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Far-ultraviolet observations of the neutral comae of Comet Hale-Bopp (C/1995 01) near perihelion

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Abstract. The Ultraviolet Imager on the Polar spacecraft observed the neutral oxygen and carbon comae of Comet Hale-Bopp (C/1995 01) at far-ultraviolet wavelengths near perihelion on March 31 and April 2, 1997. The OI (1304) coma was circularly symmetric with a diameter of about 5 million km. The coma was smaller in the longer wavelength (1400–1600 Å and 1600–1800 Å) bands, which is probably due to fluorescence of neutral carbon at 1561 Å and 1657 Å. The production rate for O calculated from the observed OI (1304) flux was $(9.8 \pm 2.5) \times 10^{30}$. Using this value the estimated production rate for OH was $(8.9 \pm 2.5) \times 10^{30}$ and for H_2O was $(1.0 \pm 0.3) \times 10^{31}$.

Introduction

The composition of comets is of interest since the main observed constituents, water, carbon monoxide and carbon dioxide, are also typical of ices in the primordial solar system that constitutes the Oort cloud, the suspected origin of comets. The relative abundance of the two most abundant molecules, H_2O and CO, in the nucleus ices may be similar to the ratio of their outgassing production rates. Far from the Sun, generally beyond 3 to 4 AU (astronomical units), sublimation of the more volatile species such as CO may skew the relative production rates to higher values. For example, an anomalously high production rate for CO, the most volatile of these molecules, was reported for Comet Hale-Bopp at 6.5 AU [*Biver et al.*, 1996]. Within 3.5 AU the production rate of OH, whose parent molecule is H_2O, exceeded that of CO [*Biver et al.*, 1997]. Near perihelion the relative production rates may provide a more accurate estimate of the relative composition of the cometary ice [*Crovisier et al.*, 1997].

Spectrometric ultraviolet observations of Comet Hale-Bopp at pre-perihelion heliocentric distances between 6.8 and 2.7 AU were made by the International Ultraviolet Explorer (IUE) and the Hubble Space Telescope [*Weaver et al.*, 1997] and at 0.97 AU by *Woods et al.* [2000]. Post-perihelion observations at 0.92 AU were reported by *McPhate et al.* [1999] and between 0.94–0.98 AU by *Woods et al.* [2000]. Near perihelion at 0.91 AU the Ultraviolet Imager (UVI) [*Torr et al.*, 1995] mounted on a despun platform on the Polar spacecraft in Earth orbit obtained two-dimensional images of Comet Hale-Bopp at far-ultraviolet wavelengths. Here we present UVI observations of the neutral carbon and oxygen comae from which production rates for C, O, OH, H_2O and CO were estimated.

Observations

The UVI camera consists of a set of far-ultraviolet, narrow-band reflection filters, a three-mirror wide field of view (8°) imaging system, and a microchannel plate (MCP) image intensifier. The CsI photocathode coating on the MCP enhanced the rejection of longer wavelengths. Images were acquired with a 36.8s integration period. The image is registered in a 200 by 228 pixel CCD detector with an angular resolution of 2.1 by 2.4 arc minutes. The single-pixel resolution in the vertical dimension is degraded to 10 pixels by a small oscillatory motion (wobble) of the spacecraft. Image processing with the Pixon algorithm [*Puetter*, 1995] was able to remove the effect of the wobble from the images by using the wobble-degraded image of a star as the point spread function. The narrow-band ultraviolet filters [*Zukic*, 1993] were optimized for observation of Earth's aurorae. The 1280–1340 Å filter was designed to isolate OI (1304) atomic oxygen. The 1400–1600 Å and 1600–1800 Å filters separate the short and long wavelength emission lines of the Lyman-Birge-Hopfield molecular nitrogen (N_2) band. Although N_2 has never been identified in any comet [*A'Hearn and Festou*, 1990] there are fluorescent emission lines from neutral carbon, carbon monoxide, and sulfur within the bandpass of the latter two filters. The most prominent spectral lines in these bands are the atomic carbon multiplets at 1561 Å and 1657 Å. The fourth positive band for CO has many weak lines from 1400–1750 Å, with the strongest at 1478 Å and 1510 Å, and sulfur has an emission line at 1814 Å.

A sequence of 71 images of the neutral oxygen coma at 1304 Å were acquired on April 1, 1997 between 0940 and 1025 UT. A series of shuttered images following these observations were used to subtract the background offset in the CCD prior to multiplication by the flat field image and absolute calibration scalar. The flat field image was first created during laboratory calibration and was later recalibrated in flight using images of sunlit airglow. The calibration scalar converts instrument counts to photon flux at the wavelength (1304 Å) expected in the observation. Extraneous scattered light from the Sun was removed by subtracting the average of each pixel over the 71 images (excluding the location of the comet). A single "mean" image of the comet, shown in

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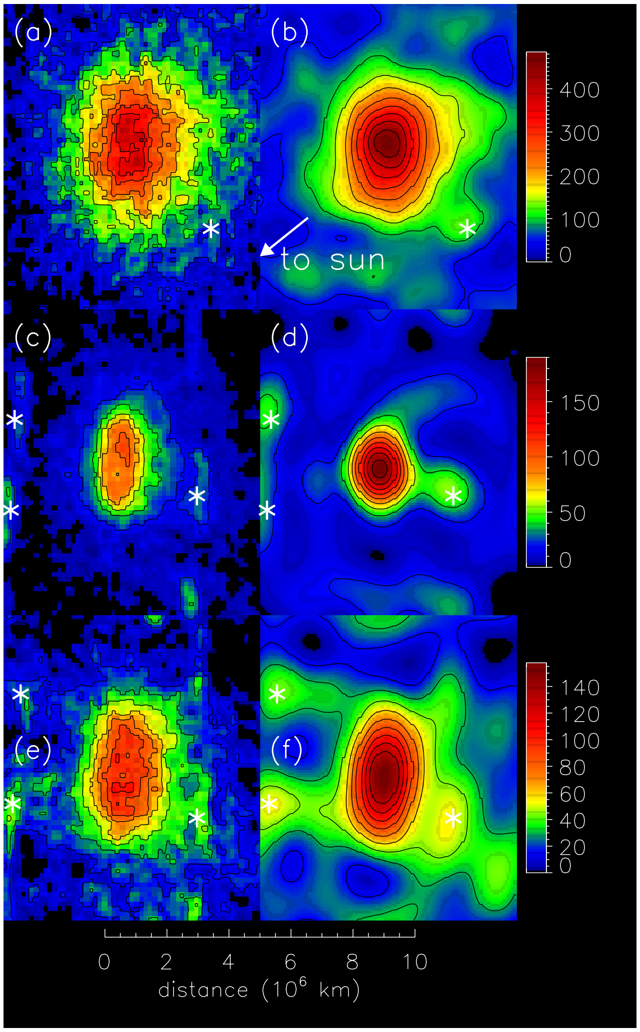

Plate 1. The coma of Comet Hale-Bopp constructed from a series UVI images of the spectral lines (a) OI (1304), (c) CI (1561) and (e) CI (1657). Images (b), (d) and (f) are the respective Pixon reconstructions. The scale unit is Rayleighs (R) and the contours levels are (a,b) 50 R and (c-f) 20 R. Extraneous UV sources (presumably stars) are indicated by asterisks.

Plate 1a, was produced by averaging each pixel at a fixed position relative to the comet over the set of images. Noise spikes 3 standard deviations above the mean due to penetrating radiation in the detector were removed. The asterisks indicate the location of resolved but unidentified UV sources. The broadening in the vertical direction and dual peak intensity is the result of spacecraft "wobble" motion that also decreases the maximum intensity.

Although the spacecraft motion degrades the image resolution, production rates can be recovered from the total photon flux observed in the coma. A minor correction to the background was modeled by fitting a smooth surface to the background noise to guarantee that summation over any region not including the comet or stars would be zero. Extraneous luminosity from stars near the comet was also removed. No FOV correction was required since the images extended beyond the measurable limit of the comae. The total flux for OI (1304) is shown in Table 1. Although some contamination from CII (1335) may be included on the basis of the spectrum obtained by *McPhate et al.* [1999] it should be at least an order of magnitude smaller than that of OI (1304), and the sensitivity of the instrument at this wavelength is less than half the value at 1304 Å. A reconstructed image using the Pixon algorithm shown in Plate 1b exhibits a circularly symmetric neutral oxygen coma with a diameter on the order of 5 million km. Celestial north is up and the Sun is to the left, as indicated by the arrow. The dust tail of the comet was not observed in this wavelength although dust particles may generate neutral oxygen through photodissociation of sublimating water ice and other volatile ices [*McCoy et al.*, 1986].

Images from a sequence of 87 exposures with the 1400–1600 Å band filter shown in Plate 1c and 61 exposures with the 1600–1800 Å filter shown in Plate 1e were obtained on March 31, 1997 during the intervals 1510–1653 UT and 1716–1753 UT, respectively. The total photon flux for CI (1561) and CI (1657) listed in Table 1 are obtained from the luminosity measured in the respective filters above calibrated for these wavelengths and neglecting all other sources. The absolute calibration factor for these filter measurements is the largest source of uncertainty (about 60%) owing to a significant variation of the spectral sensitivity with angle in the instrument (the comet was observed at 3° to 4° from the boresight) and since the CI emission lines occurred at the edge of the filter bandpass. The 1304 Å measurement has a much smaller uncertainty since the filter bandpass is centered on this wavelength, the comet image was closer to the instrument boresight and there was less scattered sunlight in the images. The Pixon reconstructed images for CI (1561) and CI (1657) are shown in Plates 1d and 1f. The vertical elongation of the coma may be due to an unknown UV source behind the comet, to incomplete removal of the wobble distortion or to imprecise registration of the simultaneously processed images. The diameter of the coma in this image is about 2-3 million km.

Production Rates

The production rates for neutral carbon and oxygen atoms were estimated from the measured luminosity for the respective emission lines. This method avoids modeling of the radial profile but is more sensitive to background subtraction. It is also assumed that the emissions are not optically thick. *Weaver et al.* [1999] noted a flattening of the emissions within a cometocentric distance of about 10^5 km (2 arcseconds near perihelion) which were suspected to be due to optical thickness. In our images this would be on the order of a single pixel. The photon flux at the camera, Γ, for C and O is related to the production rate Q by $g\tau Q = 4\pi R^2 \Gamma$ where R is the comet-Earth distance, g is the probability that a solar photon will be resonantly scattered or produced by resonance fluorescence, and τ is the lifetime of the scattering species. Although the product $g\tau$ is independent of heliocentric distance, the individual factors are uncertain within about a factor of 2. The values for g and τ near perihelion are listed in Table 1 along with the derived production rates for O and C. The independent estimates of carbon production from these 2 emission lines are remarkably similar despite the large error in the calibration. This can be accounted for if the absolute calibration scalar in both filters, the largest source of error, is systematically underestimated.

Table 1. Photon Fluxes and Production Rates

emission (Å)	Γ (10^3 s^{-1} cm^{-2})	uncertainty (percent)	g (a) (s^{-1})	τ (s)	Q (10^{30} s^{-1})
OI (1304)	13	25	1.01×10^{-5}	6.7×10^5 (b)	9.8
CI (1561)	3.1	60	9.89×10^{-6}	1.7×10^6 (c)	0.95
CI (1657)	13	60	4.09×10^{-5}	1.7×10^6 (c)	0.97

Sources: (a) *Woods et al.*, 2000, (b) *Opal et al.*, 1987, and (c) *Feldman*, 1978.

We estimated Q_{CO} and Q_{H_2O}, the production rates for CO and H_2O respectively, from the production rates of C and O whose comae extend far beyond the collision-dominated region. Most of the carbon is produced by photodissociation of CO. Another source is CS, although *Biver et al.* [1997] found from radio observations that Q_{CO} was about 2 orders of magnitude greater than Q_{CS} near perihelion. We assume that CO completely dissociates to C and O with a branching ratio of 1.0, same as the value used by *Woods et al.* [2000] and about twice the value of 0.43 used by *Sahnow et al.* [1993]. From the values of Q_C shown in Table 1, $Q_{CO} = (1.0 \pm 0.6) \times 10^{30}\text{s}^{-1}$. The production rate for water was estimated from the production rate of OH. Assuming that the only immediate sources of O are CO and OH, the combination of these reactions for branching ratios of unity implies $Q_O = Q_{OH} + Q_{CO}$ and an estimate of $Q_{OH} = (8.9 \pm 2.5) \times 10^{30}\text{s}^{-1}$ is obtained. We neglect the minor source of O from the rapid dissociation of CO_2 at short radial distances. The branching ratio for the production of OH from the photodissociation of H_2O is about 0.85 [*Budzien, et al.*, 1994; *Woods et al.*, 2000]. From this the production rate for water is found to be $Q_{H_2O} = (1.0 \pm 0.3) \times 10^{31}\text{s}^{-1}$.

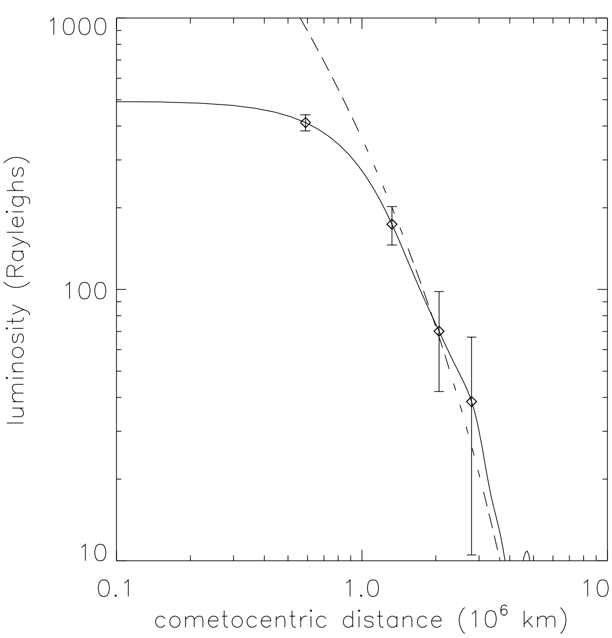

Figure 1. Radial profile of the oxygen coma from the (a) Pixon reconstructed 1304 Å image shown in Plate 1b (solid line) and (b) a single scale length *Haser* [1957] model (dashed line).

Discussion

The production rate for O estimated above is about 40% lower than the $(1.67 \pm 0.5) \times 10^{31}\text{s}^{-1}$ reported by *Woods et al.* [2000]. Their estimate includes a correction derived from the *Haser* [1957] coma model. In Figure 1 we show the radial dependence of the column-integrated brightness for the oxygen coma from Plate 1b (solid line) along with the single scale length *Haser* [1957] model (dashed line) [see *Opal and Caruthers*, 1977, for details]. This model assumes that the daughter species is primarily produced within about 10^5 km of the nucleus and therefore that a single scale length is justified. Here we have used the values in Table 1 and an outflow velocity estimated by *Woods et al.* [2000] at about 2.1 km s^{-1}. Any of the parameters could be varied by a factor of about 2 and remain within the error of the measurement. Similarly, the assumptions about the branching ratios used in deriving Q_{CO} and Q_{OH} from Q_C and Q_O and the error in the measured production rates for C and O from observations introduces uncertainties of 30% or more. Our estimate for Q_{CO} is one half of the $2 \times 10^{30}\text{s}^{-1}$ derived from radio observations of the CO molecule at perihelion [*Biver et al.*, 1997] and one third of the $(3.3 \pm 0.4) \times 10^{30}$ s^{-1} reported by *McPhate et al.* [1999]. Our value is probably underestimated given the large uncertainty in the calibration. It is also possible that the discrepancy in the Q_{CO} production rate is due to large fluctuations in its release as the surface of the comet experiences its most extreme sputtering near perihelion. During the less than 2 hour observing period for each filter the UVI did not detect any statistically significant fluctuations in the measured flux. However, the range in the reported production rates for CO referenced above indicate that changes on the order of 100% over the few days near perihelion were occurring. Our estimate for Q_{H_2O} was in good agreement with the $1 \times 10^{31}\text{s}^{-1}$ reported by *Biver et al.* [1997]. We determine the ratio of CO to H_2O production to be about 9%, which is less than the average of about 30% within 2 AU [*Huebner and Benkhoff*, 1999].

We conclude that the production rate for H_2O was $(1.0 \pm 0.3) \times 10^{31}$ s^{-1} and for OH was $(8.9 \pm 2.5) \times 10^{30}$ s^{-1}, both in reasonable agreement with other UV and radio observations near perihelion. The estimated value for the CO production rate was smaller than other observed values which may be due to the uncertainty in the calibration or fluctuations in the release of CO from the comet.

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