CH as a tracer for molecular hydrogen:

Forming synergies between its far-infrared and radio fingerprints

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The Cosmic Cycle of Dust and Gas in the Galaxy: From Old to Young Stars

IMPRS
astronomy&
astrophysics
Bonn and Cologne

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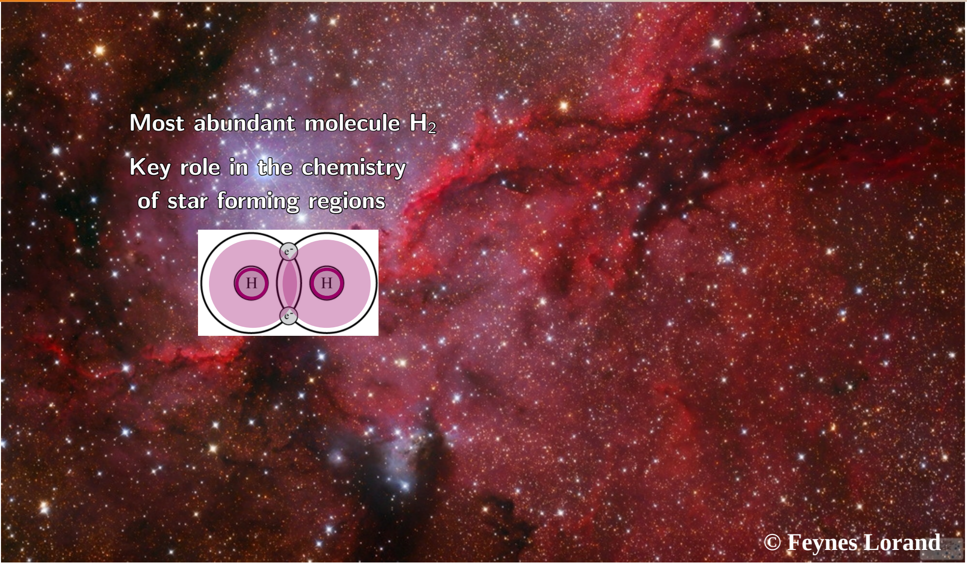
Introduction



Most abundant molecule H_2

Key role in the chemistry of star forming regions

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Introduction

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⇒ Chemical tracers

eg: **CO**

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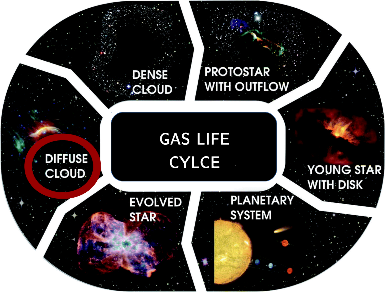

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Introduction

Most abundant molecule H_2

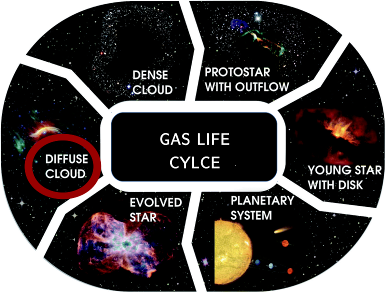
Key role in the chemistry of star forming regions

INVISIBLE

⇒ Chemical tracers

eg: CO

How reliable is CO as a tracer for H_2?



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Is CO a reliable tracer in diffuse regions?

- CO has varying abundance w.r.t. H_2 in diffuse clouds (Liszt and Pety, 2012)
- Molecular gas (H_2) exists without associated CO (Blitz et. al 1990)

$\therefore$ CO is NOT a reliable tracer

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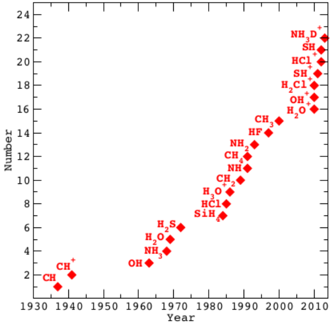
Interstellar Hydrides like CH, OH

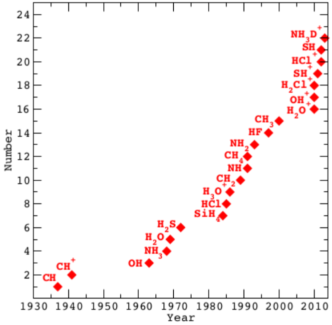
Why hydrides?



Interstellar and circumstellar hydrides, from http://www.astrochymist.org/

- First molecules discovered in the ISM (Dunham et al. 1937)
- Reservoir of heavy elements

Why hydrides?



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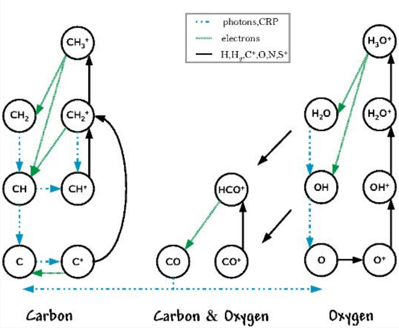


(Godard et. al 2014)

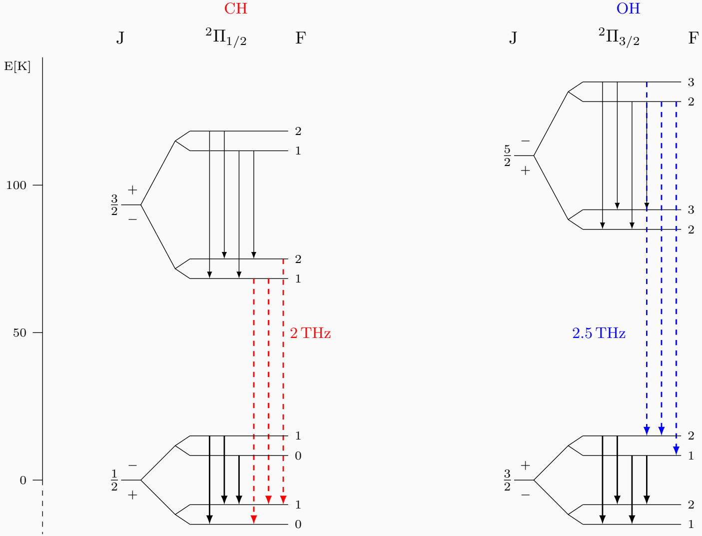
- First molecules discovered in the ISM (Dunham et al. 1937)
- Reservoir of heavy elements

- Initial products of chemical networks

  ⇒ Building blocks of interstellar chemistry

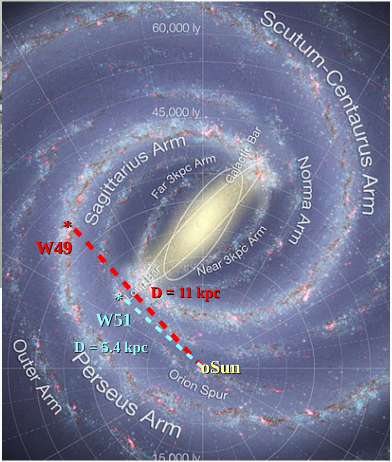
Transitions

Fundamental rotational transitions lie in the sub-mm regime



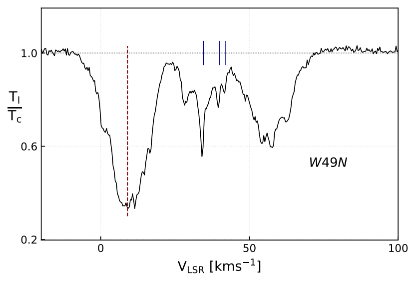
Observations

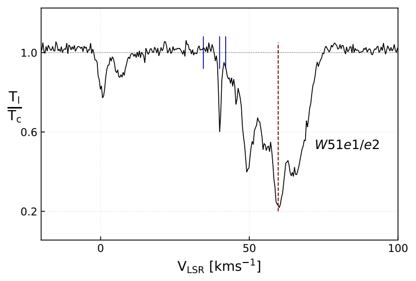
German REciever for Astronomy at Terahertz frequencies



Hydrides as diagnostics for H_2

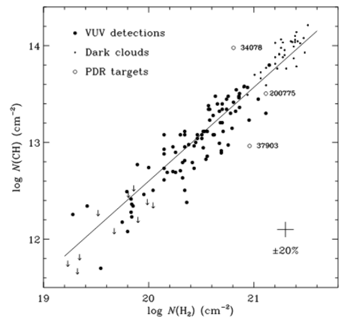
Absorption line spectroscopy → robust means of determining column densities
(independent of gas temperature, density, collisional excitation rates, etc)





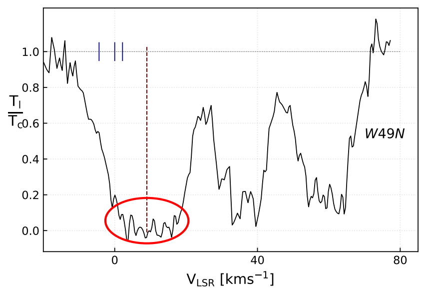
Why use CH?

- Ubiquitous
- Tight correlation with H_2, $[CH]/[H_2] = 3.5 \times 10^{-8}$



(Sheffer et al. 2008)

- Unsaturated ground state absorption



Saturated OH absorption

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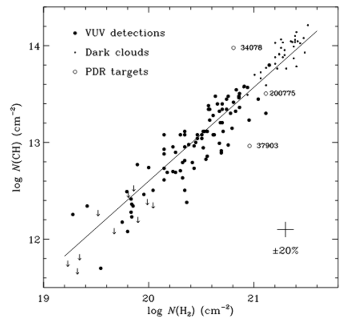

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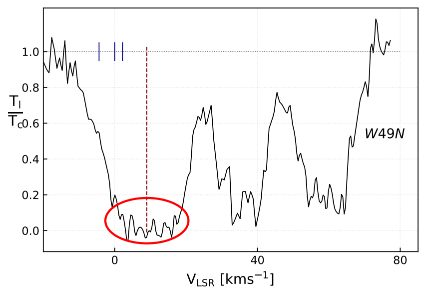

Saturated OH absorption

→ Derive column densities

Deriving column densities

Fit the spectra

Deriving column densities

Fit the spectra

Multi-Gaussian fitting

- Superposition of Gaussian profiles to describe complex features
- Uses a large number of parameters
- Lacks uniqueness

Deriving column densities

Fit the spectra

Multi-Gaussian fitting

- Superposition of Gaussian profiles to describe complex features
- Uses a large number of parameters
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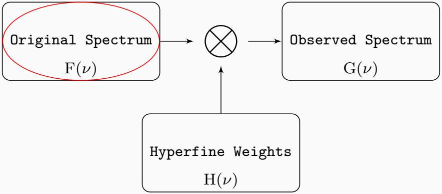
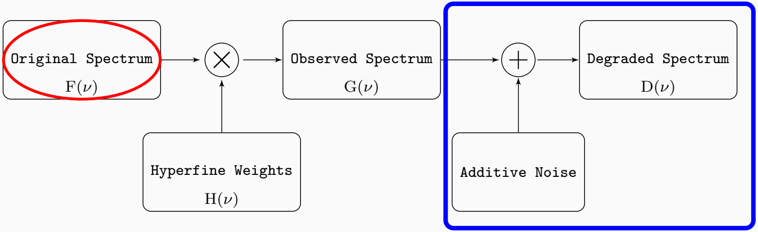
Deconvolution

- Decomposes the observed spectrum
- Division in Fourier space, $F(\nu) = \frac{G(\nu)}{H(\nu)}$



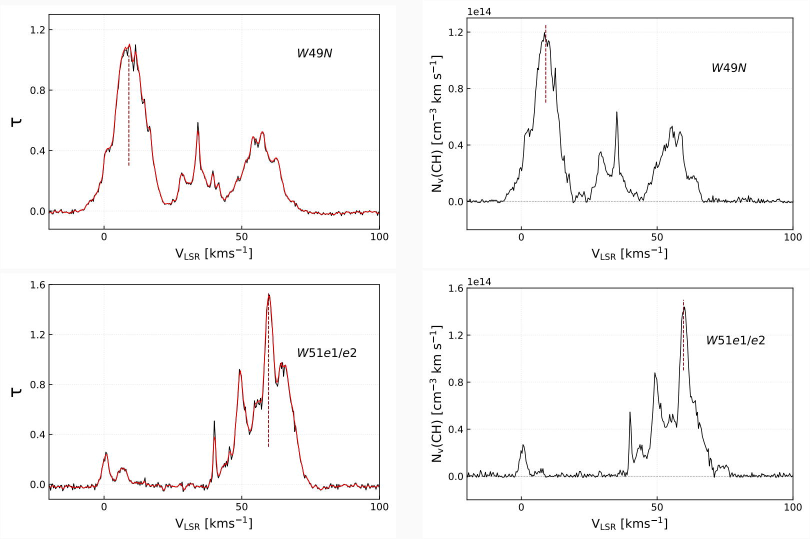
Wiener filter deconvolution



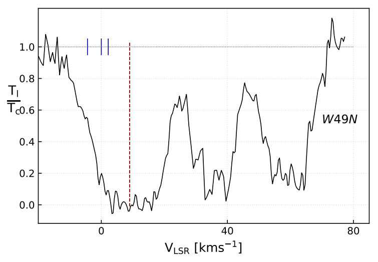
$$F(\nu) = \frac{D(\nu)}{H(\nu)} \underbrace{\frac{|H(\nu)|^2}{|H(\nu)|^2 + |\frac{1}{SNR}|^2}}_{\text{Wiener Filter}}$$

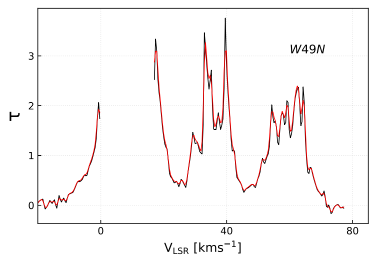
Optimized by minimizing the mean square error between the original spectrum and its Wiener filter approximation (Jacob et al. in prep)

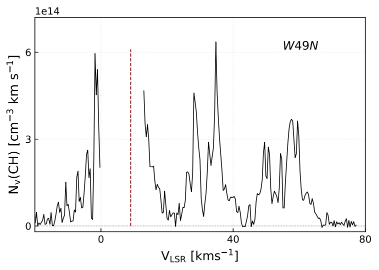
Wiener filter results



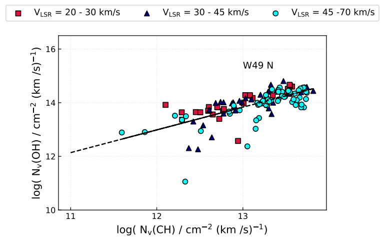
Similarly for OH

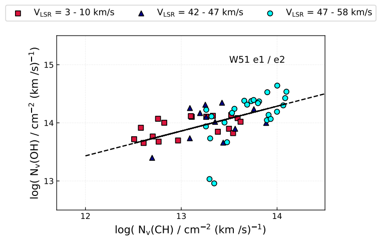






Canconical $N(OH)/N(H_2)$ relation?

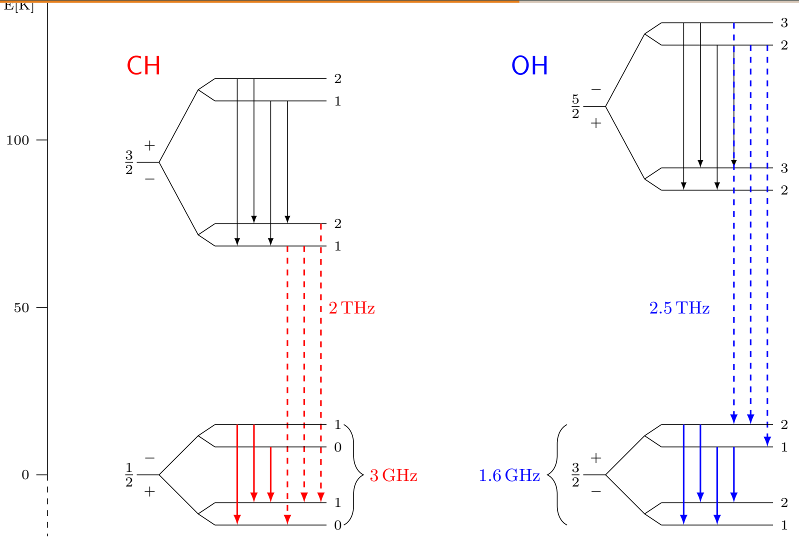




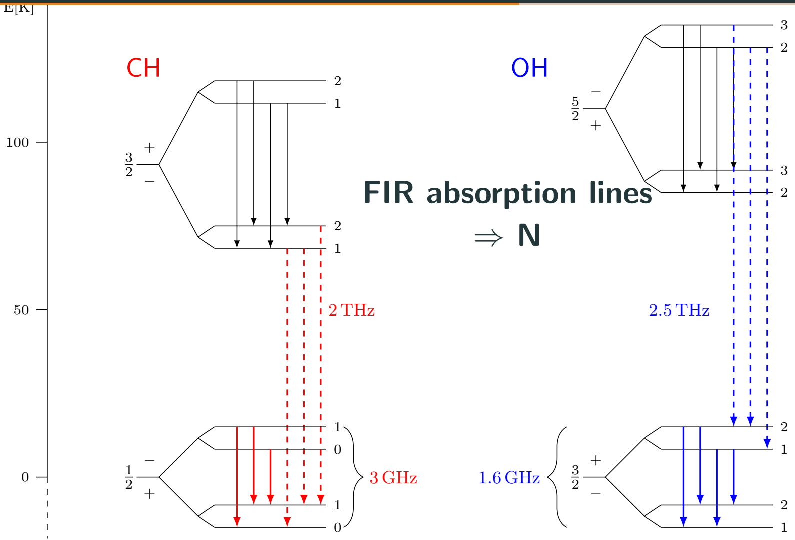
- Pearson's r-value = 0.68
- $N(OH)/N(CH) = 4.7$
- $N(OH)/N(H_2) = 1.6 \times 10^{-7}$

- Pearson's r-value = 0.68
- $N(OH)/N(CH) = 2.0$
- $N(OH)/N(H_2) = 0.7 \times 10^{-7}$

Synergy?


E[K]
100
50
0
CH
OH
$\frac{3}{2}$
+
−
2
1
2
1
2 THz
$\frac{1}{2}$
−
+
1
0
1
0
3 GHz
$\frac{5}{2}$
−
+
3
2
3
2
2.5 THz
1.6 GHz
$\frac{3}{2}$
+
−
2
1
2
1

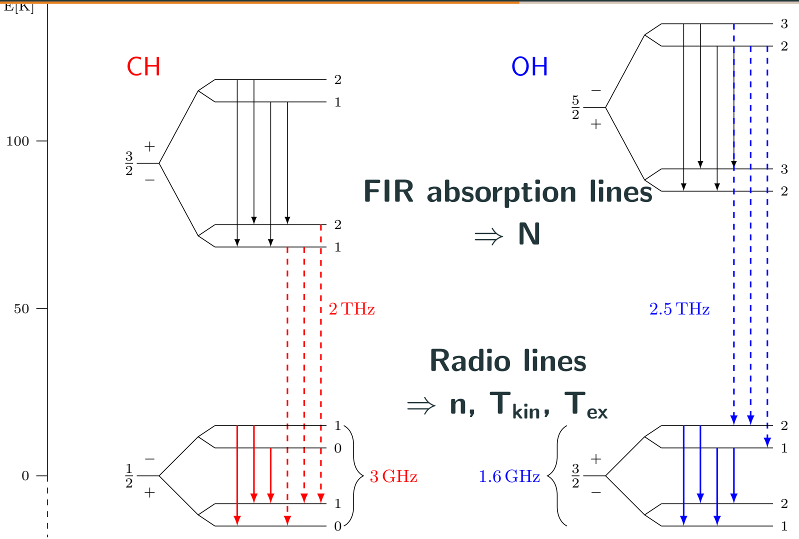
Synergy?



FIR absorption lines

⇒ N

Synergy?



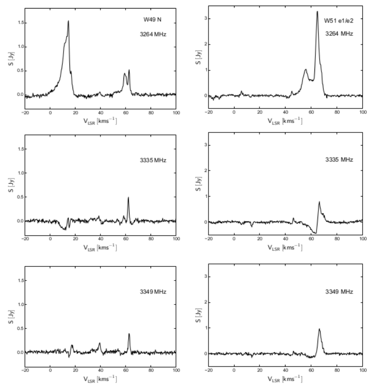
FIR absorption lines

$\Rightarrow$ N

Radio lines

$\Rightarrow$ n, T_{kin}, T_{ex}

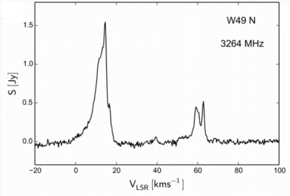
CH radio lines



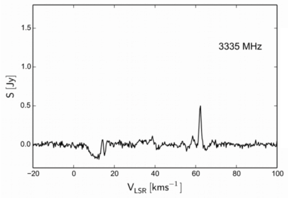
Effelsberg 100-m Telescope

© http://www.fotocommunity.de/photo/radioteleskop-effelsberg-jochen-moll/26052332

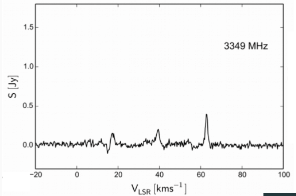
CH radio lines



Lower Satellite Line $0 \rightarrow 1$



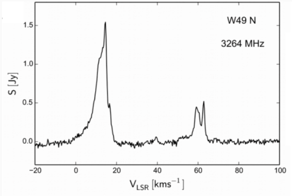
Main Satellite Line $1 \rightarrow 1$



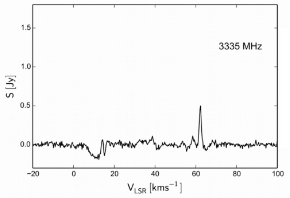
Upper Satellite Line $1 \rightarrow 0$

- At LTE, $I_{(3264)} : I_{(3335)} : I_{(3349)} = 1 : 2 : 1$
- Deviations from LTE $\Rightarrow$ interactions with radiation

CH radio lines



Lower Satellite Line
0 → 1



Main Satellite Line
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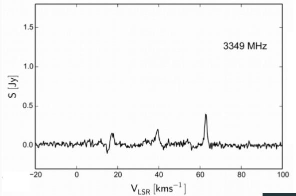
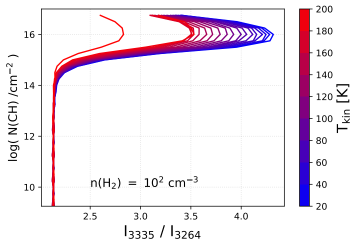


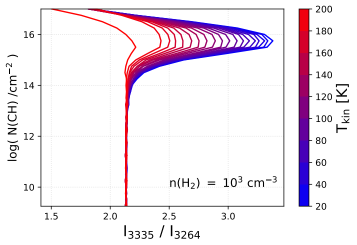
Upper Satellite Line
1 → 0

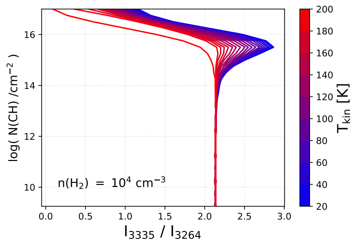
- At LTE, $I_{(3264)} : I_{(3335)} : I_{(3349)} = 1 : 2 : 1$
- Deviations from LTE $\Rightarrow$ interactions with radiation
- Requires non-LTE radiative transfer modelling
- N(CH) from FIR transitions used as input

Constraining the physical conditions

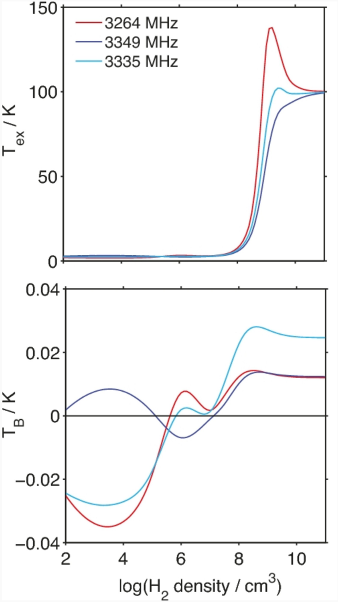
- MOLPOP-CEP (Coupled Escape Probabilty)
- Collisional rate coefficients from Dagdigian et al, 2018







RADEX models



(Dagdigian et al, 2018)

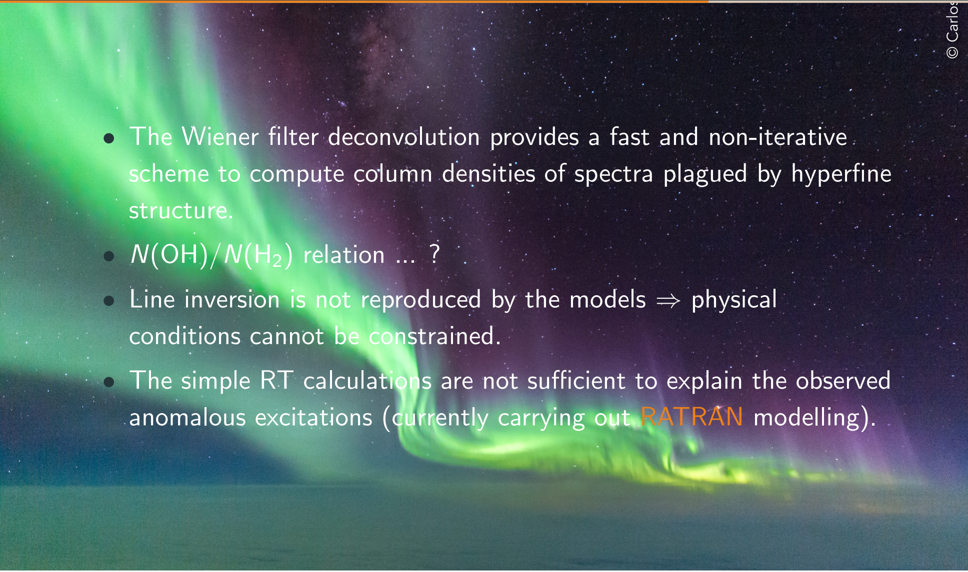
Model

- Expanding Sphere, $T_{kin} = 100\,K$, $o/p = 1.63$

Results

- $T_{ex} < T_{CMB}$ up to $n(H_2) \sim 10^7 cm^{-3}$
- T_{ex} rapidly increases at $n(H) \sim 2 \times 10^7 cm^{-3}$
- $T_{b,\ model} \nRightarrow T_{b,\ obs}$

Conclusion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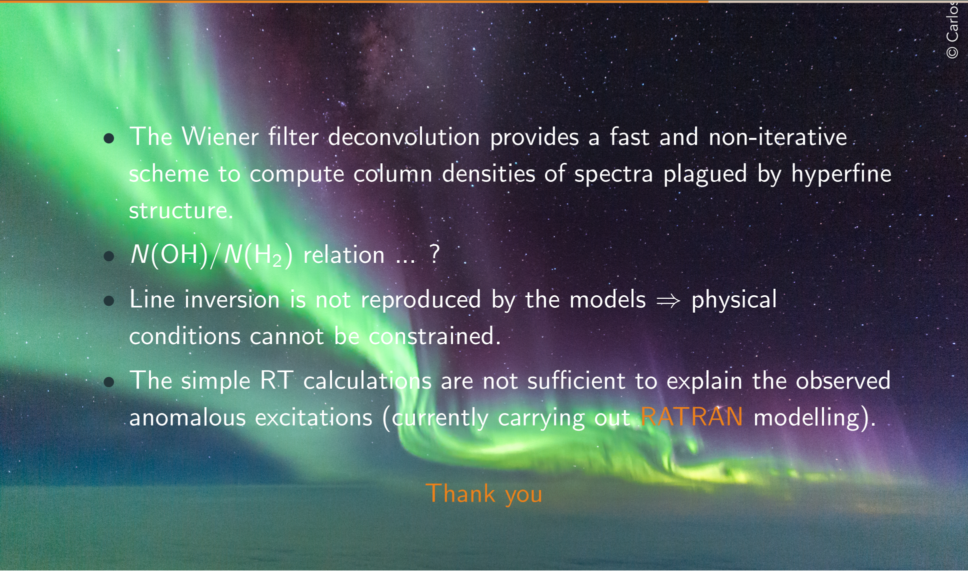
- The Wiener filter deconvolution provides a fast and non-iterative scheme to compute column densities of spectra plagued by hyperfine structure.
- $N(\mathrm{OH})/N(\mathrm{H_2})$ relation ... ?
- Line inversion is not reproduced by the models ⇒ physical conditions cannot be constrained.
- The simple RT calculations are not sufficient to explain the observed anomalous excitations (currently carrying out RATRAN modelling).

Conclusion



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Thank you

Backup slides

2 THz Transitions

Table 1: 2 THz doublet transitons. (*) indicates the transitions that were observed. The frequencies, Einstein coefficients and upper level energies are taken from the CDMS Mueller et. al, 2001 database.

Species	Transition	Hyperfine Components	Frequency [GHz]	A_E [s^{-1}]	E_U [K]
CH	$N = 2 \leftarrow 1$, $J = 3/2 \leftarrow 1/2$	$^*F = 1^- \leftarrow 1^+$	2006.74892	0.01117	96.31011
		$^*F = 1^- \leftarrow 0^+$	2006.76263	0.02234	96.31005
		$^*F = 2^- \leftarrow 1^+$	2006.79912	0.03350	96.31252
		$F = 1^+ \leftarrow 1^-$	2010.73859	0.01128	96.66158
		$F = 1^+ \leftarrow 0^-$	2010.81046	0.02257	96.66157
		$F = 2^+ \leftarrow 1^-$	2010.81192	0.03385	96.66510

Backup slides

3 GHz Transitions

Table 2: 3 GHz Λ-doubling transitions were observed. The frequencies, Einstein coefficients and upper level energies are taken from the CDMS Mueller et. al 2001 database.

Species	Transition	Hyperfine Components	Frequency [MHz]	A_E $[\times 10^{-10} s^{-1}]$	E_U [K]
CH	$N = 1$	$F = 0^- \leftarrow 1^+$	3263.79340	2.88	0.15736
	$J = 1/2$	$F = 1^- \leftarrow 1^+$	3335.47940	2.05	0.16080
		$F = 1^- \leftarrow 0^+$	3349.19260	1.04	0.16074

Backup slides

$T_{ex} = T_{CMB}$

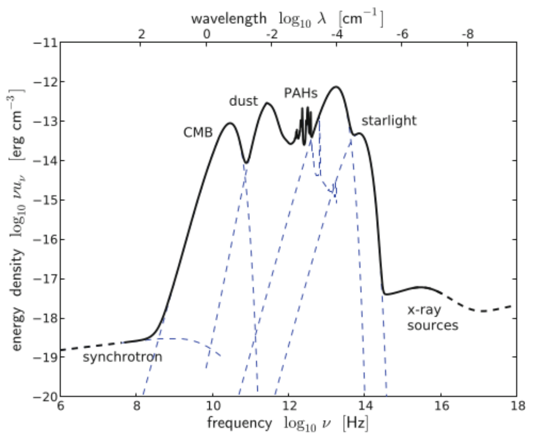
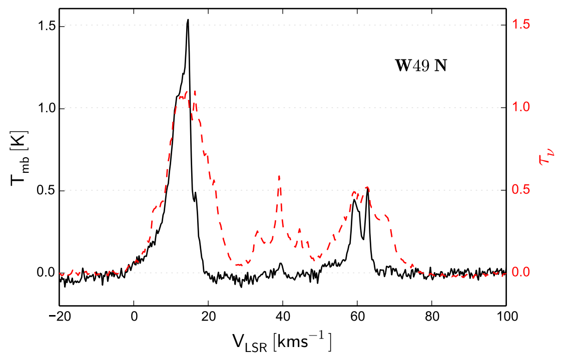


Figure 1: Schematic sketch of the energy density of the interstellar radiation field at different frequencies. (Tielens)

Backup slides



Backup slides

Critical Densities

Table 3: Critical densities of the CH 2 THz transitions at $T_{\mathrm{kin}} = 50$ K.

Collision Partner	n_{crit} [cm^{-3}] 2006.74 THz	 2006.76 THz	 2006.79 THz
H_2	5.00×10^{7}	9.95×10^{7}	1.45×10^{8}
H	8.88×10^{7}	1.76×10^{8}	2.48×10^{8}

Table 4: Critical densities of the CH 3 GHz transitions at $T_{\mathrm{kin}} = 50$ K.

Collision Partner	n_{crit} [cm^{-3}] 3.264 GHz	 3.349 GHz	 3.335 GHz
H_2	1.77	0.63	1.24
H	32.28	8.90	17.53

Backup slides

Negative Excitation Temperatures

$\frac{n_u}{n_l} = \frac{g_u}{g_l} exp(\frac{-\Delta E}{k_\mathrm{B} T_\mathrm{ex}})$

If the upper level is overpopulated for some reason,

$\frac{n_u}{n_l} > \frac{g_u}{g_l}$

Then T_ex is negative

- Since, $\tau \propto [1 - \exp(\frac{-\Delta E}{k_\mathrm{B} T_\mathrm{ex}})]$ the optical depth is also negative.
- At radio wavelengths this is called maser (microwave amplification by stimulated emission of radiation) amplification.
- Astrophysical masers are common at radio frequencies because $\Delta E \ll k_\mathrm{B} T_\mathrm{ex}$.

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Error Analysis

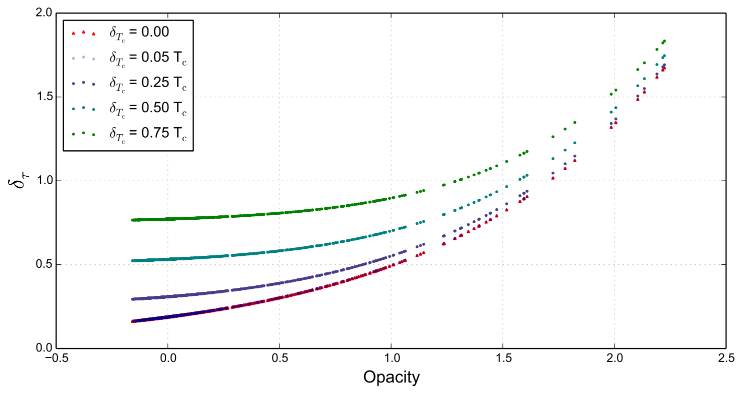

Figure 2: Displays the importance, uncertainity measures in the continuum play in derived results such as the opacity. The curves represent δT_c at 0, 5, 25, 50 and 75 % of the measured continuum level T_c.