SUBMILLIMETER WAVE ASTRONOMY SATELLITE AND ARECIBO OBSERVATIONS OF H$_2$O AND OH IN A DIFFUSE CLOUD ALONG THE LINE OF SIGHT TO W51

DAVID A. NEUFELD, MICHAEL J. KAUFMAN, PAUL F. GOLDSMITH, DAVID J. HOLLENBACH, AND RENÉ PLOME

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Abstract

Observations of W51 with the Submillimeter Wave Astronomy Satellite (SWAS) have yielded the first detection of water vapor in a diffuse molecular cloud. The water vapor lies in a foreground cloud that gives rise to an absorption feature at an LSR velocity of 6 km s$^{-1}$. The inferred water column density is $2.5 \times 10^{13}$ cm$^{-2}$. Observations with the Arecibo radio telescope of hydroxyl molecules at 10 positions in W51 imply an OH column density of $8 \times 10^{13}$ cm$^{-2}$ in the same diffuse cloud. The observed H$_2$O/OH ratio of $\sim 0.3$ is significantly larger than an upper limit derived previously from ultraviolet observations of the similar diffuse molecular cloud lying in front of HD 154368. The observed variation in H$_2$O/OH likely points to the presence in one or both of these clouds of a warm ($T \gtrsim 400$ K) gas component in which neutral-neutral reactions are important sources of OH and/or H$_2$O.

Subject headings: ISM: abundances — ISM: clouds — ISM: molecules — molecular processes — radio lines: ISM — submillimeter

1. INTRODUCTION

Since its launch in 1998 December, the Submillimeter Wave Astronomy Satellite (SWAS; Melnick et al. 2000) has detected water vapor in more than 70 molecular clouds by means of observations of the $1_{0-10_1}$ transition of ortho-H$_2$O (see, e.g., Snell et al. 2000; Ashby et al. 2000; Neufeld et al. 2000a). While emission-line observations form the core of the SWAS program on interstellar water vapor, absorption-line observations are possible toward a few bright continuum sources; these include Sagittarius B2 (Neufeld et al. 2000b, hereafter N00), Sagittarius A, W49, and W51. Absorption-line observations typically probe the water vapor abundance in several kinematically distinct foreground clouds lying along the line of sight to the source (see, e.g., N00). Under typical interstellar conditions, most water molecules are in the lower state of the $1_{0-10_1}$ transition (i.e., in the ground state of orthowater); thus, absorption-line observations have the distinct advantage of yielding water vapor column densities that are insensitive to both the physical conditions in the absorbing cloud and the assumed rate coefficients for collisional excitation of water. Typically, the H$_2$O absorption line is very optically thick, yielding only a lower limit on the water column density, but observations of optically thin absorption by the H$_2$O isotopologue (less abundant by a factor of 250–500) have led to a quantitative determination of the water column densities in foreground clouds along the Sgr B2 sight line (N00).

In this paper, we report the results of similar observations carried out toward the star-forming region W51. The results are particularly intriguing because they provide our first detection of an H$_1^6$O absorption line that is of only moderate optical depth. This feature, observed at an LSR velocity $\sim 6$ km s$^{-1}$, originates in a diffuse foreground cloud in which the water column density is small. This cloud has previously been detected by means of 21 cm absorption line observations (Koo 1997); the inferred H$_1$ column density is $\sim 10^{21}$ cm$^{-2}$.

Spaans et al. (1998, hereafter S98) have argued that measurements of OH and H$_2$O column densities in diffuse clouds provide a valuable probe of the chemistry of interstellar oxygen molecules; in particular, the OH/H$_2$O abundance ratio serves to constrain the branching ratio for the dissociative recombination of the molecular ion H$_2$O$^+$, a crucial parameter in chemical models for both diffuse and dense molecular clouds. Accordingly, we have used the Arecibo Observatory (AO) to carry out OH absorption line observations toward the same source, the results of which are also presented here.

The observations and data reduction are described in §2, and the observational results are presented in §3. In §4 we discuss the derived water and OH column densities and the constraints that they place on the oxygen chemistry in molecular clouds.

2. OBSERVATIONS

Our SWAS observations of W51 were carried out during the period 1999 April 16–2001 April 19 with the $3.5 \times 4.5$ elliptical SWAS beam centered at position $\alpha = 19^h23^m43^s, \delta = 14^\circ30'38''$ (J2000.0). All the data were acquired in standard nodded observations (Melnick et al. 2000) and were reduced using the standard SWAS pipeline. The total on-source integration time was 58.6 hr.

AO observations of the 1612, 1665, 1667, and 1720 MHz lines of OH were obtained on 2001 November 30 and December 3 toward the SWAS-observed position and nine offset positions of widely varying continuum flux. The goal of observing OH toward these offset positions was to allow
inferences to be drawn about the line excitation temperatures (see § 3.2). The offsets and on-source integration times for each observed position are given in Table 1, all positional offsets being expressed relative to the SWAS-observed position. The AO data were obtained in a series of standard nodded observations in which the source and reference positions were alternately observed for a period of 5 minutes each. The reference position was chosen to have a right ascension offset such that the source and reference positions were observed over identical tracks in azimuth and elevation. Calibration measurements were carried out using the noise diode after each source/reference position pair, and calibration observations of an astronomical continuum source were performed at the beginning of each day’s observations.

| Position | Offset $^a$ (arcmin) | Time $^b$ (s) | $T_B^c$ (K) | $W'_V(1612)^d$ (km s$^{-1}$) | $W'_V(1665)$ (km s$^{-1}$) | $W'_V(1667)$ (km s$^{-1}$) | $W'_V(1720)$ (km s$^{-1}$) |
|----------|----------------------|--------------|-------------|-----------------|-----------------|-----------------|-----------------|
| 1......... | (0, 0)               | 600          | 542.8       | -0.057 (0.001)  | -0.029 (0.002)  | -0.095 (0.002)  | +0.036 (0.002)  |
| 2......... | (-1.3, -8.3)         | 600          | 22.1        | -0.067 (0.004)  | -0.037 (0.005)  | -0.103 (0.003)  |                  |
| 3......... | (+4.0, -3.3)         | 600          | 38.1        | -0.064 (0.003)  | -0.033 (0.003)  | -0.091 (0.003)  |                  |
| 4......... | (-4.2, +2.2)         | 600          | 37.8        | -0.056 (0.003)  | -0.030 (0.003)  | -0.096 (0.003)  |                  |
| 5......... | (+7.2, -11.8)        | 1200         | 10.7        | -0.084 (0.004)  | -0.029 (0.004)  | -0.110 (0.005)  |                  |
| 6......... | (-11.0, +6.7)        | 1200         | 9.5         | -0.062 (0.004)  | -0.014 (0.005)  | -0.129 (0.005)  |                  |
| 7......... | (-13.4, -8.3)        | 1200         | 16.6        | -0.065 (0.003)  | -0.026 (0.003)  | -0.149 (0.003)  |                  |
| 8......... | (-11.0, +11.7)       | 600          | 6.6         | -0.092 (0.016)  | -0.005 (0.010)  | -0.051 (0.013)  |                  |
| 9......... | (-11.0, +16.7)       | 300          | 6.0         | -0.103 (0.014)  | +0.029 (0.014)  | -0.078 (0.015)  |                  |
| 10........ | (-11.0, +21.7)       | 300          | 6.2         | -0.082 (0.021)  | -0.042 (0.014)  | -0.039 (0.014)  |                  |

$^a$ Offset ($\alpha \cos \delta, \delta$) relative to $\alpha = 19^h23^m43^s0, \delta = 14^\circ30'38"$ (J2000.0).
$^b$ On-source integration time.
$^c$ Beam-averaged continuum brightness temperature at 1666 MHz.
$^d$ Line equivalent width ($<0$ for absorption line), with statistical errors in parentheses.

3. RESULTS

3.1. SWAS Observations of Water Vapor

Figure 1 shows the complete spectrum of the $1_{10}-1_{01}$ 556.936 GHz transition of H$_2$O obtained by SWAS toward W51. The continuum antenna temperature $T_A^*$ measured toward W51 was 0.35 K (double sideband), corresponding to a 550 GHz continuum flux density of $2.5 \times 10^3$ Jy. The quantity plotted in Figure 1 is the ratio of flux density to continuum flux density, given by $(T_A^* - 0.5T_A^{*AC})/0.5T_A^{*AC}$ under the assumption that the sideband gains are equal. The SWAS beam size is $3.3' \times 4.5'$ (FWHM) at 550 GHz. The fitted line at $V_{LSR} \sim 6$ km s$^{-1}$ is the best-fit absorption line for a cloud that is assumed to completely cover the source. The derived cloud parameters are a line-center optical depth $\tau_0$

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**Fig. 1.**—Water vapor spectrum obtained toward W51 by SWAS. The figure shows the $1_{10}-1_{01}$ pure rotational transition of H$_2$O near 557 GHz.
of 1.5, a Doppler parameter $b = 1.5 \text{ km s}^{-1}$, and a cloud LSR velocity of 6.0 km s$^{-1}$. Under the conditions typical of diffuse interstellar clouds, the population in the $^{1}J_{0}$ rotational state of water is very small, and thus the effects of stimulated emission on the $^{1}J_{0}$ optical depth can be neglected. The column density of water in the $^{2}J_{0}$ state is straightforwardly obtained as $N(\text{H}_2O) = 1.9 \times 10^{13} \text{ cm}^{-2}$. If the ortho-para ratio for water is 3, the implied total water column density is $2.5 \times 10^{13} \text{ cm}^{-2}$. The water abundance relative to H$_i$ is $10^{-8}$.

3.2. Arecibo Observations of OH

Figure 2 shows the OH spectra obtained at AO toward the 10 positions observed in W51. These spectra show the ratio of beam-averaged brightness temperature $T_B$ to continuum brightness temperature $T_{BC}$. The beam-averaged brightness temperature of the radiation incident on the AO antenna is computed according to $T_B = T_A / \eta_A + T_{\text{CMB}}$, where $T_A$ is the antenna temperature, $\eta_A \sim 0.8$ is the aperture efficiency—including atmospheric losses, as determined from calibration observations of an astronomical continuum source—and $T_{\text{CMB}} = 2.73 \text{ K}$ is the temperature of the cosmic background radiation (which is “chopped out” by our observing procedure). The size of the Arecibo main beam is $2.6' \times 3.0' (\text{FWHM})$ at 1666 MHz.

The continuum brightness temperatures $T_{BC}$ measured for each position are shown in Table 1, along with the measured equivalent width $W_v$ (in units of km s$^{-1}$) for each of the observed OH lines. Here, $W_v$ is defined as $\int(T_B - T_{BC})/T_{BC}dv$, so that a negative value of $W_v$ implies an absorption line and a positive value an emission line. Because of strong radio frequency interference, the 1720 MHz line strength could be measured reliably only toward the SWAS-observed (0, 0) position, where the absolute line strength was largest.

The results shown in Table 1 imply that the ratio of equivalent widths departs greatly from the 1:5:9:1 value expected in LTE for $W_v(1612):W_v(1665):W_v(1667):W_v(1720)$. In particular, the 1665/1667 MHz absorption line ratio is considerably smaller than the LTE value and the 1612/1667 MHz ratio considerably larger. Moreover, the 1720 MHz line is observed in emission toward the (0, 0) position, indicating the presence of weak maser amplification.

For lines of small optical depth, the equivalent width is related to the OH column density and the excitation

![Fig. 2.—OH spectra obtained toward 10 positions in W51. The red, green, blue, and magenta curves show the 1612, 1665, 1667, and 1720 MHz transitions, respectively.](image-url)
temperature $T_{ex}$ by the expression

$$W_e = 0.45k \frac{N(OH)}{10^{13} \text{cm}^{-2}} \left( \frac{T_{ex}}{K} \right) ^{-1} \frac{T_{BC} - T_{ex}}{T_{BC}} \text{ km s}^{-1},$$

(1)

where $k = \frac{1}{9}$, $\frac{5}{9}$, $\frac{1}{F}$, and $\frac{1}{F}$ for the 1612, 1665, 1667, and 1720 MHz transitions, respectively. The ratios and signs of the equivalent widths observed toward the (0, 0) position imply that $T_{ex}(1720) < 0 < T_{ex}(1612) < T_{ex}(1667) < T_{ex}(1665)$. Assuming that all the excitation temperatures are small compared to $T_{BC}$ at the (0, 0) position (i.e., small compared to 500 K), we find the ratio of excitation temperatures to be $T_{ex}(1612): T_{ex}(1665): T_{ex}(1667): T_{ex}(1720) = 0.18: 1: 0.17: 0.1: 0.29$.

Unfortunately, because the equivalent widths are a function of two unknowns—$N(OH)$ and $T_{ex}$—the OH column density and excitation cannot be derived independently for any given sight line. However, as we argue below, the variation of the equivalent widths with the background continuum brightness temperature $T_{BC}$ for the 10 sight lines we observed provides a strong argument that the entire region is covered by a large foreground cloud in which the OH column density and excitation are nearly constant. This in turn allows us to derive an estimate of $N(OH)$.

In Figure 3 (upper panel), we show the equivalent widths measured for each transition and each observed position as a function of the background continuum brightness temperature $T_{BC}$. We note immediately that the equivalent width of the 1612 MHz transition shows rather little variation over the entire set of observed positions; $W_e$ (1612) lies within 20% of $-0.08$ km s$^{-1}$ for every sight line that we observed. Referring to equation (1), we see that the near constancy of $W_e$ argues strongly that $N(OH)$ and $T_{ex}$ are nearly constant and that $T_{ex}$ is small compared to 6 K, the smallest $T_{BC}$ for any sight line that we observed. In principle, of course, $N(OH)$ and $T_{ex}$ could show large variations from one position to another, but it would seem highly improbable that such variations could conspire to yield a right-hand side for equation (1) that is nearly constant. Therefore, we shall henceforth assume that the OH column density and excitation are nearly the same toward each of the 10 positions we have observed.

It is also apparent from Figure 3 that the equivalent widths of the 1665 MHz transition and perhaps the 1667 MHz transition appear to show a systematic decline in those sight lines of smallest continuum brightness; this decline allows the line excitation temperatures to be estimated. In Figure 3 (lower panel), we plot the ratio of equivalent widths for the 1665 and 1612 MHz transitions, again as a function of the background brightness temperature. The solid curve shows the best fit to the data for a model in which the 1612 and 1665 excitation temperatures are assumed to be constant and in the 0.1: 1 ratio inferred for the (0, 0) position. The best-fit curve is obtained for $T_{ex}(1665) = 7$ K. Adopting this value for $T_{ex}(1665)$, we infer from equation (1) and the observed 1665 MHz equivalent width that the OH column density is $8 \times 10^{13} \text{ cm}^{-2}$ toward the SWAS-observed (0, 0) position.

4. DISCUSSION

Because of the relative simplicity of the chemical networks involved, diffuse molecular clouds provide a useful laboratory for testing astrochemical models; in particular, the H$_2$O/OH abundance ratio serves as a valuable probe of the chemical network that produces oxygen-bearing molecules (S98). One key uncertainty in the network concerns the dissociative recombination of H$_2$O$^+$ with electrons and, specifically, the fraction of such recombinations that produce water, $f_{H_2O}$; a quantity for which two laboratory groups have obtained highly discrepant results. According to results obtained in the flowing afterglow experiment of Williams et al. (1996), a fraction $f_{OH}$ of dissociative recombinations of H$_2$O$^+$ leads to OH, a fraction $f_{H_2O}$ to H$_2$O, and the remaining fraction $f_0 = 1 - f_{OH} - f_{H_2O}$ to O. A different experimental technique (Vejby-Christensen et al. 1997), which made use of the ASTRID heavy-ion storage ring in Denmark, yielded significantly different results (Jensen et al. 2000), viz., $f_{OH} : f_{H_2O} : f_0 = 0.74 \pm 0.02 : 0.25 \pm 0.01 : 0.013 \pm 0.005$. Similar results (although with larger error bars) were obtained (Neau et al. 2000) from the CRYRING heavy-ion storage ring facility; they were $f_{OH} : f_{H_2O} : f_0 = 0.78 \pm 0.08 : 0.18 \pm 0.05 : 0.04 \pm 0.06$.

Taken together with the ground-based observations of OH that we obtained at Areco, the SWAS observations of W51 imply an H$_2$O/OH abundance ratio of $\sim 0.3$ in the diffuse cloud that is responsible for the $f_{LSR} = 6$ km s$^{-1}$ feature. Considering the uncertainties in our determination of the H$_2$O and (particularly) the OH column densities, we estimate the H$_2$O/OH ratio to be uncertain by a factor of $\sim 2$. In comparing the observed H$_2$O/OH abundance ratio with theoretical predictions, we have used the steady state photodissociation region (PDR) model of Kaufman et al. (1999), modified so as to treat the case of a finite slab illuminated from two sides. Because H$_2$ and CO are photodissociated following line absorption, their photodissociation rates are reduced by self-shielding. In order to treat correctly the effects of self-shielding for radiation incident on both sides of the slab, the H$_2$ and CO abundances must be obtained by an iterative method.

4.1. Standard Models of Cold Diffuse Clouds

In Figure 4, we show the predicted H$_2$O and OH column densities for a variety of astrophysical parameters: the total visual extinction through the cloud $A_V$, in magnitudes, the illuminating UV field $G_0$, in units of the Habing field, and the cosm-ray ionization rate $\zeta_{cr}$. All results apply to an assumed cloud density $n_H$ of 100 H nucleons per cm$^3$. The temperature is calculated from considerations of thermal balance and is $\sim 30$ K at the cloud center. Filled squares apply to models with $f_{OH} : f_{H_2O} : f_0 = 0.75 : 0.25 : 0.0$ values suggested by the ASTRID storage ring experiment, while filled triangles apply to models with $f_{OH} : f_{H_2O} : f_0 = 0.65 : 0.05 : 0.30$ (suggested by the flowing afterglow experiment). The different astrophysical parameters for each plotted data point are described in the figure caption. Black circles represent the column densities observed toward W51 and HD 154368.

A striking feature of Figure 4 is that although the H$_2$O and OH column densities depend strongly on the assumed astrophysical parameters, their ratio is determined primarily by the assumed branching ratio $f_{H_2O}$ and shows almost no dependence on $A_V$, $G_0$, or $\zeta_{cr}$. This behavior can be understood by means of a simple “toy” model, in which we assume OH and H$_2$O to be formed by dissociative recombination of H$_2$O$^+$ and destroyed by photodissociation. The expected H$_2$O/OH ratio is given by

$$\frac{n(H_2O)}{n(OH)} = \frac{\zeta_{OH} f_{H_2O}}{\zeta_{H_2O} (f_{OH} + f_{H_2O})} \sim 0.69 \frac{f_{H_2O}}{f_{OH} + f_{H_2O}}. \quad (2)$$
where \( \zeta_{\text{OH}} = 3.5 \times 10^{-10} G_0 \exp(-1.7 \chi) \text{ s}^{-1} \) and \( \zeta_{\text{H}_2\text{O}} = 5.1 \times 10^{-10} G_0 \exp(-1.8 \chi) \text{ s}^{-1} \) are the assumed photodissociation rates for OH and \( \text{H}_2\text{O} \) (Roberge et al. 1991).\(^7\) Equation (2) yields \( \text{H}_2\text{O}/\text{OH} \) abundance ratios of 0.172 and 0.049, respectively, for the branching ratios assumed for the filled squares and triangles in Figure 4. These ratios are shown by dashed lines in Figure 4 and do indeed yield good agreement with results from the full steady state PDR model. The assumption of chemical steady state is justified by the fact that the photodissociation timescale for OH is only \( \sim 100 \exp(1.7 \chi)/G_0 \) yr.

Given standard models for cold diffuse clouds, the observed \( \text{H}_2\text{O}/\text{OH} \) abundance ratio of \( \sim 0.3 \) in W51 is consistent with the case \( f_{\text{OH}} : f_{\text{H}_2\text{O}} : f_0 = 0.75 : 0.25 : 0 \) and clearly inconsistent with the case \( f_{\text{OH}} : f_{\text{H}_2\text{O}} : f_0 = 0.65 : 0.05 : 0.30 \). Thus, if interpreted using standard models for cold diffuse clouds, the observed \( \text{H}_2\text{O}/\text{OH} \) abundance ratio argues for the laboratory results obtained in the ASTRID storage ring experiment and against those obtained in the flowing afterglow experiment.

\(^7\) The quantity \( f_{\text{H}_2\text{O}} \) appears with \( f_{\text{OH}} \) in the denominator of the second term on the right-hand side of eq. (2) because photodestruction of \( \text{H}_2\text{O} \) results in the formation of OH.
This conclusion, however, is different from that obtained by S98, who used ultraviolet absorption line observations with the Goddard High Resolution Spectrometer on the Hubble Space Telescope to place an upper limit of only 0.06 \((3 \sigma)\) on the H\(_2\)O/OH ratio in an entirely different diffuse cloud, which lies in front of the star HD 154368. Based on these observations, S98 argued for a low value of \(f_{OH}:f_{H_2O}:f_O = 0.65:0.05:0.30\) (flowing afterglow experiment). Red symbols show the results of models in which the incident UV field \(G_0\) is 5 and the cosmic-ray ionization rate \(\zeta_{cr}\) is \(1.0 \times 10^{-16} \text{ s}^{-1}\). Blue and green symbols apply, respectively, to the cases \((G_0 = 5, \zeta_{cr} = 1.8 \times 10^{-17} \text{ s}^{-1})\) and \((G_0 = 1, \zeta_{cr} = 1.0 \times 10^{-16} \text{ s}^{-1})\). In each case, results were obtained for total cloud extinctions \(A_I\) of 1, 2, 3, and 4 (from left to right as the points appear in the figure). The black dashed lines show the H\(_2\)O/OH ratios of 0.172 and 0.049 obtained for the two assumed branching ratios using the toy model described in the text. The magenta locus shows the results of enhanced temperature models (see text): from left to right, the points refer to a model in which the temperature is calculated self-consistently \((\text{filled square}; T \sim 30 \text{ K at cloud center})\) and then \((\text{crosses})\) to models in which the assumed temperature is fixed at 100, 300, 400, 500, 550, 600, 700, 800, and 1500 K.

### 4.2. Enhanced-Temperature Models of Diffuse Molecular Clouds

It has long been recognized (see, e.g., Elitzur & de Jong 1978) that neutral-neutral reactions provide an alternate production route to OH and H\(_2\)O. The reactions

\[
\text{O} + \text{H} \rightarrow \text{OH} + \text{H} ,
\]

\[
\text{OH} + \text{H} \rightarrow \text{H}_2\text{O} + \text{H}
\]

possess activation barriers that make them negligibly slow at the low temperatures typical of diffuse interstellar clouds; at temperatures above \(\sim 300 \text{ K}\), however, they become important production mechanisms for OH and H\(_2\)O (Neffeld, Lepp, & Melnick 1995). If even a small fraction of the gas in the W51 6 km s\(^{-1}\) and/or the HD 154368 cloud were sufficiently warm—as a result of a weak shock, for example—then neutral-neutral reactions might perturb the OH and H\(_2\)O column densities.

To investigate this possibility, we have obtained model predictions for PDRs in which the temperature has been fixed at a variety of temperatures between 100 and 1500 K. The results are represented by the magenta locus in Figure 4; they were obtained for the astrophysical parameters.
adopted by S98 for the HD 154368 cloud—$A_V = 2.65$ mag, $n_H = 325$ cm$^{-3}$, $G_0 = 3$—but for a branching ratio $f_{\text{H}_2\text{O}} = 0.25$ and a cosmic-ray ionization rate of $1.8 \times 10^{-17}$ s$^{-1}$. The OH and H$_2$O column densities are both clearly enhanced by neutral-neutral reactions. At moderate temperatures, the H$_2$O/OH ratio decreases because the large O/OH ratio makes reaction 3 more important than reaction 4. At temperatures higher than $\sim 600$ K, however, the effect on the ratio is reversed, and the H$_2$O/OH ratio is increased by neutral-neutral reactions.

The results obtained in enhanced-temperature models suggest a way out of the puzzle posed by the discrepant OH/H$_2$O ratios measured in the W51 $6 \text{ km s}^{-1}$ and HD 154368 clouds. If these clouds possess small (but differing) amounts of warm gas, then the OH/H$_2$O abundance ratios could differ (even though the value of $f_{\text{H}_2\text{O}}$ must, of course, be identical in both clouds). We are unaware of any observations that rule out the presence of small amounts of warm gas in these sources; indeed, the presence of such gas in diffuse clouds is predicted by certain models that seek to explain the anomalously high CH$^+$ abundances observed in many diffuse clouds as resulting from the effects of turbulence or weak shocks$^8$ (see, e.g., Joulain et al. 1998; Flower & Pineau des Forets 1998 and references therein).

Unfortunately, as discussed above, the effect of warm gas on the H$_2$O/OH ratio depends critically on the gas temperature and even switches sign at $T \sim 600$ K. Thus, if warm gas is present, the observed H$_2$O/OH ratio cannot even be used to derive a limit on $f_{\text{H}_2\text{O}}$. For example, if $\sim 5\%$ of the gas in HD 154368 were at $\sim 500$ K, then the observations of OH and H$_2$O in that source could be reconciled with the large branching ratio $f_{\text{H}_2\text{O}} = 0.25$ derived in § 4.1. Alternatively, if $\sim 0.3\%$ of the gas in the W51 cloud were at $T \sim 700$ K, then the observed H$_2$O/OH ratio would be consistent with the lower limit on $f_{\text{H}_2\text{O}}$ inferred previously by S98.

To summarize, the discrepancy between the H$_2$O/OH ratio reported here for the W51 $6 \text{ km s}^{-1}$ cloud and that reported previously for the HD 154368 cloud (S98) suggests that a component of warm ($T \gtrsim 400$ K) gas is present in one or both of these sources. The presence of this warm component makes it difficult to determine observationally the branching ratio for the dissociative recombination of H$_3$O$^+$ with electrons to form OH and H$_2$O. Our new observations of W51 cast doubt on the conclusion of S98 that the branching ratio to H$_2$O is small but do not allow the branching ratio to be determined definitively.

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8 Depending on the geometry, velocity shifts of the OH and H$_2$O lines relative to the lines of other species (e.g., H$_1$) might be an observational signature of a shock production mechanism. The velocity shifts can be very small, however, if the shock propagates at an oblique angle to the line of sight or if multiple shocks are present in the beam. Thus, the absence of any such signature in the W51 $6 \text{ km s}^{-1}$ cloud does not argue strongly against the production of OH and H$_2$O in shocks.

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