SOFIA/GREAT observations of the mercapto radical (SH) in diffuse molecular clouds

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Interstellar hydrides

Individual hydrides and formed in relatively simple reaction networks and trace distinctive aspects of the interstellar environment

For example:

- OH^+ probes the cosmic ray ionization rate
- ArH^+ probes regions of very small H_2 fraction
- HF is a proxy for molecular hydrogen
- CH^+ and SH^+ probe warm regions – heated by shocks, or the dissipation of turbulence – where endothermic reactions (e.g. $C^+ + H_2 \rightarrow CH^+ + H$) are enhanced

Interstellar hydrides

- Prior to SOFIA, 5 or 6 neutral diatomic hydrides had been detected

				CH (Swings & Rosenfeld 1937)	**NH** (Meyer & Roth 1991)	**OH** (Weinreb 1963)	**HF** (Neufeld et al. 1995)	
				SiH ? (Schilke et al. 2001)			**HCl** (Blake et al. 1985)	

Interstellar hydrides

…along with four diatomic hydride cations (to which a fifth has recently been added)

				CH^+ (Douglas & Herzberg 1941)		**OH^+** (Gerin et al. & Wyrowski et al. 2010)		
						SH^+ (Benz et al. 2010)	**HCl^+** (DeLuca et al. 2012)	**ArH^+** (Barlow et al. 2013; Schilke et al. 2014)

The mercapto radical

- SH was conspicuously absent from the list of known interstellar hydrides

				CH (Swings & Rosenfeld 1937)	**NH** (Meyer & Roth 1991)	**OH** (Weinreb 1963)	**HF** (Neufeld et al. 1995)	
				SiH ? (Schilke et al. 2001)		**What about SH ?**	**HCl** (Blake et al. 1985)	

The mercapto radical

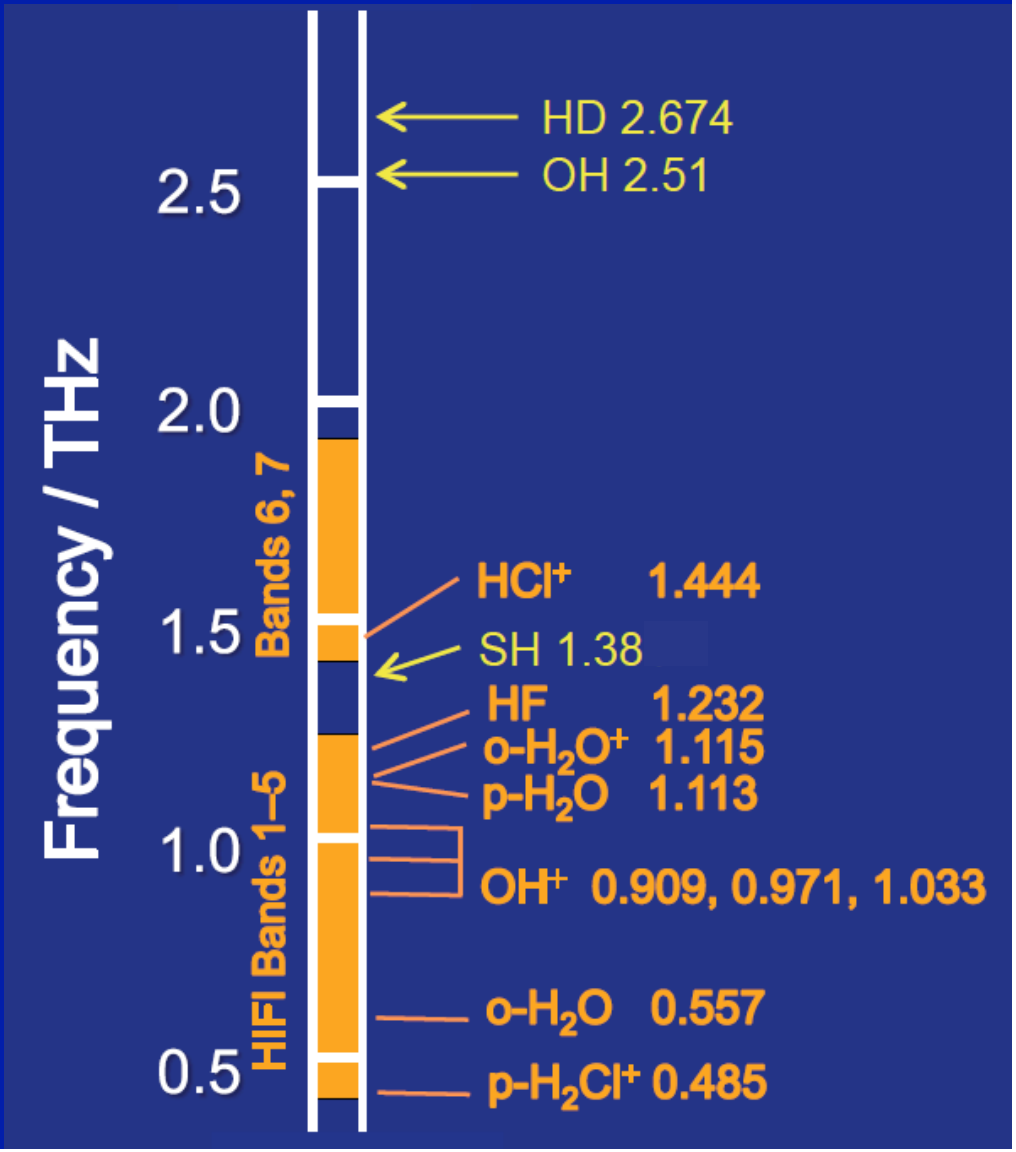
- Cold SH is unobservable from the ground
- The "ground state" rotational transition

$^2\Pi_{3/2}$ J= 5/2 → 3/2 at 1.383 THz

falls right in the gap between Bands 5 and 6 of *Herschel*'s HIFI spectrometer

The mercapto radical

- The GREAT (German REceiver for Astronomy at Terahertz frequencies) spectrometer on SOFIA has a receiver designed to cover this gap in *Herschel*/HIFI coverage (1250 – 1410 GHz)



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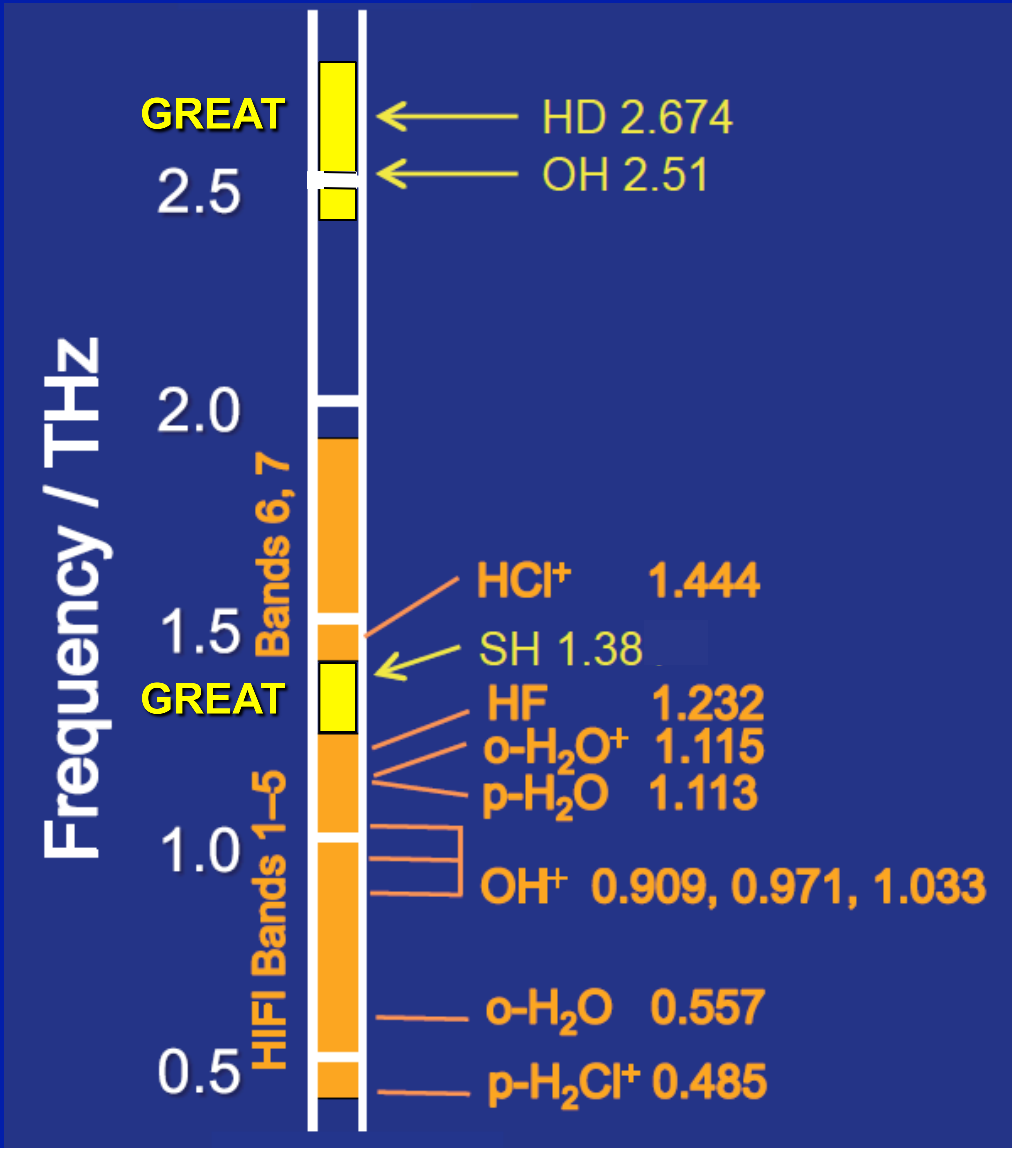
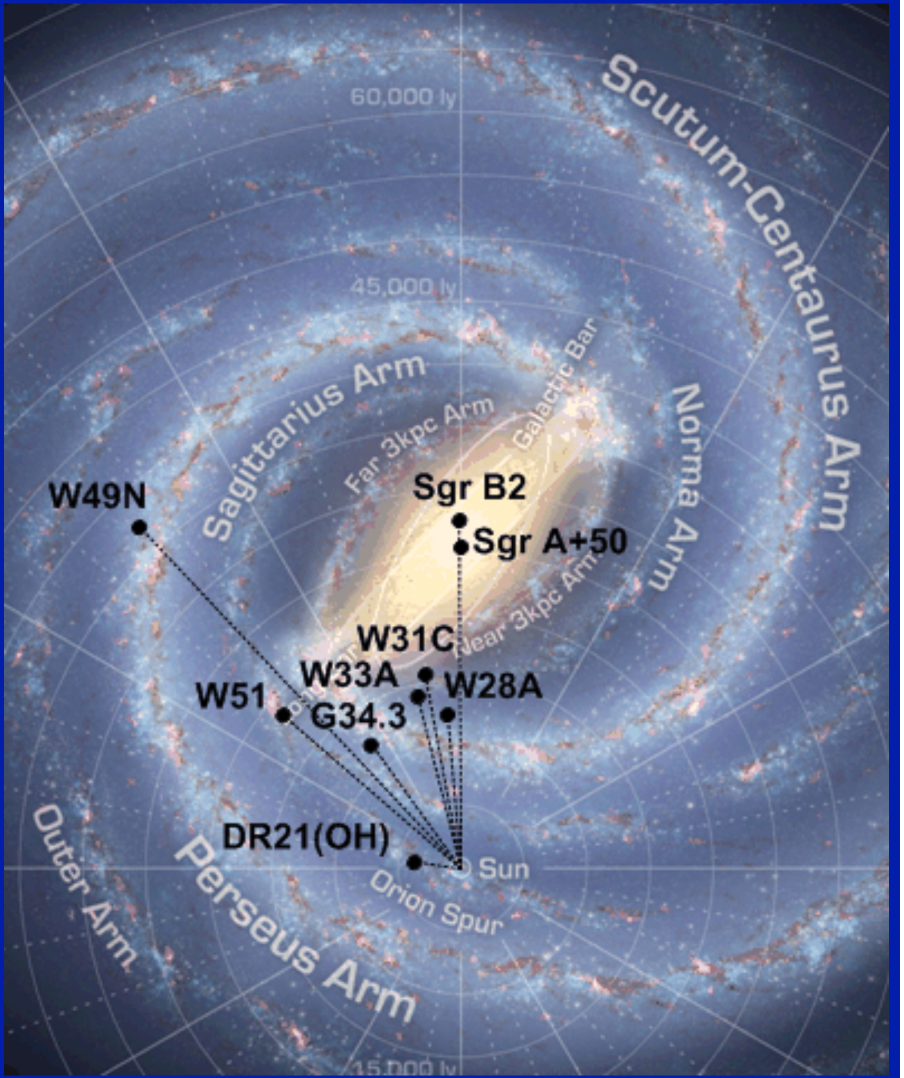


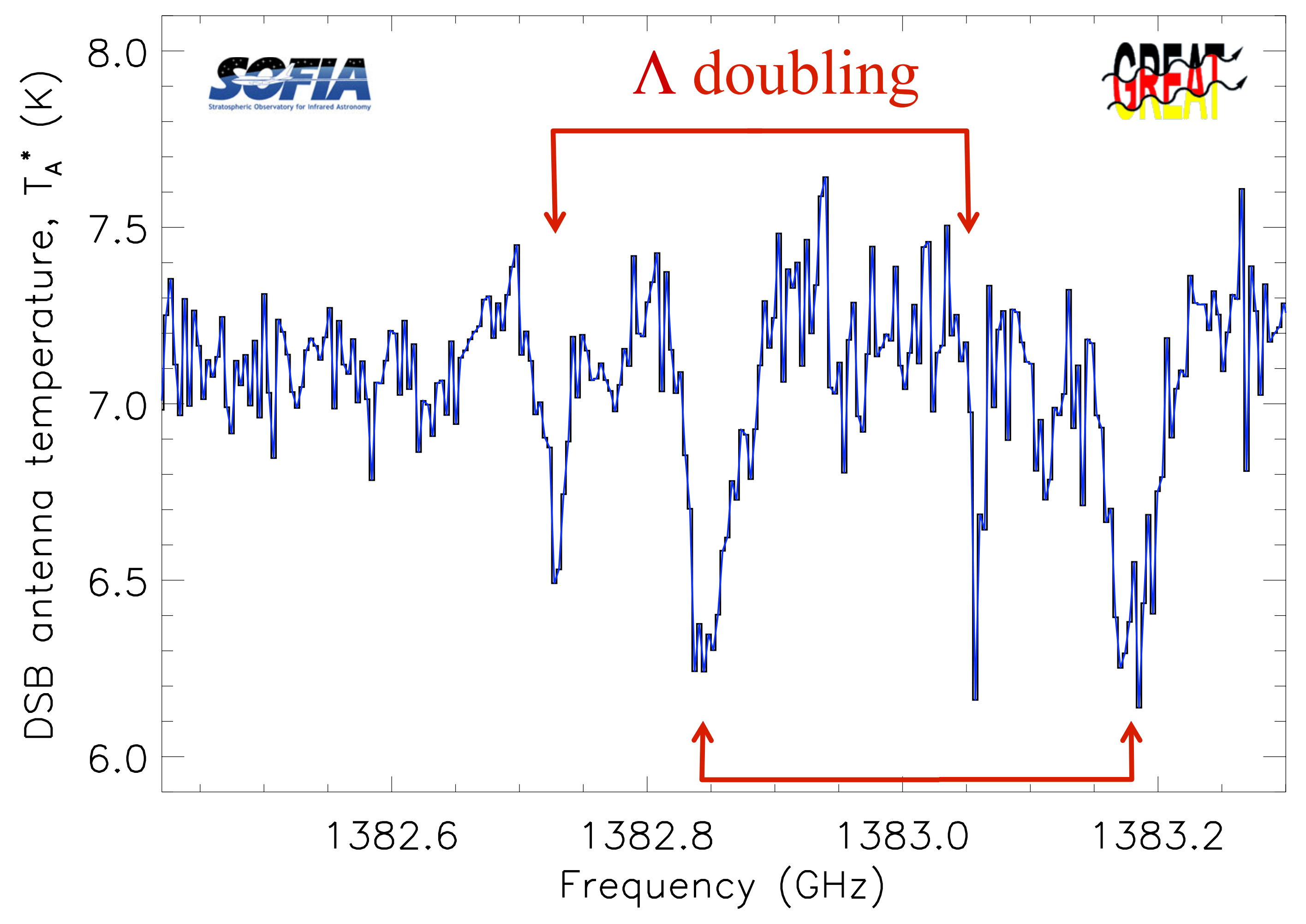
Search for SH in absorption toward W49N

- We used a very luminous region of massive star formation (W49N) as a background THz continuum source
- We searched for absorption by SH in foreground material
- This experiment was performed in a Basic Science ("General Investigator") program



Cycle 0: SH clearly detected in absorption toward W49N

Neufeld et al. 2012, A&A



Observations of SH performed toward four additional sources

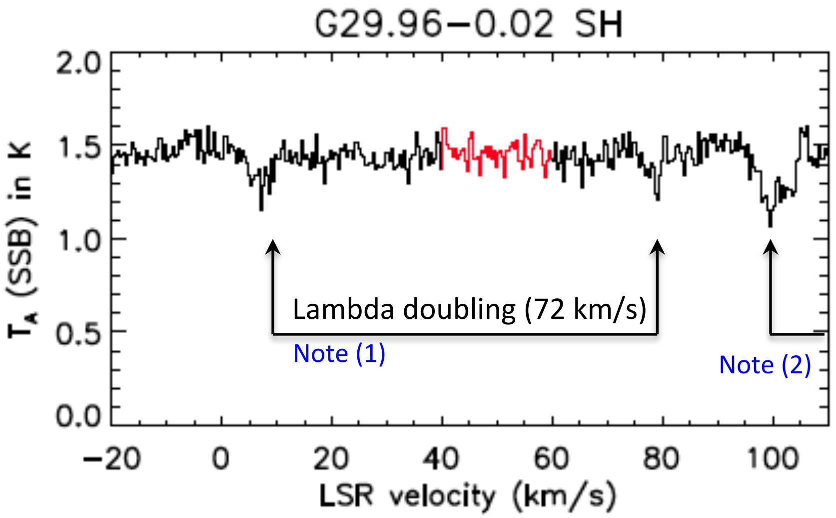
Following the first detection of interstellar SH toward W49N in Cycle 0, we observed diffuse clouds along the sight-lines to

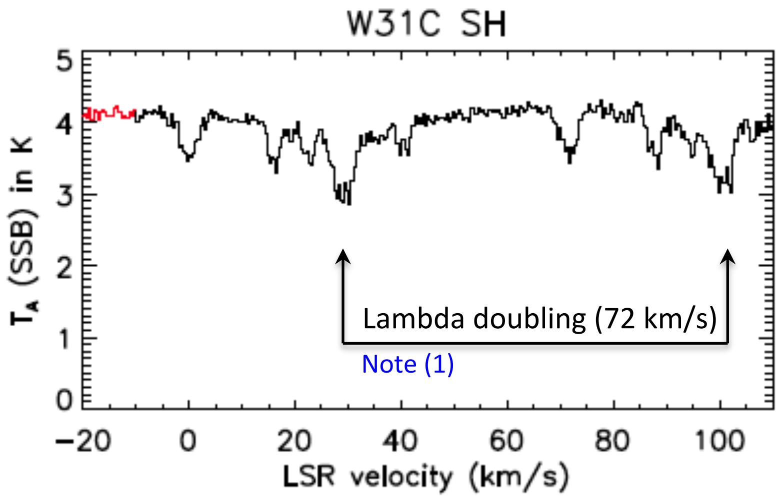
W31C*, G29.96–0.02*, G34.3+0.1*, W51**

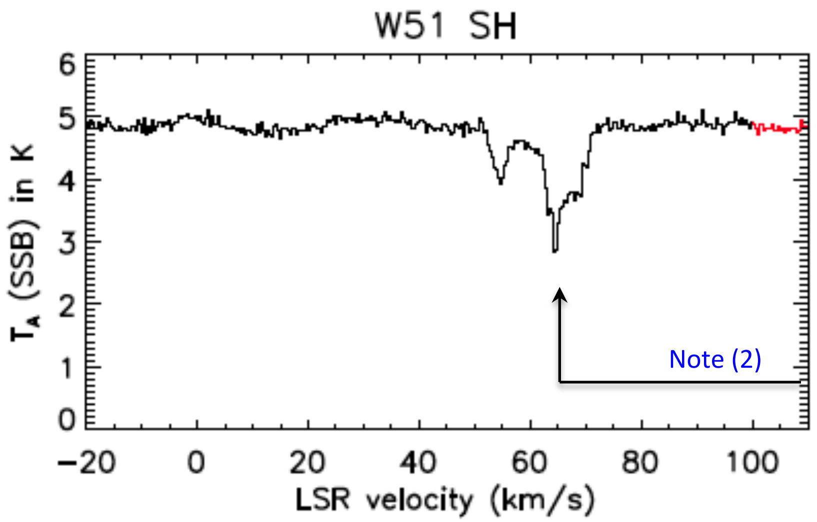
*July 2013 (Christchurch deployment)
**Nov 2013 (Palmdale deployment)

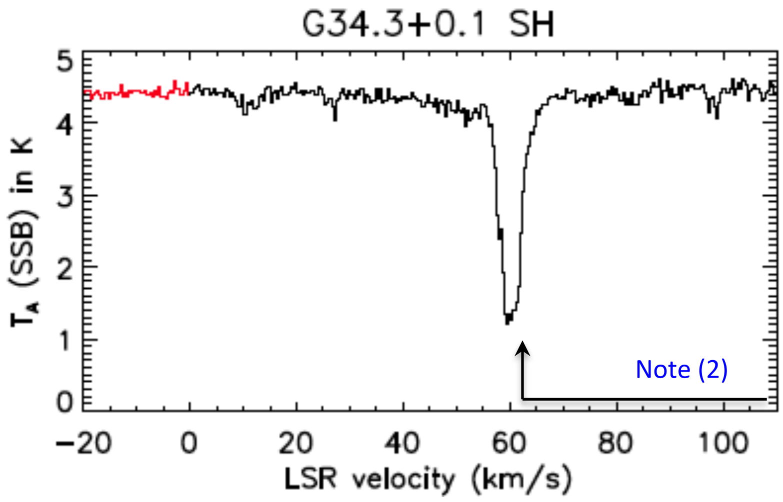
Motivation: SH is expected to trace regions where endothermic reactions can be driven by a "warm chemistry" in shocks or turbulent dissipation regions. Its abundance would be negligible in cold 80 K gas

Clear detections were obtained toward all four sources





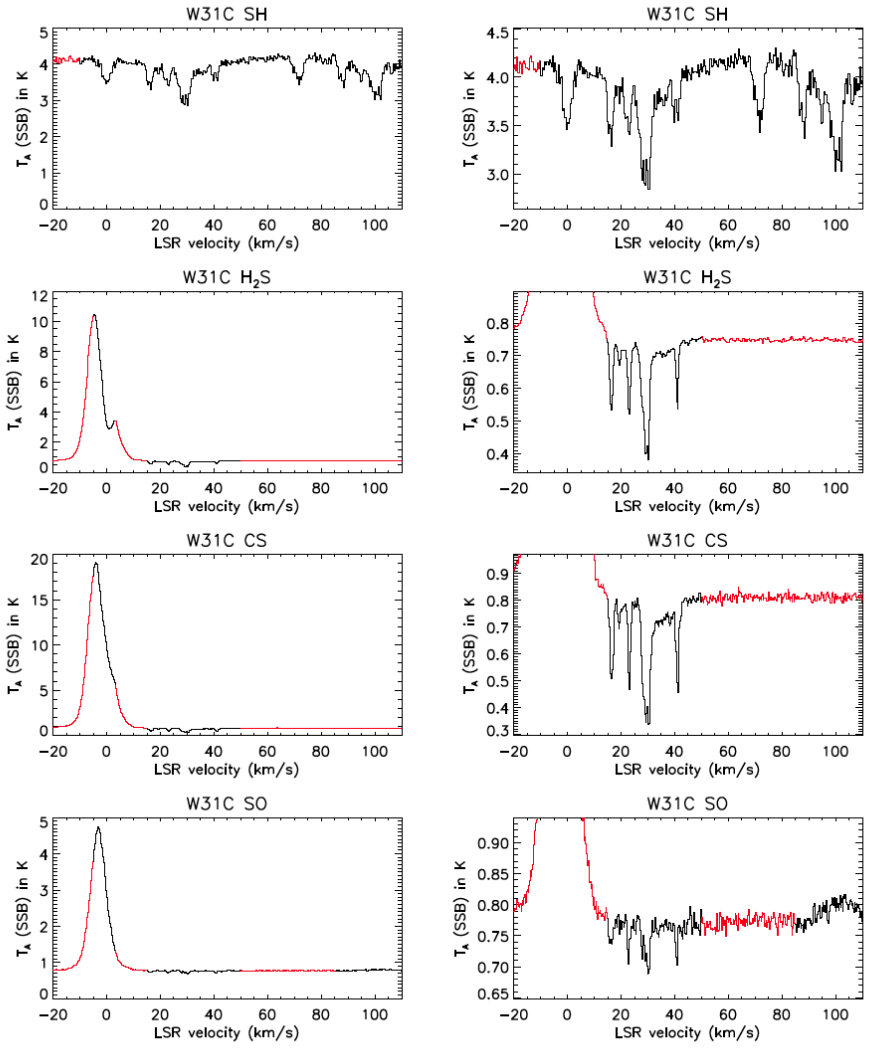




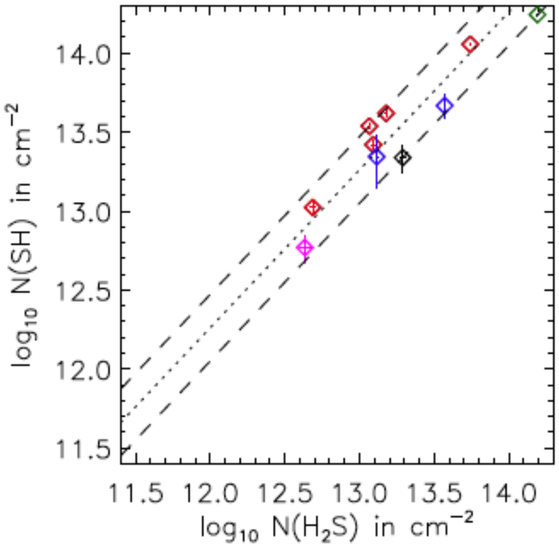
Notes

(1) there is also a hyperfine splitting of 1 – 2 km/s
(2) the other doublet member lies beyond +120 km/s and is therefore not shown in this plot

Ancillary observations of H_2S, CS and SO were performed at the IRAM 30 m



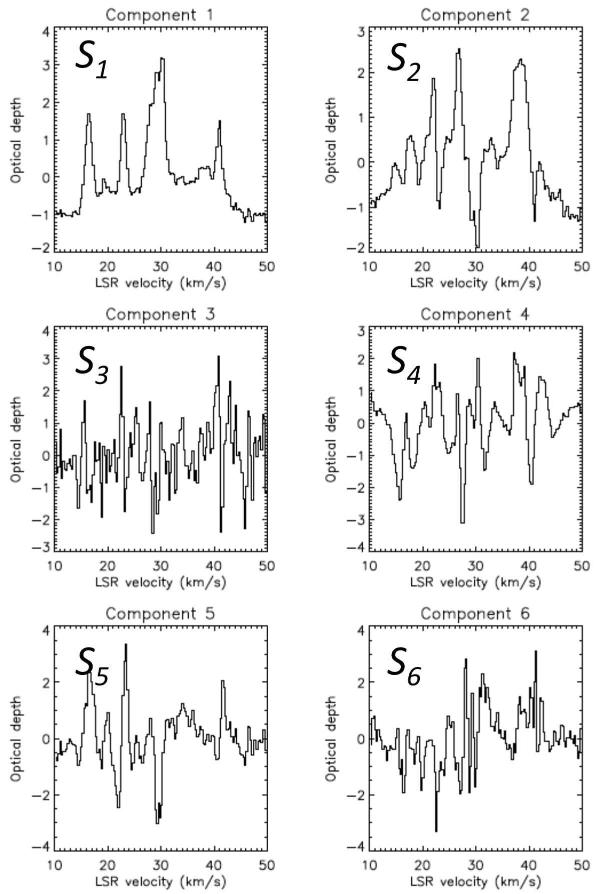
The absorption spectra are strikingly similar, with the column densities in the various absorption components being very well correlated. Example plot below shows N(SH) versus N(H_2S)



SH/H_2S ranges from 1.1 – 3.0 in ten foreground diffuse clouds detected toward five background sources

Principal component analysis

The optical depth spectra, shown by the black histograms on the right, are written as a linear combination of the six principal components shown at left. These six components are mutually orthogonal (uncorrelated) and listed in decreasing order of their contribution. The first two components are sufficient to yield a good fit to the data (red histogram on right) .



6 terms in Σ → black

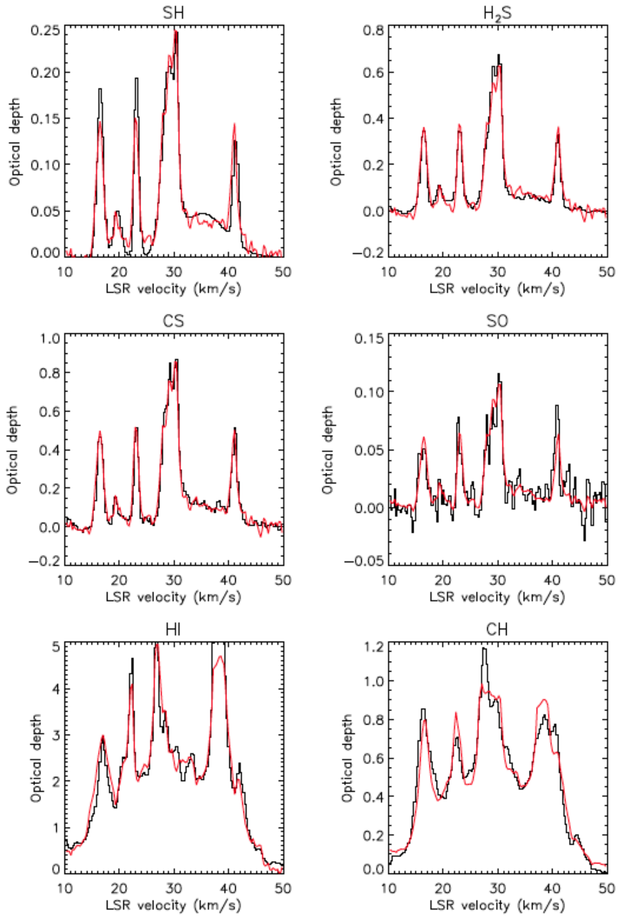
$$\tau_i(v) = a_i + b_i \sum_{j=1}^{6} C_{ij} S_j(v)$$

Gives an exact fit

2 terms in Σ → red

$$\tau_i(v) = a_i + b_i \sum_{j=1}^{2} C_{ij} S_j(v)$$

Good approximation



Principal component analysis

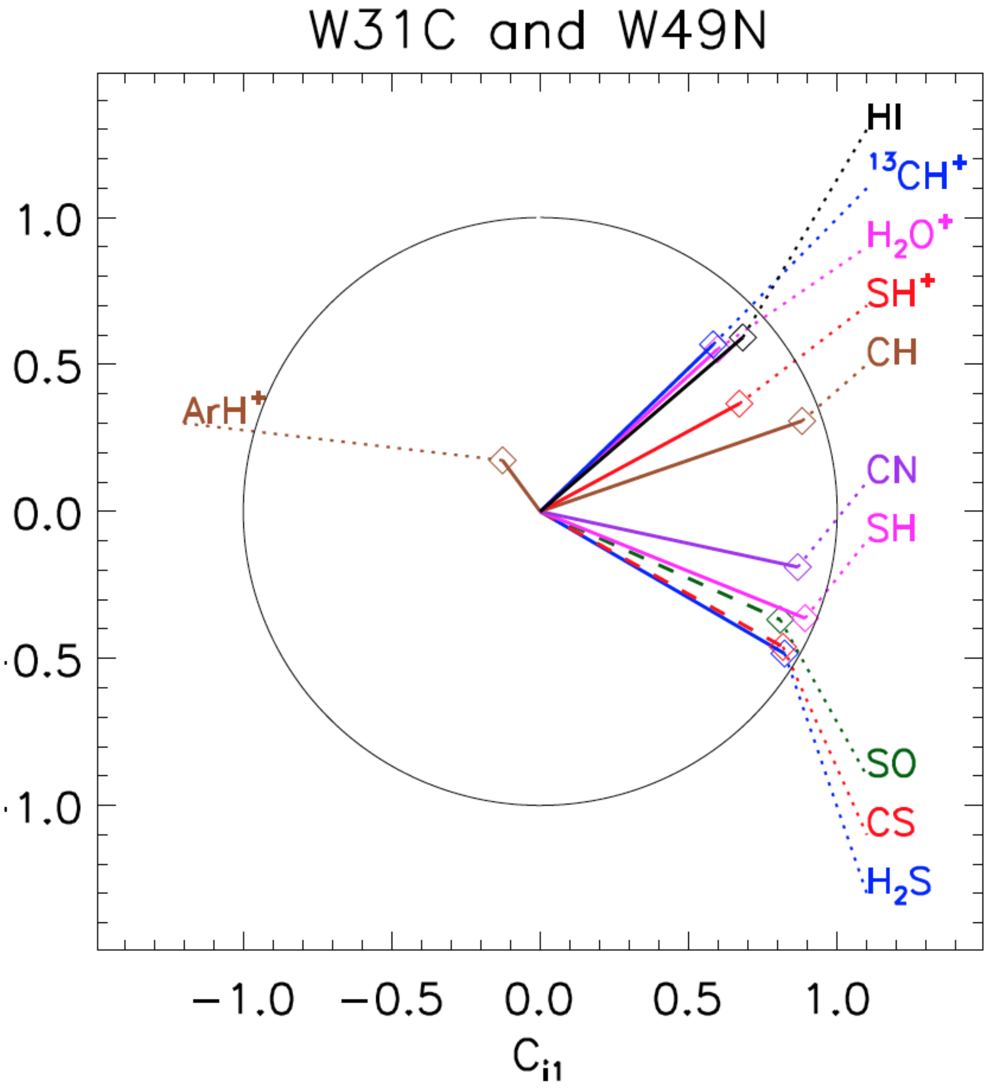
A plot of the first two coefficients, C_{i1} and C_{i2}, for each absorption line shows the similarities and differences graphically.

NOTES

(1) Except for ArH^+, all points lie close to unit circle, indicating that the first two components account for most of what is observed

➔ the correlation coefficient is roughly the cosine of the angle between any two vectors

(2) The position of the neutral sulphur-bearing molecules relative to H, CH and the other species may suggest that they are present mainly in material with a large molecular fraction (since HI traces atomic gas and CH traces H_2 in partially- or fully-molecular gas)



Molecular abundances

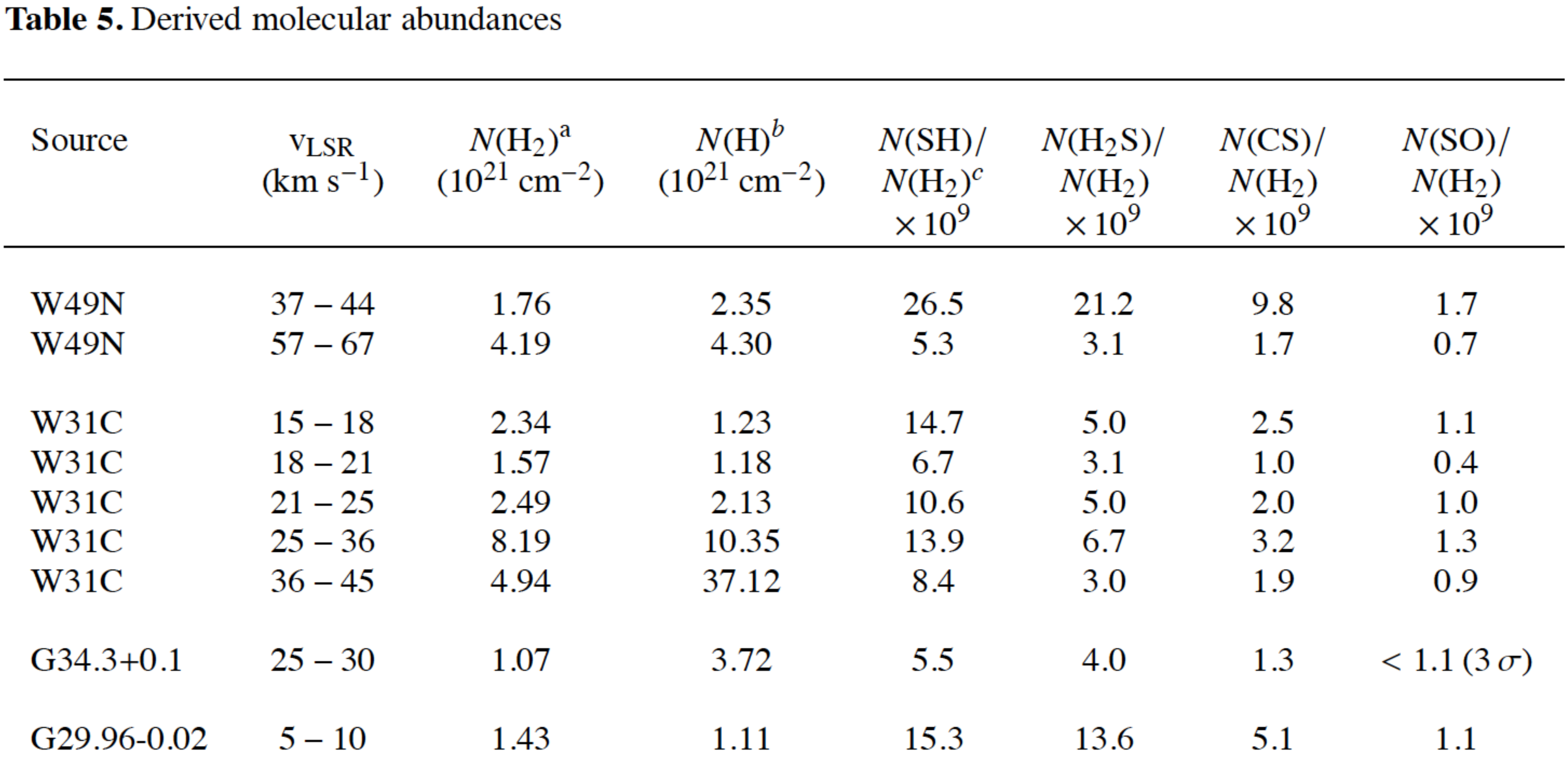
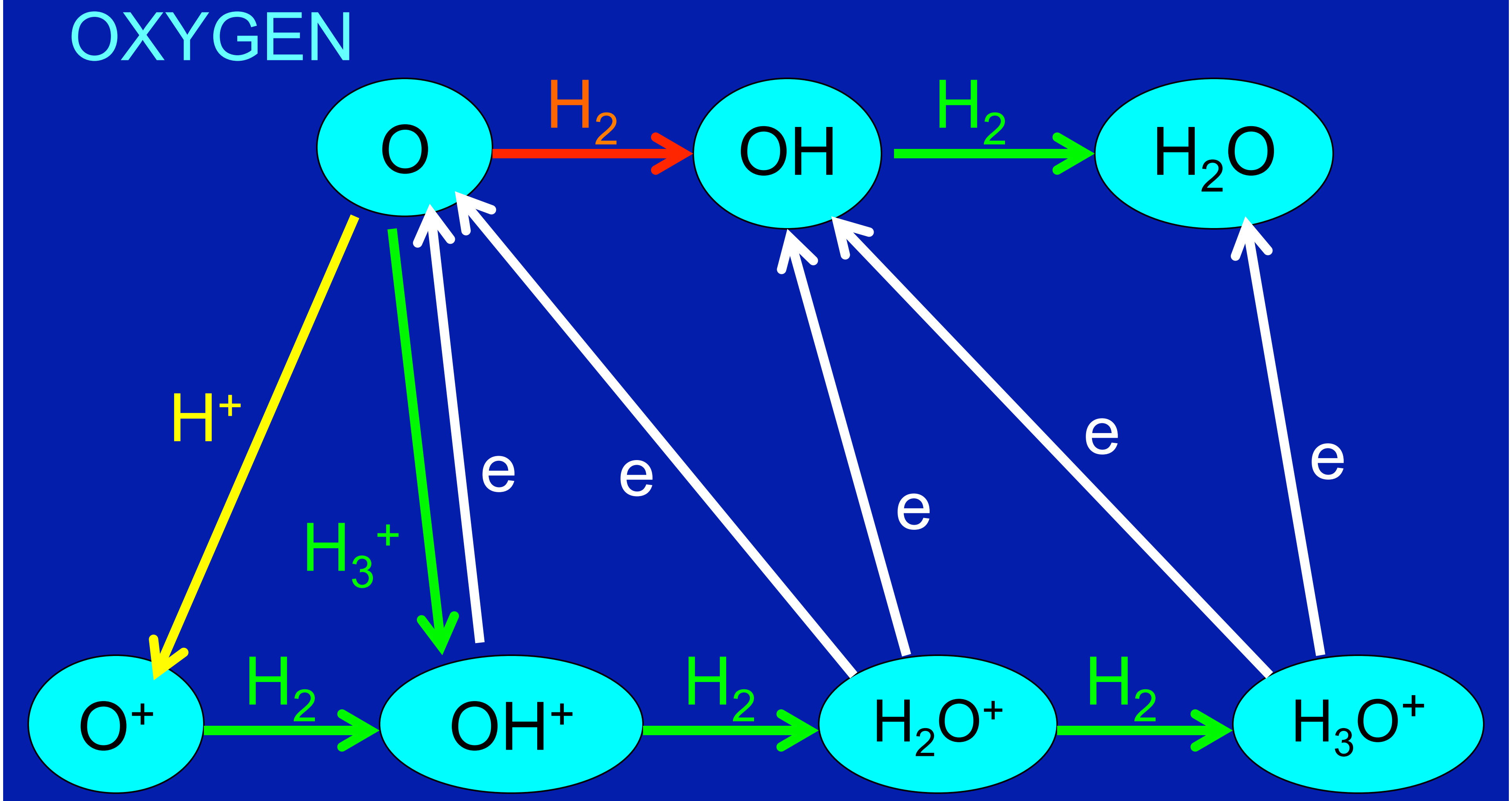


Table 5. Derived molecular abundances

Source	v_{LSR} (km s^{-1})	$N(H_2)^a$ (10^{21} cm^{-2})	$N(H)^b$ (10^{21} cm^{-2})	$N(SH)/N(H_2)^c$ $\times 10^9$	$N(H_2S)/N(H_2)$ $\times 10^9$	$N(CS)/N(H_2)$ $\times 10^9$	$N(SO)/N(H_2)$ $\times 10^9$
W49N	37 – 44	1.76	2.35	26.5	21.2	9.8	1.7
W49N	57 – 67	4.19	4.30	5.3	3.1	1.7	0.7
W31C	15 – 18	2.34	1.23	14.7	5.0	2.5	1.1
W31C	18 – 21	1.57	1.18	6.7	3.1	1.0	0.4
W31C	21 – 25	2.49	2.13	10.6	5.0	2.0	1.0
W31C	25 – 36	8.19	10.35	13.9	6.7	3.2	1.3
W31C	36 – 45	4.94	37.12	8.4	3.0	1.9	0.9
G34.3+0.1	25 – 30	1.07	3.72	5.5	4.0	1.3	< 1.1 (3σ)
G29.96-0.02	5 – 10	1.43	1.11	15.3	13.6	5.1	1.1

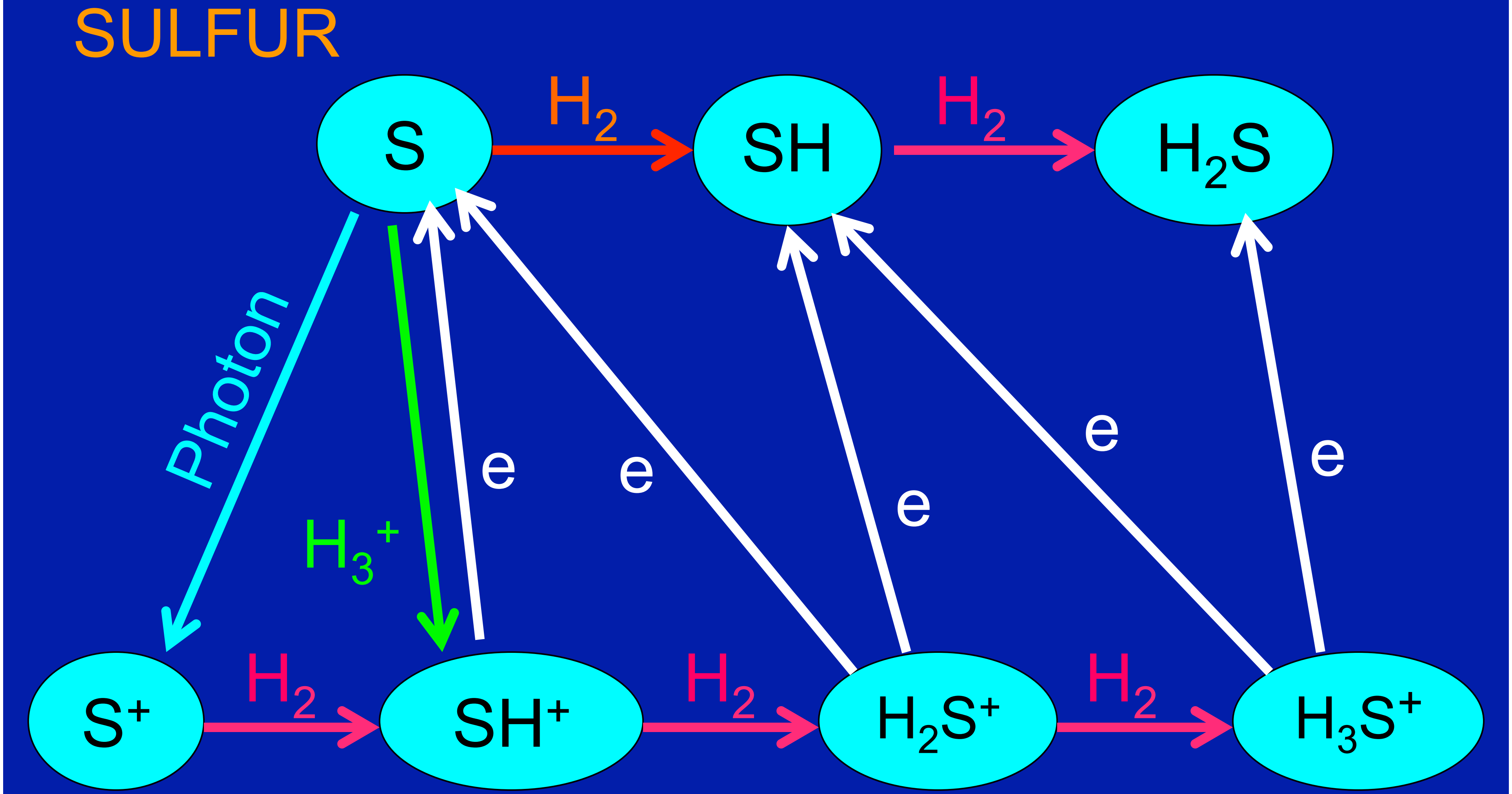
SH accounts for only ~0.1% of S nuclei, but this is still much more than is expected in cold diffuse clouds

Underlying thermochemistry



Green arrow=exothermic red=endothermic yellow=slightly endothermic

Underlying thermochemistry



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Underlying thermochemistry

OH and H_2O can be produced via two pathways:

Low temperature: ion-molecule reactions, then dissociative recombination of H_3O^+

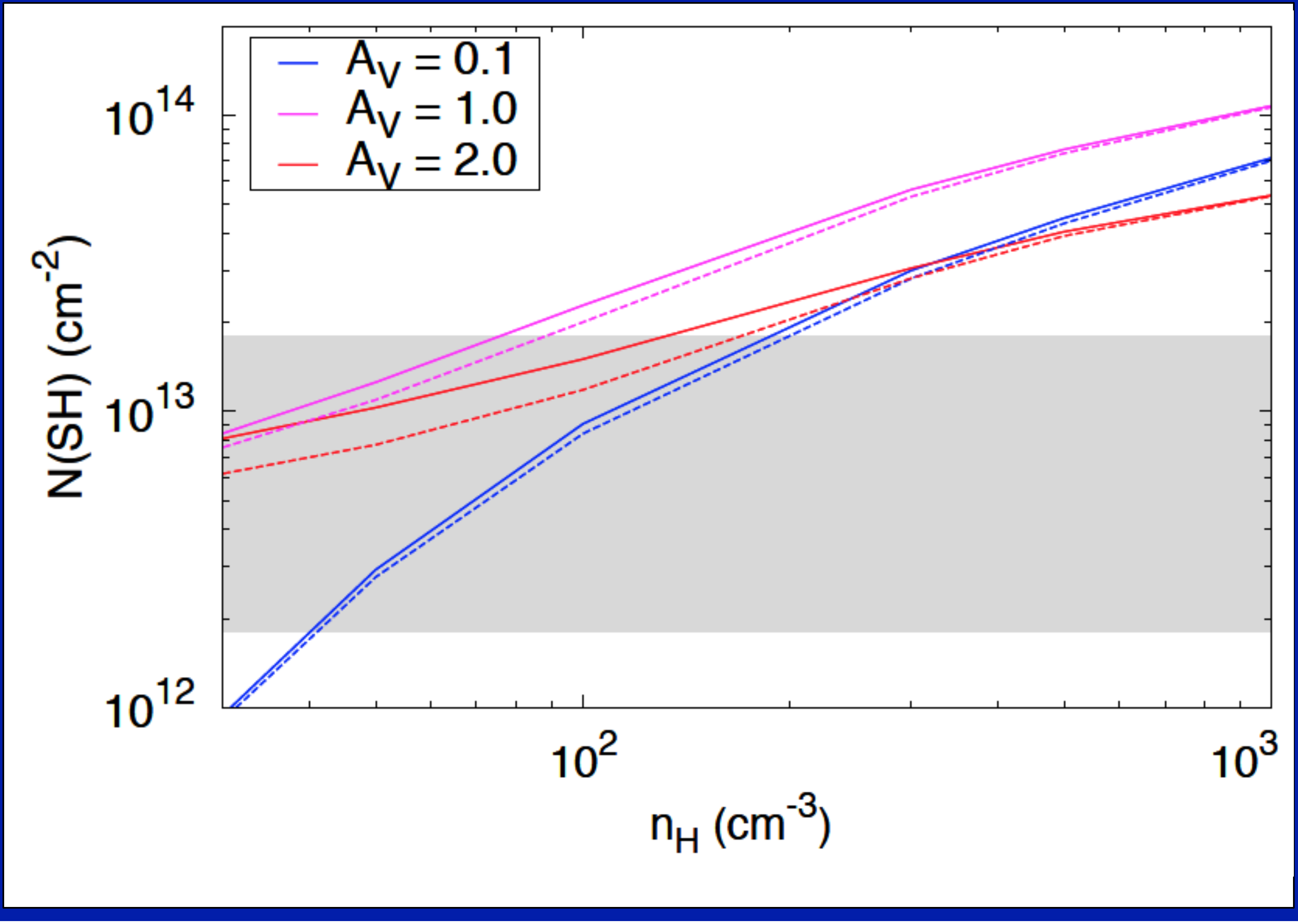
High temperature: neutral-neutral reactions

SH and H_2S are only produced at elevated temperatures:

Their presence is evidence for shocks or turbulent dissipation regions

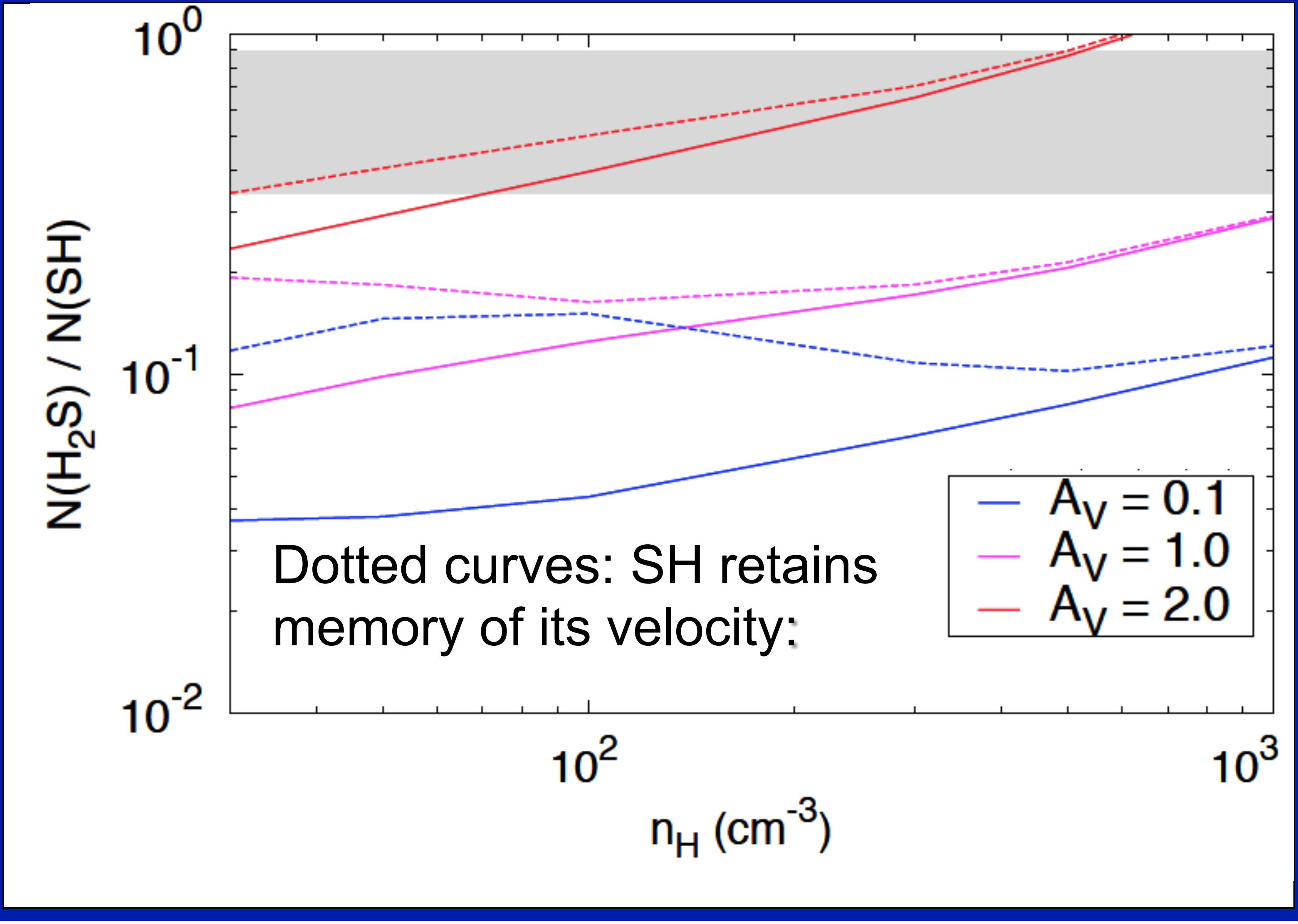
Shock model predictions:

SH column densities can be explained



Shock model predictions:

H_2S/SH is underpredicted

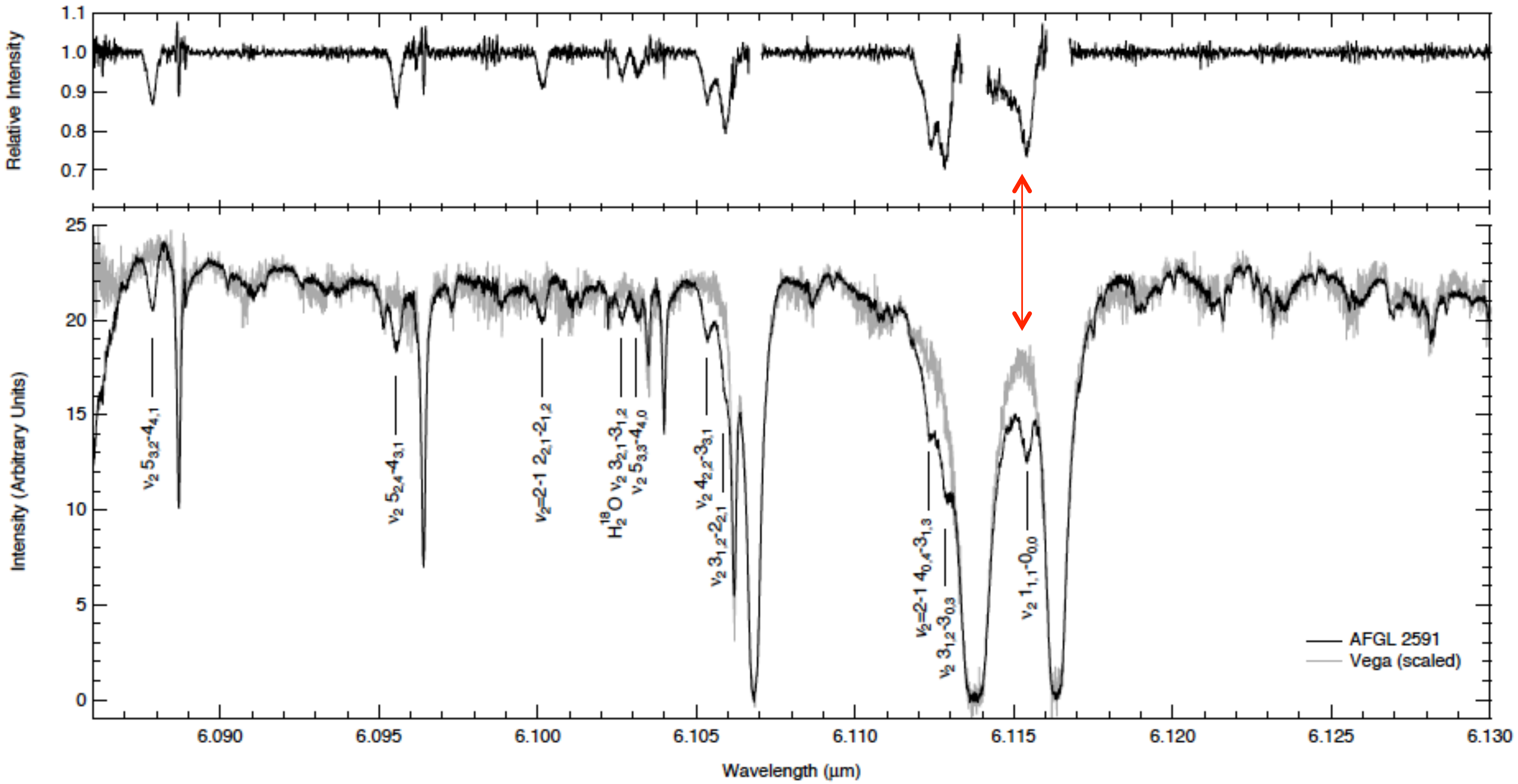


Dotted curves: SH retains memory of its velocity:

Future prospects for studies of interstellar hydrides with SOFIA

- GREAT continues to perform unique high-resolution spectroscopy, providing access to OH, OD, HD, p-H_2D^+ and SH in their ground states
- Lower frequency heterodyne spectroscopy ("downGREAT"?) would provide access to CH, ArH^+, HF, NH_3
- EXES now provides access to vibrational bands of hydrides

Recent detection of H_2O in its ground rotational state (Indriolo et al. 2015, arXiv: 1502.06611)



Summary

- SOFIA/GREAT introduces a powerful capability for heterodyne spectroscopy of interstellar hydrides at otherwise inaccessible frequencies

- It has discovered widespread absorption by interstellar SH in foreground diffuse clouds along the sight-lines to THz continuum sources

→ a key tracer of "warm chemistry"

C and S chemical networks