HyGAL III: An IR Calibration of 18cm OH Excitation from the HyGAL SOFIA Legacy Program

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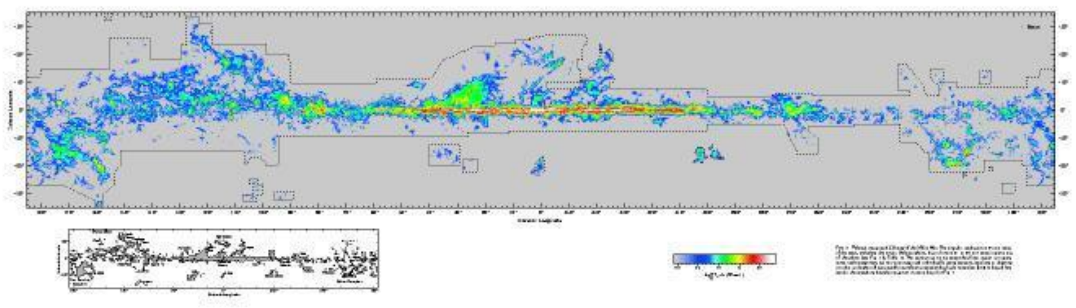
Molecular Gas in the Galaxy

Molecular clouds are the birthplace of stars and the formation of molecules are thought to be an important step for star formation. Carbon-Monoxide (CO J=1-0) is used as a conventional tracer for molecular gas because molecular hydrogen, the most abundant molecule, is non-emitting in cold molecular environments of the general ISM. CO is usually bright and the most abundant molecule aside from H_2.



OH and 'Dark' Molecular Gas

Dark Molecular Gas is inferred from observational hints that CO (molecular) and HI (atomic) lines are not tracing the total gas content as traced by dust emission or gamma rays.

The hydroxyl radical, OH, has been proposed as a low volume density tracer of this dark molecular gas, and has been shown to trace "CO-dark gas" (Allen 2015, Busch 2019, Busch 2021). In addition, OH is an important catalyst for oxygen chemistry (Gerin 2016).

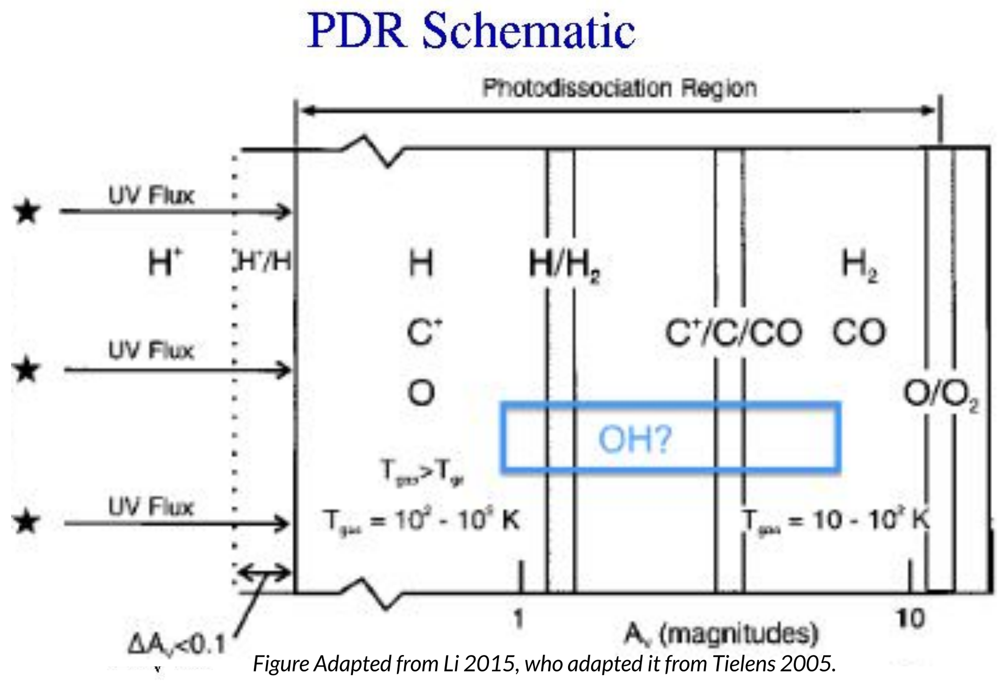


Figure Adapted from Li 2015, who adapted it from Tielens 2005.

In order to use the radio 18cm OH lines as effective tracer of molecular hydrogen, knowledge of the excitation temperatures are needed as it has been shown that T_{ex} is close to T_{CMB} leading to large uncertainties.

For example, the OH column density given by (Busch 2021):

$$\langle N(\mathrm{OH})\rangle = C_{67}\left(\frac{T_{\mathrm{ex}}^{67}}{T_{\mathrm{ex}}^{67}-T_c}\right)\int \Delta T_b^{67}(v)\,dv$$

Relies on an assumed excitation temperature, which regularly can be close to the background temperature.

HyGAL Legacy Program – Hydrides in the ISM

The ***HyGAL*** Stratospheric Observatory for Infrared Astronomy legacy program surveys six hydride molecules—ArH+,OH+,H2O+, SH, **OH**, and CH—and two atomic constituents—C+ and O—within the diffuse interstellar medium (ISM) by means of absorption-line spectroscopy toward 25 bright Galactic background continuum sources (Jacob et al. 2022).

The ***HyGAL*** survey also includes ancillary data from the Jansky Very Large Array (JVLA); which simultaneously observed 21cm HI and the four 18cm OH ground state lines (1612, 1665, 1667 and 1720 MHz).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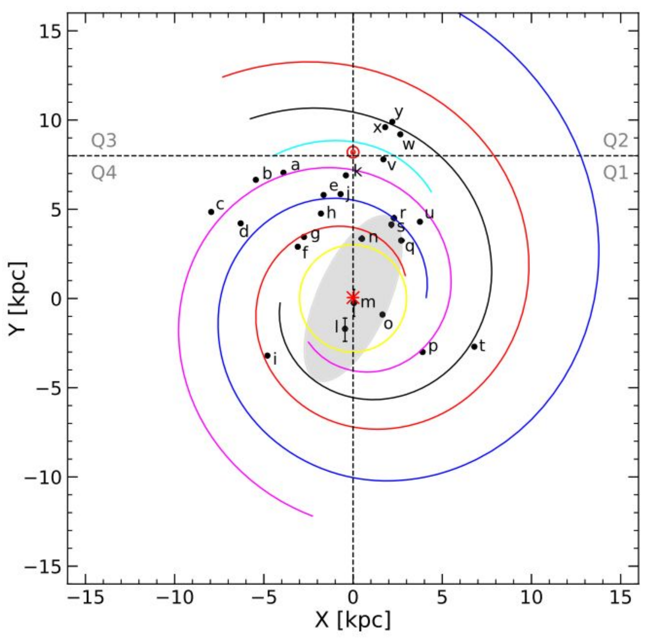


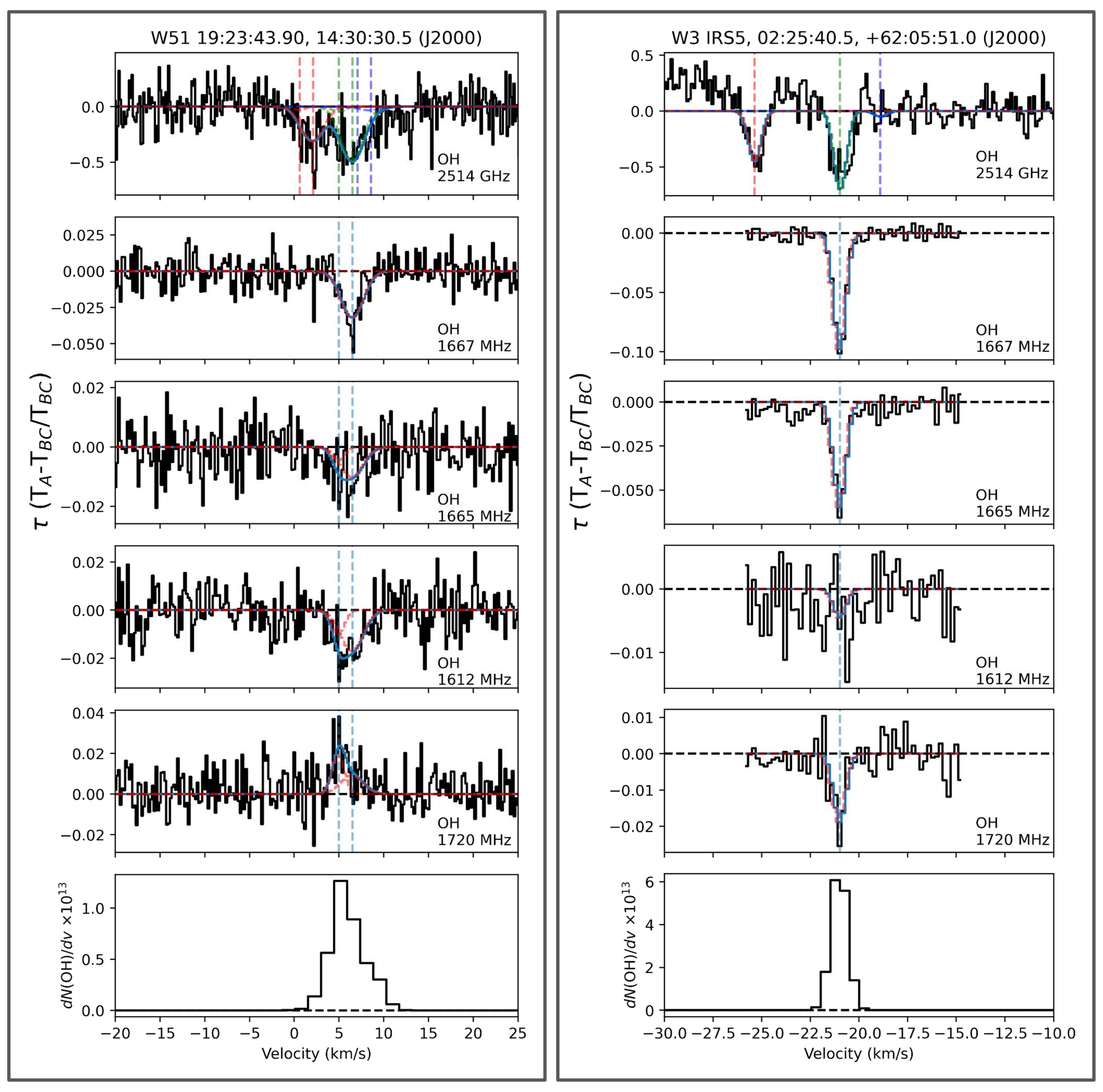
Distribution of the sight lines observed under the HyGAL program - *Jacob et al 2022*

Simultaneous Fitting to JVLA/HyGAL OH data

Reliable column densities of OH can be derived from the SOFIA GREAT 2.5 THz absorption of OH towards these background sources with the assumption that all of the OH molecules are in the ground state.

This the key to the method: with N(OH) known *a priori* from SOFIA, **The only unknown in the column density equation becomes T_{ex}** and can be directly solved directly for all four 18cm OH lines.

We simultaneously fit the four 18cm OH lines from the JVLA and the three hyperfine structure (HFS) 2.5 THz lines observed by HyGAL, preliminary results are shown below for HyGAL sources W51 (2 components) and W3 IRS5 (1 component).



Preliminary: Multi-component fitting of 2.5 THz and 1.6 GHz OH spectra in diffuse LOS clouds toward W51 and W3 IRS5. Model code was written by M. Busch using Python package LMFIT. (Newville 2014)

Excitation Temperatures of the 18cm lines

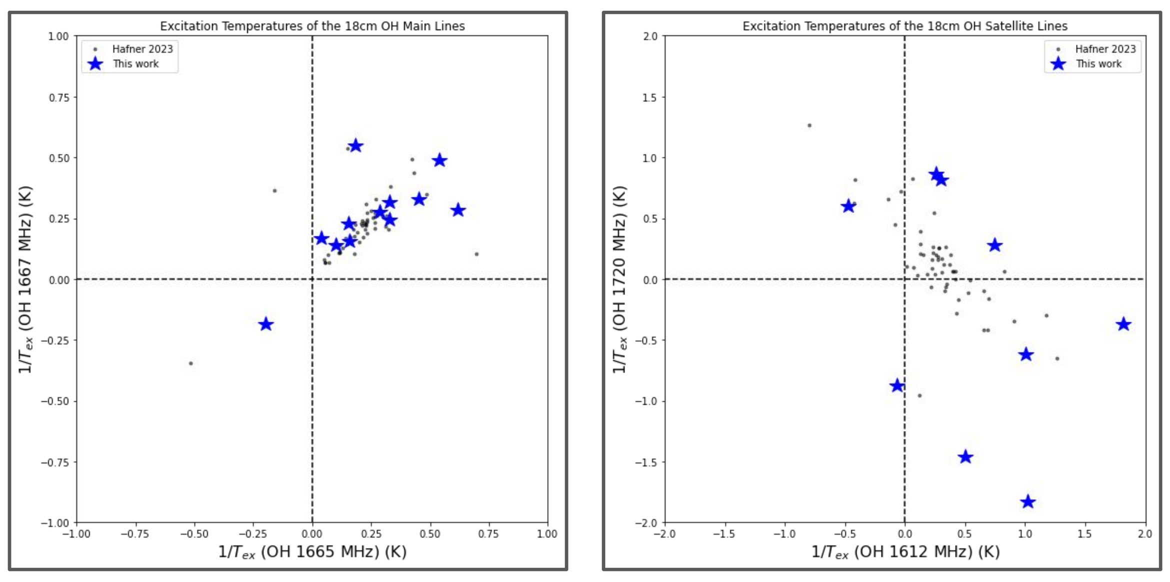
There has long been a wish to calibrate the 18cm OH lines using the 2.5 THz OH HFS line in the IR, others have realized this potential (Neufeld 2002, Wiesemeyer 2016). **HyGAL's complementary datasets on the OH molecule will now allow us to accomplish this.**

By inverting the column density equation we will derive Tex for all four OH lines for the fitted components of the sources: W51, W49, W3 IRS5, DR21, . This method has been used to calibrate CH in the past as well to some success (Lien 1984, Dailey et al. 2020).

The equivalent width of the OH lines are related to the OH column density and the excitation temperature T_{ex} (Neufeld et al. 2002):

Where, k = 1/9, 5/9, 1, 1/9 for the 1612, 1665, 1667 and 1720 MHz transitions.

$$W_v = 0.45\,k\,[N(\mathrm{OH})/10^{14}\mathrm{cm}^{-2}]\,[T_{ex}/\mathrm{K}]^{-1}\,[1-T_{ex}/T_{BC}]\,\mathrm{km\,s^{-1}}$$

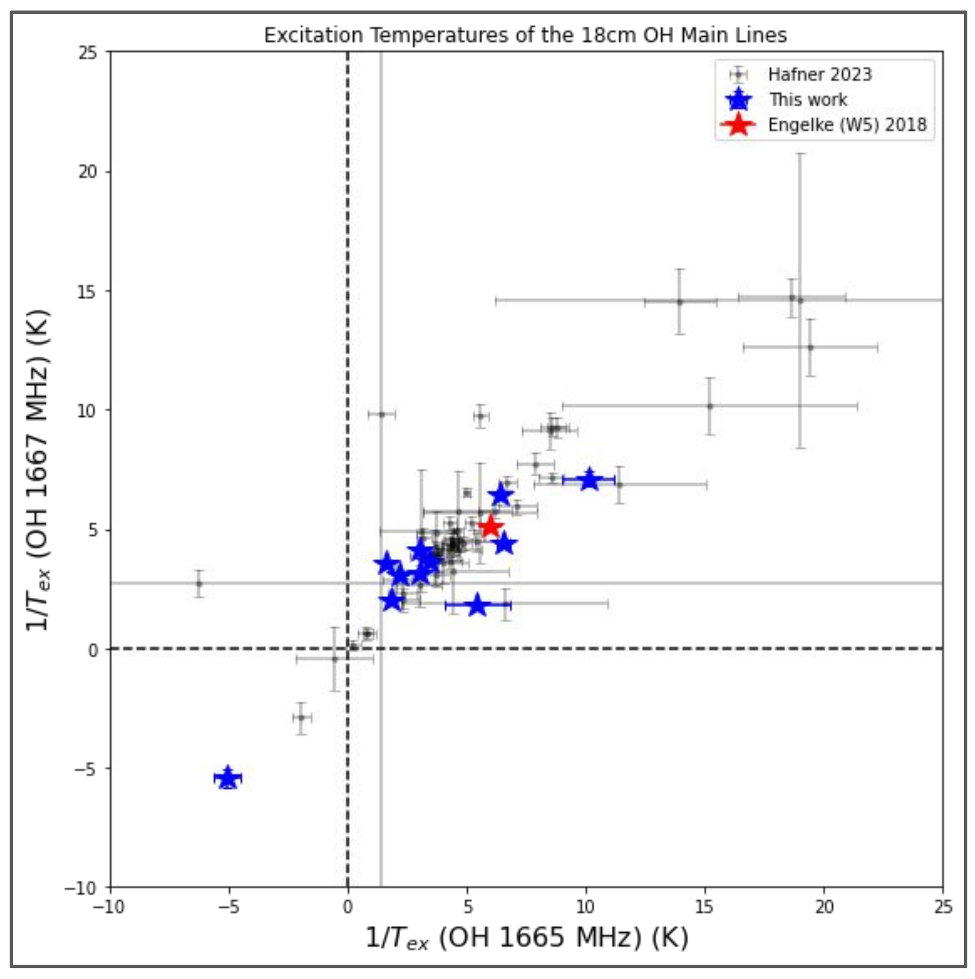


Preliminary: $1/T_{ex}$ of the 18cm OH radio lines based on SOFIA 2.5 THz OH Column Densities determinations. Errors not included.

Comparison to Other Results

The most practiced method to deriving the 18cm OH Tex relies on the ON-OFF method, where an observer points towards an absorption source and then slightly off to observe the corresponding emission profile in the lack of an absorption source. Solving the radiative transfer equations allows for one to derive Tex (e.g. Hafner 2023).

Another method relies on observing 18cm OH towards *varying continuum background*, and directly observing where the 18cm OH profiles switch from emission to absorption (Engelke 2018), although results from this method are not numerous yet. In another case, one can assume a nearly constant Tex and N(OH) of specific clouds and derive Tex based on the variation of W(OH) (Neufeld 2002). We see our method has broad agreement with the 'gold standard' of Hafner et al. 2023.



Preliminary: Comparison with the On-Off method of Hafner 2023 with our work and the continuum-background method of Engelke 2018.

Conclusions & Future Work

The first continuation of this work will be expanding the amount of clouds calibrated when the ancillary HyGAL MeerKAT observations are completed and reduced as well, southern HyGAL sources will be added to the list to calibrate the 18cm OH lines.

Comparison of other hydride lines to OH like CH and SH can also help calibrate the OH/H_2 ratio in diffuse clouds. An extension is also possible to calibrate the total amount of gas in these clouds using new 3D dust maps (e.g. Edenhofer et al. 2024). We also anticipate to be able to compare these observations with line transfer models to solve for the physical conditions of these diffuse clouds with for example, MOLPOP-CEP (Ramos 2018).


On the way: *Observations of the Southern Sky HyGAL Sources at 18cm are completed but are to be reduced.* - Rugel et al. in Prep.

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