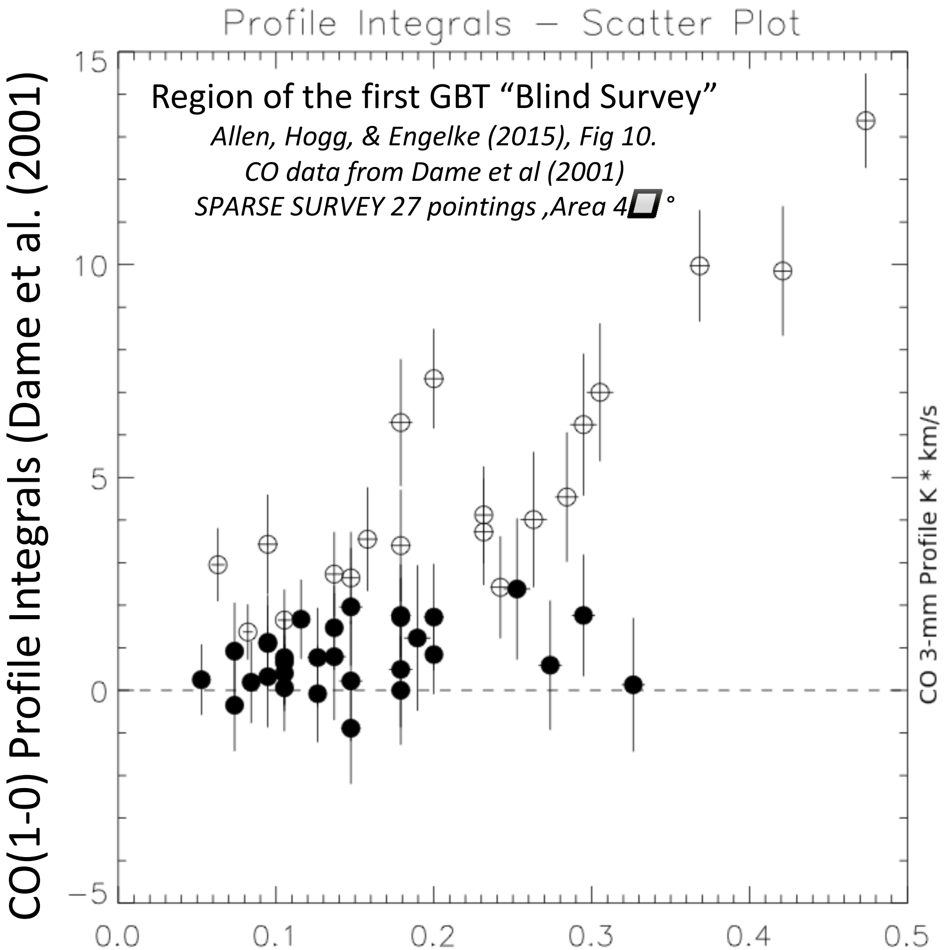
Our New GBT Surveys:

- **The "One Square Degree" survey (Busch, Allen, & Hogg):**
  - This is a "densified" survey, covering a one-square-degree region part of the original blind survey, but now with a grid spacing of one GBT FWHM at 1666.4 MHz (≈0.125°) instead of 0.5°. Also, the OSD observations are limited to the radial velocity range of the Perseus Arm, which is at a known distance from the Sun. *This exploratory program is aimed eventually at studying the spatial structure of the molecular gas seen in OH emission.*
- **The "Perseus Arm" Survey (Allen, Hogg, & Engelke):**
  - This "sparse" study of the Perseus Arm has two main aims: to *measure the "Rolling Motions" of molecular gas*, and to determine the *scale height and offset of molecular gas* from the Galactic Plane.
- **The "W5" Survey (Engelke, Allen, & Hogg):**
  - This is a "dense" survey of W5 with the goal of *comparing the molecular gas content of this star-forming region as determined in OH with the values from CO observations*.
- **These new OH survey results are now being compared with the greatly-improved CO sensitivity of the FCRAO Outer Galaxy Survey (Heyer et al 1998)**

Current Blind GBT OH Surveys



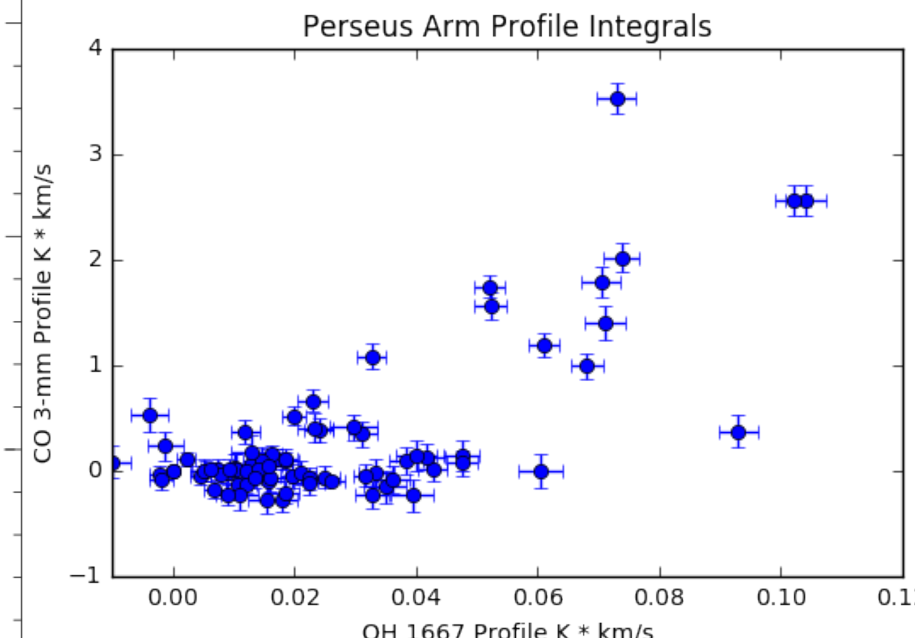
Comparing Blind Surveys



OH 1667 MHz Profile Integrals
from GBT Blind Survey

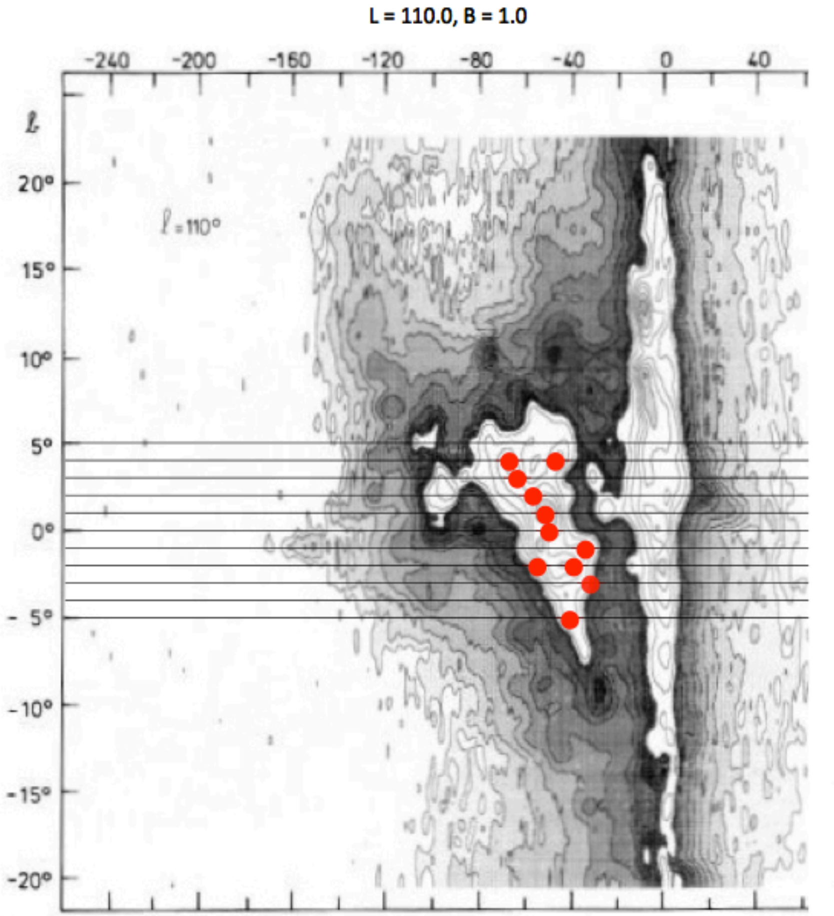
Preliminary data from the GBT
"One Square Degree Survey"

CO data from FCRAO/OGS (Heyer et al 1998)
DENSE SURVEY: 81 pointings, Area 1□°
From a paper in preparation by JHU PhD student
Michael Busch

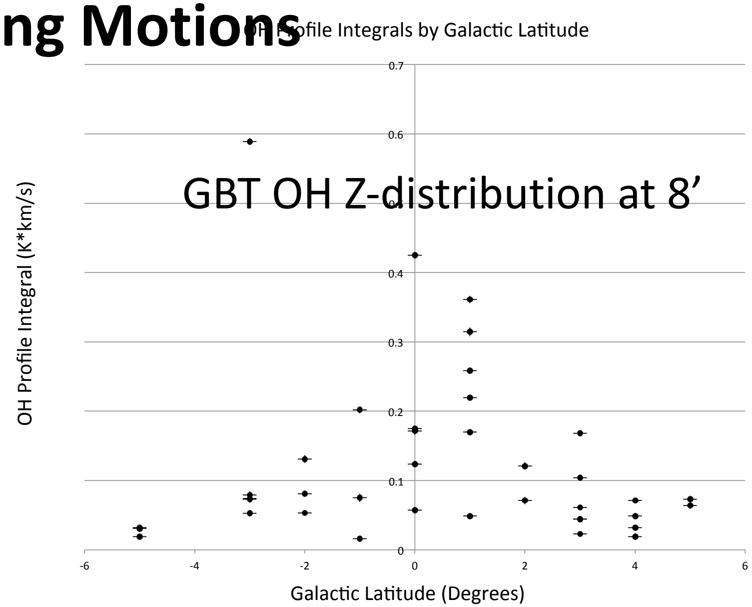


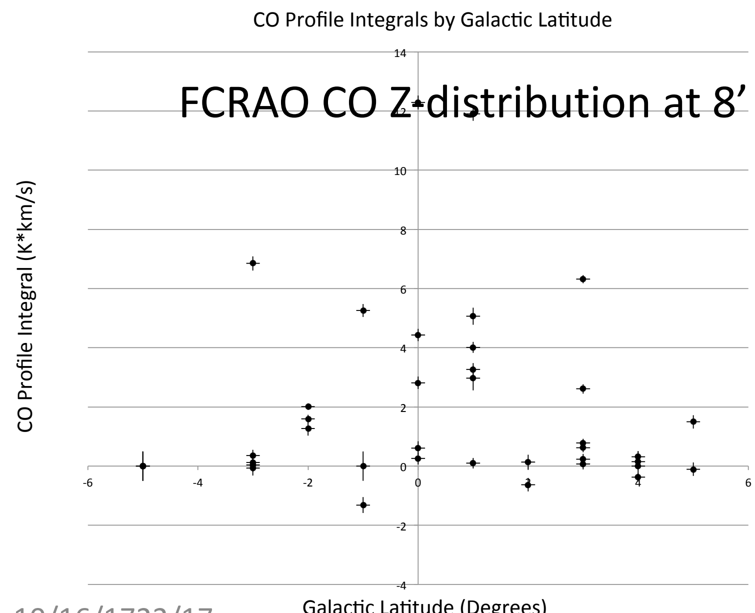
Results are consistent: Improved sensitivity in CO has not eliminated the "CO-Dark Gas"

Perseus Arm – Thickness and Rolling Motions

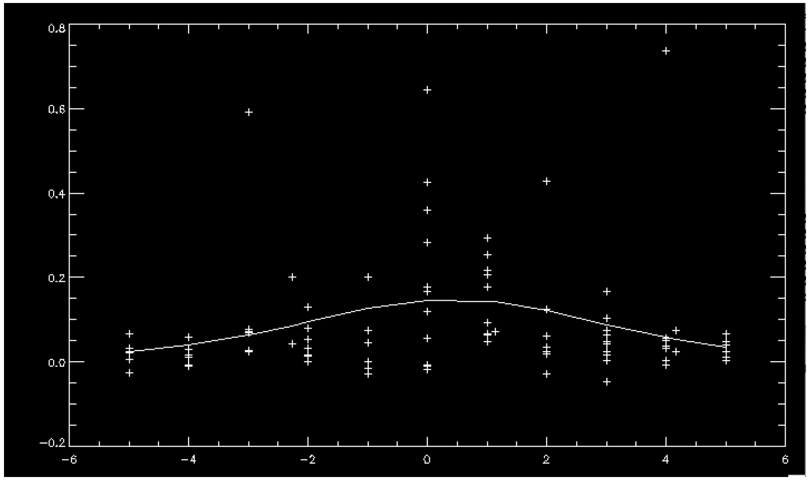


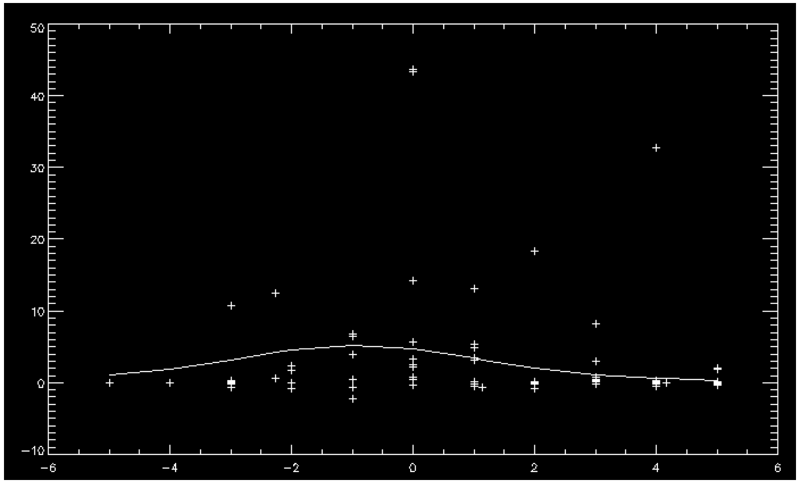
Contour map is HI from Burton et al. (1985).
Red dots are our new OH observations.
Work by R. Allen, P. Engelke, and D. Hogg





Preliminary Fits to the "static atmosphere" law:



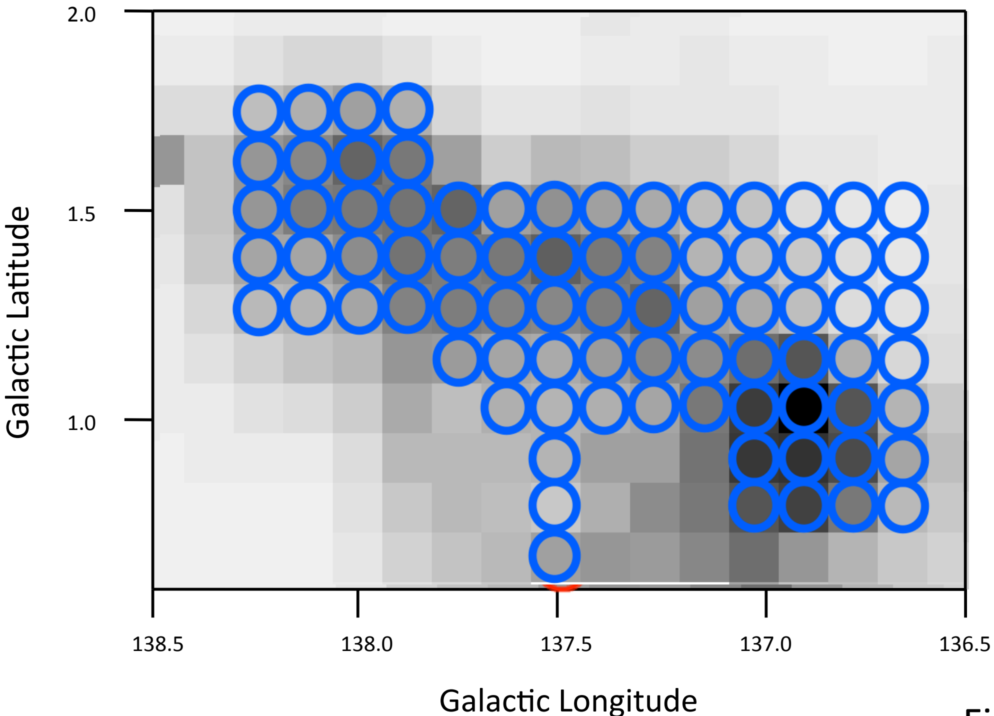


Fits to: $Y = A \bullet \mathrm{sech}^2[(B - B_0)/C]$

GBT OH(1667):
$A = 0.15 \pm 0.03$ K•km/s
$B_0 = 0.40 \pm 0.91°$
$C = 3.45 \pm 1.19°$
HWHM = 3.0°± 1.0°

FCRAO CO(1-0):
$A = 5.27 \pm 1.42$ K•km/s
$B_0 = -0.94 \pm 2.8°$
$C = 2.82 \pm 2.02°$
HWHM = 2.5°± 1.8°

Preliminary Results - W5 OH Survey



Pointings for GBT OH survey over W5.
- Background is smoothed version of 1420 MHz continuum from Taylor et al. (2003).

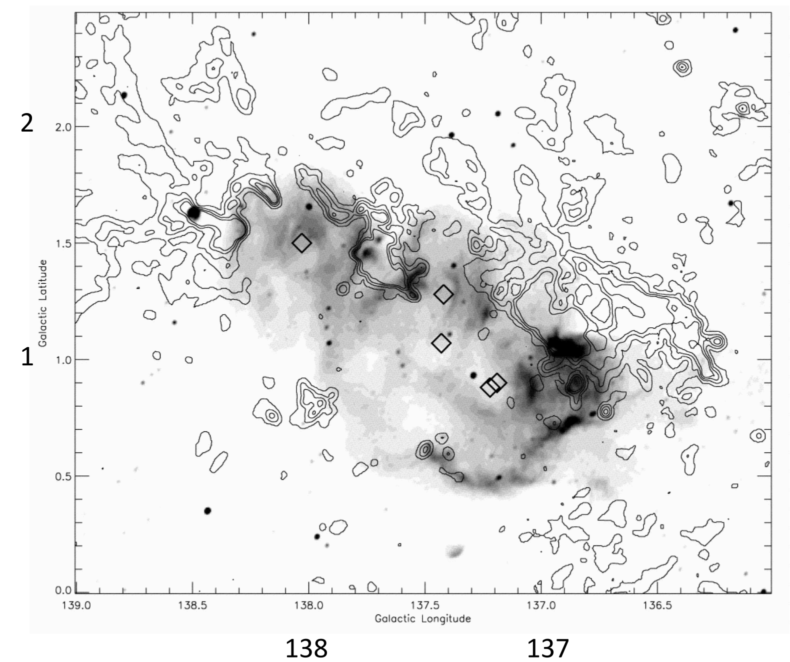


Fig. 2 from Karr & Martin (2003), showing W5.
- Grayscale is 1420 MHz continuum,
- Contours are CO(1-0) between -31 and -49 km/s,
- Diamonds are O and B stars.

Work by NRAO Reber Fellow P. Engelke

Calculating OH Column Densities

Recall that

$$N\left(OH\right) = 2.3\times10^{14}\,\frac{T_{ex}}{T_{ex}-T_C}\int\phi\left(v\right)dv$$

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

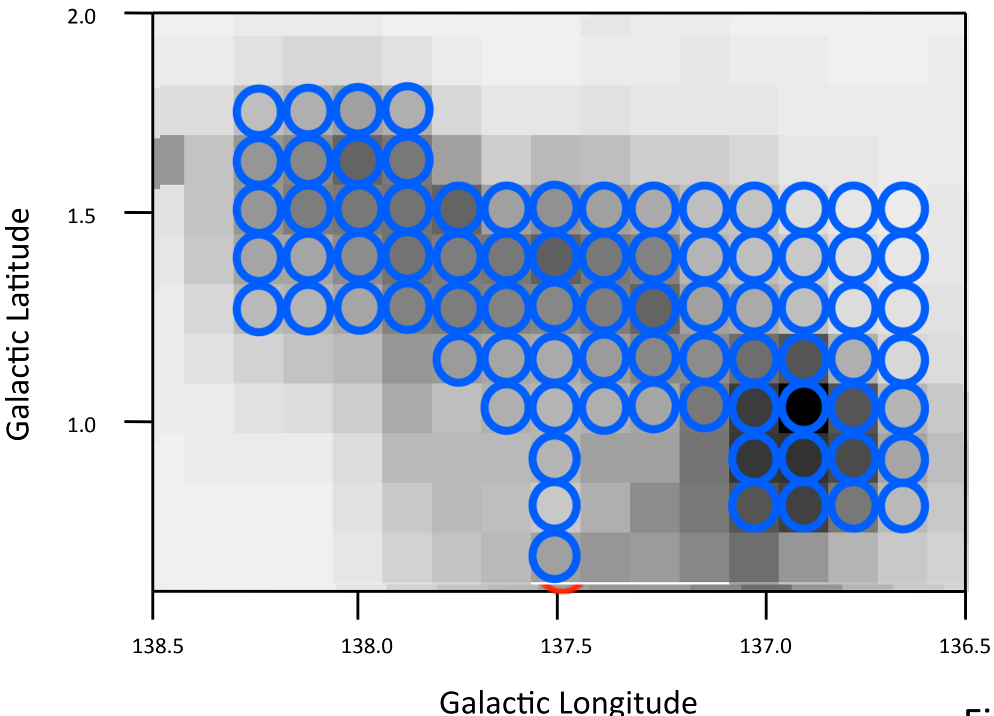
$$N\left(OH\right) = 2.3\times10^{14}\,T_{ex}\int\tau\left(v\right)dv$$

We need to know:

1) Integral under spectral lines
2) Continuum temperature T_C incident from behind OH the cloud
3) Excitation temperature of the OH transition

- This has led to an effort to measure T_{ex} directly in W5, and to a new puzzle: ***the case of the the disappearing OH emission.***

Note the varying radio continuum background …



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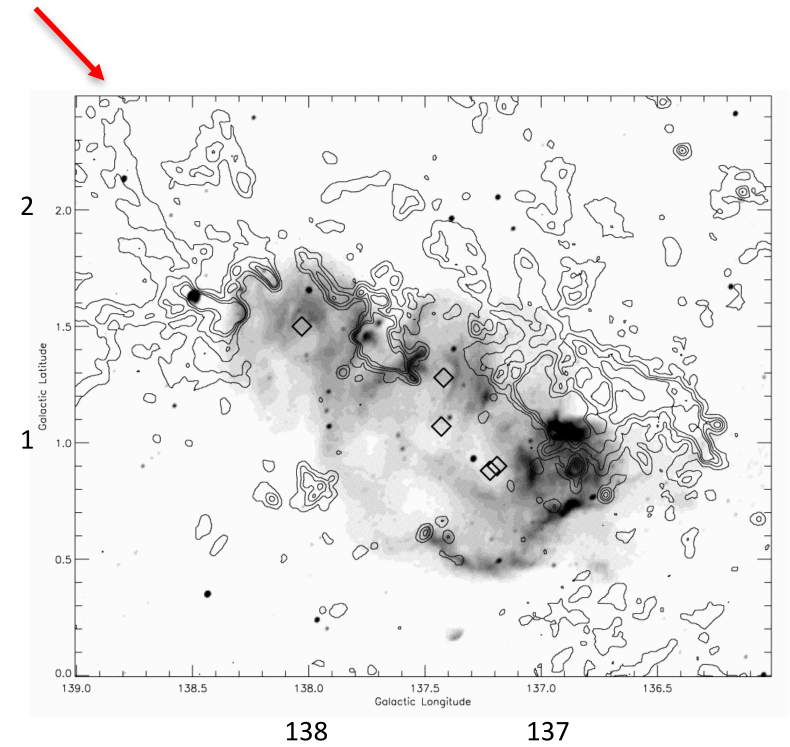

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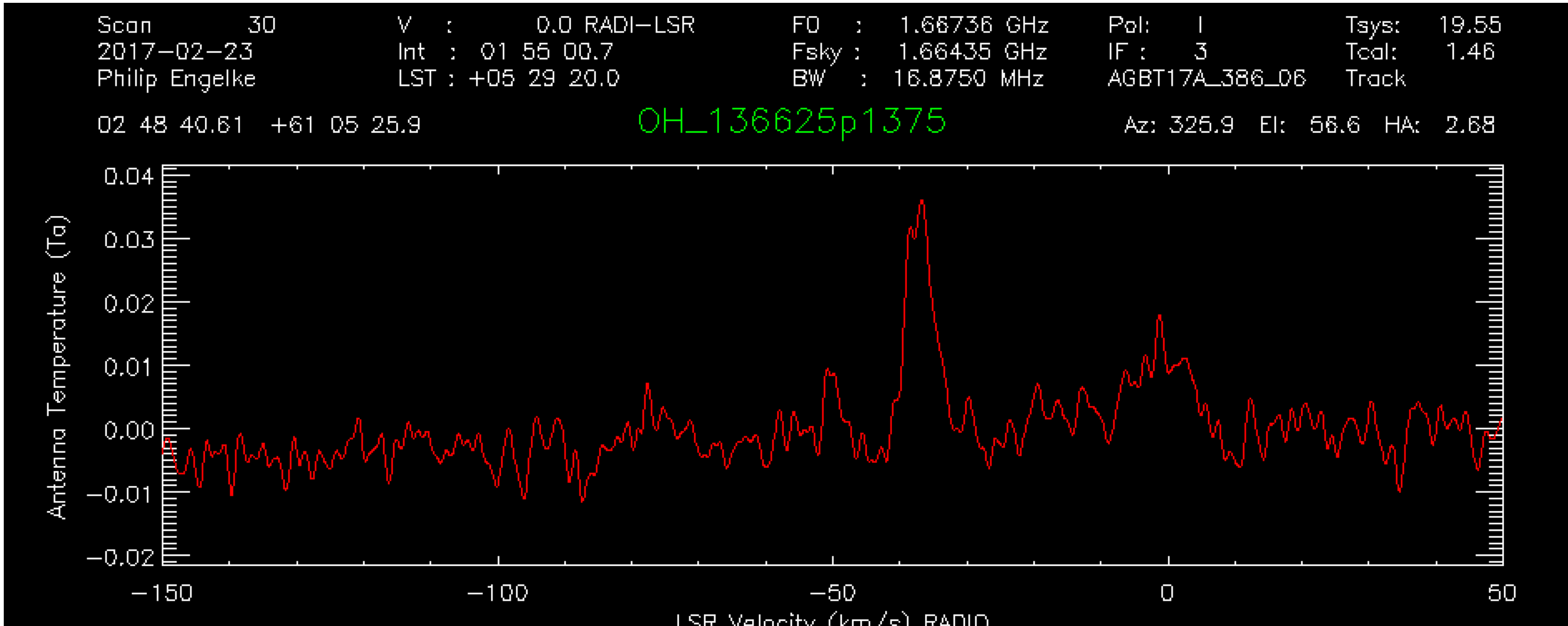
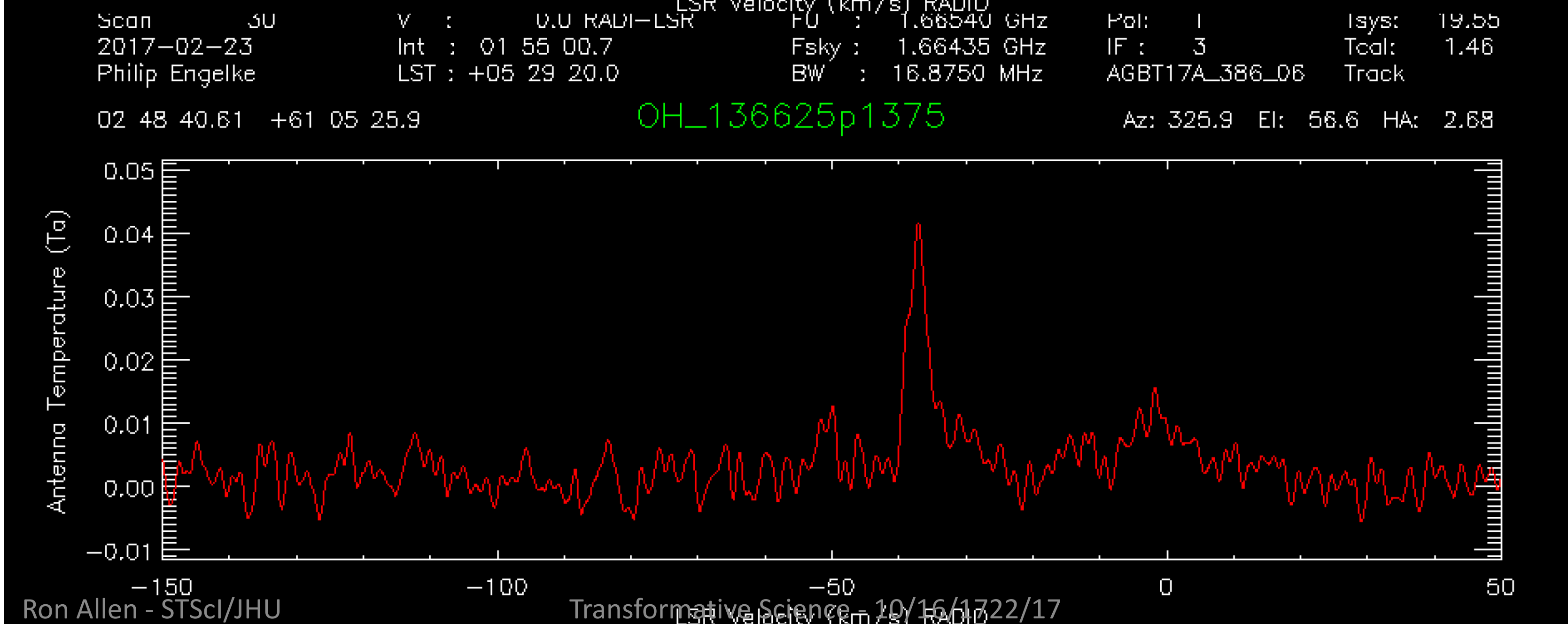
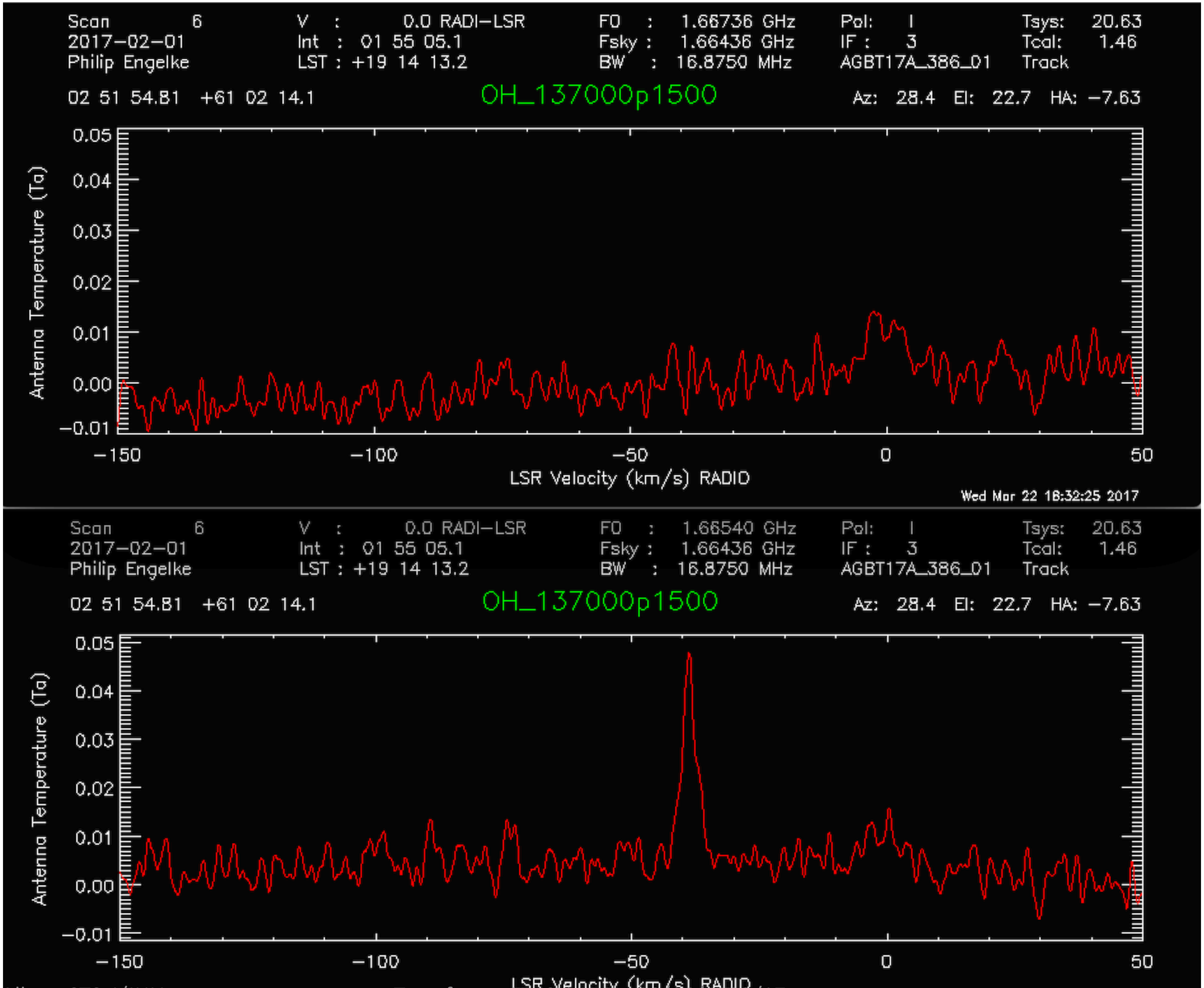


1667

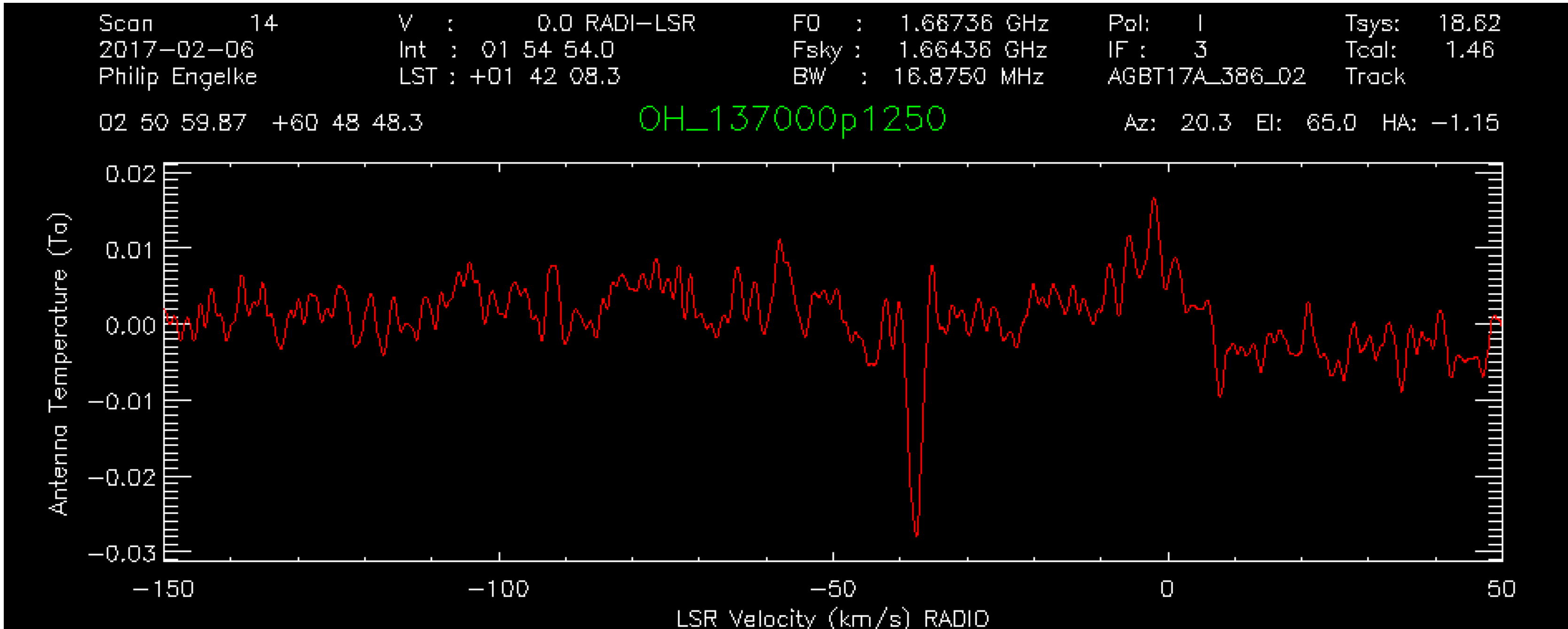
T_C
4.1 K



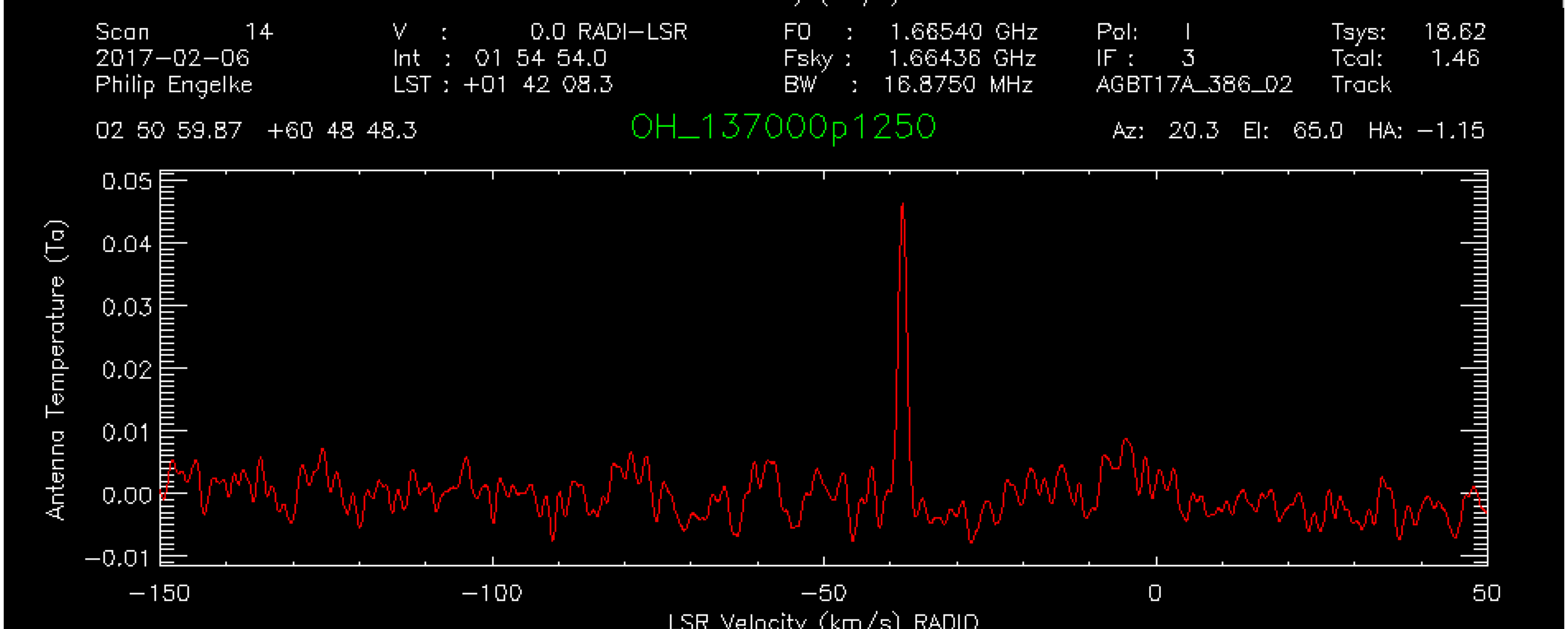
1665


Scan 6
2017-02-01
Philip Engelke
V : 0.0 RADI-LSR
Int : 01 55 05.1
LST : +19 14 13.2
F0 : 1.66736 GHz
Fsky : 1.66436 GHz
BW : 16.8750 MHz
Pol: I
IF : 3
AGBT17A_386_01
Tsys: 20.63
Tcal: 1.46
Track
02 51 54.81 +61 02 14.1
OH_137000p1500
Az: 28.4 El: 22.7 HA: −7.63
Antenna Temperature (Ta)
LSR Velocity (km/s) RADIO
Wed Mar 22 16:32:25 2017
Scan 6
2017-02-01
Philip Engelke
V : 0.0 RADI-LSR
Int : 01 55 05.1
LST : +19 14 13.2
F0 : 1.66540 GHz
Fsky : 1.66436 GHz
BW : 16.8750 MHz
Pol: I
IF : 3
AGBT17A_386_01
Tsys: 20.63
Tcal: 1.46
Track
02 51 54.81 +61 02 14.1
OH_137000p1500
Az: 28.4 El: 22.7 HA: −7.63
Antenna Temperature (Ta)
LSR Velocity (km/s) RADIO

T_C
5.0 K

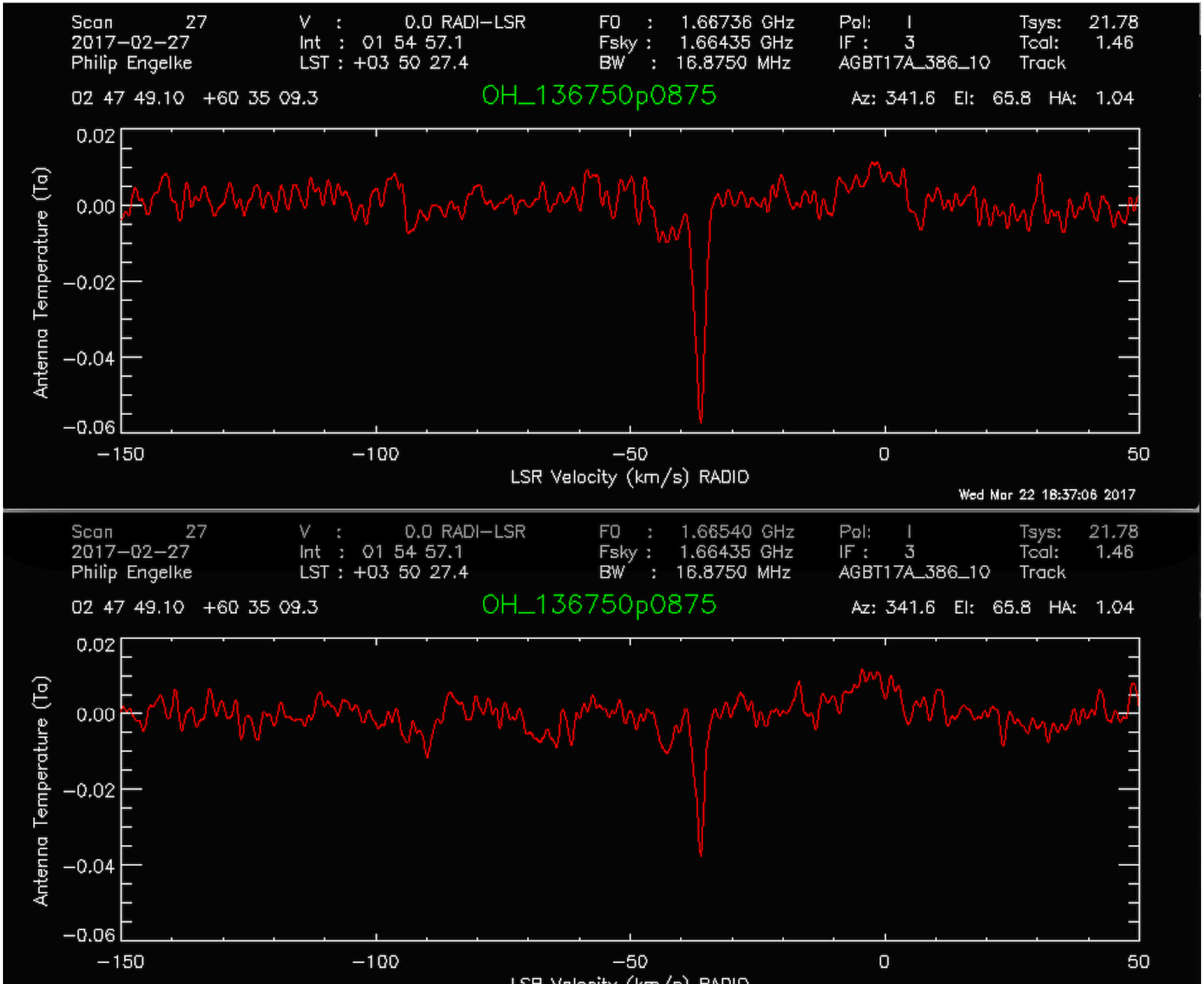


Scan 14
2017-02-06
Philip Engelke
V : 0.0 RADI-LSR
Int : 01 54 54.0
LST : +01 42 08.3
F0 : 1.66736 GHz
Fsky : 1.66436 GHz
BW : 16.8750 MHz
Pol: I
IF : 3
AGBT17A_386_02
Tsys: 18.62
Tcal: 1.46
Track
02 50 59.87 +60 48 48.3
OH_137000p1250
Az: 20.3 El: 65.0 HA: -1.15
Antenna Temperature (Ta)
0.02
0.01
0.00
-0.01
-0.02
-0.03
-150
-100
-50
0
50
LSR Velocity (km/s) RADIO



Scan 14
2017-02-06
Philip Engelke
V : 0.0 RADI-LSR
Int : 01 54 54.0
LST : +01 42 08.3
F0 : 1.66540 GHz
Fsky : 1.66436 GHz
BW : 16.8750 MHz
Pol: I
IF : 3
AGBT17A_386_02
Tsys: 18.62
Tcal: 1.46
Track
02 50 59.87 +60 48 48.3
OH_137000p1250
Az: 20.3 El: 65.0 HA: -1.15
Antenna Temperature (Ta)
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-150
-100
-50
0
50
LSR Velocity (km/s) RADIO

T_C
5.7 K



Scan 27
2017-02-27
Philip Engelke
V : 0.0 RADI-LSR
Int : 01 54 57.1
LST : +03 50 27.4
F0 : 1.66736 GHz
Fsky : 1.66435 GHz
BW : 16.8750 MHz
Pol: I
IF : 3
AGBT17A_386_10
Tsys: 21.78
Tcal: 1.46
Track
02 47 49.10 +60 35 09.3
OH_136750p0875
Az: 341.6 El: 65.8 HA: 1.04
Antenna Temperature (Ta)
0.02
0.00
−0.02
−0.04
−0.06
−150
−100
−50
0
50
LSR Velocity (km/s) RADIO
Wed Mar 22 18:37:06 2017
Scan 27
2017-02-27
Philip Engelke
V : 0.0 RADI-LSR
Int : 01 54 57.1
LST : +03 50 27.4
F0 : 1.66540 GHz
Fsky : 1.66435 GHz
BW : 16.8750 MHz
Pol: I
IF : 3
AGBT17A_386_10
Tsys: 21.78
Tcal: 1.46
Track
02 47 49.10 +60 35 09.3
OH_136750p0875
Az: 341.6 El: 65.8 HA: 1.04
Antenna Temperature (Ta)
0.02
0.00
−0.02
−0.04
−0.06
−150
−100
−50
0
50
LSR Velocity (km/s) RADIO

T_C

8.4 K

Preliminary Excitation Temperatures from the W5 emission data alone

T_{ex_1667} = 5.1 +/- 0.5 K

T_{ex_1665} = 5.9 +/- 0.2 K

- Note that the excitation temperature for the 1667 MHz line appears to be almost 1 K lower than the excitation temperature for the 1665 MHz emission line in W5.
  - *This result is preliminary, but the difference is consistent with an old discovery by Crutcher (1979) as well as recent data (Tang et al. 2017).*
  - *We are not aware of a detailed explanation for this difference.*

(*Paper in preparation by NRAO Reber Pre-doctoral Fellow Philip Engelke*)

Why OH? - III

- **The Cons:** *OH is not as easy to observe as CO(1-0):*
  - the same reason for the easy excitation of the OH lines (very small Einstein A) coupled with the low OH abundance means **that the 18-cm emission is very faint**, and long integration times are required.
  - The faint levels of the OH emission ($T_B \lesssim$ 10-20 milliKelvin) place **stringent requirements on the stability of the receivers** and on the observing methods and data reduction procedures.
  - Low volume density mean that **OH is almost certainly "sub-thermal"**, reducing the line brightness even further and making it even harder to detect the emission, especially if $T_{ex} \approx T_C$.
- **The Pros**: *OH is a new tracer for the large-scale molecular ISM with markedly different physical properties from CO:*
  - OH is already revealing a ***more extensive distribution of molecular gas*** in the Galaxy than we suspected from CO surveys.
  - OH holds promise for becoming a ***reliable quantitative tracer*** of the molecular ISM based on known physics, and directly observable links to $N(H_2)$ via UV absorption lines of both H_2 and OH to nearby UV-bright stars.

The Future

Steps to Galactic Surveys in OH Emission - I

- Northern Hemisphere Surveys and Templates:
  - 30’ Outer Galaxy OH Emission Survey (“OGOES-30”)
  - Nominal Requirements:
    - dedicated 25m telescope
    - Fully automated telescope and data reduction
    - Lowest possible single-pixel Tsys (<20K)
    - All 4 OH lines (mainly 1665 + 1667; also 1720 for large-scale shocks in the ISM – might have to miss 1612 owing to RFI)
  - Observing time estimate for such an OH survey: (template: initial LRDS HI survey with the Penticton 85’ telescope):
    - 10 months on an 85’ telescope

Steps to Galactic Surveys in OH Emission - II

- Northern Hemisphere Surveys and Templates:
  - 8’ Outer Galaxy OH Emission Survey (“OGOES-8”)
  - Nominal Requirements:
    - GBT at L-band with Phased-Array Feed
    - Tsys < 20K on all beams at all 4 OH Frequencies (esp. 1720?)
    - Fully automated telescope and data reduction
    - Real-time calibration of the spectral baseline integrated into the reduction software
  - Rough observing time estimate for such an OH survey (example: the FCRAO OGS in CO by Heyer et al 1998):
    - ≈ 3 years on the telescope

BACKUP MATERIAL FOLLOWS