Abstract

The exceptional brightness and long observational window of comet Hale-Bopp provided a remarkable opportunity to study both the neutral coma and the plasma in the coma and ion tail. Our team of observers from UW–Madison and Goddard Space Fight Center used seven different instruments at Kitt Peak to observe cometary emission from H, OH, O, H₂O⁺, NH₂, C, CN, C₂, and the continuum. Here we present observations and model analysis for the O(¹D) ([O I] 6300 Å) emission. The data were taken by three telescopes on Kitt Peak: the Wisconsin, Indiana, Yale NRAO (WIYN), Wisconsin H-α Mapper (WHAM), and the NSO McMath-Pierce. The 3.5-meter WIYN telescope recorded up to 96 simultaneous spectra with a Multi-Object Spectrograph (MOS), the WHAM Fabry-Perot spectrometer recorded spectra and narrow-band images over a 1° field of view and the 2-inch Fabry-Perot spectrometer at the McMath-Pierce main telescope recorded high resolution (λ/Δλ = 80,000) spectra of the [O I] 6300 Å emission with a 6 arcminute field of view. The combination of MOS and Fabry-Perot data covers spatial scales ranging from 2,000 km to 1×10⁶ km. The high resolution spectra, recorded with a ~180,000 km radius field of view, show evidence of motion in the anti-sun direction. At distances greater than 300,000 km, we see a tail-ward asymmetry in the spatial distribution of [O I]. At 500,000 km, there is an excess of ~2×10⁶ photons s⁻¹ cm⁻² sr⁻¹ (30 R) in the tail-ward direction. We use the data away from the tail-ward asymmetry and a Haser model (Haser 1957) to estimate the water production rate of the comet from late February to late April 1997. We find our results are sensitive to the branching ratio of OH into the O(¹D) state. We favor using the branching ratio derived from (Nee & Lee 1984) by Hübner, Keady, & Lyon (1992).
Introduction

The release of water from the nucleus and its subsequent photochemical behavior drives much of the physical phenomena in cometary comae. Thus, one of the first tasks in understanding any cometary system is to determine that comet’s water production rate.

Direct emission from water has been detected (e.g. Mumma et al. 1996), but traditionally, the more easily observed emissions from its decay products (OH, H, and O) have been the primary means for determining the total water production rate of a comet.

We have concentrated on measuring emission from O(1D) (generally the [O I] 6300 Å line) using Fabry-Perot interferometers with resolving powers high enough to separate the cometary emission from the Earth’s airglow line. The O(1D) state is metastable, with a lifetime of \( \sim 110 \) s. As a forbidden transition, O(1D) can not be excited by solar photons and is only produced as a decay product of a dissociation or in a collision with an electron. Since most of a cometary coma is collisionally thin, emission of [O I] is therefore a direct tracer of photo-dissociating water or OH (here we ignore the contributions of other oxygen baring volatiles, such as CO). Furthermore, with the wide field of view and excellent sensitivity of our instruments (up to 1 degree and less than 1 Rayleigh, respectively), we can detect ALL of the [O I] emission from a comet. In detail, the O(1D) and water production rates are given by the following equations:

\[
Q(O(1D)) = \left( \frac{4}{3} \right) (4 \pi \Delta^2 \Omega I_{6300}) AC
\]

(1)

\[
Q(H_2O) = \frac{Q(O(1D))}{BR1 + (BR2)(BR3)}
\]

(2)
where the factor of $4/3$ corrects for the emission we do not measure in the 6364Å decay path of $O(^1D)$, $\Delta$ is the distance between the earth and the comet, $\Omega$ is the solid angle of the field of view, $I_{6300}$ is the average 6300 Å surface brightness over the field of view in photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ and $AC$ is the aperture correction. The branching ratios, $BRn$ are given in Table 1. It is important to note and is a central point in this poster, that the theoretical and experimental values for the OH to O branching ratio are significantly different.

Table 1: H$_2$O and OH photo rates and branching ratios from Hübner (1992) and Van Dishoeck and Dalgarno (1984). Hübner uses the OH cross sections of Nee and Lee (1984) in order to calculate the experimental OH reaction rates. The total OH dissociation rate of Van Dishoeck and Dalgarno is computed for a heliocentric velocity of -10 km/s. Note that BR2 is the sum of the reaction rates of water into OH + H and OH + H$^+$. 

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product</th>
<th>Reaction Rates (1/s)</th>
<th>Branching Ratios</th>
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<tr>
<td></td>
<td></td>
<td>Quiet Sun</td>
<td>Active Sun</td>
</tr>
<tr>
<td>H$_2$O + ν</td>
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<td>1.76E-05</td>
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<tr>
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<tr>
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<td>4.07E-08</td>
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<td>Nee and Lee</td>
<td>OH + ν</td>
<td>O($^3P$) + H</td>
<td>1.20E-05</td>
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<td>total rate</td>
<td>8.33E-06</td>
<td>9.91E-06</td>
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Observations

Observations of comet Hale-Bopp over a wide range of wavelengths were conducted by this team from Aug 16, 1996 through April 29, 1997. This poster presents [O I] observations from February to April 1997, which were recorded by four instruments on Kitt Peak.

On 6 nights the Hydra positioner of the 3.5-meter Wisconsin, Indiana, Yale, NRAO (WIYN) Telescope Multi Object Spectrograph (MOS) was used to place up to 96 fibers in concentric rings around the nucleus to as much as 22.5 arc minutes in radius (see Figure 3). The MOS spectra were recorded over a 300 Å range centered at 6250 Å with a resolving power of $(\lambda/\Delta\lambda) \sim 15,000$. On 4 nights a 7 by 13 array of 3 arc second fibers on 4 arc second centers known as Densepak was used on the WIYN MOS to probe the inner coma.

On three nights, the 6-inch Fabry-Perot spectrometer that comprises the Wisconsin H-α Mapper (WHAM), recorded narrow band images over a 1° field of view and spectra over a 200 km/s range (4 Å at 6300 Å) with a resolving power of $(\lambda/\Delta\lambda) \sim 30,000$.

On 29 nights a 2-inch Fabry-Perot spectrometer on the NSO McMath-Pierce main telescope recorded high resolution $(\lambda/\Delta\lambda = 80,000)$ spectra of the [O I] 6300 Å emission with a 6 arc minute field of view.

The combination of MOS and Fabry-Perot data covers spatial scales ranging from 2,000 km to $1 \times 10^6$ km.
Results

Figure 1 shows all of the [O I] spectra obtained by the WHAM spectrometer together with the model used to find the total surface brightness in the one degree WHAM field of view. Figure 2 shows one of the best spectra from the 2-inch Fabry-Perot instrument. As discussed by Oliversen & Doane (1999), the extraction of spectra from the 2-inch dataset is complicated and thus subject to large experimental uncertainties (see scatter in, e.g. Figure 8).

Because the WHAM instrument has such a large field of view and high sensitivity, we can accurately determined the total Hale-Bopp [O I] surface brightness. Applying equations 1 and 2 with the aperture correction \( AC = 1 \), we arrive directly at a water production rate. These rates are summarized in Table 2.

Table 2: The \( \text{O}(^1\text{D}) \) and water production rates derived from the WHAM spectroscopic data. The “Van Dishoeck” column gives the water production rate assuming the theoretical Van Dishoeck and Dalgarno (1984) OH to \( \text{O}(^1\text{D}) \) branching ratio. The “Lee” column uses and Hübner’s (1992) branching ratios computed with Nee and Lee’s (1984) measured OH cross section.

<table>
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<th>UT date (1997)</th>
<th>( \hat{R}_{\text{helio}} ) (AU)</th>
<th>( Q(\text{O}(^1\text{D})) ) (s(^{-1}))</th>
<th>( Q(\text{H}_2\text{O}) ) (s(^{-1})) ( \text{Van Dishoeck} )</th>
<th>( Q(\text{H}_2\text{O}) ) (s(^{-1})) ( \text{Nee} )</th>
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<td>( 3.6 \times 10^{31} )</td>
<td>( 9.2 \times 10^{30} )</td>
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Figure 1: WHAM spectra of Comet Hale-Bopp, February 22–March 5, 1997. Solid line is a model with 3 Voigt profiles in emission plus 7 Voigts in absorption representing the scattered solar spectrum. The dotted line is the same minus the cometary [O I] emission line.
Figure 2: One of the better 2 inch Fabry-Perot spectra of comet Hale-Bopp taken on April 14, 1997. The field of view is 200,000 km in radius, centered on the comet head. The red tail on the velocity distribution is consistent with material flowing tail-ward.

Figure 3 shows the March 5 WHAM [O I] image overlayed in contour with the dust emission (see bars in Figure 1 for [O I] and dust bandpasses). We discuss the remarkable asymmetry in the [O I] image elsewhere (Morgenthaler et al. 1999). For the construction of the radial profiles in this work, we ignore the emission from the quadrant centered about the anti-sunward vector.
Figure 3: Hale-Bopp image with [O I] emission is shown in color, dust in contours. Circles show approximate positions Hydra annuli.

Model

In order to estimate the effects of collisional quenching and electronic excitation of the [O I] line, we created a simple model of the water and OH distributions in the coma of Hale-Bopp using the Haser formulation (Haser 1957). We modeled the water distribution as a single component and the OH as a two component Haser model. The O(\(^1\)D) column density is then:

\[
C_{OI} = C_{OH} \times R_3 + C_{\text{water}} \times R_1,
\]

(3)
where $C_{OH}$ and $C_{water}$ are the column densities of OH and water, respectively and $R_3$ and $R_1$ are the reaction rates corresponding to the BR3 and BR1 in Table 1. The [O I] 6300 Å surface brightness in Rayleighs ($1$ Rayleigh is $\frac{10^6}{4\pi}$ photons/s/sr) is then:

$$B_{OI} = \frac{3}{4} \frac{C_{OI}}{10^6}.$$  \hspace{1cm} (4)

Recall the factor of $\frac{3}{4}$ is necessary since $\frac{3}{4}$ of the O($^1\text{D}$) states emit a 6364Å photon.

We calculate the effect of quenching using a simple steady-state model:

$$R_1 n_{water}(r) + R_3 n_{OH}(r) = \frac{1}{\tau_{[\text{O I}]} n_{[\text{O I}]}(r) + n_{[\text{O I}]}(r) * n_{water}(r) q_{OI, water}}$$  \hspace{1cm} (5)

where the $n$ values are the number densities of the various species at radius $r$ from the nucleus and $q_{OI, water}$ is the O($^1\text{D}$) on water quenching rate of Streit et al. (1976).

To calculate electronic excitation we use the the surface brightness of the [O I] 1356 Å measured by McPhate et al. (1999), the electron excitation cross section of this line (Stone & Zipf 1974) multiplied by 0.36 (Morrison & Meier 1988; Conway, Meier, & Huffman 1988) and the [O I] 6300 cross section of Doering (1992). A rough lower limit on the electron temperature was found by lowering the assumed electron temperature until the electron excited [O I] 6300 emission became comparable to the [O I] 6300 from the Haser model.
Van Dishoeck and Dalgarno

In Figure 4 we our Haser model fit to the [O I] 6300 radial profiles recorded by WHAM and WIYN in March and April and to OH 3080 Å data recorded on April 8 (see poster 17.02 in this session). Using Van Dishoeck & Dalgarno (1984) cross sections, we arrive at reasonable velocities (water = 1 km/s, OH = 3 km/s – see poster 17.14). Assuming that electron excitation is negligible, we find a lower limit to the electron temperature of 20 eV. This is almost surely too high a temperature. Thus, electron re-excitation of [O I] may be important inside 100,000 km.

As shown in Figure 5, the water production rates derived from our [O I] data using Van Dishoeck & Dalgarno cross sections are a factor of 3-5 higher than the water production rates derived from other observations.
Figure 4: Measured and modeled radial profiles of [O I] 6300 and OH 3080 emission in comet Hale-Bopp using Van Dishoeck and Dalgarno (1984) OH theoretical cross sections. Asterisks in second plot are Densepak data from March 18.
Figure 5: Water production rate history assuming Van Dishoeck and Dalgarno (1984) OH photodissociation cross-sections. “Biver” points are from radio OH measurements (Biver 1999).
Nee and Lee

If we use the cross-sections of Nee & Lee (1984), reasonable fits to the radial profiles are obtained only with a very high OH outflow velocity (> 8 km/s) not supported by other measurements (see posters 17.02 and 17.14 in this session). However, the resulting water production rates come into line with Biver’s radio OH results (Biver et al. 1999). Unfortunately, if we change the OH lifetime, Biver’s production rates will almost certainly change as well resulting in an equal and opposite disagreement between our results!

Possible Solution

We propose a “tidy” solution to the production rate miss match discussed above: use the OH lifetime of Van Dishoeck & Dalgarno but the OH to O(1D) branching ratio of Nee & Lee. The resulting water production time history plot is Figure 8.
Figure 6: Measured and modeled radial profiles of [O I] 6300 and OH 3080 emission in comet Hale-Bopp using Nee and Lee (1984) OH measured cross sections. The second plot shows a fit with the outflow velocity pair: water = 0.5 km/s, OH = 10 km/s. The rest of the plots have the velocity pair: water = 1 km/s, OH = 8 km/s. Asterisks in the third plot are Densepak data from March 18.
Figure 7: Water production rate history assuming Nee and Lee (1984) OH photodissociation cross-sections. If these cross-sections are correct, Biver's points, which are probably based on Van Dishoeck and Dalgarno's cross-sections need to be scaled (open circles).
Figure 8: Hybrid production Rates using Nee and Lee (1984) branching ratios and the Van Dishoeck and Dalgarno (1984) OH lifetime.
Conclusion

We have recorded [O I]6300 Å data with three different instruments, two Fabry-Perot spectrometers, calibrated against NGC 7000 (the North American Nebula) and a multi-object spectrograph, calibrated against standard stars. All three of these datasets show consistent [O I] production rates. Converting these [O I] rates into water production rates using the OH to O(1D) branching ratios of Van Dishoeck & Dalgarno (1984) results in a discrepancy of a factor of 3-4 when compared with water production rates determined by OH measurements. Using the OH lifetime of Van Dishoeck & Dalgarno (1984) but the branching ratios of Nee & Lee (1984), our results become more consistent with other water production rates. Though we make no statement about the implications of these results to the physics of the OH cross-sections, we do note that other authors have commented on the problems of the Van Dishoeck & Dalgarno cross-sections (e.g. Cochran & Schleicher 1993). Problems with the OH to O(1D) branching ratio may also be the reason that [O I]6300 determinations of water production have been particularly discrepant in the words of one author (Schleicher, Millis, & Birch 1988). On the other hand, the possibility that the radio measurements of Biver et al. are low due to quenching in the OH radio data (Schloerb 1988) must also be carefully considered.

The authors would like to thank Jason McPhate for providing a spatially resolved profile of the 1356 Å emission in comet Hale-Bopp.
References


Conway, R., Meier, R., & Huffman, R. 1988, Planet. Space Sci., 36, 963


Oliversen, R., & Doane, N. E. 1999, In preparation

Schloerb, F. P. 1988, Astrophysics, 332, 524


Van Dishoeck, E. F., & Dalgarno, A. 1984, Icarus, 59, 305
Cometary NH$_2$, Airglow OH

$V_{\text{comet}} = -30.2 \text{ km/s}$

Area = 13.30 Rayleighs

Airglow [OI] 6300.304
Cometary NH$_2$, Airglow OH

$V_{\text{comet}} = -30.2$ km/s
Area = 13.30 Rayleighs

Airglow, [OI] 6300.304
Preliminary Hale-Bopp Water Production Rates
Using Van Dishoeck and Dalgarno (1984) OH Lifetime
and Branching Ratios

<table>
<thead>
<tr>
<th>Date</th>
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**Legend:**
- **Harris OH**
- **Biver**
- **WIYN**
- **WHAM**
- **2-inch**
Using Nee and Lee (1984) OH lifetime and Branching Ratios
Preliminary Hale-Bopp Water Production Rates

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[Diagram showing the dates and production rates]
Preliminary Hale-Bopp Water Production Rates

Using Van Dishoeck and Dalgarno (1984) OH Lifetime

and Nee and Lee [OI] Branching Ratio

Production Rate (molecules of water per second)

Date

2/22/97
3/1/97
3/8/97
3/15/97
3/22/97
3/29/97
4/5/97
4/12/97
4/19/97

2-inch
WHAM
WIYN
Biver
Harris OH

1.00E+30
1.00E+31
1.00E+32