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HUBBLE SPACE TELESCOPE ULTRAVIOLET IMAGING AND HIGH-RESOLUTION SPECTROSCOPY OF WATER PHOTODISSOCIATION PRODUCTS IN COMET HYAKUTAKE (C/1996 B2)

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ABSTRACT

Comet Hyakutake (C/1996 B2) provided a target of opportunity for performing a systematic study of water photodissociation products in which we obtained data from three instruments on the *Hubble Space Telescope* (*HST*). The *HST* Goddard High Resolution Spectrograph (GHRS) was used to measure the line profile of hydrogen Lyα (H Lyα) at six locations around the coma of the comet, ranging from the nucleus to a displacement of 100,000 km, and covering different directions compared with the comet-sun line. GHRS yielded line profiles with a spectral resolution (FWHM ~ 4 km s^{-1}) that was a factor of 2–3 better than any previous H Lyα or Hα ground-based measurements. The Wide Field Planetary Camera 2 (WFPC2) and the Woods filter were used to obtain H Lyα images of the inner coma. The faint object spectrograph (FOS) was used to determine the OH production rate and monitor its variation throughout the *HST* observing sequence. The GHRS H Lyα line profiles show the behavior of a line profile that is optically thick in the core for positions near the nucleus (<5000 km) and gradually becoming more optically thin at larger displacements and lower column abundances. A composite H Lyα image constructed from four separate WFPC2 exposures is consistent with the relative fluxes seen in GHRS observations and clearly shows the dayside enhancement of a solar illuminated optically thick coma. These data were analyzed self-consistently to test our understanding of the detailed physics and chemistry of the expanding coma and our ability to obtain accurate water production rates from remote observations of gaseous hydrogen (H) and hydroxyl (OH), the major water dissociation products. Our hybrid kinetic/hydrodynamic model of the coma combined with a spherical radiative transfer calculation is able to account for (1) the velocity distribution of H atoms, (2) the spatial distribution of the H Lyα emission in the inner coma, and (3) the absolute intensities of H and OH emissions, giving a water production rate of $(2.6 \pm 0.4) \times 10^{29}$ s^{-1} on 1996 April 4.

Subject headings: comets: individual (Hyakutake) — molecular processes — ultraviolet: solar system

1. INTRODUCTION

Comets are believed to be the most primitive bodies in the solar system and are thus the most representative of the material present during its formative stages. Obtaining accurate chemical and elemental compositions of comets as a group provides the best evidence regarding the physical and compositional conditions present in the early solar system. For this reason, one of the primary goals of cometary astronomy is to determine the abundances of observable species in the atmospheres or comae of comets. By use of models which account for the chemical production and loss and also the motion of that species in the coma, the production rate of that species, and by inference that of its parent, can be derived.

Water is the most abundant primary constituent in the gaseous coma which is formed by vaporization of the nucleus (Delsemme 1982, 1991). We have a basic understanding of the photochemical production of H, H_2, OH, O, and various ions from water. However, information about the basic photochemical rates and kinetics of the photodissociation of water and OH has been inconsistently applied in the analyses of observations which limit the true accuracy of published production rates to no better than 50%–100%. These are in addition to uncertainties in absolute calibration and knowledge of the solar radiation output. In order to test our understanding and our best models for cometary comae, a program of observations with three instruments on the *Hubble Space Telescope* (*HST*) was planned to perform a systematic study of two of the major water photodissociation products (H and OH) on the next bright target-of-opportunity comet. Upon the discovery of comet Hyakutake (C/1996 B2) in late January of 1996 and the realization that it would become a sufficiently bright target, our program was initiated and subsequently performed during the first week of 1996 April.

These observations provide direct information about the velocity distribution of H atoms produced in comets, which, in turn, is diagnostic of the various photodissociation processes. Because of conservation of energy and momentum in the primary water dissociation reaction (producing H + OH), a measurement of the ejection speed of the H atom also yields that of the OH radical by the ratio of the masses. The ejected speed of OH has been a matter of some debate (Crovisier 1989; Combi, Bos, & Smyth 1993; Cochran & Schleicher 1993; Wu & Chen 1993; Budzien, Festou, & Feldman 1994). Our *HST* observations are used to provide a direct test of the models and model parameters

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used in interpreting remote observations of water dissociation.

The history of observations of the emission of hydrogen Lyα (H Lyα) at 1216 Å in comets began with the ultraviolet measurements by *OGO 5* (Bertaux & Blamont 1970; Bertaux, Blamont, & Festou 1973) and *OAO 2* (Code, Houcke, & Lillie 1972). Later rocket and *Skylab* based electrographic cameras measured the spatial distribution of the large H Lyα coma in comet Kohoutek (Carruthers et al. 1974; Feldman et al. 1974). Resonant scattering of solar H Lyα photons which enables us to detect H atoms in the coma also produces a radiation (pressure) force that is comparable to that of solar gravity. The resulting spatial distortion of the coma is diagnostic of the velocity distribution of the H atoms exiting the inner (within 10^5 km) coma. Parametrized multi-Maxwellian point-source models for the shape of the H coma model (Keller & Meier 1976; Meier et al. 1976) demonstrated that most of the hydrogen in the coma was most likely to be produced in the photodissociation of water (peak near 17–19 km s^{-1}) and that of its daughter OH radical (peak near 8 km s^{-1}). A variable low-speed component was explained qualitatively as a thermalized component of initially high-speed H atoms, which are slowed in the inner coma through collisions with slow-moving (~ 1 km s^{-1}) heavy molecules (mostly water).

Subsequent Monte Carlo models by Combi & Smyth (1988a, 1988b) included the full photochemistry, exothermic photodissociation ejection speeds, hydrodynamic water outflow, and multiple collisions between the H atoms and the heavy molecules in the inner coma. These models showed that the multi-Maxwellian velocity distributions of the parametrized models and the corresponding sets of weighting parameters of the best fit to coma images provide smoothed approximations to those obtained with the explicit Monte Carlo models. Most importantly, the velocity distributions in the Monte Carlo models follow directly from the physical/chemical assumptions and not from adjustable parameters. However, the agreement of the different kinds of models demonstrates that the solutions are not unique and that direct observations of H velocities via Doppler-broadened line profiles would provide another independent model constraint. Similar Monte Carlo models have already been applied to a variety of radio and optical line profile observations of a number of species in comet Halley (Combi 1989; Smyth, Combi, & Stewart 1991; Smyth, Marconi, & Combi 1995) and have also been combined with a one-dimensional spherical radiative transfer model for H Lyα scattering and successfully applied to *IUE* observations of comets Giacobini-Zinner and Halley (Combi & Feldman 1992, 1993).

The H Lyα line shape in comet Kobayashi-Berger-Milon (C/1975 N1) had been measured with the Copernicus satellite with results reported by Festou et al. (1979), improving on early measurements of Keller, Bohlin, & Tousey (1975). Vectorial models were presented for single water coma outflow speeds of 0.5 and 1.0 km s^{-1}. The overall width of the line profile was consistent with a water source of H having a velocity in the vicinity of 19 km s^{-1} and a more extended OH source with velocities in the range of 6–8 km s^{-1}, having been suggested earlier by Keller & Meier (1976); however, the spectral resolution (FWHM = 14 km s^{-1}) was only barely able to resolve the intrinsic cometary line. Since then much progress has been made on our understanding of the solar photodissociation of OH by near-UV and Lyα photons (Schleicher & A'Hearn 1982, 1988; van Dishoeck & Dalgarno 1984) enabling the more comprehensive and physics-based approach provided here.

The hydrogen Balmer α emission (Hα) at 6563 Å in comets is excited through absorption of solar photons from the Lyman series, H Lyβ and higher, and subsequent cascade to the 2 ^2S excited state. The first such observations of the line profile in comet Kohoutek were made using a pressure-scanned Fabry-Perot (F-P) interferometer by Huppler et al. (1975). F-P observations of Hα in comet Halley have recently been analyzed with a derivation of the Combi & Smyth (1988a, 1988b) model and described by Smyth et al. (1993). The spectral instrument profiles for most of these F-P observations can be represented by a Gaussian with an FWHM of about 10 km s^{-1}, showing the influence of the wider cometary hydrogen line. The effective apertures for these observations have had radii in the range of 3′–5′ or typically a few $\times 10^5$ km projected at the comet. Brown & Spinrad (1993) have reported high-resolution echelle spectra of comets Austin (C/1989 X1) and Levy (C/1990 K1) with a FWHM velocity resolution of ~ 7.5 km s^{-1} along a slit covering distances up to about 10,000 km. The structure of the line suggested the possibility of some velocity components for hydrogen atoms higher than have been predicted even from the latest assessments of laboratory data (Wu & Chen 1993). Such a structure has never been reported in any of the F-P observations.

There has been some difficulty in understanding the widths of radio OH line profiles in terms of what is expected from water photodissociation (Crovisier 1989). Some observations point to a slower ejection velocity (~ 0.9 km s^{-1}) than is normally predicted photochemically (1.05 km s^{-1}). Budzien et al. (1994) have examined water photochemistry, its variation with solar activity, and the effects on the distribution of OH in the coma and on extracted water production rates, and find no evidence for slower velocities. Through conservation of momentum in the primary water dissociation reaction (H + OH) a measurement of the ejection speed of the H atom also yields that of the OH radical.

Direct observations of H velocities would prove invaluable for obtaining more precise information on the cometary dissociation products. By measuring the Doppler broadening of line profiles, independent velocity information can be retrieved which can, in turn, be used to test the models that are needed for correct determination of water production rates. Measuring the H Lyα line at distances of $\leq$few $\times 10^4$ km from the nucleus primarily samples the region in which the direct water source of H dominates. The OH source is important for distances greater than 10^5 km.

2. OBSERVATIONS

The *HST* Goddard High Resolution Spectrograph (GHRS) was used to measure the H Lyα line profile at 6 locations around the coma of comet Hyakutake (C/1996 B2) with a spectral resolution of ~ 4 km s^{-1} full width half-maximum (FWHM), much better than had been obtained previously. Images of the spatial distribution of H Lyα in the inner coma were made with the Wide Field Planetary Camera 2 (WFPC2) using the far-UV Woods filter. The Faint Object Spectrograph (FOS) was used to measure the brightness of the OH (0–0) band emission at 3085 Å to provide an independent measure of the water production rate and to monitor any time-dependent variation throughout the observing sequence. The *HST* obser-

TABLE 1

GHRS H Lyα Results for C/Hyakutake

Date (1996 April) (UT)	Position (km)	Exposure (s)	Brightness (kR)	
			Observed	Model[a]
3.360	Nucleus-centered	1305.6	59.7	81.0[b]
3.432	5298 sunward	1468.8	67.0	70.7
3.499	5335 tailward	1468.8	57.7	55.0
3.566	5368 normal[c]	1468.8	66.0	64.0
3.633	33507 sunward	2937.6	52.9	48.4
3.829	111085 sunward	5875.2	28.0	26.3

[a] Monte Carlo and spherical radiative transfer models with a water production rate of 2.8×10^{29} s^{-1}.

[b] The temperature used in the calculation is too high for the near nucleus ($< 1''$) region.

[c] This spectrum was recorded at a location displaced perpendicular (normal) to the comet-Sun line.

TABLE 2

Water Production Rates from FOS OH Measurements

Date (1996 April) (UT)	r (AU)	Δ (AU)	B (kR)	Q (H_2O) (10^{29} s^{-1})
3.29.........	0.846	0.313	300	2.30
3.78.........	0.835	0.328	310	2.38
4.18.........	0.826	0.341	310	2.14

Note.—Value r = heliocentric distance in AU, Δ = geocentric distance in AU, B = OH (0–0) band brightness in kilorayleighs, and Q (H_2O) = water production rate in 10^{29} s^{-1}.

vations were made during a 27 hr period on 1996 April 3 and 4. A detailed description of the observations follows.

Line profiles of the H Lyα emission were measured using the echelle-A grating and the 0″.23 square small science aperture (SSA) on GHRS. Observations were made at 6 locations around the coma as detailed in Table 1. The spectra in Figures 1*a*–1*f* clearly show the comet emission Doppler shifted from the geocoronal hydrogen emission by the radial component of the relative velocity of the comet from Earth ($\sim$54 km s^{-1}). The line profile becomes apparently wider as the nucleus is approached because of the strong optical depth saturation in the line center at the large column abundances encountered there. The widths of the bases of all the lines are reasonably consistent with the standard picture of maximum H atom velocities with a peak near 18 km s^{-1} as well as some components in excess of 20 km s^{-1} expected for water and OH photodissociation. There is no clear evidence in the H Lyα observations for a high speed components as suggested from past Hα observations (Brown & Spinrad 1993), although the noise level in the *HST* observations may not have been quite as good even when degraded to the spectral resolution of the groundbased Hα observations. Perhaps the previous identification might have been due to a chance coincidence of a minor rotational line of either C_2, NH_2, or H_2O^+ (which are ubiquitous in the red portion of cometary spectra) or to a remnant of the solar Hα Fraunhofer line subtraction.

FOS spectra of OH in Comet Hyakutake were taken near the beginning, middle, and end of the *HST* observing sequence. The 3″.7 × 1″.2 aperture was used with grating G270H yielding spectra covering the range from 2200 to 3300 Å. The main purpose of the measurement was to record the (0–0) vibronic band brightness of OH at 3085 Å, although along with the (0–0) band, the (1–1) and (1–0) bands of OH, as well as emissions from molecular sulfur (S_2) and CS were seen by Weaver et al. (1996) in their more broad-based UV spectroscopy program of comet Hyakutake with *HST*. A summary of our FOS observations of OH is given in Table 2.

WFPC2 images of the comet are shown in Figures 2*a* and 2*b* (Plate 27). The sunward direction is toward the upper right corner of each image which covers a square region of about 14,000 km on a side. Figure 2*a* shows the inner dust coma taken with the red F675W filter. Although this image was recorded for the purpose of correcting the predicted position of the comet from the orbital ephemeris, it also provides a good spatial reference for understanding the H Lyα distribution. The ejection of dust and three distinct spiral dust jets are visible toward the sunward side of the nucleus. Using current estimates of the rotation period of about 6.25 hr for the nucleus of comet Hyakutake (Schleicher et al. 1996) the curvature of the jet spirals implies projected dust velocities of about 400 m s^{-1}. A rotation period of twice this value has also been suggested by Larson et al. (1996). This velocity is consistent with that expected from various dusty-gas dynamic calculations for micron-sized dust particles (Gombosi, Nagy, & Cravens 1986). Also visible toward the antisunward side (*lower left*) is the narrow dust trail. Two of the small fragments of the nucleus which have been reported by numerous observers are apparent in more contrast enhanced versions of this image.

Figure 2*b* shows an image taken with the far-UV Woods filter, which has a bandpass of 1200–2200 Å. For a comet observation, practically all the emission in the image comes from a combination of cometary and geocoronal H Lyα. To serve as a check, one image was taken with a combination of the Woods filter and the F130LP filter (a long pass filter that excludes the H Lyα region of the spectrum) which would have shown any substantial excess emission at wavelengths above 1300 Å. Nothing was apparent above the noise level. The brightness of all other emissions (by far dominated by the fourth positive system of CO from 1300–1570 Å) should have contributed less than a maximum of $\sim$3 kR to a total brightness which is in the range of roughly 90 kR. The absolute calibration of WFPC2 with the Woods filter at H Lyα has been estimated from a report by the WFPC2 team (Clarke et al. 1995). The upper left region of the image is artificially depressed because of the non–flat field of the rotated Woods filter image. A black dot marks the location of the nucleus. This image was constructed from four separate images with a combined exposure time of 2100 s.

3. MODEL ANALYSIS

Water production rates were computed from the FOS observations of the (0–0) band OH emission using the *g*-factors from Schleicher & A'Hearn (1982, 1988) along with the hybrid Monte Carlo/gasdynamic model for OH of Combi et al. (1993). The water production rates derived from them are given in the last column of Table 2. Model analyses of the WFPC2 H Lyα image and GHRS spectra have been performed using the hydrogen Monte Carlo particle trajectory model (Combi & Smyth 1988a, 1988b) both alone in the optically thin limit, and in combination with a

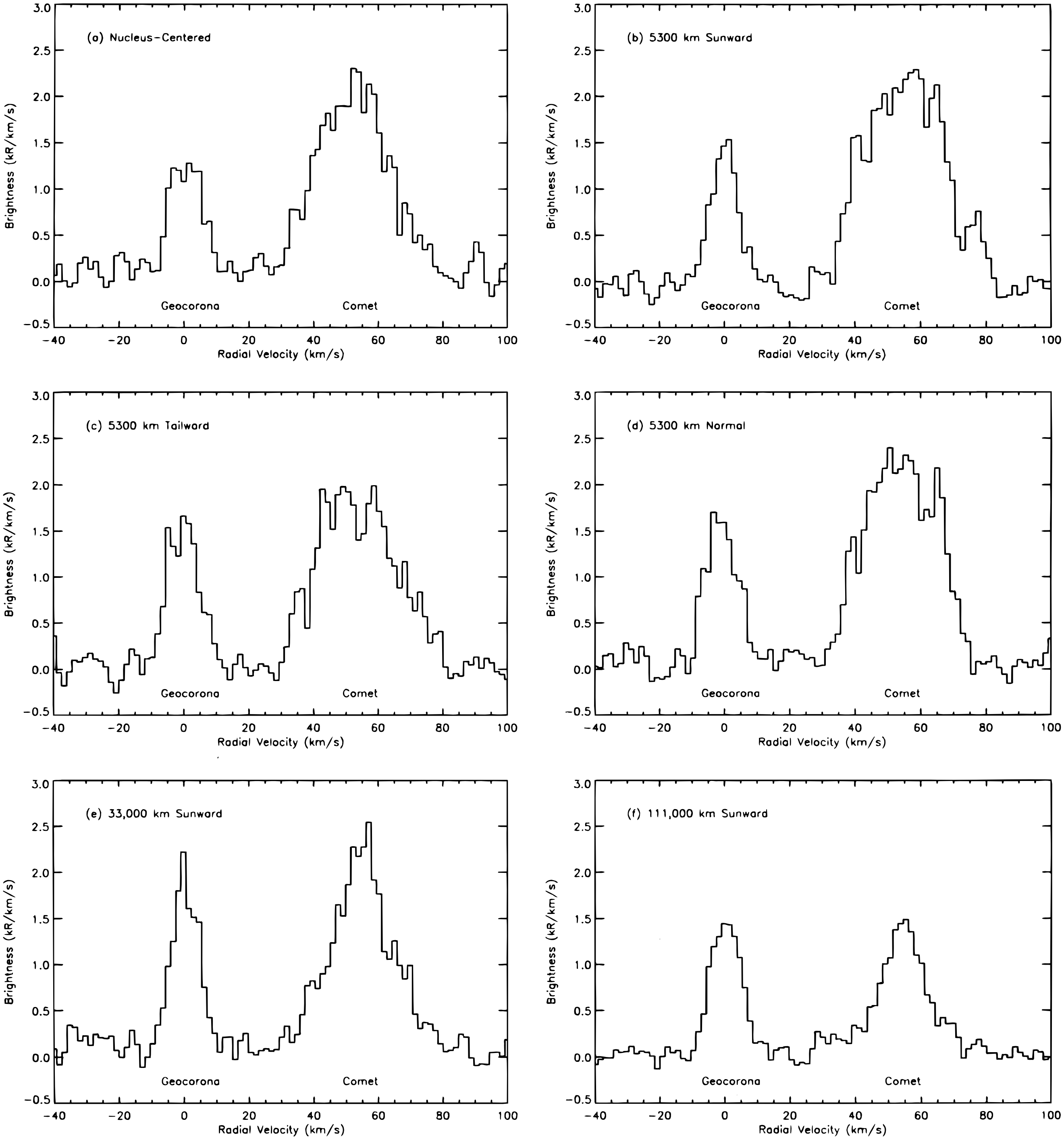

FIG. 1.—GHRS spectra of the H Lyα region of the spectrum of Comet Hyakutake (1996 B2). In (*a*)–(*f*) each of the spectra, at the six positions noted, are the emissions from H atoms in the coma of the comet on the right and from the H geocorona on the left. The spectra are plotted on an Earth-referenced Doppler velocity scale in km s^{-1}. The brightness scales for all are the same for easy comparison. See text for a discussion.

spherical radiative transfer calculation (Combi & Feldman 1992, 1993) in the optically thick case, to evaluate multiple scattering and opacity effects within about 10^5 km from the nucleus. The fluorescence rate of H Lyα was calculated using the daily measurement of the solar H Lyα flux (3.0×10^{11} photons cm^{-2} s^{-1}) from the SOLSTICE instrument on the *Upper Atmosphere Research Satellite* (*UARS*) as described by Woods et al. (1996), and the standard quiet-Sun solar line profiles from Lemaire et al. (1978) as discussed previously by Combi & Smyth (1988b). The use of the SOLSTICE data enables us to account for the variability of the solar H Lyα flux with solar rotation. The model computes the variable *g*-factor for the heliocentric velocity of each atom. The physics and chemistry used in the models for the analysis of the H and OH observations are internally self-consistent.

In Figure 3 is a contour plot of the radiative transfer model brightness (kR) for H Lyα covering the same scale as the image in Figure 2*b*. The model gives a good quantitative match to the integrated brightnesses in the five offset positions in the GHRS spectra (see Table 1) and to the image, except within 1000–2000 km from the nucleus where

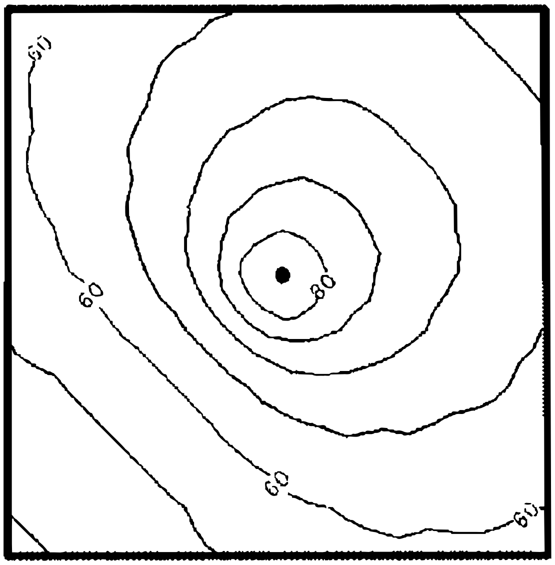

FIG. 3.—Model brightness contours for the coma of Comet Hyakutake (1996 B2). The brightness contours in kilorayleighs were computed from the combination of the Monte Carlo model for the distribution of the H atoms in the coma and the spherical radiative transfer model for illumination from the sunward direction. The scale is the same as the images shown in Fig. 2. Although the H atom distribution in the coma is spherical, a aspherical axisymmetric distribution of H Lyα radiation is produced by multiple scattering in the optically thick coma. An optically thick line-of-sight integration was done for the comet's observational geometry.

the oversimplified assumption of an average constant (and large) temperature in the radiative transfer model, which is only appropriate for the outer coma, breaks down. The H atoms within $\sim$1000 km from the nucleus are nearly thermalized with the cool ($T \ll 1000$ K) outflowing coma and are not represented by the high temperature ($\sim$6500 K) appropriate for most of the optically thick coma (10^3–10^5 km) in the model. The current radiative transfer model uses a radial isothermal H atom density distribution to represent the velocity dispersion of H atoms from the Monte Carlo model. A more sophisticated radiative transfer calculation than is now available for the full line profile, which incorporates the details of the spatial variation of the velocity distribution, is required.

Figures 4*a* and 4*b* show comparisons of the line profile predicted in the optically thin limit by the Monte Carlo H model for the observations at 111,000 and 33,000 km, respectively. The intrinsic model line profiles accumulated at a velocity resolution of 1 km s^{-1} were convolved with the instrument spectral function determined from spectral lines of the internal calibration source. The radiative transfer model predicts that the coma is optically thin at 10^5 km. This is borne out by the very good agreement of the model with the data at 111,000 km. At 33,000 km the coma is predicted to be partially optically thick giving about a 25% reduction in integrated brightness. This also is borne out by the model-data comparison in Figure 4*b*. The model fits to the calibrated integrated brightnesses with the radiative transfer calculation would imply a water production rate of 3.0×10^{29} s^{-1} if all of the observed hydrogen in the inner coma results from water. However, extra hydrogen from hydrocarbons as methanol, ethanol, acetylene, and formaldehyde (see Mumma et al. 1996a, 1996b) should produce hydrogen at the level that requires lowering this production rate by about 3%–9% over a wide range of assumptions. Accounting for this yields a water production rate from the H observations of 2.8×10^{29} s^{-1}, compared with the average value of 2.3×10^{29} s^{-1} determined from the model analysis of the FOS OH observations.

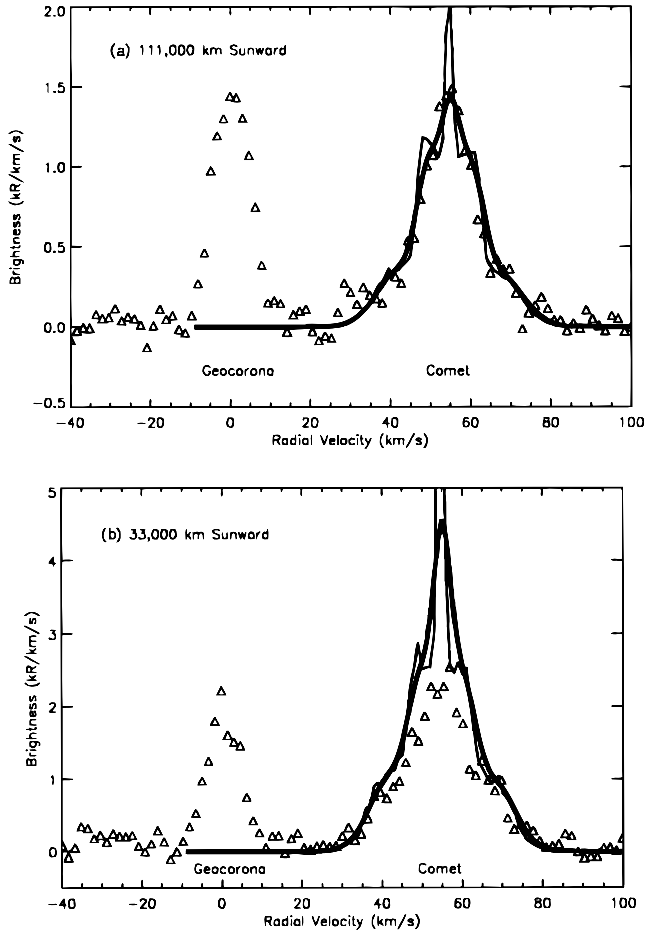

FIG. 4.—Comparison of GHRS line profiles with optically thin model. (*a*) Comparison of the observed line profile taken with GHRS at 111,000 km sunward of the nucleus (*triangles*) with the optically thin model convolved with the GHRS instrument spectral function (*thick solid line*). The thin line shows the intrinsic comet line profile calculated by the model at a much higher velocity resolution of 1 km s^{-1}. The separate contributions of thermalized H (*central peak*), H from OH (*inner shoulder*), and H from H_2O (*outer shoulder*), easily seen in the intrinsic profile, are visible but somewhat smeared by the instrument spectral function, in the convolved model and the data. (*b*) Same optically thin model but compared with the observed line profile at 33,000 km. The model-data comparison shows that the coma is clearly not optically thin at this location. It is mostly the top of the central peak which is saturated and, therefore, not observed. Our simple spherical radiative transfer calculation, which cannot compute full line profiles does accurately reproduce the integrated flux in the observed line.

The uncertainty in the value of the water production rate determined from the OH measurement is about $\pm$20%, owing to uncertainties in the *HST* FOS calibration (5%), the (0–0) band fluorescent rate or *g*-factor (5%), and the model parameterization coming mainly from the water lifetime and branching ratios (10%). For the production rate from the H measurement the uncertainty is slightly larger, and the relative mix from the various contributions is different. There are uncertainties owing to the fluorescence rate coming from the *UARS*/SOLSTICE integrated solar H Lyα flux measurement and from the assumed line profile shape which together are worse than for OH. On the other hand, the uncertainty due to the model parameterization does not have as big an effect for H as it does for OH. The uncertainty in the abundance of H from hydrocarbons yields an additional ±3%. Therefore, the final water production rates are $(2.3 \pm 0.5) \times 10^{29}$ and $(2.8 \pm 0.7) \times 10^{29}\ \mathrm{s}^{-1}$ from OH and H, respectively, consistent with one another to within the expected uncertainty ranges.

Bertaux et al. (1997) have presented H Lyα results obtained with the Solar Wind ANisotropies (SWAN) instrument on the *Solar and Heliospheric Observatory* (*SOHO*) satellite. Measurements were taken on many days over an extended period of time, including observations on 1996 April 2 and 6, 2 days to either side of our observations. They compare their results to a number of preliminary water production rates in comet Hyakutake most of which have appeared in various IAU circulars. Hicks & Fink (1997) also have presented water production rates obtained from analyses of observations of the forbidden $\mathrm{O}(^1D)$ at 6300 Å. Water production rates are in agreement to within both the unavoidable uncertainties and the differences owing to model parameterizations and parameter values. Some differences may even be due to real temporal variations in the comet. However, as discussed in the introduction, due to the fundamental model parameterization and numerical parameter differences, a detailed comparison is not possible at this time without complete self-consistent reanalyses of all the other data.

4. DISCUSSION

Our standard quiet Sun water photodissociation model (Combi & Smyth 1988a, 1988b; Combi 1989) where the main branch for dissociation of water and the principal components of exothermic velocity are given by

$$\mathrm{H_2O} + h\nu \rightarrow \mathrm{H}(17.8\ \mathrm{km\ s^{-1}}) + \mathrm{OH}(1.05\ \mathrm{km\ s^{-1}})\ ,$$

and which accounts for partial thermalization of H atoms by the outflowing heavy coma gas, is able to explain the observed H-atom Doppler line profile, the spatial distribution of H atoms in the inner coma, and the absolute abundances of H and OH. Our model parameterization is consistent with the quiet sun limit of the full solar activity dependent formulation of water photochemistry of Budzien et al. (1994). We believe this model-data agreement provides further evidence that this type of formulation is on solid ground and that this approach (or an equivalent one) is preferred for extracting water production rates from observations of the photochemical fragments of water molecules.

The absence of the thermalized peak in the profile measurements taken close to the nucleus (≤33,000 km) results from saturation of the line center (i.e., optical depth effects) and not from any resolution limitation in the observations. The thermalized peak is clearly present in the line profile at 111,000 km. The peak and its contribution relative to the high speed components (wings) are reproduced by the model. The agreement obtained gives confidence in the combination of the partial thermalization calculation, the hybrid kinetic/hydrodynamic description of coma outflow speed and temperature, and the underlying photochemical rates and energetics, employed in our model. Our success also means that spatially offset H Lyα measurements can serve as a useful method for measuring water production rates in comets, providing at least as accurate a picture as can be obtained from the more common OH measurements.

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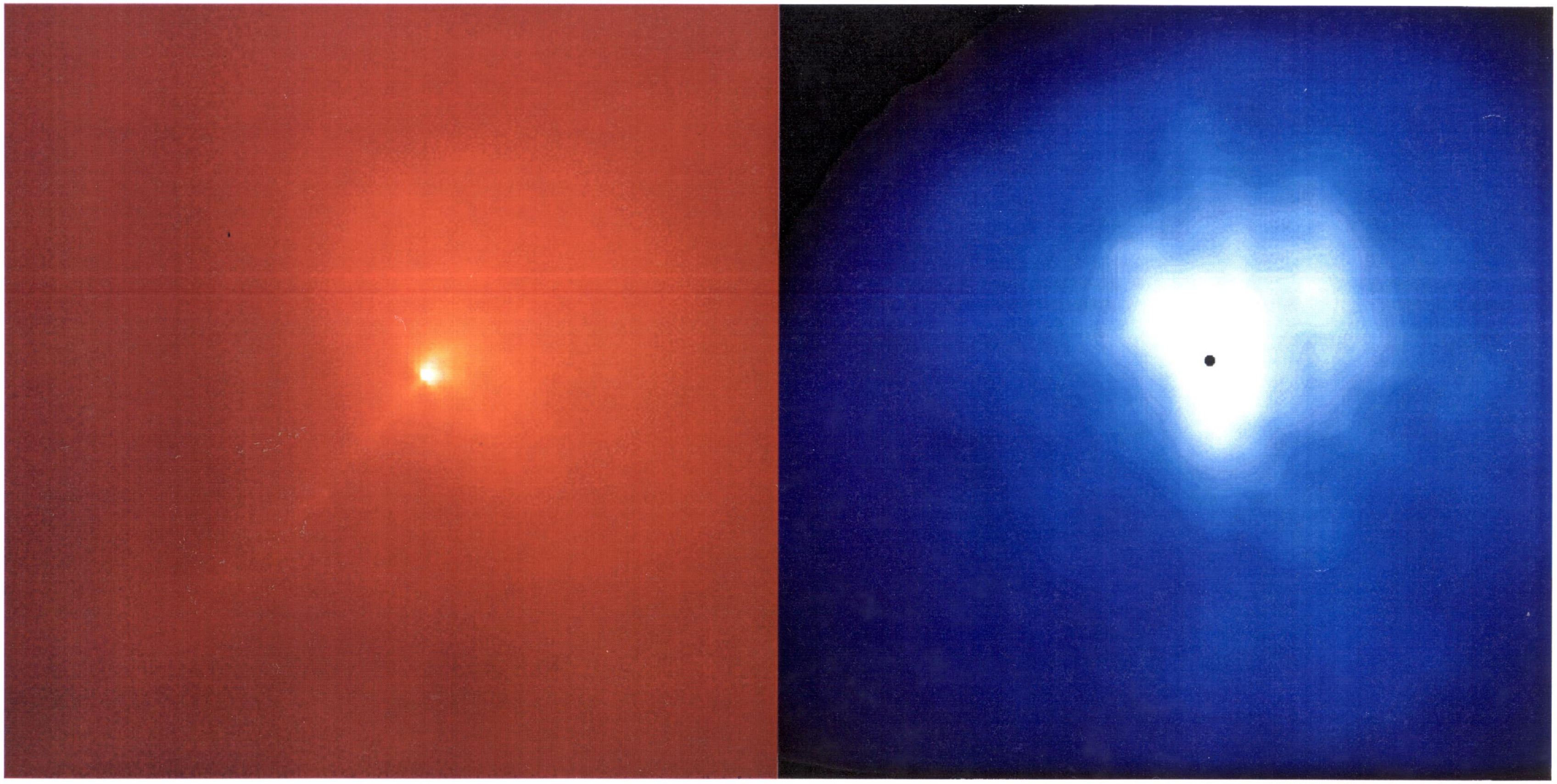

Fig. 2.—Images of the inner coma of Comet Hyakutake (1996 B2) in the visible and far-UV. The spatial scale is nearly 14,000 km on a side, and the Sun is toward the upper right corner of the image. (*a*) Image of the inner coma was taken by WFPC2 with the red F675W filter, which passes mostly sunlight at 6750 Å reflected from micron-sized dust particles. Three spiral dust jets are seen in the sunward hemisphere. In contrast enhanced versions of this image the antisunward grain trail or spike (barely visible here) as well as two of the many "condensations," which probably represent clumps of material broken off the nucleus days earlier, are easily visible. (*b*) WFPC2 image was taken with the far-UV Woods filter, having a bandpass of 1200–1600 Å. For a comet this effectively makes a H Lyα filter since this emission dominates the far-UV spectrum. Black dot is added to show the location of the nucleus.

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