OH^+ and H_2O^+: Probes of the Molecular Hydrogen Fraction and Cosmic-Ray Ionization Rate

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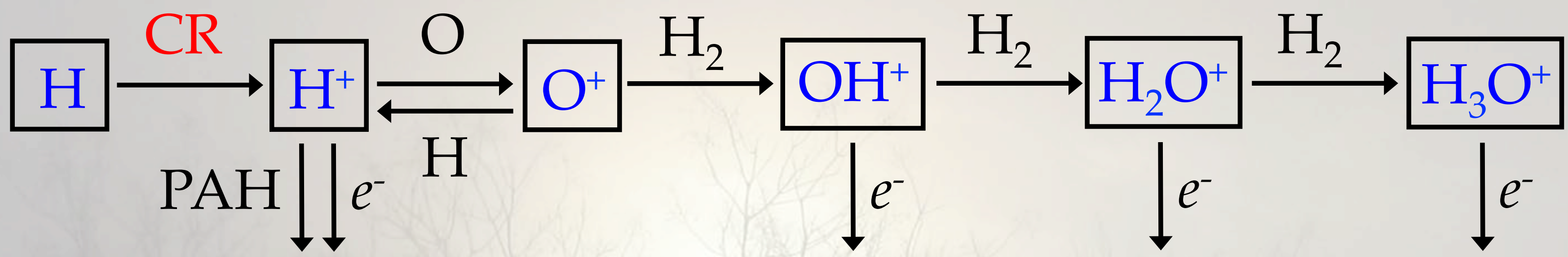
Outline

- Motivations
- Oxygen chemistry
- Observations
- Example Spectra
- Results
  - Molecular hydrogen fraction
  - Cosmic-ray ionization rate
- Where do we go from here?

Motivation

- OH^+ and H_2O^+ were unobserved prior to the launch *Herschel*
- Possible intermediaries in the process of H_2O formation
- Oxygen chemistry begins with ionization of atomic hydrogen, likely by cosmic rays
- Relative abundances of oxygen ions depend on competition between reactions with H_2 and destruction via electrons

Oxygen Chemistry



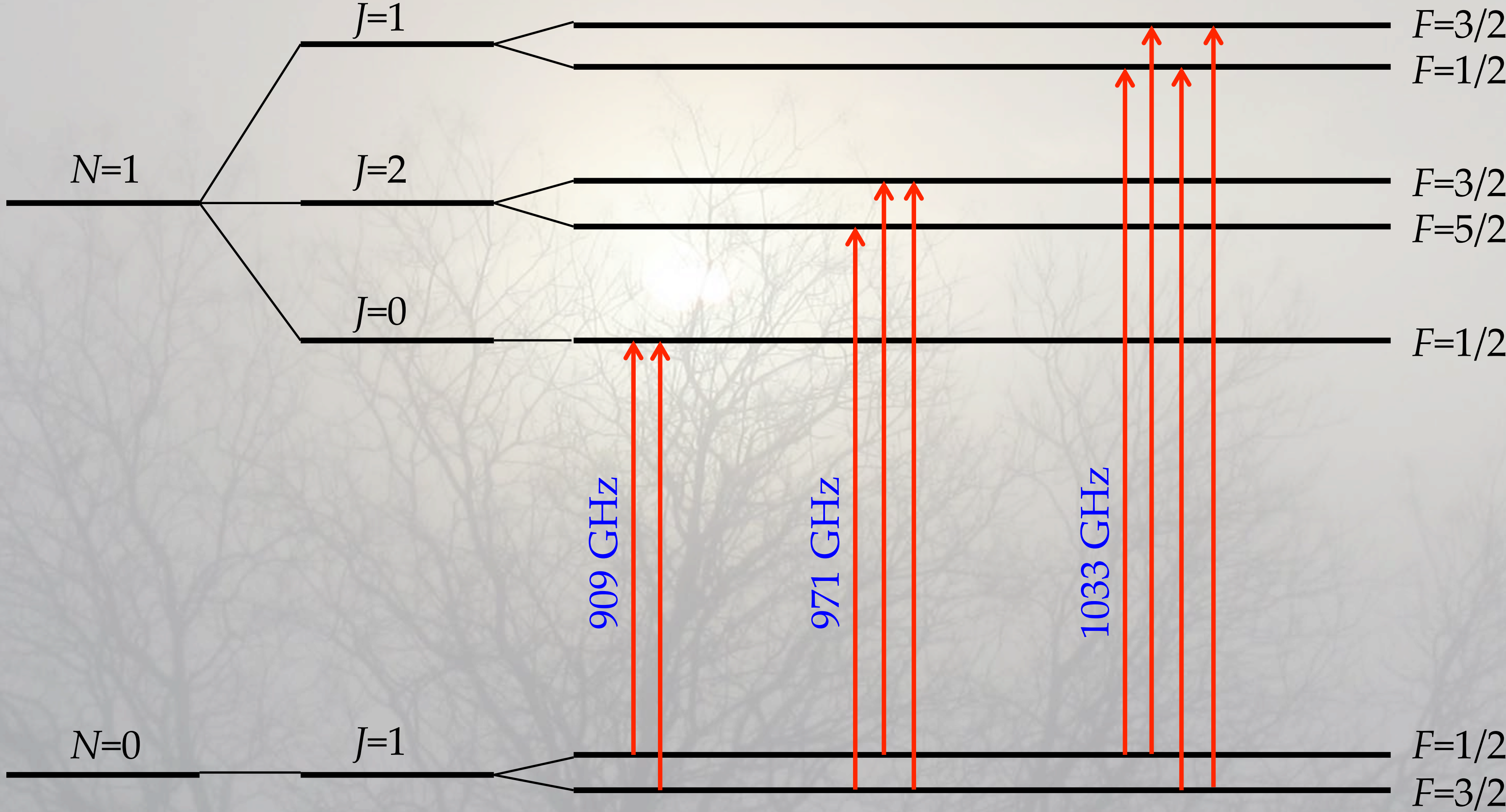
- $CR + H \rightarrow H^+ + e^- + CR'$
- $H^+ + O \rightarrow O^+ + H$
- $O^+ + H_2 \rightarrow OH^+ + H$
- $OH^+ + H_2 \rightarrow H_2O^+ + H$
- $H_2O^+ + H_2 \rightarrow H_3O^+ + H$
- $OH^+ + e^- \rightarrow$ products
- $H_2O^+ + e^- \rightarrow$ products
- $H_3O^+ + e^- \rightarrow$ products
- $O^+ + H \rightarrow H^+ + O$
- $H^+ + e^- \rightarrow H + h\nu$
- $H^+ + PAH \rightarrow PAH^+$

Target List

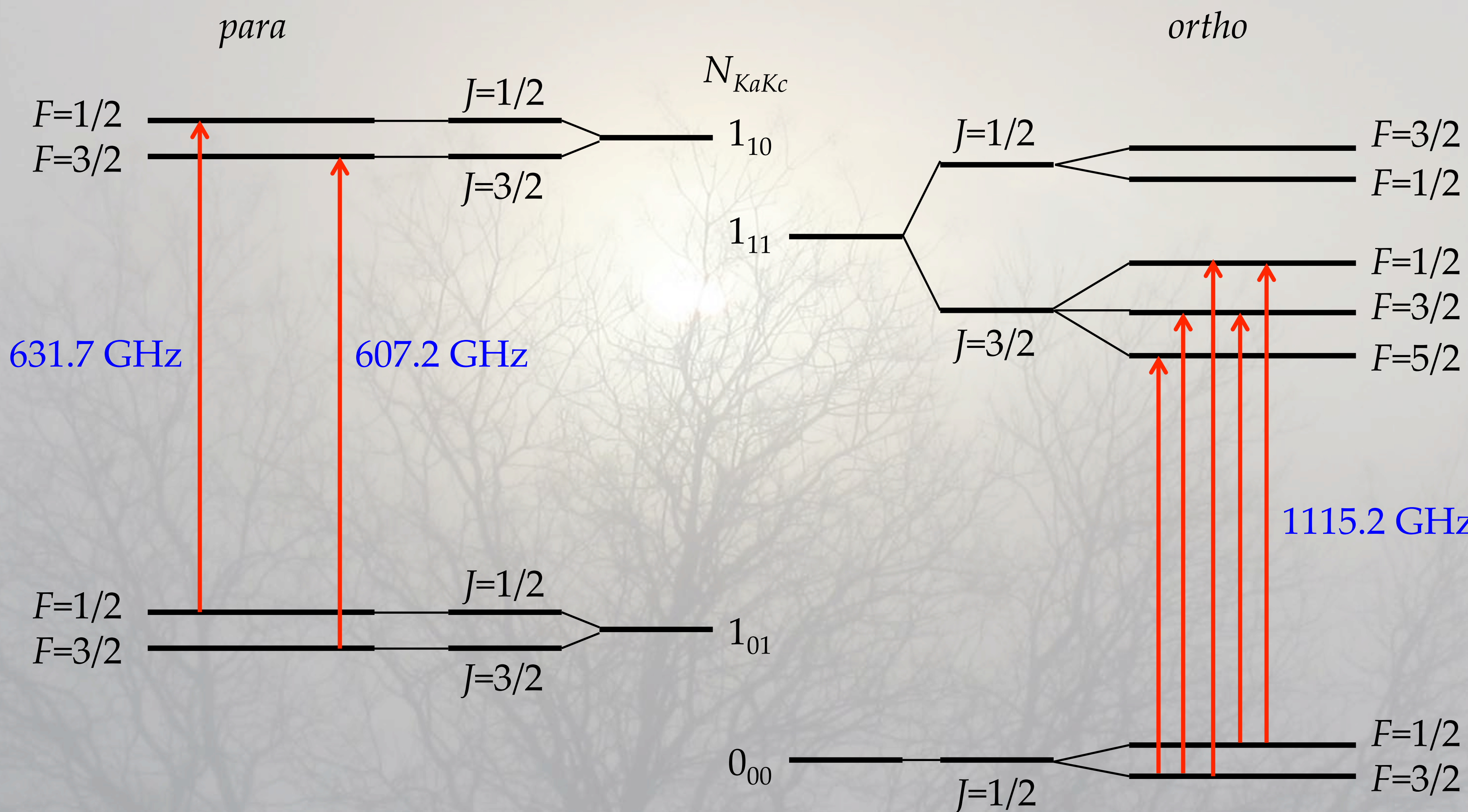
Target	Right Ascension	Declination	Gal. Long.	Gal. Lat.	Program
SgrA*+20 km s^{-1} cloud	17h 45m 37.4s	$-29^{\circ}\ 05'\ 40''.0$	359.8653	−0.0831	P
SgrA*+50 km s^{-1} cloud	17h 45m 50.5s	$-28^{\circ}\ 59'\ 53''.3$	359.9724	−0.0737	P
W28A (G005.88−00.39)	18h 00m 30.5s	$-24^{\circ}\ 03'\ 59''.9$	5.8857	−0.3924	PW
W31C (G010.62−00.38)	18h 10m 28.7s	$-19^{\circ}\ 55'\ 50''.0$	10.6234	−0.3838	P
W33A (G012.91−00.26)	18h 14m 39.2s	$-17^{\circ}\ 52'\ 00''.5$	12.9078	−0.2592	PW
G029.96−00.02	18h 46m 03.8s	$-02^{\circ}\ 39'\ 22''.0$	29.9556	−0.0163	NW
G034.3+00.1 (W44C)	18h 53m 18.9s	$+01^{\circ}\ 14'\ 57''.3$	34.2577	0.1521	PW
W49N	19h 10m 13.1s	$+09^{\circ}\ 06'\ 12''.5$	43.1657	0.0123	P
W51 $e_1e_2^{\dagger}$	19h 23m 43.6s	$+14^{\circ}\ 30'\ 29''.2$	49.4879	−0.3871	NPW
AFGL 2591	20h 29m 24.7s	$+40^{\circ}\ 11'\ 18''.7$	78.8862	0.7091	W
DR21(OH)	20h 39m 00.9s	$+42^{\circ}\ 22'\ 48''.6$	81.7214	0.5713	PW
W3 IRS5	02h 25m 40.6s	$+62^{\circ}\ 05'\ 51''.0$	133.7168	1.2156	W
W3(OH)	02h 27m 03.8s	$+61^{\circ}\ 52'\ 24''.6$	133.9473	1.0642	N

N – dneufeld_1 (OT1)
P – PRISMAS (KPGT)
W – WISH (KPGT)

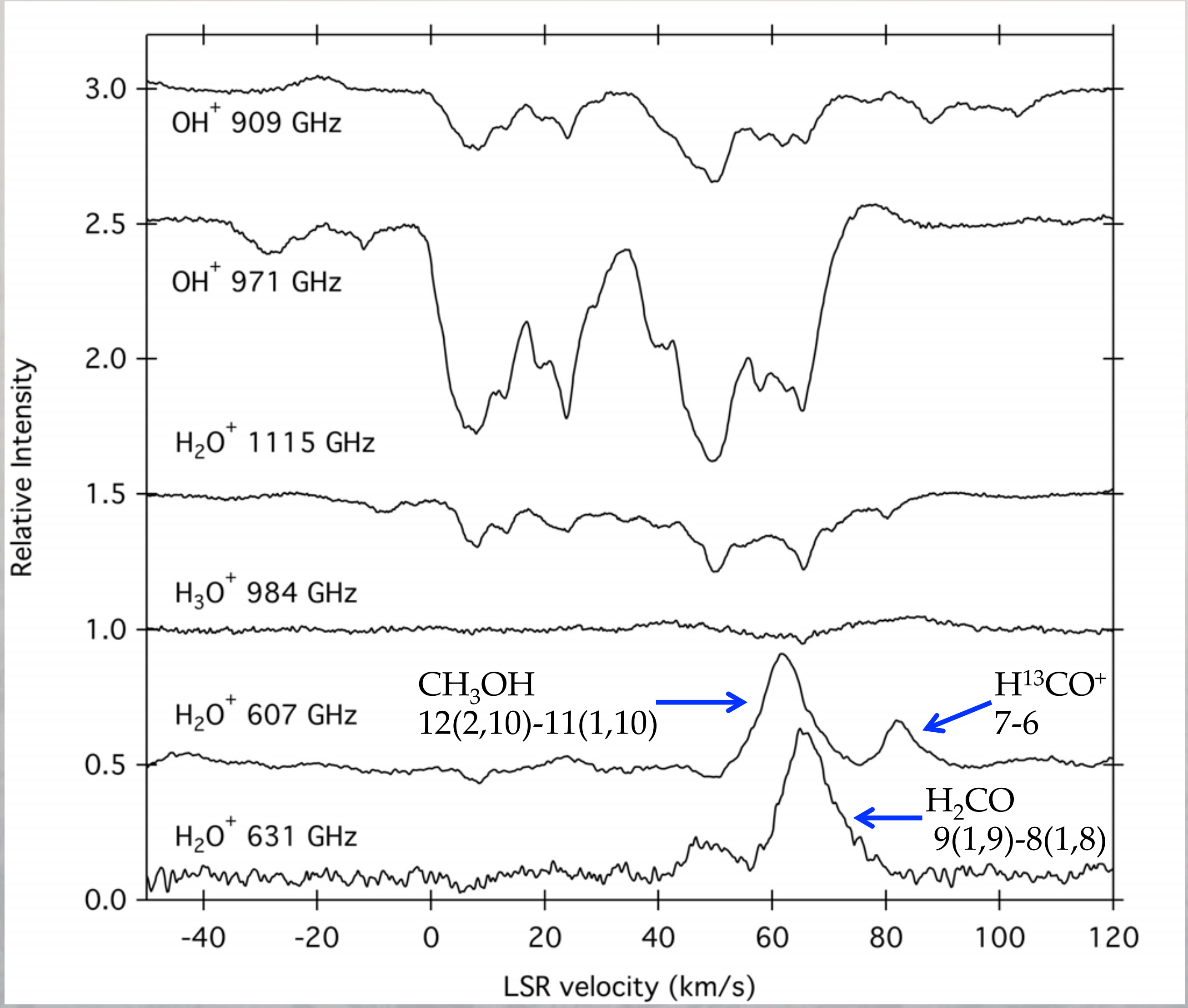
OH^+ Transitions



H_2O^+ Transitions

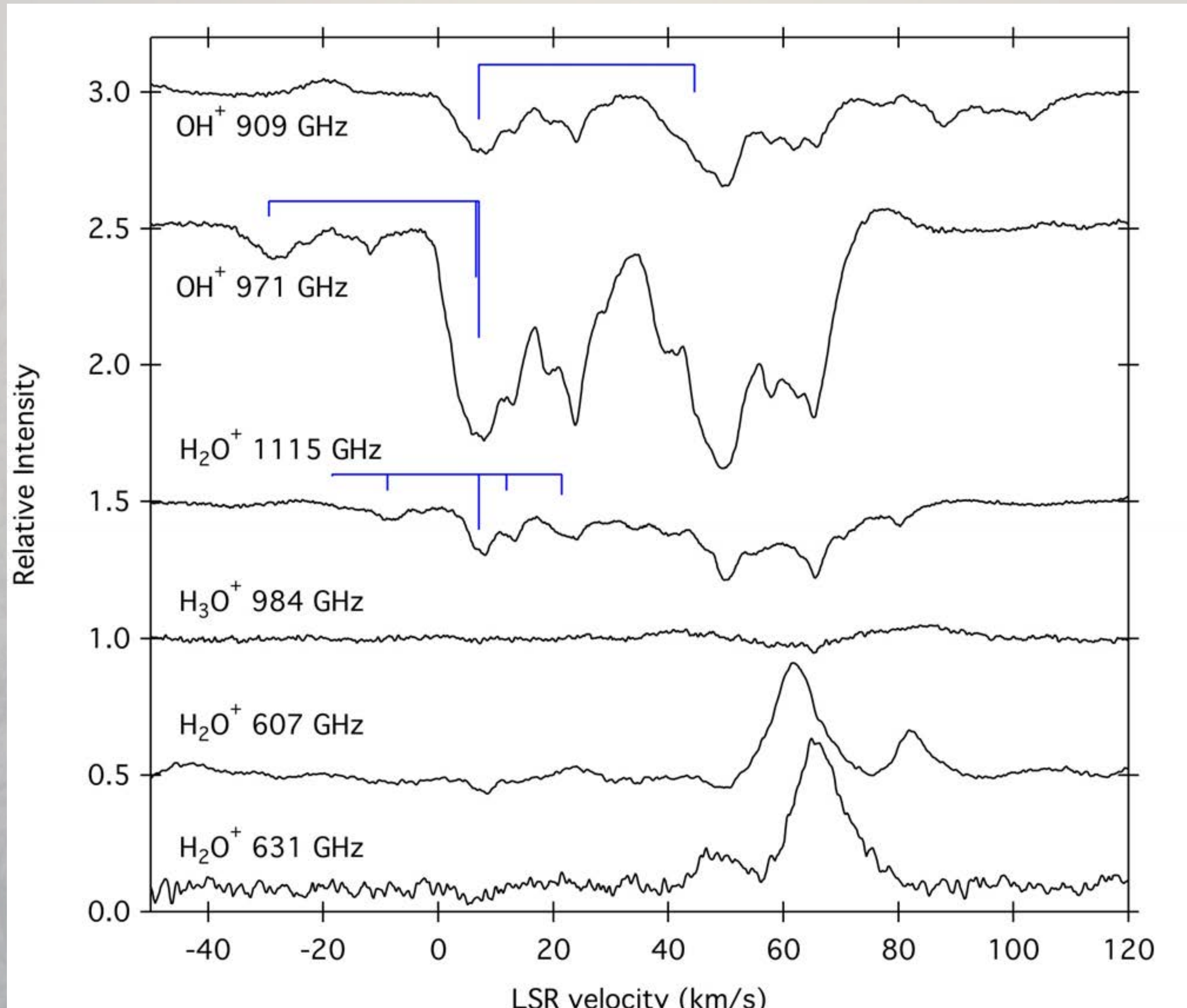


W51 Spectra



Relative Intensity
LSR velocity (km/s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-40
-20
0
20
40
60
80
100
120
OH+ 909 GHz
OH+ 971 GHz
H2O+ 1115 GHz
H3O+ 984 GHz
H2O+ 607 GHz
H2O+ 631 GHz
CH3OH
12(2,10)-11(1,10)
H13CO+
7-6
H2CO
9(1,9)-8(1,8)

W51 Spectra



Relative Intensity
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OH+ 909 GHz
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H2O+ 1115 GHz
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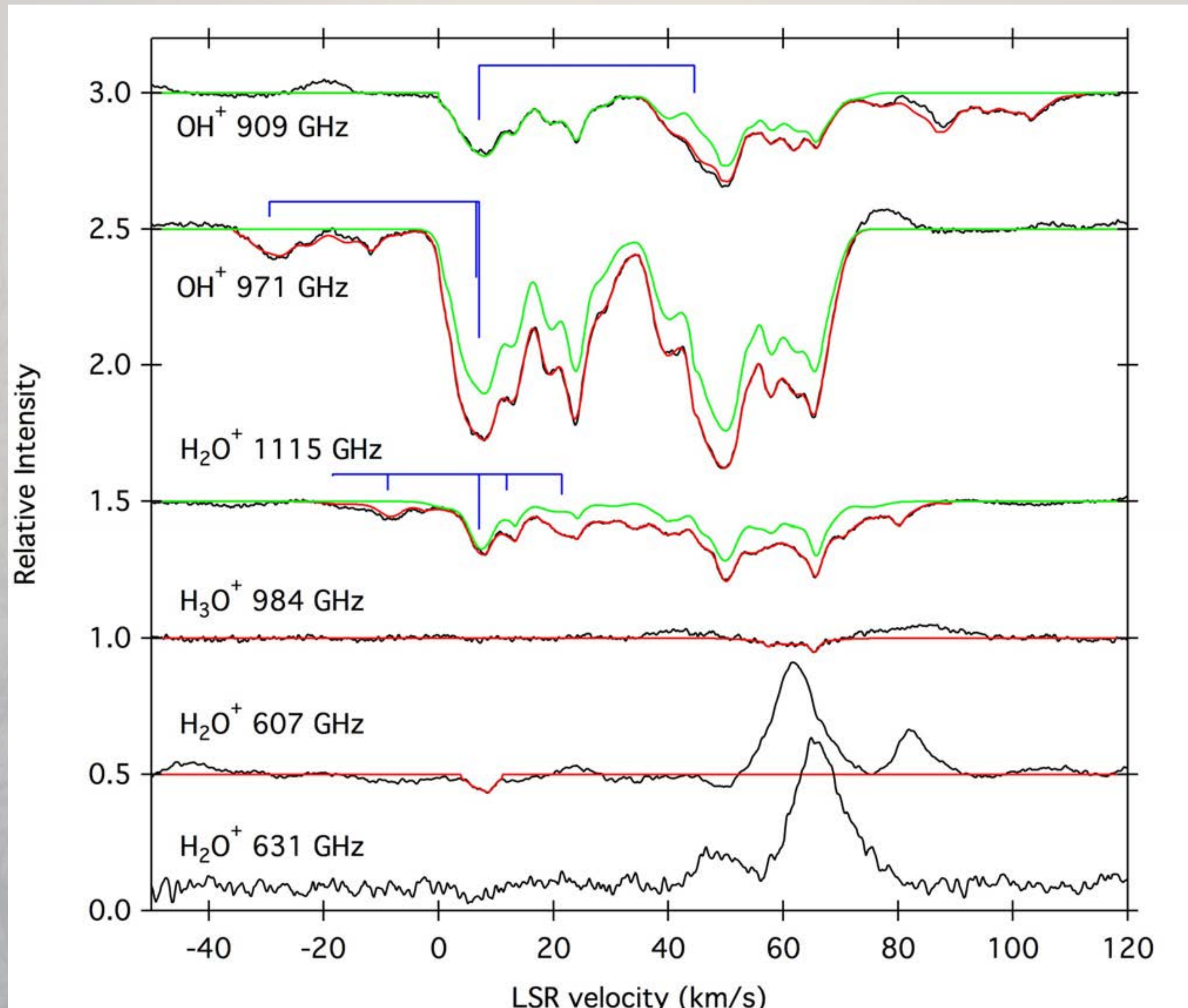
LSR velocity (km/s)

W51 Spectra



3.0
2.5
2.0
1.5
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Relative Intensity
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H2O+ 631 GHz
-40
-20
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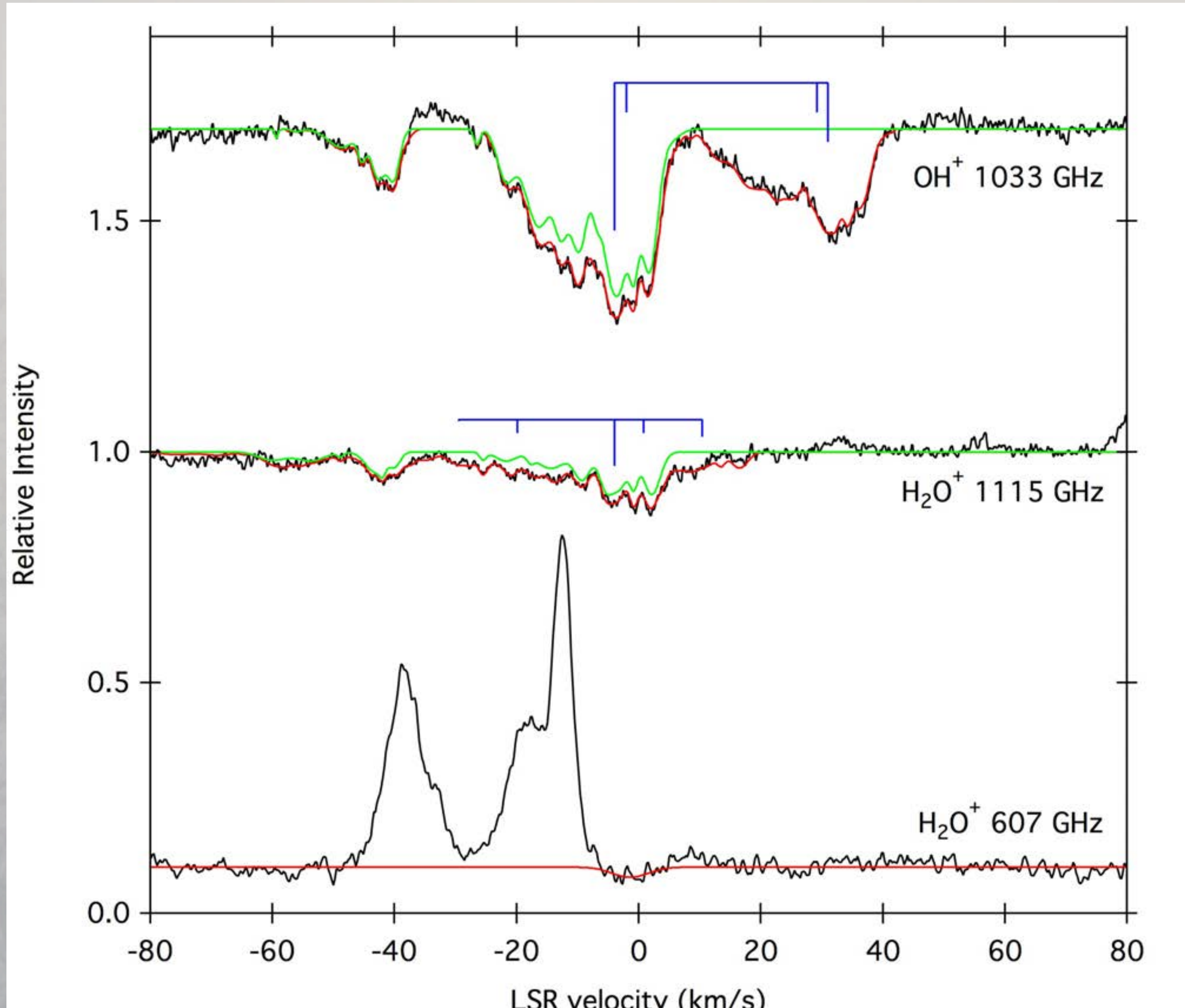
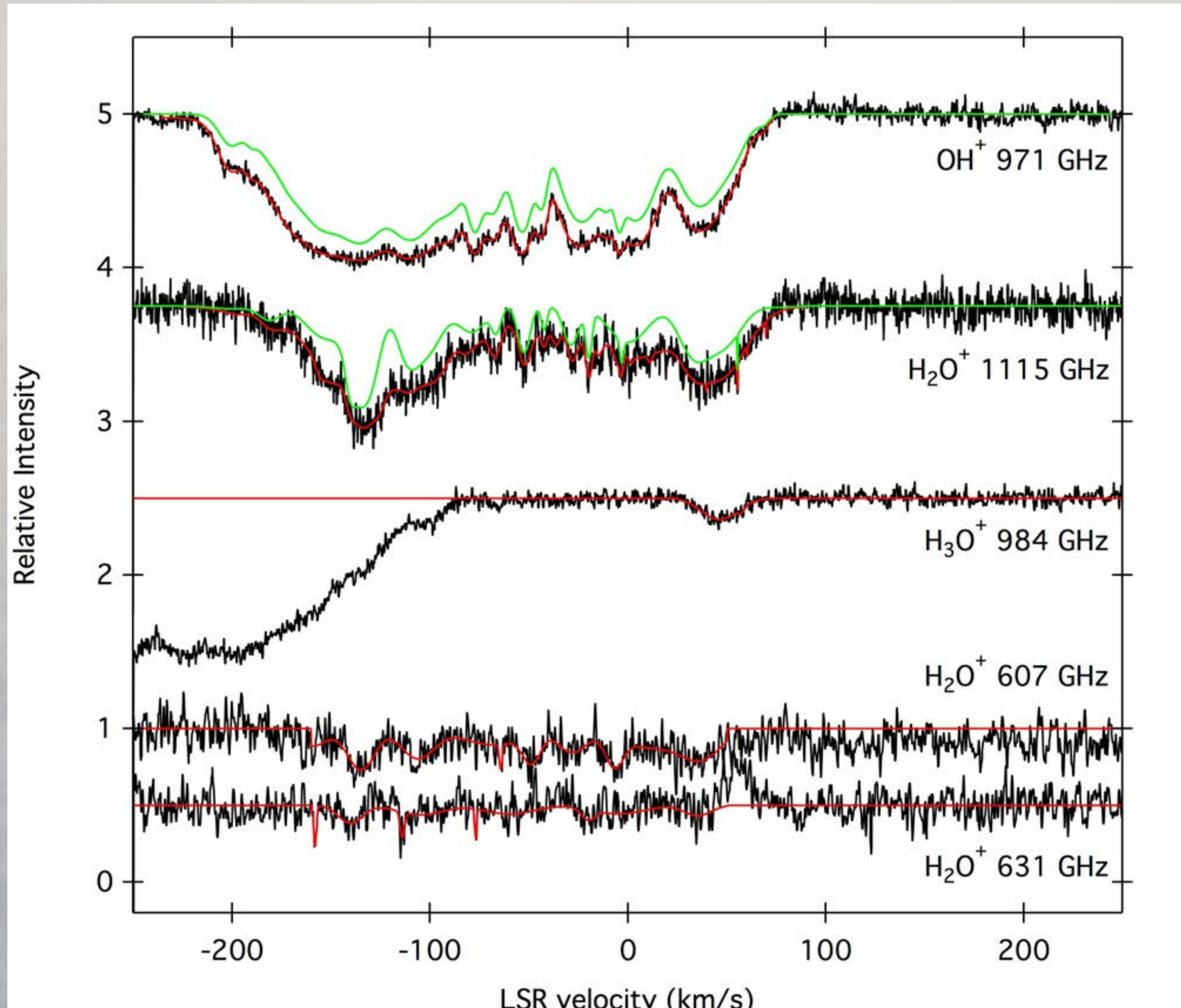
20
40
60
80
100
120
LSR velocity (km/s)

W3 IRS 5 Spectra



Sgr A* +50 km/s Spectra



W51 Results

LSR velocity	***N*(OH⁺)**	***N*(o-H_2O^+)**	***N*(p-H_2O^+)**
(km/s)	(10^{12} cm^{-2})	(10^{12} cm^{-2})	(10^{12} cm^{-2})
-4—11	32.9	4.52	1.53
11—16	11.1	1.34	<0.54
16—21	8.4	0.61	<0.51
21—33	18.5	1.35	<1.20
33—42	9.6	1.50	<0.93
42—55	52.2	7.45	
55—62	17.8	2.98	
62—75	20.4	4.73	

Molecular Hydrogen Fraction

$$f(H_2) \equiv \frac{2n(H_2)}{n(H) + 2n(H_2)}$$

Assume steady-state chemistry for H_2O^+

$OH^+ + H_2$ | $H_2O^+ + H_2$ | $H_2O^+ + e^-$

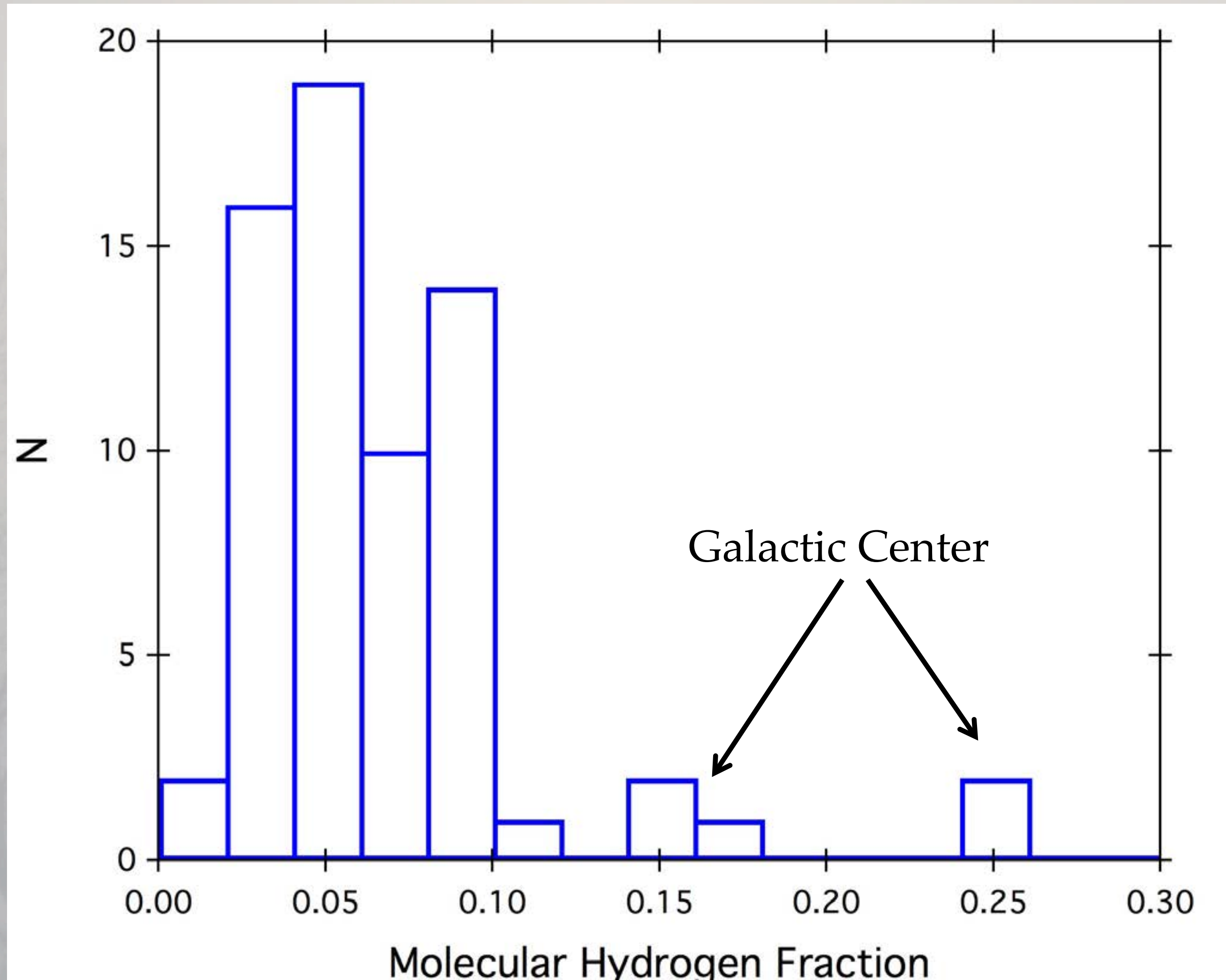
$$n(OH^+)n(H_2)k(OH^+|H_2) = n(H_2O^+)[n(H_2)k(H_2O^+|H_2) + n_e k(H_2O^+|e^-)]$$

$$f_{H_2} = \frac{2x_e k(H_2O^+|e^-)/k(OH^+|H_2)}{N(OH^+)/N(H_2O^+) - k(H_2O^+|H_2)/k(OH^+|H_2)}$$

W51 Results Continued

LSR velocity (km/s)	***N*(OH⁺)** (10^{12} cm^{-2})	***N*(o-H_2O^+)** (10^{12} cm^{-2})	***N*(p-H_2O^+)** (10^{12} cm^{-2})	***f*(H_2)**
-4—11	32.9	4.52	1.53	0.046
11—16	11.1	1.34	<0.54	0.040
16—21	8.4	0.61	<0.51	0.023
21—33	18.5	1.35	<1.20	0.023
33—42	9.6	1.50	<0.93	0.053
42—55	52.2	7.45		0.048
55—62	17.8	2.98		0.057
62—75	20.4	4.73		0.085

Molecular Hydrogen Fraction



Cosmic-Ray Ionization Rate

where ζ_{H} is defined as the rate per H atom

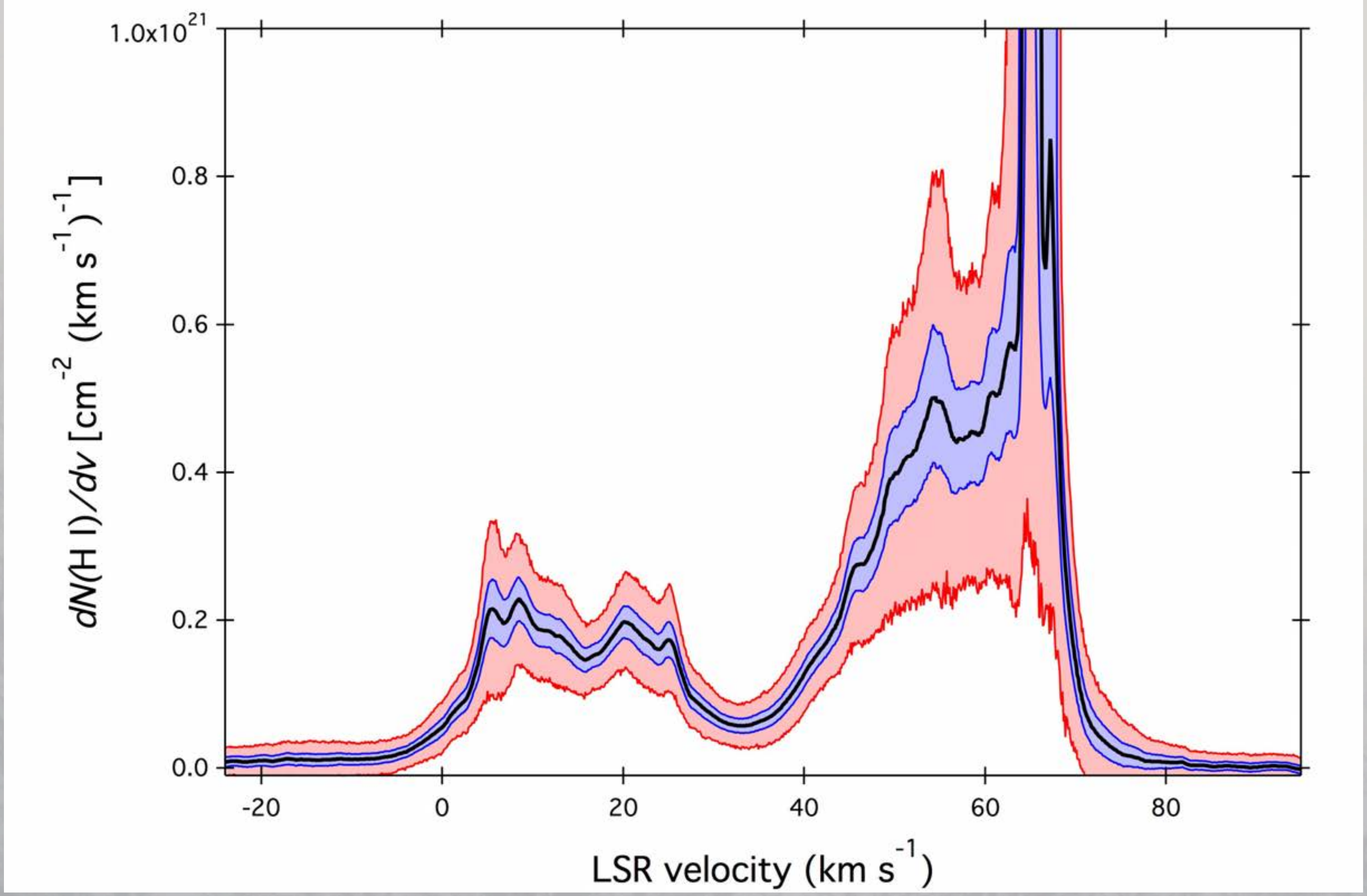
Assume steady-state chemistry for OH^+

CR + H — $OH^+ + H_2$ — $OH^+ + e^-$

$$\epsilon\zeta_{\mathrm{H}} n(\mathrm{H}) = n(\mathrm{OH}^+)[n(\mathrm{H}_2)k(\mathrm{OH}^+|\mathrm{H}_2) + n_e k(\mathrm{OH}^+|e^-)]$$

$$\epsilon\zeta_{\mathrm{H}} = \frac{N(\mathrm{OH}^+)}{N(\mathrm{H})} n_{\mathrm{H}} \left[\frac{f_{\mathrm{H}_2}}{2} k(\mathrm{OH}^+|\mathrm{H}_2) + x_e k(\mathrm{OH}^+|e^-)\right]$$

21 cm Data for W51



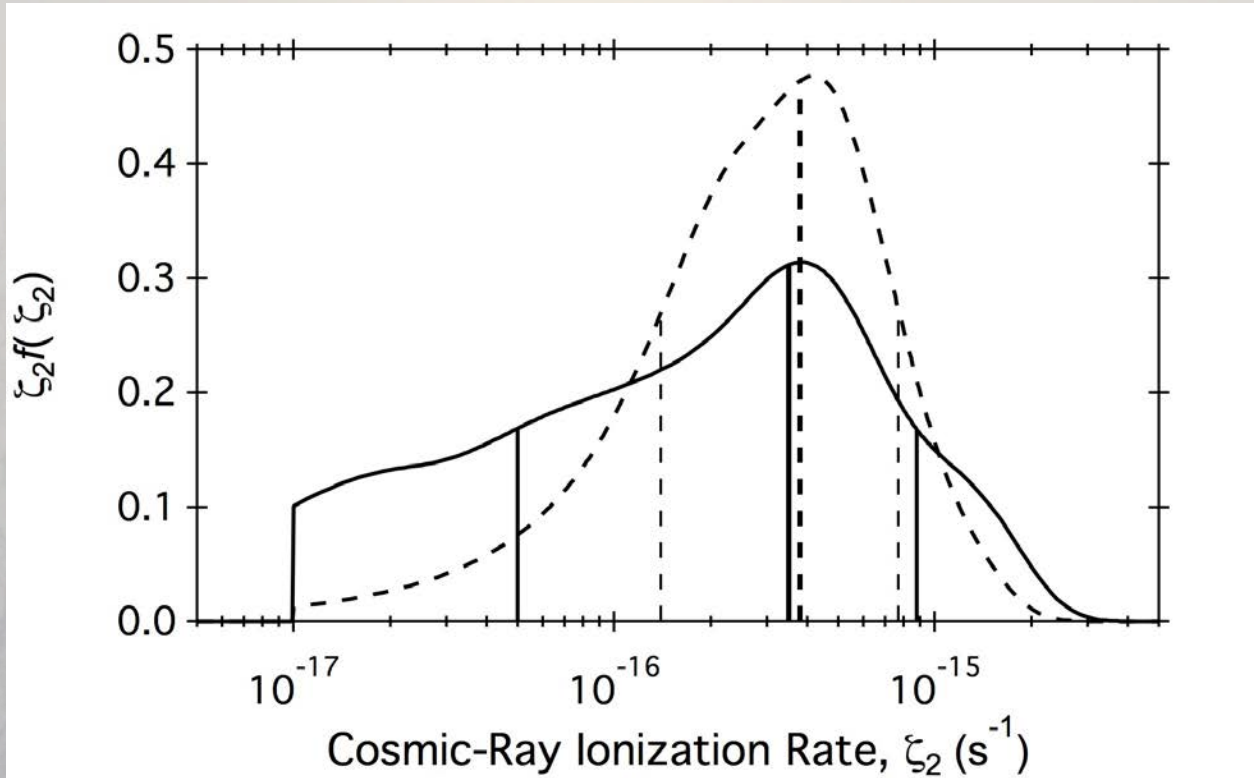
H I data processed by Benjamin Winkel

W51 Results Concluded

LSR velocity	$N(OH^+)$	$N(o\text{-}H_2O^+)$	$N(p\text{-}H_2O^+)$	$f(H_2)$	N(H I)	$\epsilon\zeta_H$	ζ_2
(km/s)	(10^{12} cm^{-2})	(10^{12} cm^{-2})	(10^{12} cm^{-2})		(10^{21} cm^{-2})	(10^{-17} s^{-1})	(10^{-16} s^{-1})
-4—11	32.9	4.52	1.53	0.046	1.94	1.96	4.29
11—16	11.1	1.34	<0.54	0.040	0.84	1.38	3.02
16—21	8.4	0.61	<0.51	0.023	0.88	0.71	1.56
21—33	18.5	1.35	<1.20	0.023	1.42	0.97	2.13
33—42	9.6	1.50	<0.93	0.053	0.84	1.46	3.21
42—55	52.2	7.45		0.048	4.43	1.40	3.06
55—62	17.8	2.98		0.057	3.25	0.74	1.63
62—75	20.4	4.73		0.085	>1.54	<2.44	<5.36

Assumed ϵ=0.07

Distribution of Ionization Rates



Summary

- OH^+ and H_2O^+ have been surveyed in 75 velocity components across 13 sight lines
- Column densities suggest these species reside in primarily atomic gas; $f(H_2)<0.1$
- The distribution of cosmic-ray ionization rates peaks near $\zeta_2=4\times10^{-16}$ s^{-1}, similar to results from H_3^+, and is well probed down to about 10^{-17} s^{-1}

Future Work

- Search for correlations between the ionization rate and Galactocentric radius
- Consider alternative means of observing both OH^+ (APEX, VLT UVES) and H_2O^+ (VLT CRIRES)
- Combine results with those found by other tracers of the ionization rate to better understand the cosmic-ray flux and particle propagation