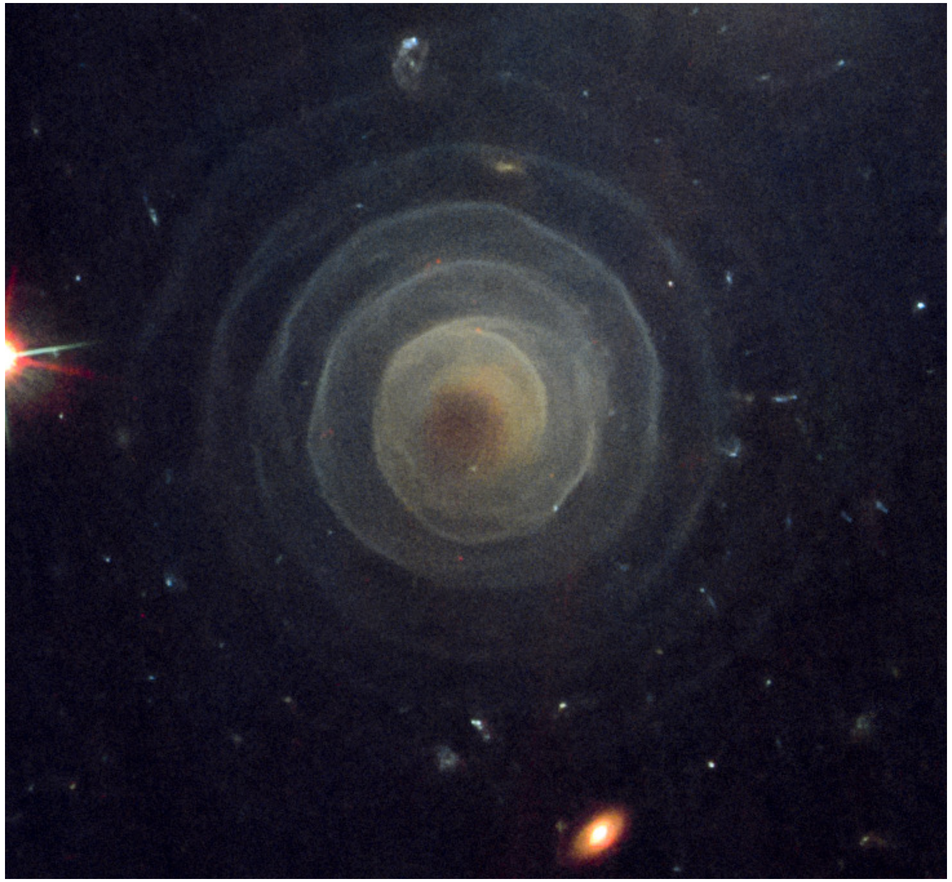

Searching for Diatomic Hydrides in the Winds of Evolved Stars

Mark A. Siebert – mas5fb@virginia.edu

Ignacio Simon[2], Christopher N. Shingledecker[3,4,5], P. Brandon Carroll[6], Andrew M. Burkhardt[1,6], Shawn Thomas Booth[2], Anthony J. Remijan[2], Brett A. McGuire[2,6,7], Rebeca Aladro[8], and Carlos A. Duran[8]

[1]Department of Astronomy, University of Virginia [2]National Radio Astronomy Observatory [3]Department of Physics and Astronomy, Benedictine College, [4]Center for Astrochemical Studies, Max-Planck-Institute for Extraterrestrial Physics, [5]Institute for Theoretical Chemistry, University Stuttgart, [6]Harvard-Smithsonian Center for Astrophysics, [7]Department of Chemistry, Massachusetts Institute of Technology, [8]Max-Planck-Institut für Radioastronomie

Our Galactic Ecosystem, Lake Arrowhead, CA

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DIATOMIC HYDRIDES IN THE ISM

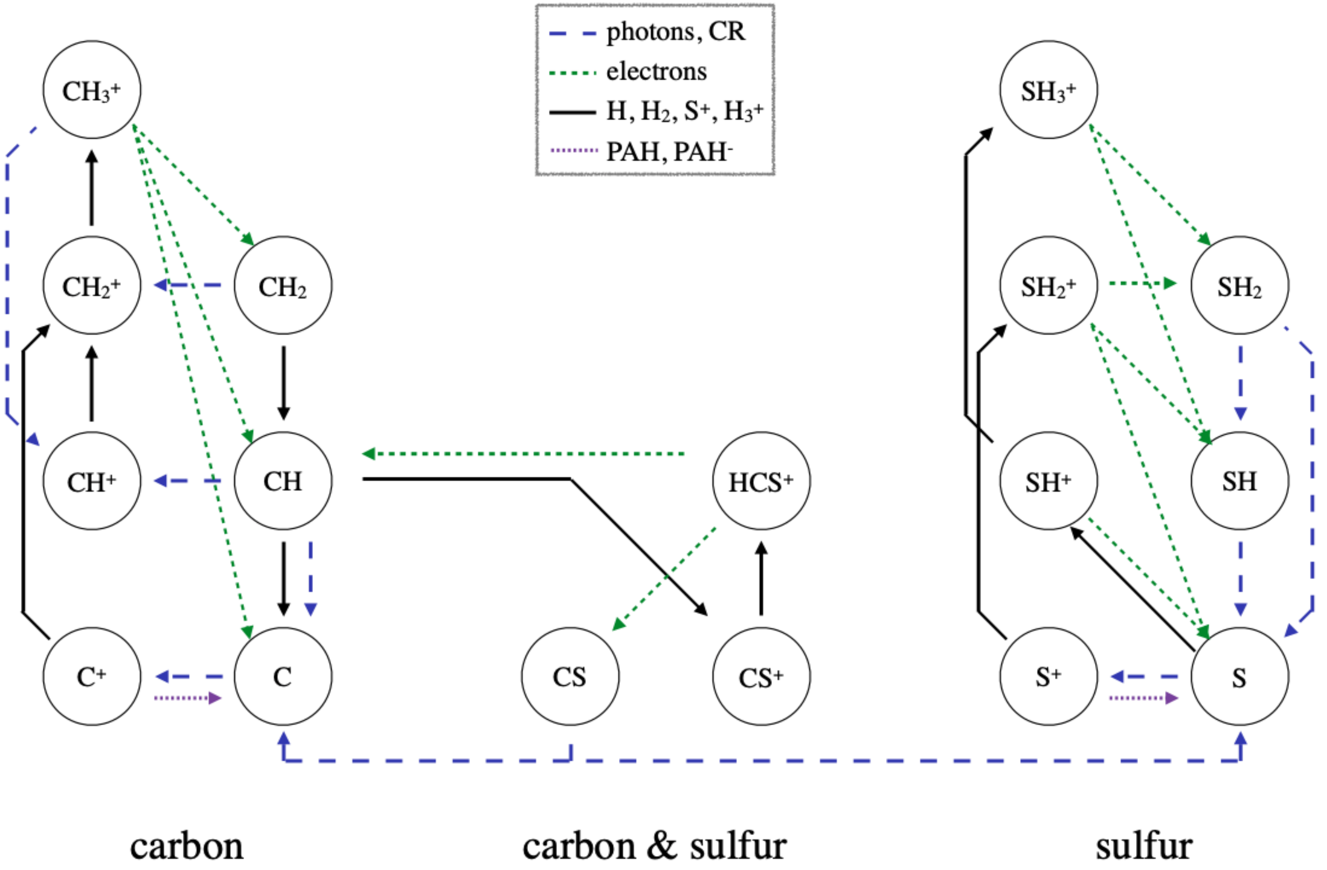
- Underpin much of interstellar chemistry
- Swings & Rosenfeld (1937) – First identification of methylidyne (CH) in space

- Neutrals: CH OH NH HCl HF SH
- Ions: CH^+ OH^+ SH^+ HCl^+ ArH^+ HeH^+

- Hydrogen → most abundant reactant in ISM
- Precursors to more complex species like ammonia (NH_3), methane (CH_4)

UV driven chemistry

Godard et al. (2014)



Diatomic hydrides offer a way for us to track the dominant chemical processes in any given interstellar environment.

NEUTRAL SPECIES

- Three main gas phase pathways for diatomic hydrides
- In general, neutral hydrides are difficult to form directly. Instead, CR and UV ionization drives hydride chemistry in most environments.
  - Diffuse clouds, PDRs
- Neutral hydrides thus require dissociative recombination of heavier ions

  e.g. $CH_3^+ + e^- \rightarrow CH + H_2$

Element	Ionization potential (eV)	Endothermicity (Kelvin equivalent = $\Delta E/k_B$) for			Driver
		$X + H_2 \rightarrow XH + H$	$X^+ + H_2 \rightarrow XH^+ + H$	$X + H_3^+ \rightarrow XH^+ + H_2$	
He	24.587	No reaction	Exothermic, but primary channel is to He + H + H$^+$	29,000	
C	11.260	11,000	4,300 ✓		Warm gas
N	14.534	15,000	230	10,000	Cosmic rays
O	13.618	920 ✓	✓	✓	Warm gas or cosmic rays
F	17.423	✓		10,000	None needed
Ne	21.564	No reaction	Exothermic, but primary channel is to Ne + H + H$^+$	27,000	
Si	8.152	17,000	15,000		Warm gas
P	10.487	19,000	13,000		Warm gas
S	10.360	10,000	10,000 ✓		Warm gas
Cl	12.968	515	✓		UV with hν > 12.97 eV
Ar	15.760	No reaction	✓	6,400	Cosmic rays

Gerin et al. (2016)

Requires high temperature, high density, source of atoms.

ENVELOPES OF EVOLVED STARS

- Inner wind conditions allow reactions to reach **equilibrium** before traveling outward

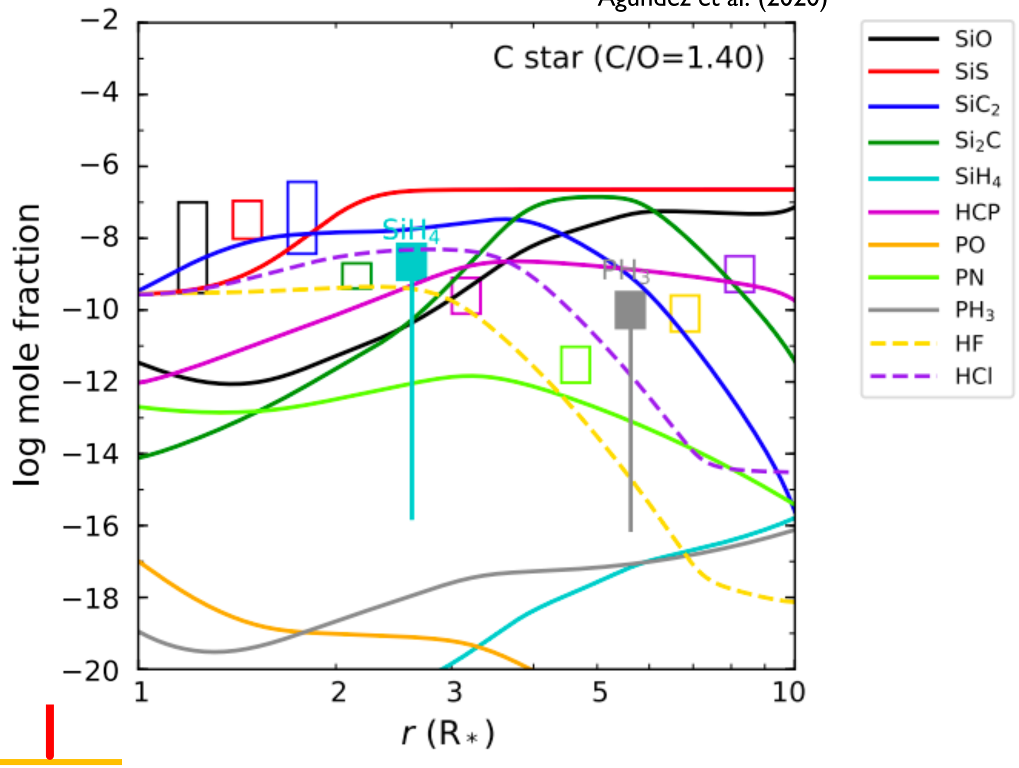
- Parent molecules and dust form near stellar surface
- Processed into daughter molecules in outer regions

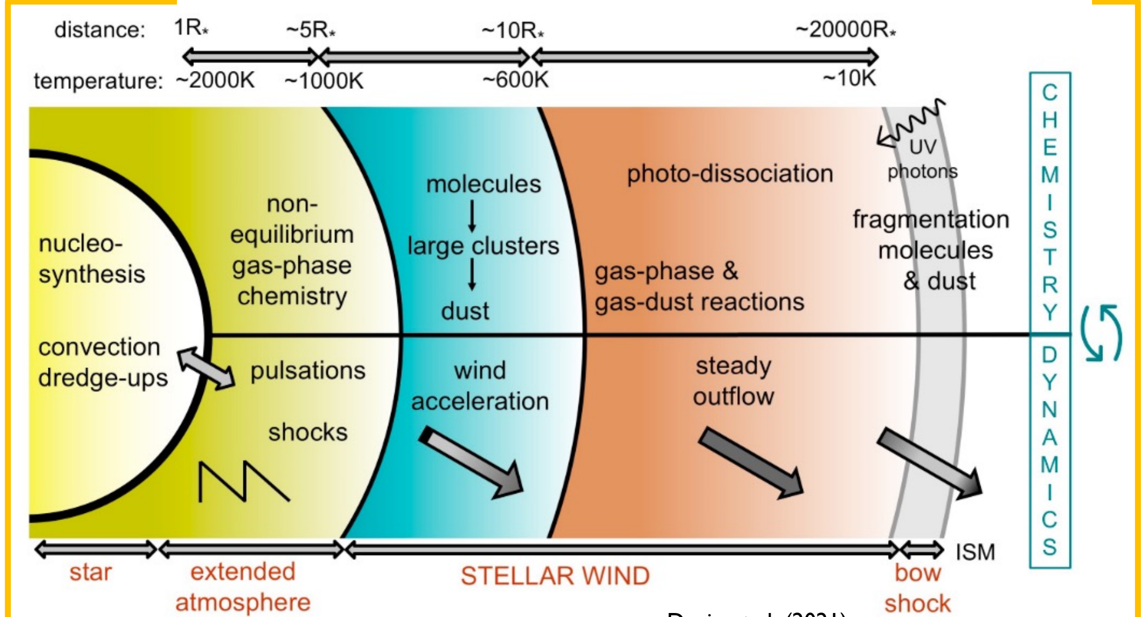
- Hydrides detected toward evolved stars

  HCl HF OH SH NH_3 PH_3 H_2O H_2S CH_4 SiH_4

Silane (SiH_4), phosphine (PH_3), ammonia (NH_3), and water (H_2O) have been observed to be much more abundant than equilibrium models predict.

Agúndez et al. (2020)





Decin et al. (2021)

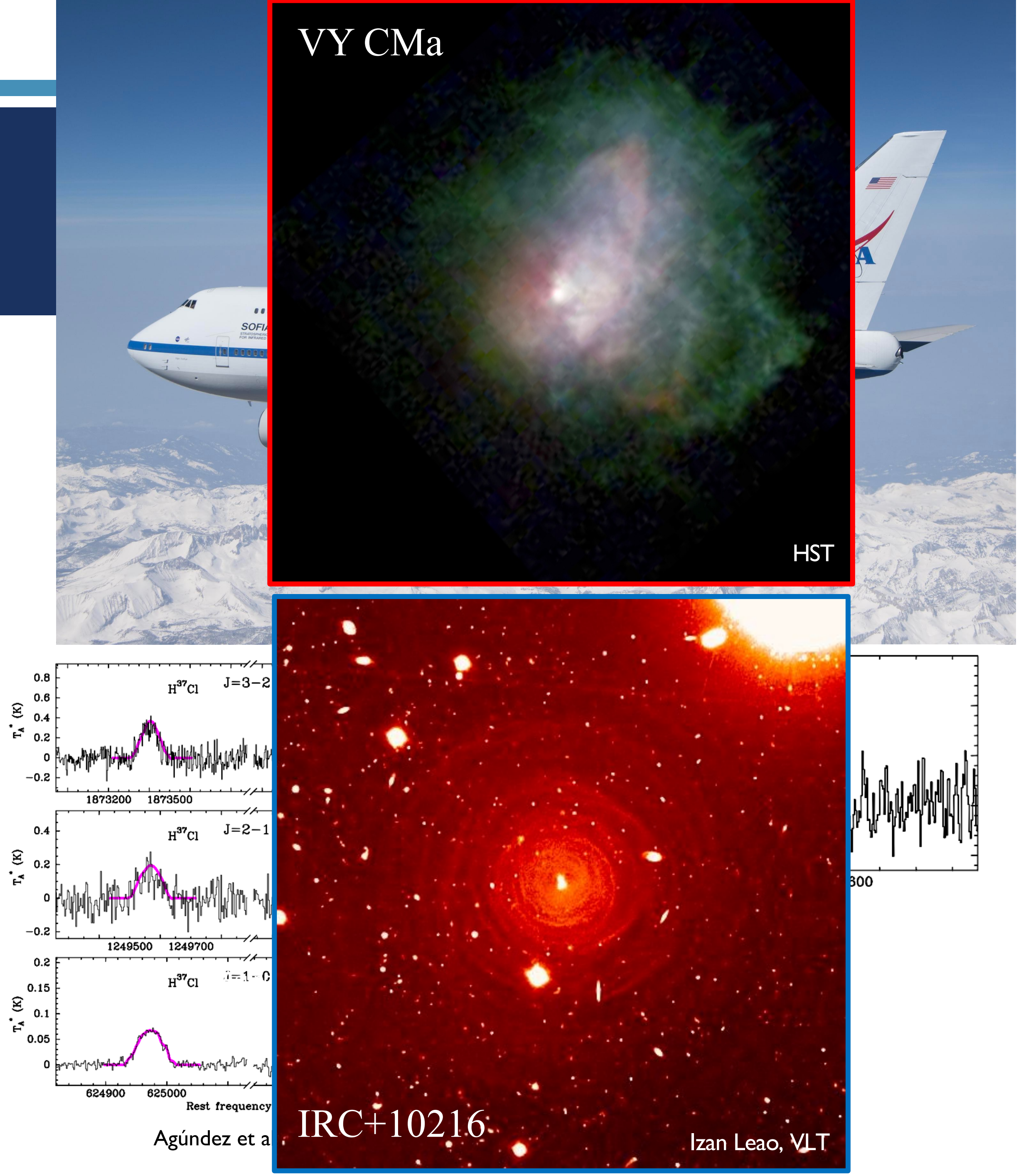
SOFIA - SEARCHING FOR LIGHT HYDRIDES IN CSES

- SOFIA GREAT – German Receiver for Astronomy at Terahertz Frequencies
  - 4GREAT upgrade
- Similar frequency coverage and spatial resolution as Herschel HIFI

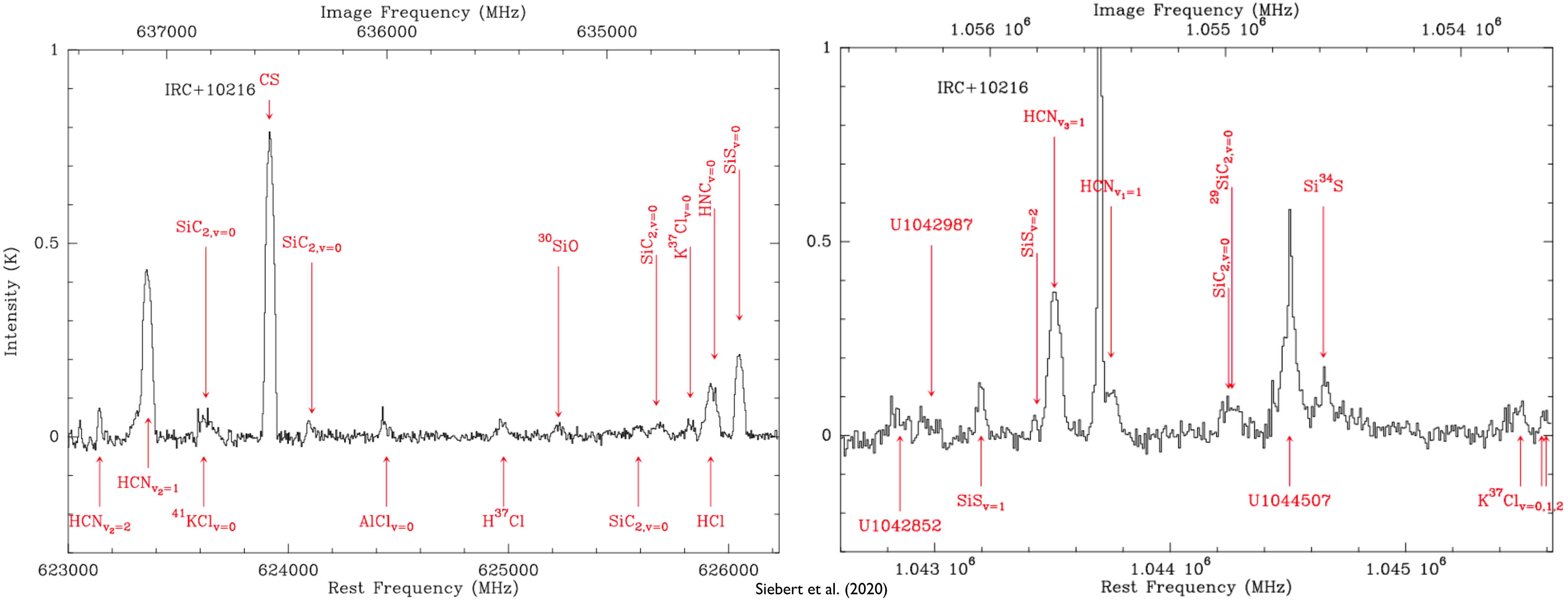
- **Targeted transitions of three neutral hydrides:**

SiH ($^2\Pi_{1/2}$)	J = 3/2 → 1/2	624.925 GHz
	J = 5/2 → 3/2	1043.918 GHz
PH ($^3\Sigma^-$)	N = 3 → 2 , J = 4 → 3	1507.640 GHz
FeH ($^4\Delta$)	Ω = 5/2 , J = 7/2 → 5/2	1324.771 GHz

E_{up} ~ 30 – 300 K



SOFIA GREAT SPECTRA



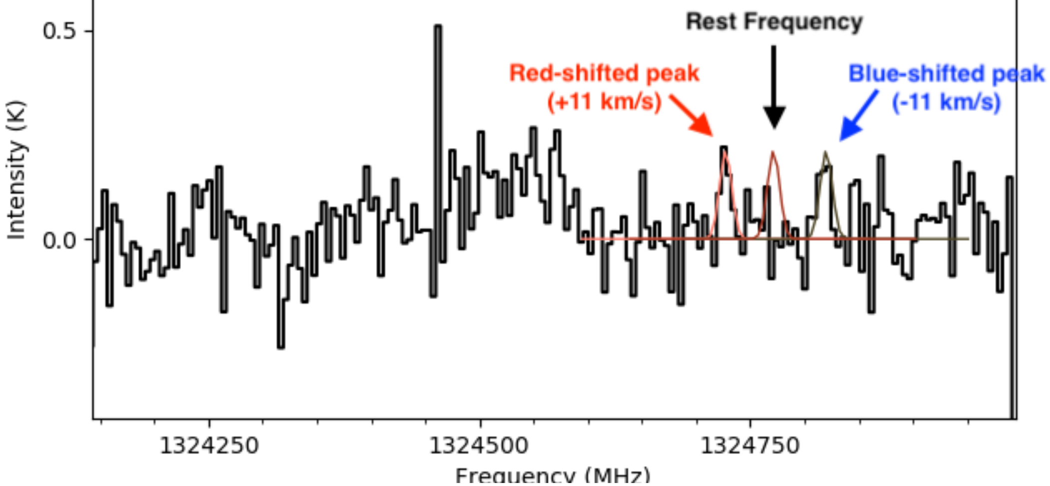
Siebert et al. (2020)

VY CMa
$2 \times 10^{17}\ \mathrm{cm}^{-2}$, $f < 3 \times 10^{-5}$
N/A
$2 \times 10^{14}\ \mathrm{cm}^{-2}$, $f < 3 \times 10^{-8}$

Placi

Assume

1. S t
2. D t
3. Spherically symmetric
4. Optically thin



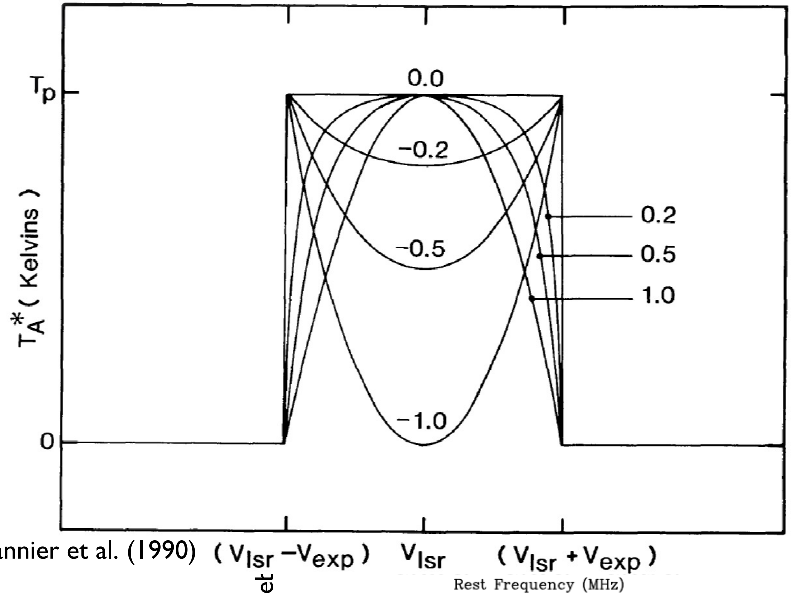
SOFIA DDT 75_0058:
"Further Investigation of FeH Toward IRC+10216"

2 additional hours of observing time on this transition

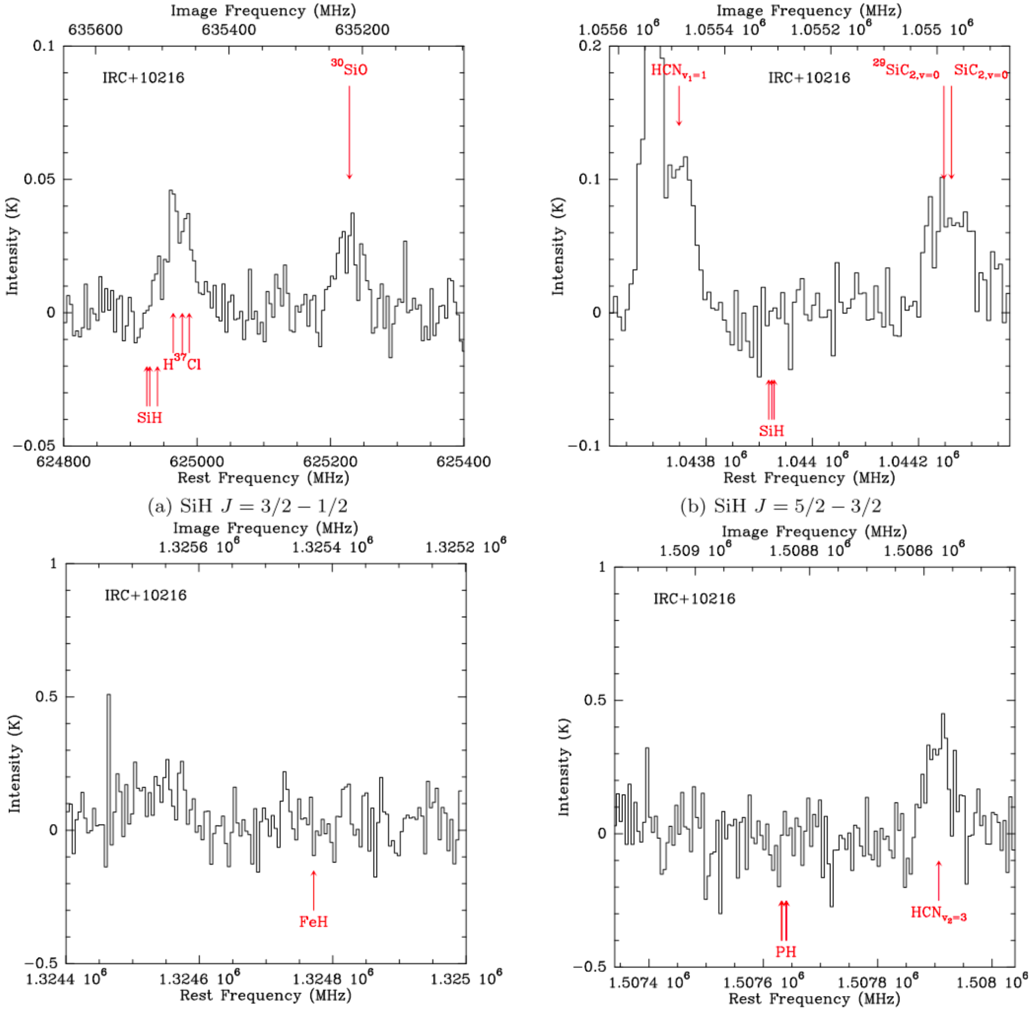
$$N_T = \frac{1}{2}\frac{3k}{8\pi^3}\sqrt{\frac{\pi}{\ln 2}} \frac{Q e^{\frac{E_u}{T_{ex}}} \int T dV}{B S_{ij} \mu^2 \eta_B} \frac{1}{1-}$$

$$N_{H_2} = \frac{\dot{M}}{\pi R V_{exp} \mu m_H}$$

$$f_{H_2} = N_T / N_{H_2}$$



Wannier et al. (1990)



(a) SiH $J = 3/2 - 1/2$

(b) SiH $J = 5/2 - 3/2$

(c) FeH $\Omega = 5/2, J = 5/2 - 7/2$

(d) PH $N = 3 - 2, J = 4 - 3$

Rest Frequency (MHz)

(b) SiH $J = 5/2 - 3/2$

SUMMARY OF RESULTS

- Searched for SiH, PH, and FeH toward the envelopes of IRC+10216 and VY CMa using SOFIA GREAT
- Though none of the target hydrides were clearly detected, we were able to place strict upper limits on their abundances
- **Siebert et al. 2020 + Keady & Ridgeway 1993 + Agúndez et al. 2014b :**

$$\frac{[\mathrm{SiH}]}{[\mathrm{SiH_4}]} < 1.4 \quad , \quad \frac{[\mathrm{PH}]}{[\mathrm{PH_3}]} < 4 \qquad \textbf{observed}$$

- **Agúndez et al. 2020 :** $$\frac{[\mathrm{SiH}]}{[\mathrm{SiH_4}]} \sim 1\times10^{6} \quad , \quad \frac{[\mathrm{PH}]}{[\mathrm{PH_3}]} \sim 1\times10^{4} \quad \textbf{under TE}$$
- In CSEs, growth of hydride molecules occurs much faster than predicted by equilibrium
- H-addition on grain surfaces is likely very important
- Further modeling and observational efforts are needed to fully understand this
- FeH could be a daughter molecule formed in the outer regions of IRC+10216, but confirmation is needed

THANK YOU!

References:

Accolla, M., Santoro, G., Merino, P., et al. 2021, ApJ, 906

Agúndez, M., Martínez, J. I., de Andres, P. L., Cernicharo, J., & Martín-Gago, J. A. 2020, A&A, 637, A59

Gerin, M., Neufeld, D. A., & Goicoechea, J. R. 2016,ARA&A, 54, 181

Godard, B., Falgarone, E., & Pineau des Forêts, G. 2014,A&A, 570, A27

Swings, P., & Rosenfeld, L. 1937, ApJ, 86, 483

Ziurys, L. 2006, PNAS, 103, 12274