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THE DISTRIBUTION OF WATER EMISSION IN M17SW

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ABSTRACT

We present a 17-point map of the M17SW cloud core in the $1_{10} \rightarrow 1_{01}$ transition of ortho-H_2O at 557 GHz obtained with *SWAS*. Water emission was detected in 11 of the 17 observed positions. The line widths of the H_2O emission vary between 4 and 9 km s^{-1}, and are similar to other emission lines that arise in the M17SW core. A direct comparison is made between the spatial extent of the H_2O emission and the ^{13}CO $J = 5 \rightarrow 4$ emission; the good agreement suggests that the H_2O emission arises in the same warm, dense gas as the ^{13}CO emission. A spectrum of the $H_2^{18}O$ line was also obtained at the center position of the cloud core, but no emission was detected. We estimate that the average abundance of ortho-H_2O relative to H_2 within the M17 dense core is approximately 1×10^{-9}, 30 times smaller than the average for the Orion core. Toward the H II region/molecular cloud interface in M17SW the ortho-H_2O abundance may be about 5 times larger than in the dense core.

Subject headings: ISM: abundances — ISM: clouds — ISM: molecules — radio lines: ISM

1. INTRODUCTION

M17SW is a prototypical giant molecular cloud core at a distance of approximately 2.2 kpc (Chini, Elsässer, & Neckel 1980) that was first studied in detail by Lada (1976). The dense core lies adjacent to a large optical H II region and is oriented such that the H II region/molecular cloud interface is viewed nearly edge-on. Because of this favorable geometry, this region has been the subject of numerous investigations studying the effect of UV radiation on heating, dissociation, and ionization of the gas within the molecular cloud. The detection of emission from neutral and ionized fine structure lines of atomic carbon and high-J CO lines (Keene et al. 1985; Harris et al. 1987; Genzel et al. 1988; Stutzki et al. 1988; Meixner et al. 1992) well away from the H II region/molecular cloud interface suggests that the UV photons penetrate deep into the M17SW cloud core. The ability of the UV photons to penetrate into the cloud has been attributed to the clumpy structure of the cloud core. Indirect evidence for a clumpy cloud structure had been previously suggested by Snell et al. (1984), however high resolution observations of CO and CS presented by Stutzki & Güsten (1990) reveal more directly the complex structure of this cloud core.

Besides studies of the water maser emission at 22 GHz, only one attempt has been made to detect water in M17SW. Waters et al. (1980) report a marginal detection of the 183 GHz line of water toward the dense core. With the *Submillimeter Wave Astronomy Satellite* (*SWAS*) we have observed the lowest energy rotational transition of ortho-H_2O and ortho-$H_2^{18}O$. These transitions have upper state energies only 27 K above the ortho-water ground state, making observations with *SWAS* a powerful means to probe water in the warm, dense molecular gas of M17SW. In this Letter we present a 17-point map that reveals extended H_2O emission from this region. Observations of the $H_2^{18}O$ transition were made toward the center of the cloud core. Based on these observations we estimate the relative abundance of ortho-water in M17SW and compare the results with that found for the extended water emission detected in Orion by *SWAS* (Snell et al. 2000).

2. OBSERVATIONS AND RESULTS

The observations of H_2O in M17SW were obtained by *SWAS* during the period 1999 March–1999 June and the observations of $H_2^{18}O$ were obtained during 1999 August–1999 October. The data were acquired by nodding the satellite alternatively between M17 and a reference position free of molecular emission. Details concerning data acquisition, calibration, and reduction with *SWAS* are presented in Melnick et al. (2000). Observations of the $1_{10} \rightarrow 1_{01}$ transition of H_2O at a frequency of 556.936 GHz were obtained at 17 positions in the cloud. The offsets of the 17 spectra relative to position $\alpha = 18^h20^m22\overset{s}{.}1$, $\delta = -16°12'37''$ (J2000) are given in Table 1. The absolute pointing accuracy of *SWAS* is better than 5″ (Melnick et al. 2000). Integration times for these observations were typically 3–7 hr per position, except the center position which had an integration time of 80 hr. In the opposite receiver sideband of H_2O, we simulataneously obtained spectra of the ^{13}CO $J = 5 \rightarrow$ 4 transition. The center position in M17SW was also observed in $H_2^{18}O$ at a frequency of 547.676 GHz for nearly 100 hr. The *SWAS* beam is elliptical, and at the frequency of the water transitions has angular dimensions of $3\overset{'}{.}3 \times 4\overset{'}{.}5$. The data shown in this Letter are not corrected for the measured *SWAS*

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TABLE 1
WATER LINE PARAMETERS AND ABUNDANCE DETERMINATION

$\Delta\alpha$ (arcmin)	$\Delta\delta$ (arcmin)	$\int T_A^* dV$ (K km s^{-1})	$\sigma(\int T_A^* dV)$ (K km s^{-1})	V_{LSR} (km s^{-1})	ΔV (km s^{-1})	x(o-H_2O)
6.4	6.4	···	0.21	···	···	$< 9 \times 10^{-9}$
3.2	6.4	0.86	0.15	18.2	5.9	6×10^{-9}
3.2	3.2	1.00	0.11	21.9	7.9	5×10^{-9}
3.2	0.0	0.65	0.11	21.0	4.8	1×10^{-9}
3.2	–3.2	···	0.14	···	···	$< 1 \times 10^{-9}$
0.0	6.4	0.49	0.14	18.0	3.9	4×10^{-9}
0.0	3.2	1.21	0.15	18.9	8.1	2×10^{-9}
0.0	0.0	3.29	0.05	20.4	8.2	1×10^{-9}
0.0	–3.2	1.27	0.11	18.6	5.6	1×10^{-9}
–3.2	6.4	···	0.21	···	···	$< 8 \times 10^{-9}$
–3.2	3.2	0.71	0.16	18.1	4.3	2×10^{-9}
–3.2	0.0	1.67	0.11	21.2	9.4	1×10^{-9}
–3.2	–3.2	0.63	0.17	18.7	7.6	2×10^{-9}
–6.4	6.4	···	0.34	···	···	$< 6 \times 10^{-8}$
–6.4	3.2	···	0.16	···	···	$< 1 \times 10^{-8}$
–6.4	0.0	0.62	0.21	16.4	9.3	8×10^{-9}
–6.4	–3.2	···	0.16	···	···	$< 3 \times 10^{-8}$

main beam efficiency of 0.90.

We also made use of the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope to acquire data for our analysis. A map of a $12' \times 12'$ region was obtained in the $J = 1 \rightarrow 0$ transition of ^{13}CO and combined with the lower signal-to-noise ratio map of Wilson, Howe, & Balogh (1999), and a map of a $6' \times 6'$ region was obtained in the $J = 6 \rightarrow 5$ ($K = 0, 1, 2, 3, 4$) transitions of CH_3CCH. These data are used to provide an estimate of the temperature and column density of the gas for our analysis of the water emission.

Sixteen of the seventeen H_2O spectra were obtained on a 4 by 4 grid with a spacing of 3′.2. These spectra, shown in their relative positions on the sky, are presented in Figure 1. Also shown in this figure are spectra of the $J = 5 \rightarrow 4$ transition of ^{13}CO. A much larger map of the $J = 5 \rightarrow 4$ transition of ^{13}CO obtained by *SWAS* is presented in Howe et al. (2000). The strongest H_2O emission of 0.38 K was detected toward the map reference position located at the center of the dense core. The seventeenth spectrum was obtained 6′.4 east and 6′.4 north of the reference position, but no water emission was detected. For the positions where H_2O was detected, we fit the emission with a Gaussian line shape; the results of this fitting are presented in Table 1. The emission at the center of M17SW is about 5 times weaker than the narrow component of the H_2O

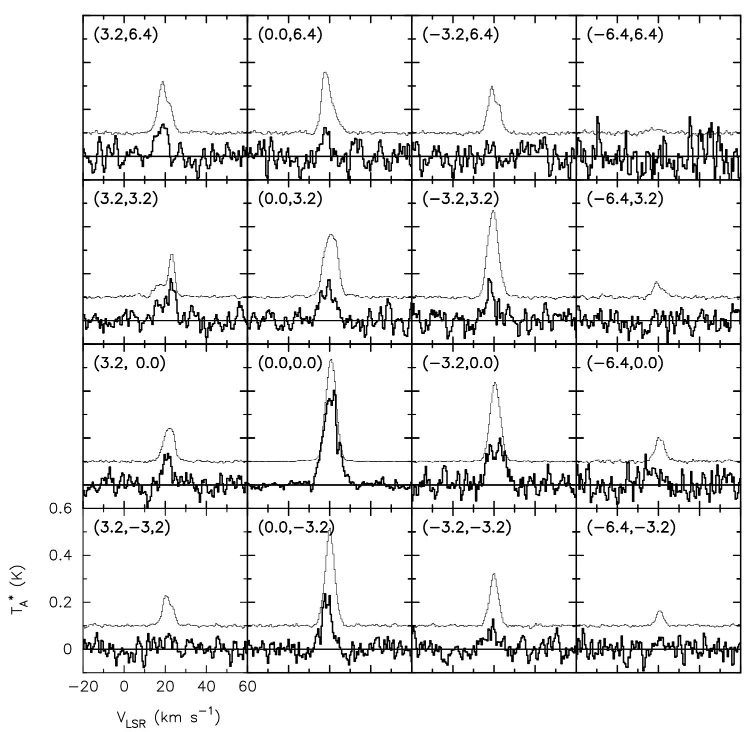

FIG. 1.— Spectra of the $1_{10} \rightarrow 1_{01}$ transition of ortho-H_2O (*heavy lines*) and the $J = 5 \rightarrow 4$ transition of ^{13}CO (*light lines*) obtained in M17SW. The ^{13}CO spectra are divided by a factor of 10 in all cases except at positions (0.0, 0.0) and (-3.2, 0.0) where the spectra are divided by 20. The sixteen spectra of each transition make up a 4×4 map obtained on a regular grid separated by 3′.2. The spectra are shown in their correct relative positions on the sky. Offsets in arcminutes relative to position $\alpha = 18^h20^m22^s.1$, $\delta = -16°12'37''$ (J2000) are indicated on each spectrum.

emission detected in Orion by *SWAS* (Snell et al. 2000). The H_2O FWHM line widths vary between 4 and 9 km s^{-1} and are very similar to those found for CS and CO emission in this region (Lada 1976; Snell et al. 1984; Stutzki & Güsten 1990). Although the H_2O spectra appear singly peaked, comparison with ^{13}CO $J = 5 \rightarrow 4$ spectra (see Fig. 1) indicates that in some directions the H_2O emission may be slightly self-absorbed. When differences in angular resolution are taken into account, the spatial extent of the H_2O emission is similar to that found in CS and the lower rotational transitions of $C^{18}O$ and ^{13}CO (Snell et al. 1984; Stutzki & Güsten 1990; Wilson et al. 1999). A more direct comparison of the spatial distributions can be made between the H_2O emission and the ^{13}CO $J = 5 \rightarrow 4$ emission obtained simultaneously with *SWAS*. The results shown in Figure 1 reveal a very strong correlation between the emission in these two lines. The gas probed by the ^{13}CO $J = 5 \rightarrow 4$ emission has temperatures in the range 30 to 60 K and densities $> 1 \times 10^5 cm^{-3}$ (Howe et al. 2000). The similarity in emission properties suggests that the H_2O emission arises from the same warm, dense gas that gives rise to ^{13}CO emission as well as the emission in CS and the lower rotational transitions of CO.

Figure 2 shows an expanded view of the H_2O spectra obtained toward the center of the M17SW core along with a spectrum of $H_2^{18}O$ obtained in the same direction. No $H_2^{18}O$ emission was detected. Using the same line width and line center velocity determined from a gaussian fit to the H_2O line at the center, we fit the $H_2^{18}O$ line and set a 3σ upper limit on the integrated intensity, $\int T_A^* dV < 0.15$ K km s^{-1}. Thus the integrated intensity ratio of $H_2O/H_2^{18}O$ is > 22 (3σ).

3. ANALYSIS

Snell et al. (2000) present an analytical expression for the relative abundance of ortho-water in the low-collision rate or effectively thin limit based on the work of Linke et al. (1977). For large optical depths, the low-collision rate limit is satisfied if $C\tau_o/A << 1$, where C is the collisional de-excitation rate coefficient, τ_o is the line center optical depth, and A is the spontaneous emission rate. In this limit, the water integrated intensity increases linearly with increasing water column density. Linke et al. (1977) showed that this limit will be met if the main beam antenna temperature is sufficiently weak, and satisfies

$$T_{\rm mb} \ll \frac{h\nu}{4k}\exp(-h\nu/kT_K). \quad (1)$$

In this limit the line intensity is proportional to the column density of water irrespective of the line optical depth. At a kinetic temperature of 40 K, the 557 GHz line of water is effectively thin if the antenna temperature is less than 3.4 K. The maximum observed intensity for the H_2O emission in M17SW is 0.42 K, after correction for the *SWAS* main beam efficiency. Therefore, unless the area filling factor for the H_2O emission is much smaller than 0.1, the H_2O emission in M17SW is effectively optically thin.

Based on the simple analytical expression, we can estimate the water abundance in the M17SW core. The M17SW core has a density of approximately 6×10^5 cm^{-3} (Snell et al. 1984; Wang et al. 1993), and based on our FCRAO ^{13}CO observations, the core has an H_2 column density of 2×10^{23} cm^{-2}. The kinetic temperature of the core is estimated to be 50 K based on the analysis of our CH_3CCH observations. Using the main-beam–corrected integrated intensity of the water emission toward the center of M17SW of 3.6 K km s^{-1} we estimate the

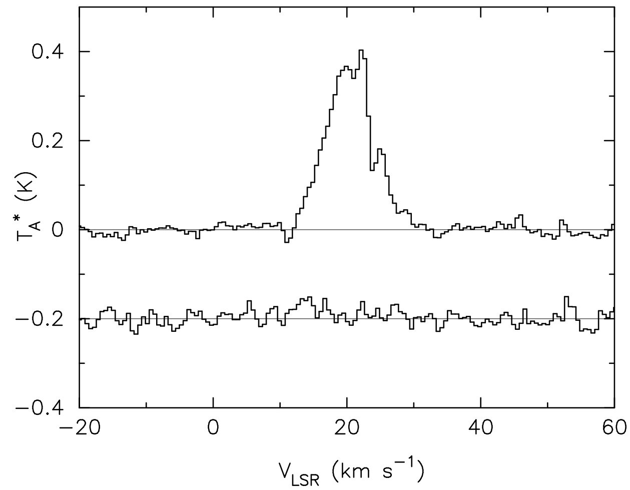

FIG. 2.— Spectra of H_2O (*top*) and $H_2^{18}O$ (*bottom*) obtained with *SWAS* toward the center of the M17 cloud core at position $\alpha = 18^h20^m22^s.1$, $\delta = -16°12'37''$ (J2000).

beam average relative abundance of ortho-H_2O to be 8×10^{-10}. Since the dense core in M17SW is large and fills most of the *SWAS* main beam, this abundance estimate should be reasonably accurate.

The determination of the abundance of ortho-H_2O throughout our map requires a more detailed model of the temperature, density, column density, and velocity dispersion of the gas in M17SW. Analysis of our CH_3CCH data yields temperatures of 50 K toward the center of the core, decreasing to 30 K where the CH_3CCH emission became too weak to detect. These temperatures agree well with those found by Bergin et al. (1994) and Howe et al. (2000). Beyond the point where CH_3CCH is detectable, we use the kinetic temperatures derived in Howe et al. (2000), which were generally in the range of 25 to 45 K. The density studies of Snell et al. (1984), Wang et al. (1993), and Bergin, Snell, & Goldsmith (1996) all indicate that the density across the M17SW core is relatively uniform and has a value of 6×10^5 cm^{-3}. The dense core is elongated north/south with a long axis of approximately 6′ and a short axis of approximately 4′. Beyond the core, we assume the density is 1×10^5 cm^{-3} based on the analysis of Wilson et al. (1999) and Howe et al. (2000). The gas column density was derived from the ^{13}CO data assuming LTE and a $^{13}CO/H_2$ abundance ratio of 1.5×10^{-6}. The velocity dispersion of the gas along each line of sight was determined from the ^{13}CO line width.

We modeled the H_2O emission identically to that described in Snell et al. (2000) for the Orion cloud core. We used both the para- and ortho-H_2 collision rates with ortho-H_2O (Phillips, Maluendes, & Green 1996) and assumed that the ratio of ortho-to para-H_2 is in LTE (which at 40 K implies an ortho-to-para ratio of 0.1). As in the Orion analysis, we do not include the continuum emission from dust; however, Snell et al. (2000) argue that this will have only a minor impact on the derived water abundance. The 5 lowest levels of ortho-water are included in our calculations. We define the physical properties of M17SW on a 44 arcsec grid, much smaller than the *SWAS* resolution. We proceed by assuming a water abundance, and then compute the emission that would be predicted within the *SWAS* beam. We then vary the H_2O abundance until the predicted emission agrees with observations. Thus, for each of the 17 positions we determine the best average H_2O abundance for the gas that contributes to that *SWAS* observation. For positions with no detections, we used the 3σ upper limit on the integrated intensity to establish a limit on the H_2O abundance. We note that where H_2O was detected, our model predicts that the emission is optically thick, but effectively thin, although we do not make either assumption in our model.

The results of our abundance analysis are presented in Table 1. With the exception of the region northeast of the core center, the abundance of ortho-H_2O relative to H_2 is approximately constant with values between 1 and 2×10^{-9} and consistent with our estimates based on the analytical expression. However, in the three positions in the northeast corner of the map shown in Figure 1, the relative abundance of ortho-H_2O is roughly a factor of 5 larger than that found toward the core. The region of enhanced H_2O abundance lies toward the interface between the H II region and the molecular cloud (Felli, Johnston, & Churchwell 1980). However since the physical conditions, particularly density and temperature, are not as well known for this region, the abundance determination is more uncertain.

We have also determined the abundance of H_2O based solely on our observations of $H_2^{18}O$ toward the core center. Using the same model described above, we derive a 3σ upper limit on the ortho-$H_2^{18}O$ abundance of 6×10^{-11}. Assuming a ratio of $H_2O/H_2^{18}O$ of 500, provides a 3σ upper limit of 3×10^{-8} for the relative abundance of ortho-H_2O. If our model of the H_2O line is correct, then the $H_2^{18}O$ line should have an integrated intensity about 20 times smaller than our 3σ upper limit, making this line nearly impossible to detect with *SWAS*.

Our modeling has ignored several potentially important effects that were discussed in Snell et al. (2000). The most important effects are line scattering by an extended halo that might surround the M17SW core, and cloud structure on angular scales much smaller than 44″. The fact that the emission lines of H_2O are not strongly self-absorbed and that there is good agreement between the spatial extent of the H_2O emission and that of optically thin tracers of the dense core, provide strong arguments against line scattering being significant in this source. Even if scattering were important for H_2O, the optical depth in the $H_2^{18}O$ line would be 500 times smaller and the effect of line scattering (in $H_2^{18}O$) would be negligible.

The M17SW core is known to have substantial structure on a variety of angular scales. We have assumed that on angular scales less than 44″ that the the area filling factor of H_2O-emitting gas is near unity. If the area filling factor is instead very small, our modeling will underestimate the optical depth of the H_2O emission and consequently the importance of collisional de-excitation. However, unless the area filling factor is less than 0.1, the presence of cloud structure will not impact our determination of the H_2O abundance. Stutzki & Güsten (1990) estimated that the area filling factor of the gas within M17SW to be greater than unity, well above the limit that would cause concern. However, regardless of the impact of scattering and unresolved structure on the H_2O analysis, these effects will be unimportant for $H_2^{18}O$ and the non-detection of $H_2^{18}O$ implies that the fractional abundance of ortho-H_2O cannot be greater then 3×10^{-8}.

4. DISCUSSION AND SUMMARY

SWAS has made the first detection of thermal water emission from M17 SW. The emission observed by *SWAS* is consistent in line width, line velocity, and spatial extent with the emission arising predominately from the warm dense core gas. The *SWAS* observations allow us to make the first estimate of the water abundance in this well-studied core. The average abundance of ortho-H_2O relative to H_2 in the cloud core is (1–2) $\times10^{-9}$. Northeast of the core, toward the H II region/molecular cloud interface, the relative water abundance is approximately five times larger. Based on the $H_2^{18}O$ spectrum, the 3σ upper limit on the relative H_2O abundance is 3×10^{-8}. Uncertainties in the derived abundance of water are dominated by the uncertainties in the physical conditions primarily density. In the effectively thin limit, the abundance of H_2O is inversely proportional to the density (see Snell et al. 2000). Therefore, if we had assumed a smaller average density, we would have derived a proportionally higher water abundance. The study of Bergin et al. (1996) concludes that the bulk of the column density toward the M17 core arises in the dense gas. Thus, we believe that uncertainties in the density and density structure cannot conspire to increase the water abundance by more than an order of magnitude.

The average relative abundance of water in the M17SW core is 30 times smaller than the average in Orion (Snell et al. 2000). Although there is substantial variation in the H_2O abundance in Orion, the abundance is always significantly larger than in the M17SW. Only near the interface with the H II region in M17SW does the abundance of H_2O approach values found for Orion. The enhanced abundance of water in this interface region could be a result of the evaporation of water-ice–rich mantles from interstellar grains exposed to radiation from the H II region. Further discussion of the chemical implications of these H_2O abundance results is presented in Bergin et al. (2000).

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