Probing diffuse and translucent clouds* with interstellar hydrides**

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*Gas that is mainly neutral (x_e </~ 10^{-4}), not self-gravitating, and mainly cold (T </~ 80 K)

Dust attenuation can be significant, but the material is still affected (through grain photoelectric heating, photodissociation, photoionization) by the interstellar UV radiation field (emanating from hot stars throughout the Galaxy)

Molecules containing one heavy element atom with one of more hydrogen atoms

Recent discoveries of molecules in the diffuse ISM

Key facilities for submillimeter spectroscopy over the past 10 years


Herschel (HIFI)


APEX

SOFIA (GREAT)

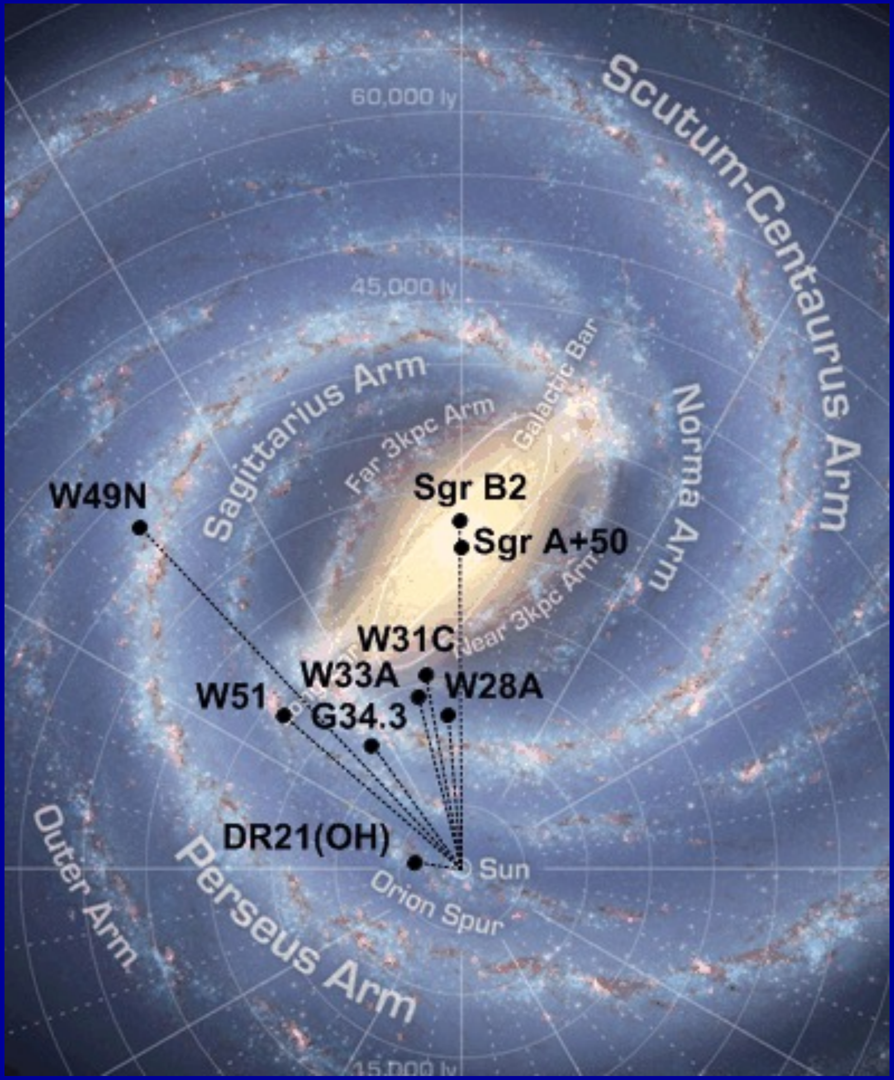
Recent discoveries of molecules in the diffuse ISM

OH^+	Wyrowski et al. 2010	APEX
SH^+	Menten et al. 2011	APEX
H_2O^+	Gerin et al. 2010	Herschel
HF	Neufeld et al. 2010	Herschel
HCl^+	de Luca et al. 2013	Herschel
H_2Cl^+	Lis et al. 2010	Herschel
SH	Neufeld et al. 2012	SOFIA
ArH^+	Schilke et al. 2014	Herschel

All hydrides with high frequency rotational transitions that are unobservable from the ground or observable only from superb submillimeter sites

Absorption line observations

- We can use a very luminous region of massive star formation as a background THz continuum source
- This allows us to search for absorption by gas in foreground material
- A very “clean” experiment that provides robust measurements of molecular column densities



Hydrides in the diffuse interstellar medium

First diffuse ISM detection obtained in the past ten years

Molecule	Average abundance relative to H or H_2	Average abundance (fraction of gas phase elemental[a])
CH	3.5×10^{-8}	1.3×10^{-4}
CH_2	1.6×10^{-8}	6×10^{-5}
CH^+	6×10^{-9}	4×10^{-5}
OH	8×10^{-8}	8×10^{-5}
H_2O	2.4×10^{-8}	2.4×10^{-5}
OH^+	1.2×10^{-8}	2.4×10^{-5}
H_2O^+	2×10^{-9}	4×10^{-6}
H_3O^+	2.5×10^{-9}	2.5×10^{-6}
NH	8×10^{-9}	6×10^{-5}
NH_2	4×10^{-9}	3×10^{-5}
NH_3	4×10^{-9}	3×10^{-5}
HF	1.4×10^{-8}	0.4
SH	1.1×10^{-8}	4×10^{-4}
H_2S	5×10^{-9}	1.8×10^{-4}
SH^+	1.1×10^{-8}	9×10^{-4}
HCl	1.5×10^{-9}	0.004
HCl^+	8×10^{-9}	0.04
H_2Cl^+	3×10^{-9}	0.02
ArH^+	3×10^{-10}	1×10^{-4}

Gerin et al, ARAA 2016

Using hydride molecules as diagnostic probes

Small molecules, especially hydride molecules, have simple formation mechanisms

→ carefully interpreted, they provide unique information of general astrophysical interest

Measuring the cosmic-ray ionization rate

Tracers of the H_2 fraction

Tracers of gas heated by shocks and turbulence

Different hydrides are highly specific probes, because small thermochemical differences lead to large differences in chemical behavior

Thermochemistry for different elements

I.P > 13.6 eV
→ neutral 🟣

I.P < 13.6 eV
→ ionized 🔵

☑ Important formation pathway

Element	Ionization Potential (eV)	Endothermicity (Kelvin equivalent $\Delta E/k_B$) for $X + H_2 \rightarrow XH + H$	$X^+ + H_2 \rightarrow XH^+ + H$	$X + H_3^+ \rightarrow XH^+ + H_2$	Driver
C 🔵	11.260	11000	4640 ☑		Warm gas
N 🟣	14.534	15000	230	10000	?
O 🟣	13.618	940 ☑	☑	☑	Warm gas or cosmic rays
F 🟣	17.423	☑		10000	None needed
Ne 🟣	21.564	No reaction	Exothermic, but primary channel is to $Ne + H + H^+$	27000	
Si 🔵	8.152	17000	15000		Warm gas
P 🔵	10.487	19000	13000		Warm gas
S 🔵	10.360	10000	10000 ☑		Warm gas
Cl 🔵	12.968	450	☑		UV with $h\nu > 12.97$ eV
Ar 🟣	15.760	No reaction	☑	6400	Cosmic rays

Exothermic reaction of element in its main ionization state

Endothermic reaction of element in its main ionization state

Exothermic reaction of element **not** in main ionization state

Endothermic reaction of element **not** in main ionization state

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Discovery of cosmic rays by Victor Hess

Victor F. Hess, center, departing from Vienna about 1911, was awarded the Nobel Prize in Physics in 1936. (New York Times, August 7, 2012, page D4)

Interaction with the interstellar gas

- High energy (E > 280 MeV) cosmic rays create γ-rays via

  $CRp + p \rightarrow CRp + p + \pi^0$

  $\pi^0 \rightarrow \gamma + \gamma$

- Lower energy cosmic rays ionize and heat the ISM

  $CRp + H \rightarrow CRp + H^+ + e$

  $CRp + H_2 \rightarrow CRp + H_2^+ + e$

  The ionization of H and H_2 is followed by reactions leading to other molecular ions

What CRIR is inferred from observations of the ISM?

Cloud types in the ISM (Snow and McCall, 2006, ARAA)

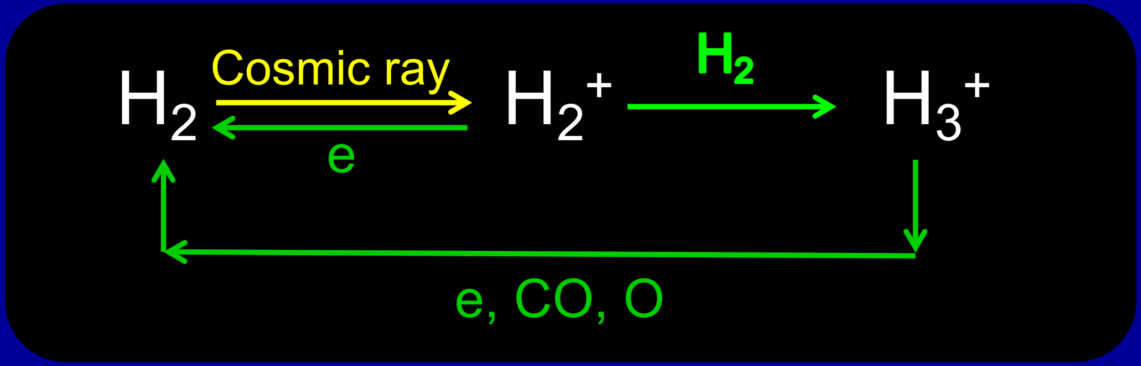
Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n_{H_2} < 0.1$	$f^n_{H_2} > 0.1$ $f^n_{C+} > 0.5$	$f^n_{C+} < 0.5$ $f^n_{CO} < 0.9$	$f^n_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

Observations of $H^{13}CO^+$
➔Avg. $\zeta_p(H) = 1.1 \times 10^{-17}$ s^{-1}
(van der Tak & van Dishoeck 2000)

Measuring the cosmic-ray ionization rate in diffuse *molecular* clouds with H_3^+

In diffuse *molecular* clouds, H_3^+ production follows ionization of H_2



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Observations of H_3^+
➔Avg. $\zeta_p(H) = 1.5 \times 10^{-16}\ s^{-1}$
(Indriolo and McCall 2012)

Observations of $H^{13}CO^+$
➔Avg. $\zeta_p(H) = 1.1 \times 10^{-17}\ s^{-1}$
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The CRIR in diffuse *molecular* clouds

Variation with cloud $N(H_2)$:

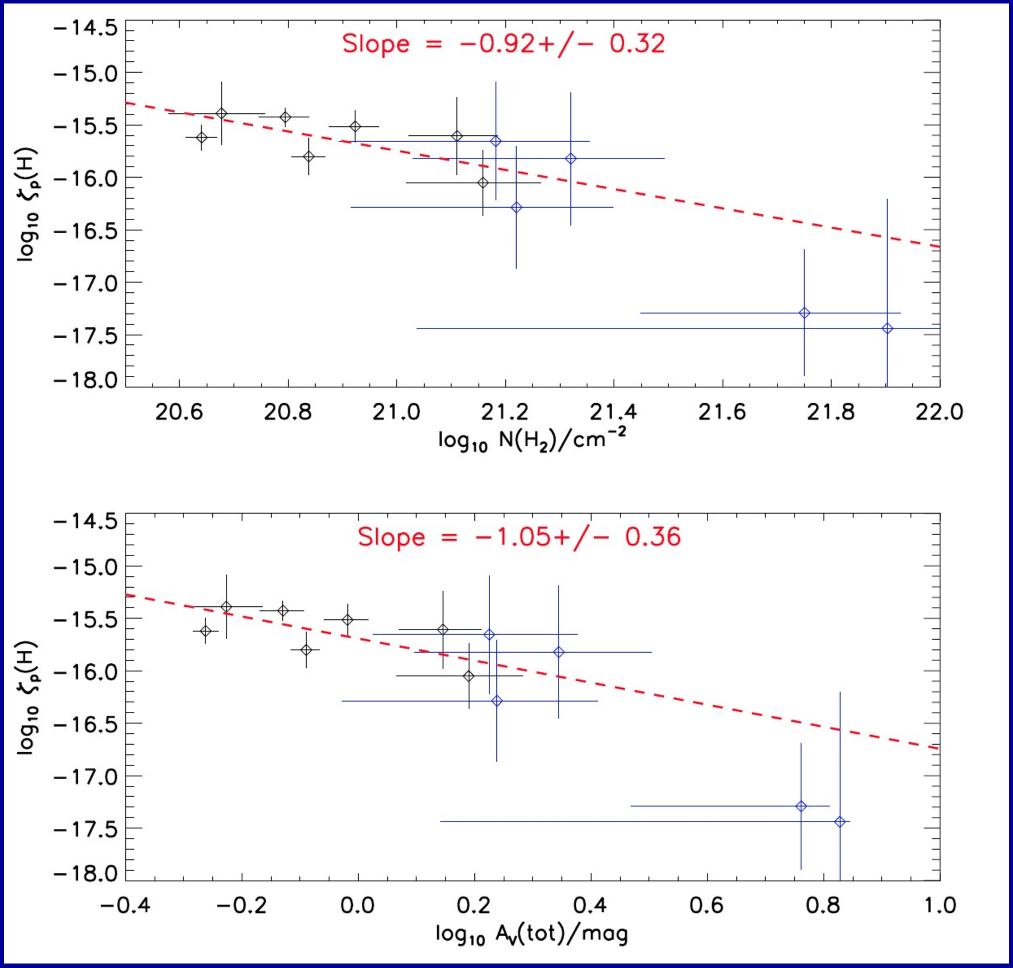
Black points: clouds <u>with</u> direct measurements of H_2

Blue points: clouds <u>without</u> direct measurements of H_2

Marginally significant evidence for a decline in $\zeta_p(H)$ with $N(H_2)$ or $A_V(tot)$

Effect of shielding?

Consistent with the difference between the CRIRs derived for diffuse and dense molecular clouds (factor ~ 20)



Neufeld and Wolfire 2017

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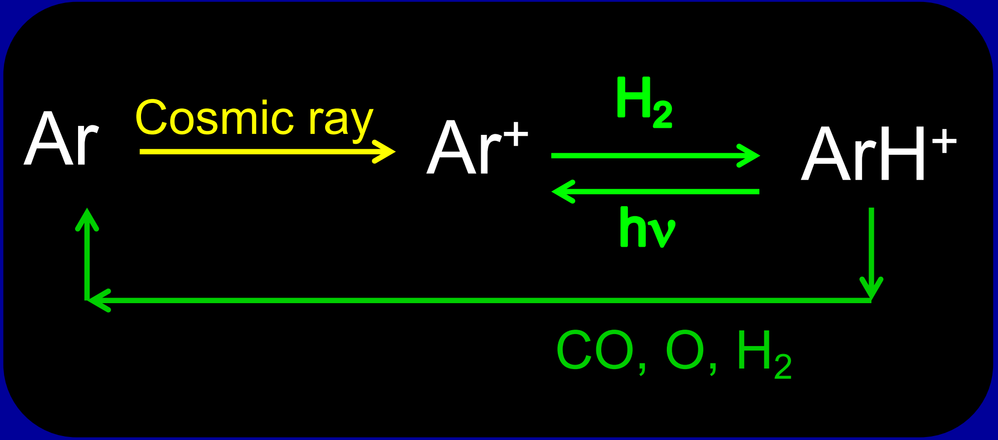
?

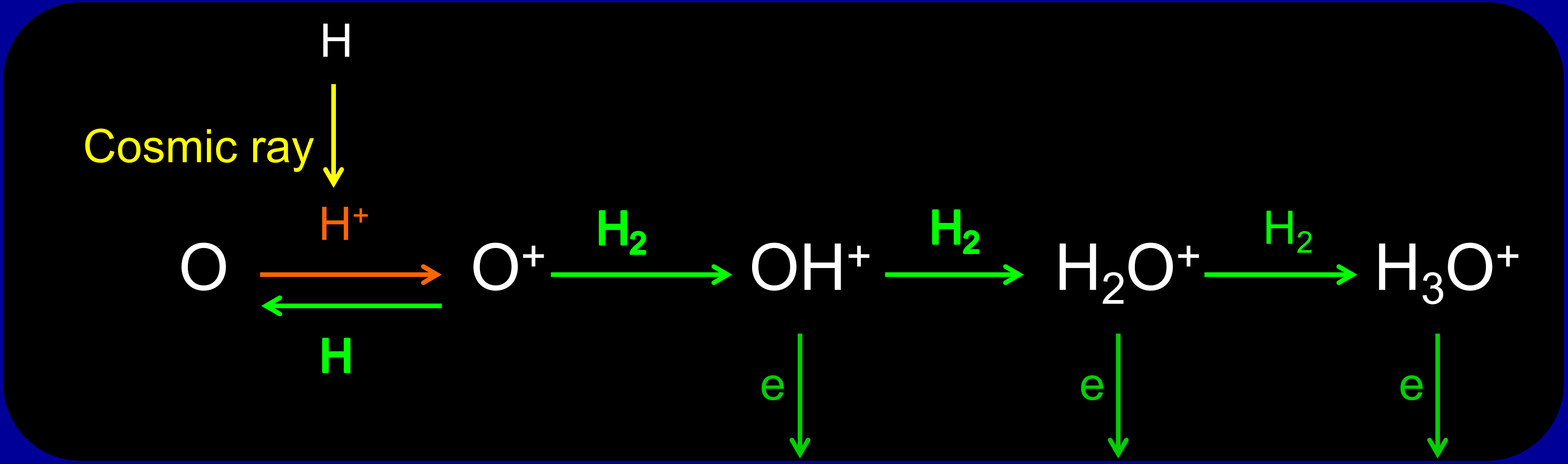
From H_3^+
$\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16}\ s^{-1}$
(with marginal evidence for decline with A_V(tot))

Observations of $H^{13}CO^+$
➔Avg. $\zeta(H) = 1.1 \times 10^{-17}\ s^{-1}$
(van der Tak & van Dishoeck 2000)

Measuring the cosmic-ray ionization rate in diffuse *atomic* clouds with OH^+, H_2O^+, ArH^+

O and Ar are not ionized by UV radiation longward of the Lyman limit, so ArH^+, OH^+ and H_2O^+ formation must be initiated by CR ionization





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From OH^+, H_2O^+ and ArH^+
$\zeta_p(H) = 2.2 \pm 0.3 \times 10^{-16}\ s^{-1}$
(at solar circle)

May change with new, improved measurements of the rate for $OH^+ + e \rightarrow O + H$

From H_3^+
$\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16}\ s^{-1}$
(with marginal evidence for decline with A_V)

From HCO^+ (van der Tak & van Dishoeck 2000)
$\zeta_p(H) = 1.1 \times 10^{-17}\ s^{-1}$

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Tracers of the H_2 fraction

Tracers of gas heated by shocks and turbulence

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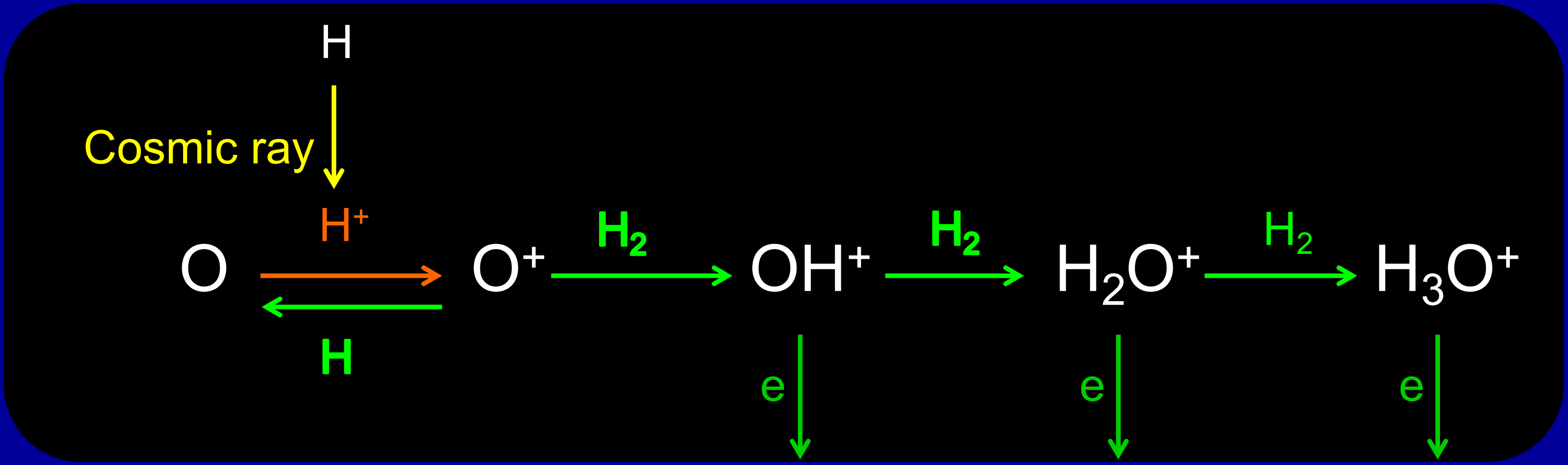
Molecular ions also probe the H_2 fraction

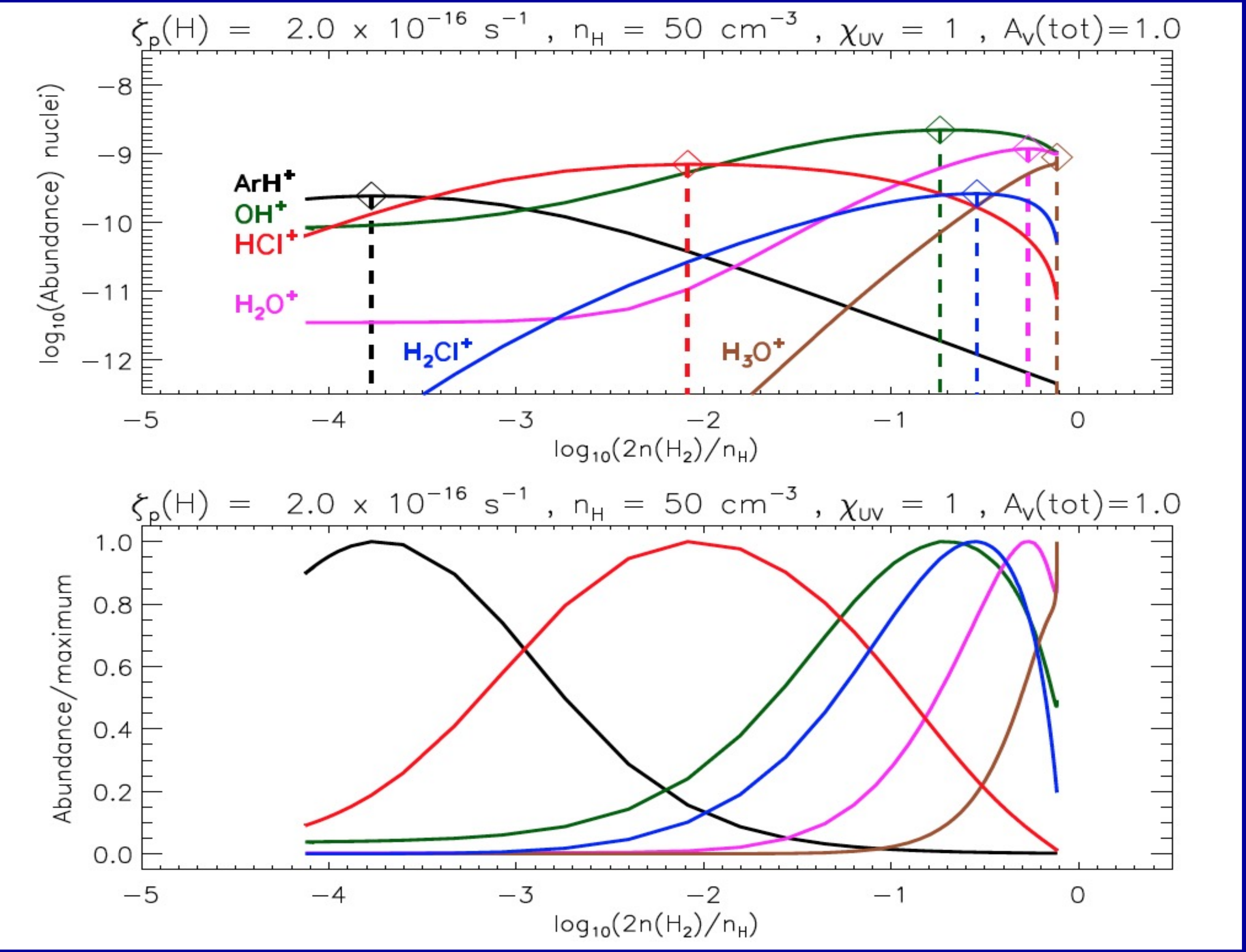
Competition between dissociative recombination with electrons and H_2 abstraction reactions means that molecular ion abundances depend on the H_2 fraction

Example: OH^+/H_2O^+ is a decreasing function of $f(H_2)$



A combination of molecular ions can probe the distribution function for $f(H_2)$

Model predictions
(Neufeld & Wolfire, 2016, ApJ)



Molecular ion abundances constrain models for the diffuse ISM

Bialy et al. 2019

The Astrophysical Journal, 885:109 (11pp), 2019 November 10 Bialy et al.

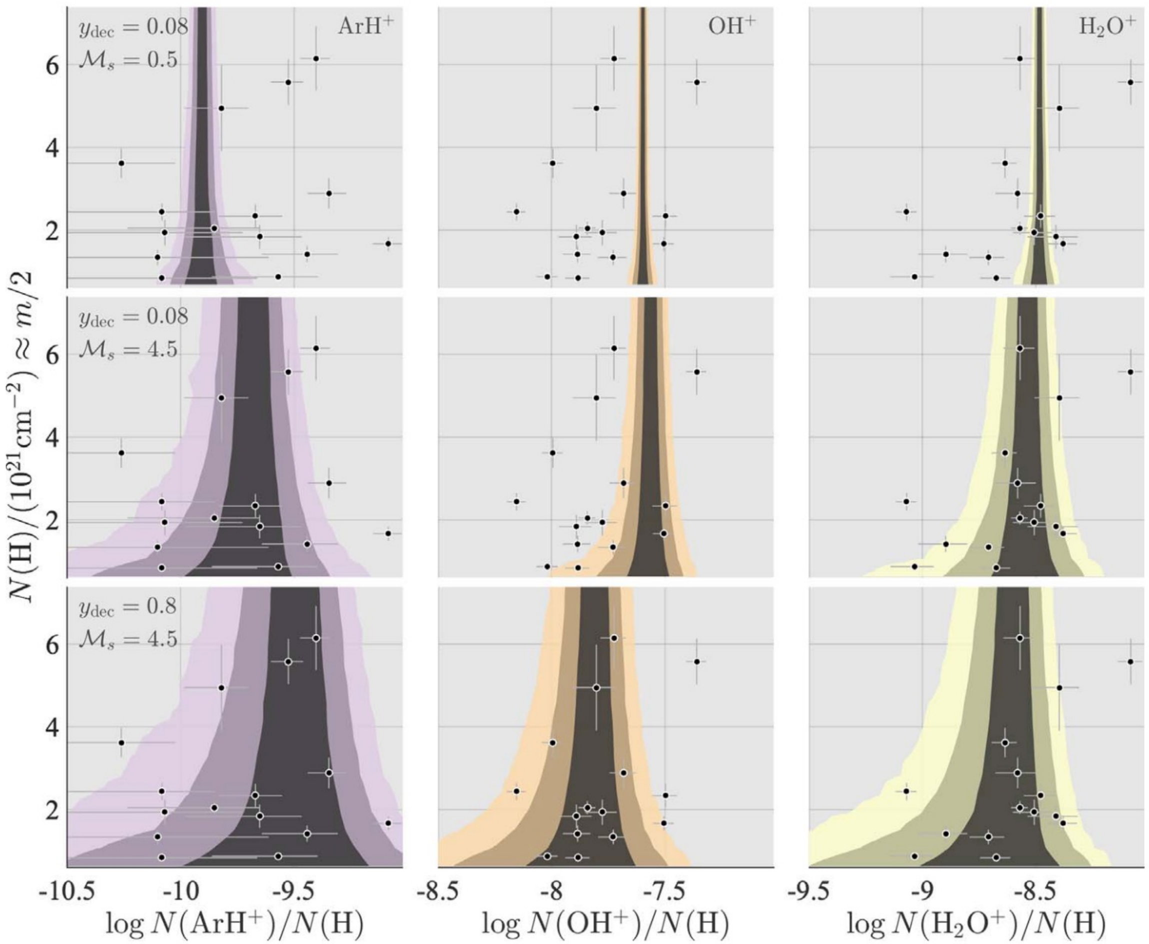


Figure 5. The grand PDFs of ArH^+, OH^+, H_2O^+ as functions of N(H) (which is $\propto$ to the number of clouds along the LoS, *m*.), for different (y_{dec}, $\mathcal{M}_s$) combinations. All models assume $I_{UV} = 1$, $\zeta_{-16} = 4$, $\langle n \rangle = 30$ cm^{-3}, $\langle A_V \rangle = 0.3$. In each panel, the three shaded regions correspond to the 68, 95, 99.7 percentiles about the median (at constant N(H)). The observations are indicated by dots with error bars.

Molecular ion abundances constrain models for the turbulent ISM

The observed abundances favor a model with fairly strong turbulence-driven density fluctuations (middle panel)

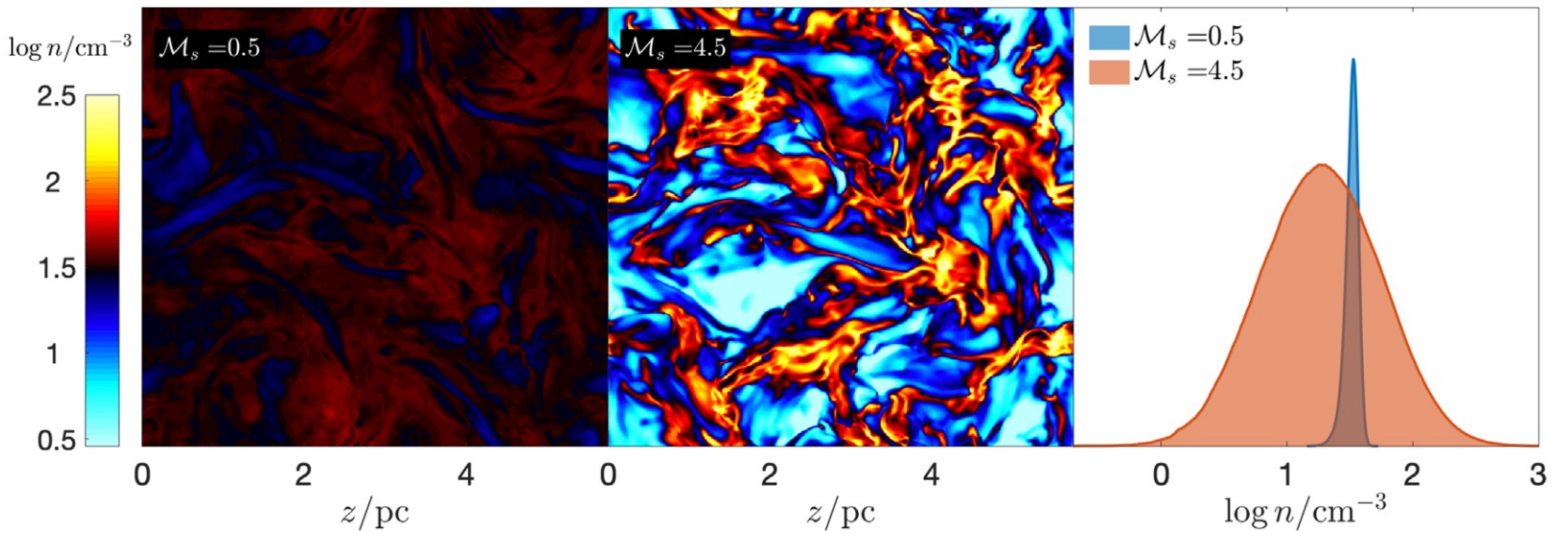


Figure 2. Density cuts through the $\mathcal{M}_s = 0.5$ and 4.5 simulations (with $y_{dec} = 0.08$), and the corresponding density PDFs.

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CH^+, SH^+ and SH as probes of "warm chemistry"

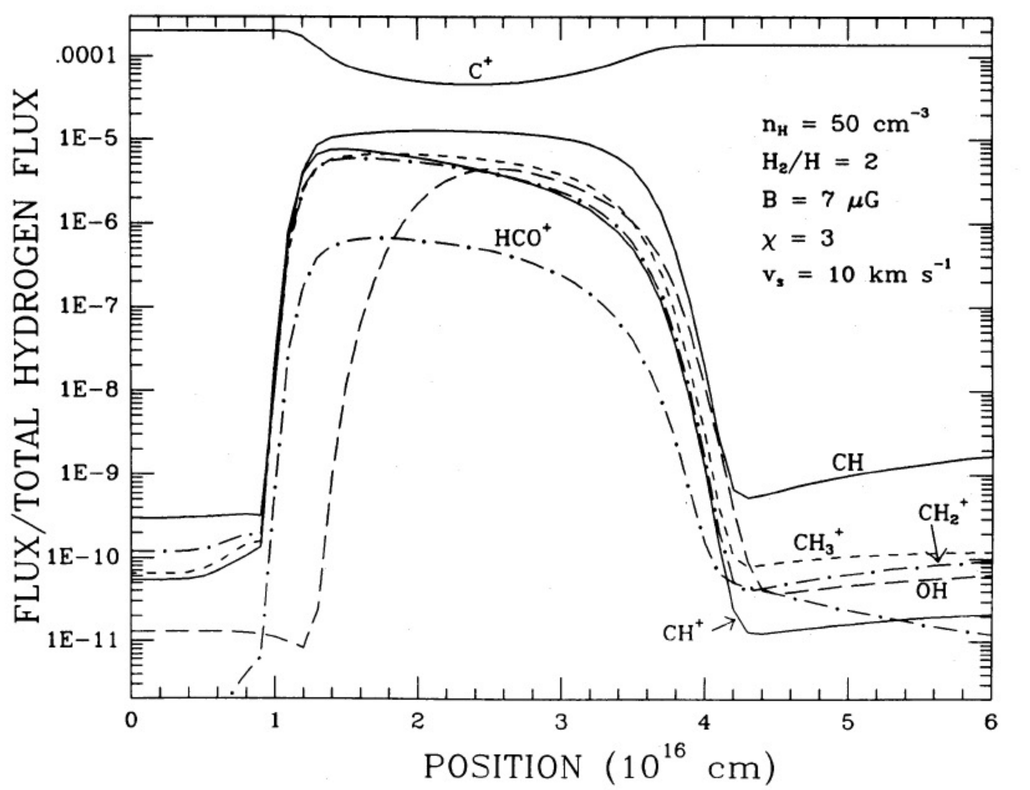
- None of C^+, S^+ nor S can react exothermically with H_2, but have reaction endothermicities of 4640K, 10^4 K and 10^4K respectively

- Observed CH^+, SH^+ and SH abundances are much greater than what would be expected at the average temperature of the diffuse ISM (Godard et al. 2012; Neufeld et al. 2015)

→ Evidence for elevated temperatures or ion-neutral drift in material affected by the dissipation of turbulence.

CH^+, SH^+ and SH as probes of "warm chemistry"

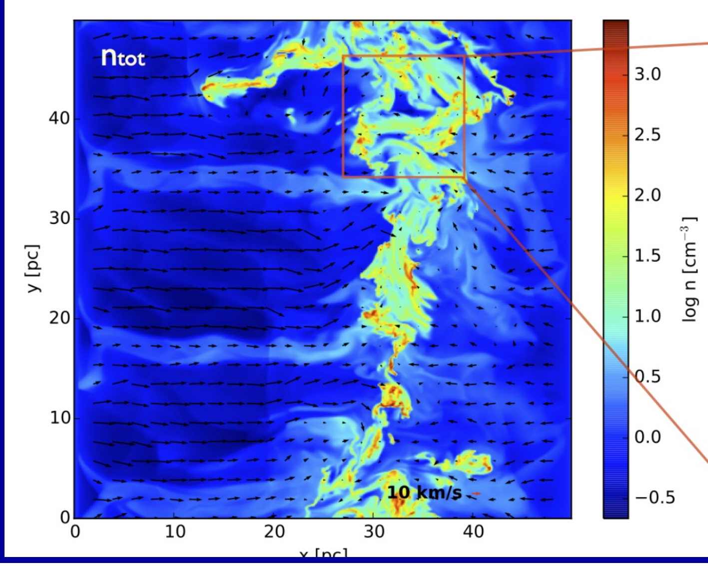
The abundance of CH^+ has long been recognized as anomalous, but recent observations of SH^+ and SH corroborate the presence of a ubiquitous "warm chemistry."

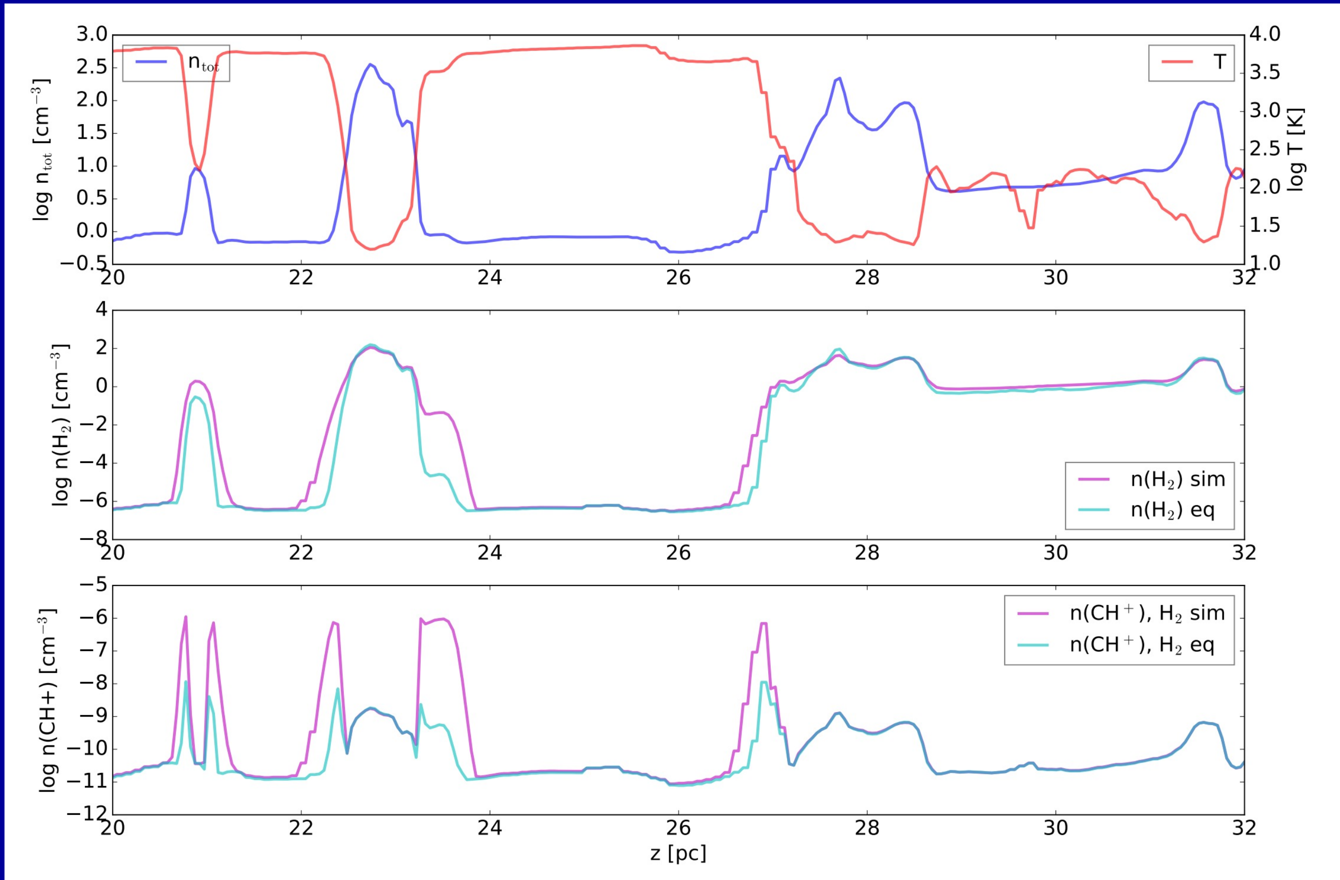


CH^+ prediction

Draine and Katz 1986, ApJ

Simulations of the turbulent ISM (Validivia et al. 2017)





Summary

New observations of hydrides, combined with sophisticated models for the chemistry of turbulent media, show great promise for advancing our understanding of the diffuse ISM

Upcoming talks in this session

Paul Goldsmith: FIR fine structure line observations

Arshia Jacob: HyGAL: Characterizing the Galactic ISM with observations of hydrides

Michael Rugel: JVLA follow-up survey of OH and HI

Also, Michael Busch (poster): OH emission from the diffuse ISM