

## INFRARED OH PROMPT EMISSION AS A PROXY OF WATER PRODUCTION IN COMETS: QUANTITATIVE ANALYSIS OF THE MULTIPLLET NEAR $3046\text{ cm}^{-1}$ IN COMETS C/1999 H1 (LEE) AND C/2001 A2 (LINEAR)

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### ABSTRACT

We report quantitative measurements of OH vibrational prompt emission in comets C/1999 H1 (Lee) and C/2001 A2 (LINEAR) based on high-dispersion infrared spectra acquired at the Keck Observatory atop Mauna Kea, Hawaii. Effective  $g$ -factors for four OH lines near  $3046\text{ cm}^{-1}$  (in the 1–0 band) were obtained from simultaneous detections of OH and H<sub>2</sub>O. The measured spatial distribution of this OH “quadruplet” traces that of H<sub>2</sub>O, as expected if the excited OH is produced directly by water photolysis. These results establish OH prompt emission as an alternative (and convenient) proxy for water in comets. Possible limitations to the approach are discussed. Extension to other OH multiplets in the  $L$  band will permit direct comparison with theoretical models for the rotational population distribution of the free OH radicals produced by H<sub>2</sub>O photolysis in cometary atmospheres.

*Subject headings:* comets: general — comets: individual (C/2001 A2) — comets: individual (Lee (C/1999 H1)) — infrared: solar system

### 1. INTRODUCTION

Water is the principal parent volatile in comets, and its sublimation controls the release of other molecules within 3–4 AU from the Sun. For this reason, studies of H<sub>2</sub>O release from the cometary nucleus and the water’s subsequent destruction (primarily via photodissociation) have been of significant interest in cometary science. In this work we establish a new approach for extracting water production rates in comets through near-infrared (NIR) observations of prompt emission (PE) from a dissociation fragment (OH). In addition, such studies will help to clarify the process of H<sub>2</sub>O photodissociation by solar ultraviolet radiation.

The mixing ratios of H<sub>2</sub>O and other species encode information about the formation temperatures and processing histories of cometary ices (Mumma et al. 1993). While comets are often grouped according to their orbital properties, in recent years the emergence of accurate abundance measurements (from multiple spectral regions) for the dominant volatile (water) and a number of other parent species (HCN, CH<sub>3</sub>OH, CO, C<sub>2</sub>H<sub>6</sub>, CH<sub>4</sub>, etc.) has begun to permit a taxonomic classification based on chemistry (Biver et al. 2002; Mumma et al. 2003). High-dispersion cross-dispersed infrared (IR) spectrometers sample a wide spectral range that often permits simultaneous observations of water and less abundant volatiles. By using one instrument on one telescope, many sources of systematic error are eliminated, and accurate abundance measurements are more easily obtained. The improved accuracy in mixing ratios enables identification of chemical differences among comets while also permitting a search for chemical heterogeneity within a given comet.

Well-determined water production rates are needed as a “baseline” for extracting accurate relative abundances for trace volatile species. The sole proven method for directly measuring cometary H<sub>2</sub>O from ground-based observatories is through nonresonance “hot-band” fluorescence in spectral regions of high atmospheric transmittance (Mumma et al. 1996; Dello Russo et al. 2000, 2002, 2004). Nine hot-bands are now used; the most fruitful regions are near 2.0, 2.9, and 4.6  $\mu\text{m}$ , yet these bands may not be sampled in observations that target other spectral regions (e.g., the “cometary organics” region from  $\sim 3.3$ – $3.6\ \mu\text{m}$ ). Knowledge of the H<sub>2</sub>O rotational temperature and ortho-para ratio (OPR) are needed to fully constrain water production rates via the hot-band method. The accuracy of retrieved H<sub>2</sub>O production rates may be limited when an insufficient number of emission lines are sampled to determine these parameters.

We present quantitative analyses of OH PE in two comets, and we show that these analyses represent an alternative method for measuring water production. This method increases the IR spectral range over which a simultaneous measurement of water and other parent species is possible.

### 2. OH PROMPT EMISSION AS A TRACER OF COMETARY WATER

Our approach is based on so-called “prompt emission” from the OH radical, produced by dissociative excitation of water. The excitation mechanism for PE differs fundamentally from that of fluorescence; in PE, photodissociation of water produces OH radicals in vibrationally excited and rotationally hot states (Carrington 1964; Yamashita 1975; Andresen et al. 1984). These states cannot be excited by fluorescence of the rotationally cold (quiescent) OH found in the extended coma.

Mumma (1982) first suggested using this PE at IR wavelengths to trace the parent species (see also Weaver & Mumma 1984). Subsequent work on OH PE focused on both the ultraviolet (observational searches by Bertaux [1986] and Budzien & Feldman [1991]) and the IR spectral regions (modeling of integrated band emission by Crovisier [1989] and of the 1–0 band

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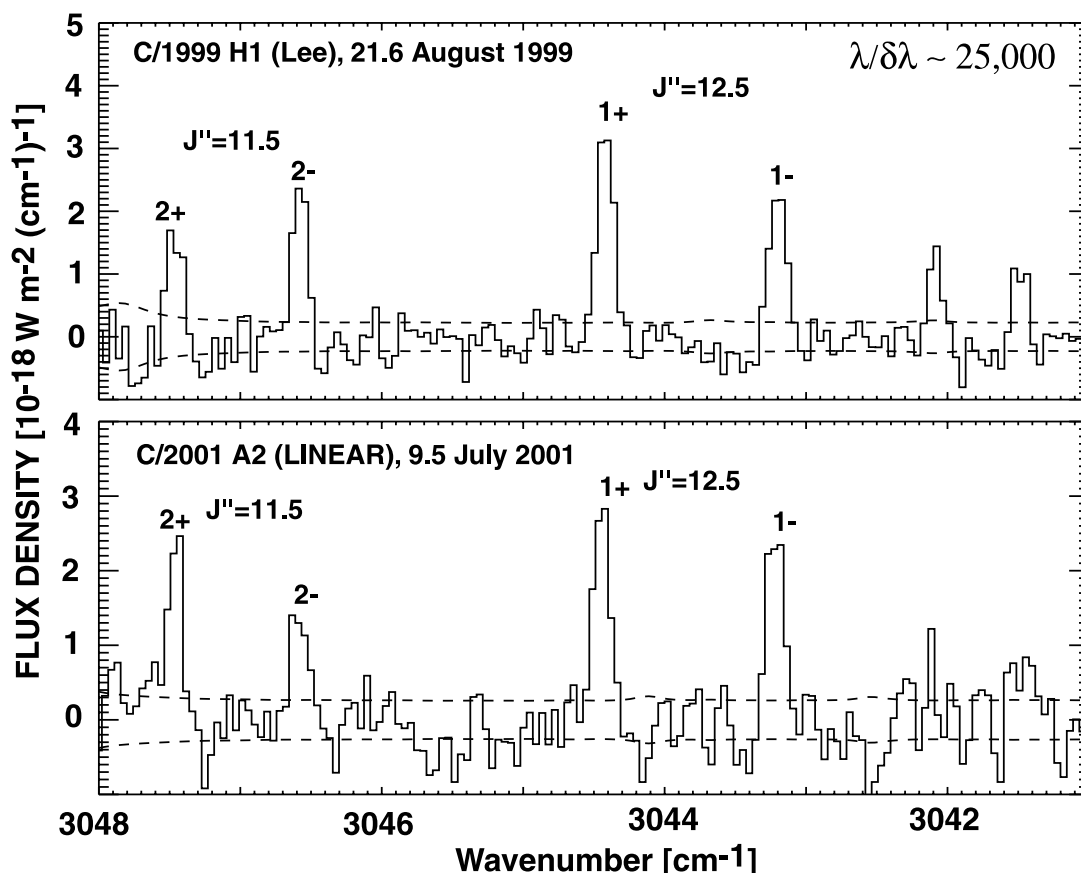


FIG. 1.—High-dispersion ( $\lambda/\delta\lambda \sim 25,000$ ) spectra of two comets showing OH emission near  $3046 \text{ cm}^{-1}$ . The x-axis corresponds to the cometary rest reference frame. The dashed lines represent the  $\pm 1 \sigma$  noise level. These P-branch lines originate from highly excited rotational states of OH ( $J'' = 11.5$  and  $J'' = 12.5$ ) that are not populated significantly in the quiescent coma. In the figure,  $2 \equiv {}^2\Pi_{1/2}$ ,  $1 \equiv {}^2\Pi_{3/2}$ , and plus and minus signs indicate the  $\Lambda$ -doublet components (Maillard et al. 1976). The two lines at  $3041.5$  and  $3042.1 \text{ cm}^{-1}$  (e.g., upper panel) are also likely due to OH ( $J'' = 8.5$ ,  $2-1$  band) and will be discussed in a subsequent paper.

rotational envelope [at  $300 \text{ K}$ ] near  $2.8 \mu\text{m}$  by Bockelée-Morvan & Crovisier [1989]). However, the IR models did not explore the production of rotationally hot quantum states, such as those described here.

Two factors potentially make IR PE of OH a compelling proxy for  $\text{H}_2\text{O}$ : (1) the rotationally hot states leading to IR PE can be produced directly by  $\text{H}_2\text{O}$  photolysis, but neither fluorescence of nor collisions with quiescent OH in the cometary coma can efficiently populate them; and (2) the newly created OH radical radiates PE within milliseconds after dissociation of its parent  $\text{H}_2\text{O}$ , thereby minimizing collisional quenching. For these reasons the distribution of OH PE is expected to trace the spatial distribution of its parent  $\text{H}_2\text{O}$  (Crovisier 1989; Bockelée-Morvan & Crovisier 1989; Mumma et al. 2001).

OH PE was detected near  $3.0 \mu\text{m}$  in comets C/1996 B2 (Hyakutake; Brooke et al. 1996; Magee-Sauer et al. 2002), C/1995 O1 (Hale-Bopp; Magee-Sauer et al. 1999), and C/2000 WM1 (Gibb et al. 2003), but quantitative estimates of the emission efficiencies ( $g$ -factors) were not provided. Mumma et al. (2001) sampled the overall chemistry in comet C/1999 H1 (Lee) by observing almost the entire  $L$  band ( $2.9\text{--}3.7 \mu\text{m}$ ), and OH PE quadruplets were observed throughout this region. They compared their measured  $\text{H}_2\text{O}$  production rate with OH PE line intensities and obtained the combined emission efficiency for the quadruplet near  $3046 \text{ cm}^{-1}$ ; however, the measurements of  $\text{H}_2\text{O}$  and OH were made not on the same day but on consecutive days. Mumma et al. suggested that the detailed quantitative (including line-by-line) investigation of these multiplets in C/1999

H1 and other comets was needed to establish the general usefulness of OH PE as a proxy for  $\text{H}_2\text{O}$ . The current paper initiates that work by presenting results for both line-by-line and combined  $g$ -factors of this quadruplet in two comets. Our results are based on simultaneous measurements of water and OH PE and include error estimates for the derived empirical parameters. We also discuss evidence for possible variations in the OH PE  $g$ -factors that should be considered when this emission is used as a proxy of water.

### 3. OH PROMPT EMISSION IN TWO COMETS

We present results obtained on two dates for each of two comets: C/1999 H1 (Lee), taken on UT 1999 August 19.6 ( $R_h = 1.049 \text{ AU}$ ,  $\Delta = 1.381 \text{ AU}$ ) and 1999 August 21.6 ( $R_h = 1.076 \text{ AU}$ ,  $\Delta = 1.348 \text{ AU}$ ), and C/2001 A2 (LINEAR), taken on UT 2001 July 9.5 ( $R_h = 1.161 \text{ AU}$ ,  $\Delta = 0.276 \text{ AU}$ ) and 2001 July 10.5 ( $R_h = 1.173 \text{ AU}$ ,  $\Delta = 0.282 \text{ AU}$ ). Detailed observing logs are given in Mumma et al. (2001) and Gibb et al. (2003). High-resolution cometary spectra were acquired with the cryogenic near-infrared spectrometer (NIRSPEC; McLean et al. 1998) at the Keck Observatory atop Mauna Kea, Hawaii. NIRSPEC uses a  $1024 \times 1024$  pixel detector array and a long slit, thus providing spatially resolved spectra. This high-sensitivity, cross-dispersed instrument enables simultaneous detection of a number of species, including  $\text{H}_2\text{O}$  and OH\* (the asterisk denotes that the radical is both vibrationally and rotationally excited). A thorough description of our spectral data analysis, from the processing of “raw” frames to deriving

production rates via the so-called “ $Q$ -curve” formalism, is presented elsewhere (e.g., Dello Russo et al. 1998; Magee-Sauer et al. 1999; DiSanti et al. 2001). Four OH lines from the  $P$ -branch of the (1–0) band are shown in Figure 1. Among the various OH quadruplets in the  $L$  band, these four lines are relatively strong, and there is no evidence of spectral overlap with other cometary emissions.

The nature of PE requires that its spatial distribution track that of the parent volatile; by contrast, the fluorescent emission from quiescent OH exhibits a much flatter distribution that does not peak at the nucleus (e.g., Weaver et al. 1999). In Figure 2 we compare intensities for H<sub>2</sub>O and OH in comet Lee as a function of distance from the nucleus. We normalized the two distributions by summing over 7 pixels centered on the peak and scaling to a common value. The two distributions are congruent; the OH intensity peaks at the nucleus and traces the spatial distribution of a native species. The good agreement between the spatial profiles of water and OH intensities is consistent with the view that H<sub>2</sub>O is the parent of OH\*. However, the distribution of OH\* is also in agreement with the spatial profile of dust, which is very similar to the H<sub>2</sub>O profile in comet Lee. Analysis of comets for which the H<sub>2</sub>O and dust spatial profiles are different will test the (unlikely) possibility that OH\* comes from dust. Figure 2 clearly demonstrates that the OH\* intensity distribution is characteristic not of a fluorescent but of a prompt mechanism. With the reasonable assumption that H<sub>2</sub>O is the source of OH\*, we now explore using this OH PE for extracting water production rates.

#### 4. EFFECTIVE $g$ -FACTORS FOR TWO COMETS

Given the correlation between the spatial distributions of H<sub>2</sub>O and OH\*, it is straightforward to determine the effective emission efficiency (equivalent  $g$ -factor) for OH PE. We first obtained production rates for water using the established methodology (Dello Russo et al. 2000, 2002) but with a recently improved H<sub>2</sub>O fluorescence model that includes the hot-bands

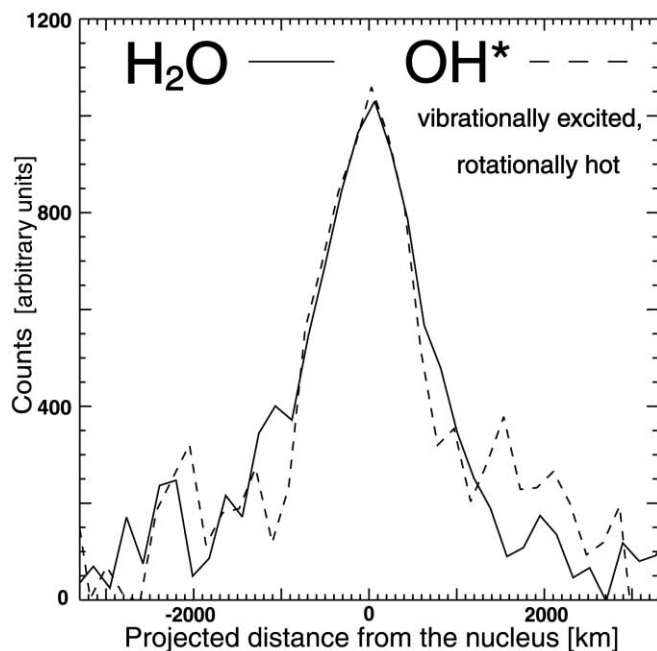


Fig. 2.—Spatial profiles of water and OH emission near  $3046\text{ cm}^{-1}$  in C/1999 H1. The OH profile represents the summed signal in all four lines shown in Fig. 1. The distributions of water and OH are similarly correlated in comet C/2001 A2.

near  $2.9\ \mu\text{m}$  (Dello Russo et al. 2004). The new model incorporates up-to-date calculations for the fluorescence efficiencies of a number of H<sub>2</sub>O lines in this spectral region. In addition, several lines have been found to introduce systematic effects in the extraction of H<sub>2</sub>O production rates and have been eliminated from the analysis (Dello Russo et al. 2004). It should be emphasized that including the spectral region near  $2.9\ \mu\text{m}$  not only significantly increases the number of water emission lines used to extract (more accurate) production rates (see Table 1, footnote e) but also for the first time enables truly simultaneous detections of H<sub>2</sub>O and OH PE.

The water production rates for the four dates (in the order given at the beginning of the previous section) were  $(13.4 \pm 1.3)$ ,  $(14.3 \pm 1.3)$ ,  $(3.8 \pm 0.3)$ , and  $(4.3 \pm 0.4) \times 10^{28}$  molecules  $\text{s}^{-1}$ , respectively. We then applied the aforementioned  $Q$ -curve formalism to the PE profile. The PE  $g$ -factor was adjusted until the water production rate deduced from the OH data ( $Q^*$ ) equaled the production rate directly obtained from water lines ( $Q$ ). This approach is legitimate; given the simultaneity of OH and H<sub>2</sub>O observations, the direct water measurements provide a “calibrator” for the PE efficiency.

For OH\*, we summed the individual spatial profiles of the four emission lines and obtained the effective  $g$ -factor for the entire  $3046\text{ cm}^{-1}$  quadruplet using the aforementioned  $Q$ -curve approach. (The combined  $g$ -factor is expected to be less sensitive to effects that might cause line-by-line variations.) We also derived  $g$ -factors for each individual line in the two comets. We followed the formalism outlined in Bevington & Robinson (1992) and Taylor (1982) to evaluate the uncertainties in the derived  $g$ -factors. These errors result from the  $Q$ -curve modeling uncertainties of  $Q$  and  $Q^*$ . Note that the error analysis in the derivation of production rates, which here propagates to the determination of  $g$ -factors, has been extensively used for our studies of cometary volatiles (e.g., Dello Russo et al. 2002).

Table 1 presents quantitative results for C/1999 H1 and C/2001 A2. The values of the combined effective  $g$ -factors are consistent with the sums of the line-by-line measurements. The weighted mean values are recommended for extraction of water production rates in future comets.

## 5. DISCUSSION

### 5.1. Prompt Emission from OH\* and $[O(^1D)]$

Our results demonstrate that OH PE traces the spatial distribution of H<sub>2</sub>O in the inner coma and that the effective  $g$ -factors in two comets fall within a relatively narrow range of values. Thus, IR PE may be a useful additional method for measuring water production in comets. It is appropriate to ask whether hidden factors might limit the applicability of this approach. To this end the related technique at optical wavelengths provides a useful guide. PE from dissociatively excited  $[O(^1D)]$  (at 630 nm) has been a useful proxy for water for many years (e.g., Morgenthaler et al. [2001] and references therein). The initial steps in developing this method were consistent with water being the sole parent of  $[O(^1D)]$  (Spinrad 1982). However, it is now accepted that a significant fraction of  $[O(^1D)]$  is produced from other precursors (OH, CO, CO<sub>2</sub>), especially in the outer coma (e.g., Festou & Feldman 1981; Morgenthaler et al. 2001). In addition, because  $[O(^1D)]$  is a forbidden transition, it has a comparatively long lifetime ( $\sim 120$  s), so collisional quenching may be important in high-density regions near the nucleus.

By contrast, no major production mechanisms for OH PE, other than photolysis of H<sub>2</sub>O, are known, and the radiative

TABLE 1  
EFFECTIVE  $g$ -FACTORS AT 1 AU<sup>a</sup> FOR THE OH PE (1–0) BAND QUADRUPLLET NEAR 3046 cm<sup>-1</sup>

Line ID <sup>b</sup>	$\nu_0$ (cm <sup>-1</sup> )	Comet/UT Date	Emission Efficiency at 1 AU (10 <sup>-8</sup> photons s <sup>-1</sup> [H <sub>2</sub> O molecules] <sup>-1</sup> )
P11.5 2 <sup>+</sup> .....	3047.4576	C/1991 H1 (1999 Aug 19)	5.53 ± 2.66
		C/1991 H1 (1999 Aug 21)	4.60 ± 0.62
		C/2001 A2 (2001 Jul 9)	3.81 ± 0.64
		C/2001 A2 (2001 Jul 10)	2.68 ± 0.40
		Weighted Mean <sup>c</sup>	3.39 ± (0.30; 0.48)
P11.5 2 <sup>-</sup> .....	3046.5508	C/1991 H1 (1999 Aug 19)	4.54 ± 1.29
		C/1991 H1 (1999 Aug 21)	4.42 ± 0.54
		C/2001 A2 (2001 Jul 9)	2.39 ± 0.40
		C/2001 A2 (2001 Jul 10)	2.75 ± 0.39
		Weighted Mean	3.02 ± (0.24; 0.47)
P12.5 1 <sup>+</sup> .....	3044.4280	C/1991 H1 (1999 Aug 19)	5.76 ± 1.22
		C/1991 H1 (1999 Aug 21)	4.54 ± 0.58
		C/2001 A2 (2001 Jul 9)	4.58 ± 0.70
		C/2001 A2 (2001 Jul 10)	4.22 ± 0.58
		Weighted Mean	4.53 ± (0.34; 0.22)
P12.5 1 <sup>-</sup> .....	3043.2137	C/1991 H1 (1999 Aug 19)	2.88 ± 0.60
		C/1991 H1 (1999 Aug 21)	3.98 ± 0.46
		C/2001 A2 (2001 Jul 9)	3.99 ± 0.64
		C/2001 A2 (2001 Jul 10)	2.56 ± 0.34
		Weighted Mean	3.16 ± (0.23; 0.38)
Combined <sup>d</sup> .....		C/1991 H1 (1999 Aug 19)	19.3 ± 3.2
		C/1991 H1 (1999 Aug 21) <sup>e</sup>	18.1 ± 2.1
		C/2001 A2 (2001 Jul 9)	15.4 ± 1.9
		C/2001 A2 (2001 Jul 10)	12.5 ± 1.3
		Weighted Mean	14.8 ± (0.9; 1.5)

<sup>a</sup> The  $g$ -factors are assumed to vary as the inverse square of the heliocentric distance.

<sup>b</sup> P11.5 designates  $P$ -branch,  $J'' = 11.5$ , etc.;  $2 \equiv {}^2\Pi_{1/2}$ ,  $1 \equiv {}^2\Pi_{3/2}$ ; plus and minus signs indicate the  $\Lambda$ -doublet components (Maillard et al. 1976).

<sup>c</sup> Two standard error estimates for the weighted means are given in parentheses: the first entry is the standard deviation of the mean (its square equals the inverse of the sum of the reciprocal squares of the individual error bars), while the second entry is equal to the square root of the sample variance of the mean divided by the square root of the sample size (e.g., Arkin & Colton 1970; Bevington & Robinson 1992). The first error indicates how well the mean is determined, while the second error describes the scatter about the mean. For four empirical values, a 95% confidence interval is obtained by multiplying the latter error by 3.18 (instead of by 2.0, as commonly assumed), accounting for the small-number statistics (Arkin & Colton 1970; Hoel 1984).

<sup>d</sup> Derived from the spatial profiles of OH\* formed by summing over the four individual lines (as shown for C/1999 H1 in Fig. 2).

<sup>e</sup> Mumma et al. (2001) compared H<sub>2</sub>O data taken on 1999 August 20 (3 lines near 5  $\mu$ m) to OH PE data from 1999 August 21 and reported  $g = 20$ , in the same units as used here, without providing an error estimate. The present work used H<sub>2</sub>O data from 1999 August 21 (25 lines near 2.9  $\mu$ m) measured simultaneously with the OH PE lines. The similarity between the previous and the current value of the combined  $g$ -factor for this particular date suggests that the water production rates were similar on these two dates.

lifetime of OH\* (several milliseconds) is much shorter than that of [O(<sup>1</sup>D)]. At thermal velocities ( $\sim 10^4$  cm s<sup>-1</sup>) the collision time is about 1 ms for densities of the order of 10<sup>15</sup> cm<sup>-3</sup>, so collisional relaxation of OH\* is negligible throughout the observed coma. Moreover, OH PE increases the spectral range over which H<sub>2</sub>O and organics can be sampled within the same instrument setting (i.e., simultaneously). For these reasons the OH PE-based approach might be very useful; it is therefore important to assess potential limitations that might be revealed as more multiplets are analyzed in these and additional comets.

### 5.2. Possible Effects of the Rotational Temperature of the Parent

Is the effective  $g$ -factor for OH PE sensitive to the rotational temperature of the parent H<sub>2</sub>O? Mumma et al. (2001) suggested that the OH PE-based method for quantifying water production should be insensitive to  $T_{\text{rot}}$  because the end prod-

uct distribution (OH\*) tends to average over the initial state distribution of H<sub>2</sub>O, causing the rotational distribution of OH PE to have “little memory” of the precursor’s rotational distribution prior to photolysis. The retrieved  $T_{\text{rot}}$  of water was 80<sup>+6</sup><sub>-4</sub> K and 76<sup>+4</sup><sub>-3</sub> K for C/1999 H1 (for 1999 August 19 and 1999 August 21, respectively) and 98<sup>+6</sup><sub>-5</sub> K and 105<sup>+6</sup><sub>-3</sub> K for C/2001 A2 (for 2001 July 9 and 2001 July 10, respectively). Additional observations spanning a broader range in  $T_{\text{rot}}$  are needed in order to assess whether (and to what extent) the state of excitation of water influences the  $g$ -factors for OH PE. Note that at much lower  $T_{\text{rot}}$  only a few states of water are populated, and quantum mechanical details such as the Franck-Condon principle and predissociation probabilities to specific exit channels may become important.

### 5.3. Possible Effects of Solar Activity

The effective  $g$ -factor might also depend on solar activity. Water dissociation occurs through two molecular band systems

(Andresen et al. 1984; Crovisier 1989). The first system is responsible for most of the photolysis rate and is relatively insensitive to solar variability. The second system is dominated by solar Ly $\alpha$  emission. The Ly $\alpha$  intensity varies significantly during the 11 yr solar cycle, but this channel provides less than one-half of the total production of OH even under active Sun conditions. The two dates of observation presented herein fall near solar maximum; observations of future comets may provide a test for possible dependence of  $g$ -factors on solar activity.

#### 5.4. Possible Effects of Heliocentric Distance

Detections of OH PE near 3046 cm<sup>-1</sup> have been reported for heliocentric distances up to  $\sim 1.4$  AU (Gibb et al. 2003). Kawakita et al. (2003) did not detect OH PE in comet 153P/Ikeya-Zhang when the comet was near  $R_h = 1.5$  AU. Their observations were done at a resolving power of  $\sim 10,000$ . They derived an upper limit for the water production rate based on the preliminary  $g$ -factor for the combined quadruplet given by Mumma et al. (2001). This upper limit was significantly lower than the H<sub>2</sub>O production rate deduced from the radio observations spanning several dates prior to and following their observations, leading these authors to the suggestion that the emission mechanism of OH has to be reexamined for larger heliocentric distances. This possibility cannot be overruled until more comets are observed under such conditions. If a change in the  $g$ -factor is the sole cause of Kawakita et al.'s non-detection, this  $g$ -factor would be significantly lower than the value of Mumma et al. (2001), which is on the upper edge of our 95% confidence interval (see Table 1, footnote c). However, additional effects should also be taken into account.

Kawakita et al. (2003) performed their observations at  $R_h \sim 1.5$  AU,  $\Delta \sim 0.6$  AU, and with a small observational beam size. Small beams are heavily weighted toward water (and other species, including OH\*) released very close to the nucleus. Release of water from icy grains may play an increasingly important role at larger heliocentric distances. Water could then have a significantly extended source region. OH PE would still track the spatial distribution of H<sub>2</sub>O, and thus it too would exhibit an extended source. The combination of small beam size and small geocentric distance could then cause the extended source to be undersampled. The inferred emission efficiencies of OH PE might be underestimated, unless H<sub>2</sub>O and OH were observed together in the same instrument setting. In addition, if a hypervolatile, such as CH<sub>4</sub>, were released directly from (or close to) the nucleus, it could show an apparent enhancement relative to OH PE (E. L. Gibb et al., in preparation), perhaps leading to an overestimate of its mixing ratio relative to H<sub>2</sub>O.

Our current database does not support a significant change in the effective  $g$ -factors at  $R_h \sim 1.5$ – $1.6$  AU. We observed comet C/2001 A2 on UT 2001 August 4.5 ( $R_h = 1.510$  AU,  $\Delta = 0.578$  AU, 12 minutes on source) and UT 2001 August 10.5 ( $R_h = 1.594$  AU,  $\Delta = 0.673$  AU, 20 minutes on source). On August 4 we have a very tentative detection ( $3.5 \sigma$  level) of only the strongest (according to Table 1) OH line (P12.5 1<sup>+</sup>). The resulting water production rate based on the established  $g$ -factor ( $Q = [1.5 \pm 0.5] \times 10^{28}$  molecules s<sup>-1</sup>) is consistent with the value derived independently from the water hot-band lines near 2.9  $\mu$ m ( $Q = [1.1 \pm 0.2] \times 10^{28}$  molecules s<sup>-1</sup>). The upper limits for water production rates based on the  $g$ -factors of the three nondetected lines are all higher than the directly measured value. Summing the flux at the expected positions

of the four OH lines results in a possible detection, but only at the  $2.9 \sigma$  confidence level ( $Q = [0.8 \pm 0.3] \times 10^{28}$  molecules s<sup>-1</sup>). This also agrees with the value from the 2.9  $\mu$ m analysis.

We did not detect any of the OH PE lines on August 10.5. All established upper limits (based on the individual  $g$ -factors and their combined value) exceed the directly measured value for that date ( $Q = [0.6 \pm 0.1] \times 10^{28}$  molecules s<sup>-1</sup>). We can conclude that our current data do not support a drastic change in the proposed  $g$ -factors for heliocentric distances of 1.5–1.6 AU (the nondetection may be a result of low water production rates). We note, however, that using lower  $g$ -factors for OH on August 10 will increase our derived  $Q$ ; thus, these observations do not test the aforementioned possibility. Clearly, additional observations are required.

## 6. CONCLUSION

Beyond obtaining production rates of cometary water, studies of OH PE promise to test models for OH\* production (through H<sub>2</sub>O photolysis) in comets. We plan to extend our analysis to other OH lines in our existing database of comet spectra and to observations of future comets. Ultimately this will lead to the construction of a database of absolute  $g$ -factors for the lines observed in the  $L$  band and will help constrain models that predict branching ratios for production of OH rotational states.

This work outlines the quantitative basis for deriving cometary water production rates using near-infrared prompt emission from OH. We derive effective  $g$ -factors for the prompt emission lines near 3046 cm<sup>-1</sup> on two dates for each of two comets. Our results have immediate significance for groups conducting high-resolution IR spectroscopy of comets, a field that is rapidly developing. On a broader scale, they are of interest because they relate to the principal parent volatile in comets, H<sub>2</sub>O.

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