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## SUBMILLIMETER WAVE ASTRONOMY SATELLITE OBSERVATIONS OF EXTENDED WATER EMISSION IN ORION

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### ABSTRACT

We have used the *Submillimeter Wave Astronomy Satellite* to map the ground-state  $1_{10} \rightarrow 1_{01}$  transition of ortho- $\text{H}_2\text{O}$  at 557 GHz in the Orion molecular cloud.  $\text{H}_2\text{O}$  emission was detected in Orion over an angular extent of about  $20'$ , or nearly 3 pc. The water emission is relatively weak, with line widths ( $3\text{--}6 \text{ km s}^{-1}$ ) and  $V_{\text{LSR}}$  velocities ( $9\text{--}11 \text{ km s}^{-1}$ ) consistent with an origin in the cold gas of the molecular ridge. We find that the ortho- $\text{H}_2\text{O}$  abundance relative to  $\text{H}_2$  in the extended gas in Orion varies between 1 and  $8 \times 10^{-8}$ , with an average of  $3 \times 10^{-8}$ . The absence of detectable narrow-line ortho- $\text{H}_2^{18}\text{O}$  emission is used to set a  $3\sigma$  upper limit on the relative ortho- $\text{H}_2\text{O}$  abundance of  $7 \times 10^{-8}$ .

*Subject headings:* ISM: abundances — ISM: clouds — ISM: individual (Orion) — ISM: molecules — radio lines: ISM

### 1. INTRODUCTION

We present a map of the water emission from the central portion of the Orion molecular cloud obtained with the *Submillimeter Wave Astronomy Satellite* (SWAS). These results provide the first definitive detection of water in the extended, cold molecular gas. The Orion molecular cloud has been the focus of many studies of water, and besides the strongly masing transition at 22 GHz, numerous transitions of  $\text{H}_2\text{O}$  and  $\text{H}_2^{18}\text{O}$  have been detected from the ground (Waters et al. 1980; Phillips, Kwan, & Huggins 1980; Kuiper et al. 1984; Cernicharo et al. 1994; Gensheimer, Mauersberger, & Wilson 1996; Cernicharo et al. 1999), from the *Kuiper Airborne Observatory* (Zmuidzinas et al. 1995; Timmermann et al. 1996), and from the *Infrared Space Observatory* (Harwit et al. 1998; González-Alfonso et al. 1998; van Dishoeck et al. 1998). With the exception of the broad  $\text{H}_2^{18}\text{O}$  line emission observed toward BN/KL by Zmuidzinas et al. (1995), all of the transitions detected have upper states lying from 200 to 700 K above the ground state and many are likely masing. In most cases this emission arises from the hot gas associated with BN/KL, however Cernicharo et al. (1994) report spatially extended emission from the  $3_{13} \rightarrow 2_{20}$  transition of water at 183 GHz.

SWAS observed the  $1_{10} \rightarrow 1_{01}$  transitions of ortho- $\text{H}_2\text{O}$  at 556.936 GHz and of ortho- $\text{H}_2^{18}\text{O}$  at 547.676 GHz. These transitions have upper state energies of only 27 K above the ortho- $\text{H}_2\text{O}$  ground state, and thus are unique probes of water in the cooler molecular gas. The emission obtained with SWAS toward BN/KL (Melnick et al. 2000a) is composed of both a broad velocity feature associated with the shocked gas and a narrow feature that likely arises from the quiescent gas in the Orion

molecular ridge. The abundance of water relative to  $\text{H}_2$  in the shocked gas is of order  $4 \times 10^{-4}$ , making water one of the most abundant molecules in the hot gas. The focus of this Letter is the kinematically narrow and spatially extended component of the water emission detected in Orion.

### 2. OBSERVATIONS AND RESULTS

The observations reported here were acquired by SWAS during the periods from 1998 December to 1999 March and 1999 September to 1999 October. The data were taken by alternately nodding the satellite from the source to a reference position free of molecular emission. Observations of the  $1_{10} \rightarrow 1_{01}$  transition of  $\text{H}_2\text{O}$  were obtained at 40 positions in a 5 by 8 grid spaced by  $3'.2$ . The reference position for this map was at  $\alpha = 05^{\text{h}}35^{\text{m}}14.^{\text{s}}5$ ,  $\delta = -05^{\circ}22'37''$  (J2000). Integration times were typically 2 hr per position. Besides the  $\text{H}_2^{18}\text{O}$  spectrum reported by Melnick et al. (2000a) toward BN/KL, observations of  $\text{H}_2^{18}\text{O}$  were also obtained at a position  $3'.2$  south of the map reference position where the  $\text{H}_2\text{O}$  spectrum showed a strong, narrow line. The SWAS beam is elliptical, and at the frequency of the water transitions has angular dimensions of  $3'.3 \times 4'.5$ . The data were reduced using the standard SWAS pipeline described in Melnick et al. (2000b). The data shown in this paper are not corrected for the SWAS main beam efficiency of 0.90.

We also used the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope to map an approximately  $40' \times 130'$  region in the  $J = 1 \rightarrow 0$  transition of  $^{13}\text{CO}$ , a  $18' \times 23'$  region in the  $J = 1 \rightarrow 0$  transition of  $\text{C}^{18}\text{O}$ , and a  $6' \times 6'$  region in the  $J = 6 \rightarrow 5$  ( $K = 0, 1, 2, 3, 4$ ) transitions of  $\text{CH}_3\text{CCH}$ . These data are used to provide an estimate of the temperature and column density of the gas ridge for our analysis of the water emission.

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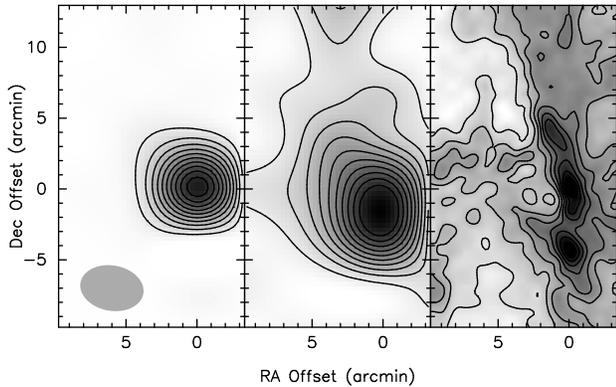


FIG. 1.— The left-hand panel shows a map of the integrated intensity of the 557 GHz  $\text{H}_2\text{O}$  line in Orion. The map contours ( $\int T_A^* dv$ ) are between 10 and 100  $\text{K km s}^{-1}$  in steps of 10  $\text{K km s}^{-1}$ . The integrated intensity is dominated by the broad emission associated with BN/KL. The middle panel shows a map of the integrated intensity of just the narrow water line component in Orion. Contours ( $\int T_A^* dv$ ) in this map are between 1 and 10  $\text{K km s}^{-1}$  in steps of 1  $\text{K km s}^{-1}$ . The right hand panel is a map of the integrated intensity of the  $^{13}\text{CO } J=1 \rightarrow 0$  emission obtained at FCRAO. Contours are between 5 and 45  $\text{K km s}^{-1}$  in steps of 5  $\text{K km s}^{-1}$ . The offsets are relative to  $\alpha = 05^{\text{h}}35^{\text{m}}14.^{\text{s}}5$ ,  $\delta = -05^{\circ}22'37''$  (J2000). The half-power size and average position angle of the SWAS beam is also shown in the first panel.

$\text{H}_2\text{O}$  emission was detected in 23 of the 40 positions observed. The left-hand panel of Figure 1 shows the integrated intensity map of the  $\text{H}_2\text{O}$  emission, which is dominated by the broad line width emission associated with BN/KL. Because of the large and slightly elliptical main beam of SWAS, this broad emission is seen in five of the map positions. Outside of these five positions the emission is narrow with line widths between 3 and 6  $\text{km s}^{-1}$ . Figure 2 provides examples of  $\text{H}_2\text{O}$  spectra obtained at three positions in the cloud. We have fitted the positions showing broad emission with two Gaussian components and include only the integrated intensity of the narrow component in the map shown in the middle panel of Figure 1. The narrow line width water emission is elongated north-south, and extends 12/8 north of BN/KL to OMC-2 and 6/4 south of BN/KL. The velocity of the narrow line width emission varies from  $V_{\text{LSR}} = 8.7$  to 11.6  $\text{km s}^{-1}$ , with a trend of increasing velocity from south to north. The line widths and velocity of the  $\text{H}_2\text{O}$  emission agree well with the emission associated with the extended molecular ridge and molecular bar. Weak  $\text{H}_2\text{O}$  emission also extends 10' east of the molecular ridge where weaker emission is detected in both  $^{13}\text{CO}$  and CN (Rodriguez-Franco, Martin-Pintado, & Fuente 1998).

### 3. WATER ABUNDANCE

The  $1_{10} \rightarrow 1_{01}$  transition of  $\text{H}_2\text{O}$  has a high critical density ( $\sim 4 \times 10^8 \text{ cm}^{-3}$ ) and is expected to have a high optical depth even for a relatively small water abundance. Thus, trapping plays an important role in the excitation of this transition. For large optical depths the “effective critical density” is approximately  $A/(\mathcal{C}\tau_o)$ , where  $\mathcal{C}$  is the collisional de-excitation rate coefficient,  $\tau_o$  is the line center optical depth, and  $A$  is the spontaneous emission rate. In the low-collision rate limit, where the density is much smaller than the effective critical density, Linke et al. (1977) and Wannier et al. (1991) derived a simple analytical expression for the antenna temperature in a two-level system. In this limit, collisional excitation always results in a photon that escapes the cloud, even though it may be repeatedly absorbed and reemitted. Thus the gas can be optically thick but effectively thin.

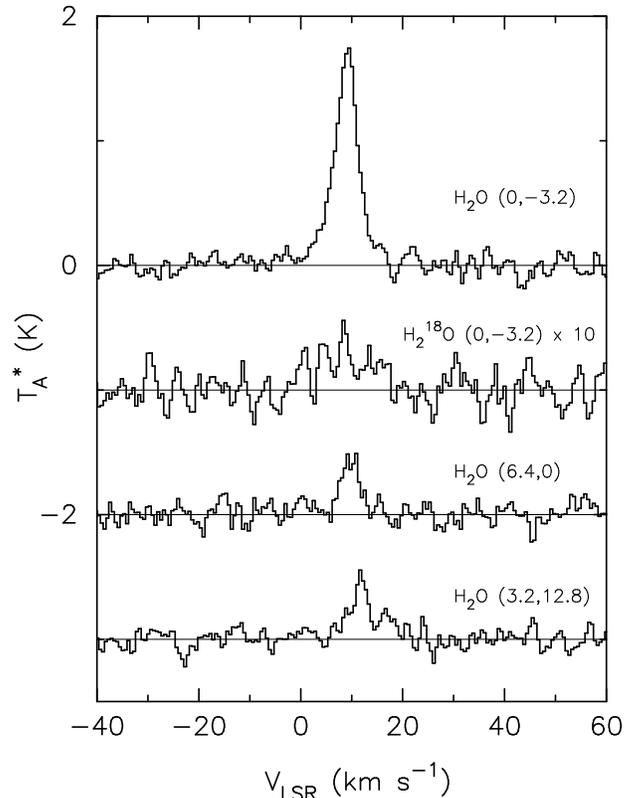


FIG. 2.— Spectra of  $\text{H}_2\text{O}$  and  $\text{H}_2^{18}\text{O}$  obtained with SWAS. In order from the top are spectra of  $\text{H}_2\text{O } 3/2$  south of BN/KL,  $\text{H}_2^{18}\text{O } 3/2$  south of BN/KL (note that the spectrum has been scaled by a factor of 10),  $\text{H}_2\text{O } 6/4$  east of BN/KL, and  $\text{H}_2\text{O } 3/2$  east and 12/8 north of BN/KL near the position of OMC-2.

Applying this approximation to water, gives the following expression for the integrated antenna temperature for the 557 GHz water line:

$$\int T_R dv = C n_{\text{H}_2} \frac{c^3}{2\nu^3 k} N(\text{o-}\text{H}_2\text{O}) \frac{h\nu}{4\pi} \exp(-h\nu/kT_K). \quad (1)$$

Note that in this limit the integrated intensity increases linearly with increasing  $\text{H}_2$  density,  $n_{\text{H}_2}$ , and ortho-water column density,  $N(\text{o-}\text{H}_2\text{O})$ , even if the line center optical depth is large. We have evaluated equation (1) using the collision rate coefficients for para- and ortho- $\text{H}_2$  from Phillips, Maluendes, & Green (1996) for a temperature of 40 K, assuming the ratio of ortho- to para- $\text{H}_2$  is in LTE (implying an ortho-to-para ratio of 0.13). The ortho-water fractional abundance,  $x(\text{o-}\text{H}_2\text{O})$ , is thus

$$x(\text{o-}\text{H}_2\text{O}) = 2.5 \times 10^{19} \frac{\int T_R dv}{N(\text{H}_2) n_{\text{H}_2}}, \quad (2)$$

where the integrated intensity of the water line has units of Kelvins kilometers per second, density has units per cubic centimeter, and column density has units per square centimeter. If we assume that the molecular ridge has  $T = 40 \text{ K}$ ,  $n_{\text{H}_2} = 1 \times 10^6 \text{ cm}^{-3}$ , and  $N(\text{H}_2) = 5 \times 10^{22} \text{ cm}^{-2}$ , then for a typical main beam corrected water integrated intensity in the ridge of 10  $\text{K km s}^{-1}$ , the relative abundance of ortho- $\text{H}_2\text{O}$  is  $5 \times 10^{-9}$ . Although the line center optical depth is over 10, the emission is still well within the low-collision rate limit, so the emission is effectively thin. This estimate ignores beam dilution which could be significant in the  $3/3 \times 4/5$  main beam of SWAS.

A detailed model of the temperature, density, column density, and velocity dispersion for the Orion molecular gas is needed

to model the water excitation and beam filling factor to derive accurate estimates of the water abundance. We have used our observations of  $\text{CH}_3\text{CCH}$  to derive the temperature along the molecular ridge in Orion using the method described by Bergin et al. (1994). We find temperatures varying from 50 K toward the center of the ridge dropping to about 25 K at the boundary of the  $\text{CH}_3\text{CCH}$  emission, consistent with temperatures found by Bergin et al. (1994). We have assumed a temperature of 25 K outside of the area of detectable  $\text{CH}_3\text{CCH}$  emission. The  $\text{H}_2$  gas column density is derived from our observations of  $^{13}\text{CO}$  assuming LTE, the temperatures described above, and a  $^{13}\text{CO}/\text{H}_2$  abundance ratio of  $1.5 \times 10^{-6}$ . The column density is derived on a  $44''$  grid defined by the  $^{13}\text{CO}$  sampling. The velocity dispersion of the gas along each line of sight is determined from the  $^{13}\text{CO}$  line width. We have assumed that the density of the gas along the molecular ridge near BN/KL is  $1 \times 10^6 \text{ cm}^{-3}$  (Batra et al. 1983; Bergin, Snell, & Goldsmith 1996; Rodriguez-Franco, Martin-Pintado, & Fuente 1998). The extension of the ridge north to OMC-2 is assumed to have a density of  $3 \times 10^5 \text{ cm}^{-3}$  based on the analysis of Batrla et al. (1983), and the density of the diffuse emission to the east of BN/KL is assumed to be  $3 \times 10^5 \text{ cm}^{-3}$  based on the CN analysis of Rodriguez-Franco et al. (1998). We have assumed that all of the gas column density toward the Orion core arises in the dense gas, consistent with the results found by (Bergin et al. 1996).

Once the temperature, density, velocity dispersion, and  $\text{H}_2$  column density are fixed, the strength of the water emission is determined only by its abundance relative to  $\text{H}_2$ . We model the water emission using a statistical equilibrium code that uses the large velocity gradient approximation to account for radiation trapping. Collisional rate coefficients are taken from Phillips et al. (1996) using both the para- and ortho- $\text{H}_2$  rates and assuming that the ratio of ortho- to para- $\text{H}_2$  is in LTE<sup>9</sup>. We include the 5 lowest levels of ortho-water in our calculations. We proceed by assuming a water abundance, computing the water emission in each of the  $44''$  regions, convolving the predicted emission with the SWAS beam, and then varying the abundance until there is agreement between the integrated intensity predicted by the model and the observations. We assume the  $\text{H}_2\text{O}$  abundance is constant across the SWAS beam. Using this technique, we find that for the 23 positions where  $\text{H}_2\text{O}$  emission was detected that the average abundance of ortho- $\text{H}_2\text{O}$  relative to  $\text{H}_2$  is  $3 \times 10^{-8}$ , with variations between 1 and  $8 \times 10^{-8}$ . For the narrow velocity component detected toward BN/KL, our results agree with Melnick et al. (2000a). The largest  $\text{H}_2\text{O}$  abundances are found east of the molecular ridge near the molecular bar and H II region.

We can also use the  $\text{H}_2^{18}\text{O}$  spectrum obtained  $3\frac{1}{2}$  south of BN/KL (see Fig. 2) to estimate the water abundance. The  $\text{H}_2^{18}\text{O}$  spectrum may show evidence for a weak broad line width component similar to that detected toward BN/KL (Melnick et al. 2000a). For the  $\text{H}_2^{18}\text{O}$  observation the long axis of the SWAS beam was oriented nearly north/south and explains why the broad  $\text{H}_2^{18}\text{O}$  emission toward BN/KL may be weakly detected at this position. We have fitted the  $\text{H}_2^{18}\text{O}$  spectrum with two components, one matching the line width and velocity of the broad velocity component seen toward BN/KL and a second narrow-line component with a width ( $5.65 \text{ km s}^{-1}$ ) and velocity ( $9.0 \text{ km s}^{-1}$ ) derived from the  $\text{H}_2\text{O}$  line detected in this direction. No evidence for a narrow-line velocity component was found in the  $\text{H}_2^{18}\text{O}$  spectrum, similar to the results found by Melnick

et al. (2000a) toward BN/KL. Using the same model as before, the  $\text{H}_2^{18}\text{O}$  data sets a  $3\sigma$  upper limit of  $7 \times 10^{-8}$  for the relative abundance of ortho- $\text{H}_2\text{O}$   $3\frac{1}{2}$  south of BN/KL, assuming a ratio of  $\text{H}_2\text{O}/\text{H}_2^{18}\text{O}$  of 500. This result is consistent with the abundance of  $4 \times 10^{-8}$  derived from the  $\text{H}_2\text{O}$  analysis.

Our modeling has ignored several potentially important effects: (1) pumping by the far-infrared radiation field of the cloud, (2) line scattering in a thin layer of gas surrounding the cloud core, and (3) clumpy cloud structure. The importance of radiation pumping can be easily estimated by computing the excitation of a molecule immersed in a dilute blackbody radiation field derived from the measurements toward BN/KL (Werner et al. 1976; Keene, Hildebrand, & Whitcomb 1982). Even using the strong radiation field present within  $1'$  of BN/KL, the fractional population in the upper rotational states ( $2_{12}$  and  $2_{21}$ ) of water will be small, and thus ignoring this radiation will have a negligible effect on our estimates of the water abundance. Toward BN/KL, Melnick et al. (2000a) have more carefully modeled the effect of dust on  $\text{H}_2\text{O}$  excitation and confirm that for the extended emission ignoring dust has only a small impact on the derived  $\text{H}_2\text{O}$  abundance.

Line scattering is of even greater concern. Because of the low excitation, but high optical depths predicted for this water transition, photons collisionally produced in the ridge may be absorbed and reemitted by an extended halo of low column density gas. In this case the abundance of water derived for the molecular ridge may be underestimated and the abundance of water in the extended structure of the Orion cloud may be overestimated. The importance of this effect for  $\text{HCO}^+$  was investigated by Cernicharo & Guelin (1987). The water line shape provides some constraints on this process. The water lines show no evidence for self-absorption as would be expected if absorption in a surrounding envelope is important. While absorption followed by emission is plausibly occurring, the photons would emerge in the line wings after a number of scatterings and most of the scattered photons would probably still be within the SWAS beam. The only exception would be if the absorbing envelope were spatially well separated from the emitting gas. Nevertheless, even if scattering were having a large impact on the  $\text{H}_2\text{O}$  emission, it is not important for  $\text{H}_2^{18}\text{O}$  and therefore the abundance limit established from the  $\text{H}_2^{18}\text{O}$  observation is valid.

The Orion cloud core may also have structure on scales smaller than modeled. If there is significant structure on scales smaller than  $44''$  we may underestimate the optical depth of water in the high column density regions. This in turn, could cause an underestimate of the collisional de-excitation rate and consequently an underestimate of the water abundance. This might be important near BN/KL; however, it is unlikely to be important in the more extended water emission regions where the emission is considerably weaker and, even with significant unresolved structure, it is unlikely the column density is sufficiently large for collisional de-excitation to be important. Regardless of its impact on  $\text{H}_2\text{O}$  this effect is unimportant for  $\text{H}_2^{18}\text{O}$  and our upper limit on the water abundance based on  $\text{H}_2^{18}\text{O}$  is unaffected. However it is important to stress that the  $\text{H}_2\text{O}$  abundances that we quote are averages over the SWAS beam, it is possible that there are significant abundance variations within the beam.

<sup>9</sup> We note that assuming an ortho- to para- $\text{H}_2$  ratio of 3 (the high temperature limit), the collision rates would be approximately 5 times larger and the derived water abundance correspondingly smaller.

## 4. DISCUSSION AND SUMMARY

*SWAS* has made the first detection of water emission from the cold, quiescent gas in the Orion molecular cloud. The water emission seen by *SWAS* has line widths and velocities characteristic of the emission from the molecular ridge. The average abundance of ortho- $\text{H}_2\text{O}$  in the cold gas is  $3 \times 10^{-8}$ , with variations between 1 and  $8 \times 10^{-8}$ . As discussed earlier, the abundance derived from the  $\text{H}_2\text{O}$  emission can be compromised by several physical processes, however a firm  $3\sigma$  upper limit on the relative water abundance  $3/2$  south of BN/KL of  $7 \times 10^{-8}$  is established from the  $\text{H}_2^{18}\text{O}$  observation.

Uncertainties in the water abundance arise entirely from systematic errors associated with uncertainties in our estimates of the density and gas column density. For instance, if a significant fraction of the gas column density is associated with much lower density gas than we assumed in our model, then our estimate of the ortho-water abundance will be underestimated. Specifically, if one-half of the gas column density originated in low-density gas, our estimate of the water abundance will be too low by approximately a factor of two. Since Bergin et al. (1996) concluded that it is unlikely that the low density gas contributes significantly to the total gas column density toward the Orion core, we believe that our estimates of the water abundance cannot be greatly in error.

Cernicharo et al. (1994) estimated the water abundance in Orion based on their observations of the  $3_{13} \rightarrow 2_{20}$  transition of para- $\text{H}_2\text{O}$  at 183 GHz. Although this masing transition arises from an upper state lying 200 K above the ground state, the emission is spatially extended and, away from BN/KL, has rel-

atively narrow line widths. Cernicharo et al. (1994) estimate a relative water abundance of at least  $10^{-5}$ . However, if the abundance of water in the cold molecular gas were as large as they estimate, then  $\text{H}_2^{18}\text{O}$  emission should have been readily detected by *SWAS* and be of comparable strength to the detected  $\text{H}_2\text{O}$  emission. In addition, the  $\text{H}_2\text{O}$  line observed by *SWAS* should be between 5 and 100 times stronger than observed, depending on position. The 183 GHz line must trace a warmer, denser component of the gas than the 557 GHz line - as suggested by the anomalous line velocity reported by Cernicharo et al. (1994) - so that the high abundance estimate does not apply to the bulk of the cloud material, which is at low temperature.

The water abundance we derive for the quiescent gas in Orion is many orders of magnitude smaller than that derived for the hot gas in Orion and other massive star forming regions (Melnick et al. 2000a; Cernicharo et al. 1999; van Dishoeck 1998). Chemical models (Bergin, Melnick, & Neufeld 1998) predict equilibrium gas-phase water abundances of order  $5 \times 10^{-7}$  in the quiescent gas, similar to the results found for the extended envelope surrounding SgrB2 (Zmuidzinas et al. 1995), but about 10 times larger than what we estimate for Orion. Further discussion of the chemical implications of these results is presented in Bergin et al. (2000).

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