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Analysis of IUE Observations of Hydrogen in Comets

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Abstract

The large body of hydrogen Lyman-alpha observations of cometary comae obtained with the International Ultraviolet Explorer satellite has gone generally unanalyzed because of two main modeling complications. First, the inner comae of many bright (gas productive) comets are often optically thick to solar Lyman-alpha radiation. Second, even in the case of a small comet (low gas production) the large IUE aperture is quite small as compared with the immense size of the hydrogen coma, so an accurate model which properly accounts for the spatial distribution of the coma is required to invert the inferred brightnesses to column densities and finally to H atom production rates. Our Monte Carlo particle trajectory model (MCPTM), which for the first time provides the realistic full phase space distribution of H atoms throughout the coma has been used as the basis for the analysis of IUE observations of the inner coma. The MCPTM includes the effects of the vectorial ejection of the H atoms upon dissociation of their parent species (H_2O and OH) and of their partial collisional thermalization. Both of these effects are crucial to characterize the velocity distribution of the H atoms. A new spherical radiative transfer calculation based on our MCPTM has been developed to analyze IUE observations of optically thick H comae. The models have been applied to observations of comets P/Giacobini-Zinner and P/Halley.

Background

Since the launch and beginning of operation of the International Ultraviolet Explorer satellite in 1978 the ultraviolet spectra of more than thirty comets have been recorded. The analysis of the observations of the atomic resonance lines of oxygen, carbon, and sulfur and of such interesting and important diatomic radicals such as OH, CO and CS has lead to a significant advance in our understanding of the elemental and (by inference) the chemical composition of many comets (Feldman 1983, 1991). Extensive observations of comets Halley and Giacobini-Zinner covering not only the periods of spacecraft flybys but also monitoring their long term secular variations have also been made (Feldman et al. 1987; McFadden et al. 1987).

Observations of comets by IUE (or any other wavelength discriminating device for that matter) typically yield directly the emission flux from some atomic or molecular transition. Most species in comets radiate by resonance fluorescence with solar radiation. Through appropriate modeling of an individual gas species, which accounts for its transport (dynamics and/or kinematics) in the coma, its production and decay mechanisms, and its radiative emission mechanism, the production rate can be determined from observations. Furthermore, observations of the spatial distribution of emitted radiation can actually be used to help specify some of the model parameters. In the analysis of the ultraviolet emission of the typically most abundant species in cometary comae, namely H, O, OH, C and CO, one principal objective is to study relative abundances (or production rates) in order to help understand the chemical composition of comets and the vaporization process of the nucleus.

Work by the many IUE comet observers has been quite successful in this type of analysis for the UV emissions of CO, OH and CS for a number of comets. However, a difficult modeling analysis problem is encountered when trying to analyze the observations of hydrogen Lyman-α radiation that is the brightest emission in the cometary UV from the most abundant species in the coma. The larger IUE entrance aperture is roughly oval in shape with a size of about 10 by 20 arcsec. Typical IUE observations are made with this aperture centered on the photometric nucleus. For a comet at an average geocentric distance of 1 AU this corresponds to sampling an area on the coma of only 7300 by 14600 km. Figure 1 shows the Lyman-α region of the spectrum of comet Halley recorded on October 20, 1985, with the large IUE aperture centered on the position of the photometric nucleus. For moderately productive comets, the large number of H atoms in this region, compounded by the large resonance scattering cross section of H atoms, yields an optically thick medium for the solar Lyman-α radiation. The optically thin models used for the analysis of other species are thus not usually adequate for H atoms in the inner coma.

The resonance scattering of the same solar Lyman-α radiation that enables the H coma to be observed, imparts on the individual H atoms a radiation-pressure acceleration that is roughly equal in magnitude to the solar gravitational acceleration. As a result of the exothermic (up to 2 eV) photodissociations of water molecules and OH radicals, and partial thermalization through collisions with heavy coma molecules, H atoms exit the inner coma with a broad range of velocities (1-25 km s^{-1}). The combination of the velocity distribution and radiation pressure acceleration produces an H coma of tremendous extent displaying a broad curved tail. The size of the H coma is usually a few tenths of an astronomical unit and can subtend an angle of up to 50^{o} when viewed in the sky. Keller and Meier (1976) constructed a model for the H coma based on a point source with a parametrized 3-component Maxwellian distribution for the H atom velocities which did a credible job of reproducing the shape and radial distribution of the coma outside the optically thick region. Meier et al. (1976) fitted the model to wide-field images of the Lyman-α coma of comet Kohoutek; this process yielded relative weights for three Maxwellians at 4, 8 and 20 km s^{-1}.

Later a model based on the physical processes that occur in the coma, photodissociation of water and OH and multiple collisions between H atoms and the heavy coma molecules, was constructed (Combi and Smyth 1988 a&b). This model is a Monte Carlo simulation that could also reproduce the Lyman-α images of comet Kohoutek. However, the velocity distribution in this model (which was similarly broad but more irregular than the Keller and Meier model) had no adjustable parameters and was a natural product of physical processes occurring in the coma. The same model has been since used to explain a similar image of the H coma of comet Halley constructed from observations by the Pioneer Venus Orbiter Ultraviolet Spectrograph when the comet was near perihelion (Smyth, Combi and Stewart 1991). The same model has been applied by the PI and Co-I of this project to model the inner regions of the H coma seen with IUE.

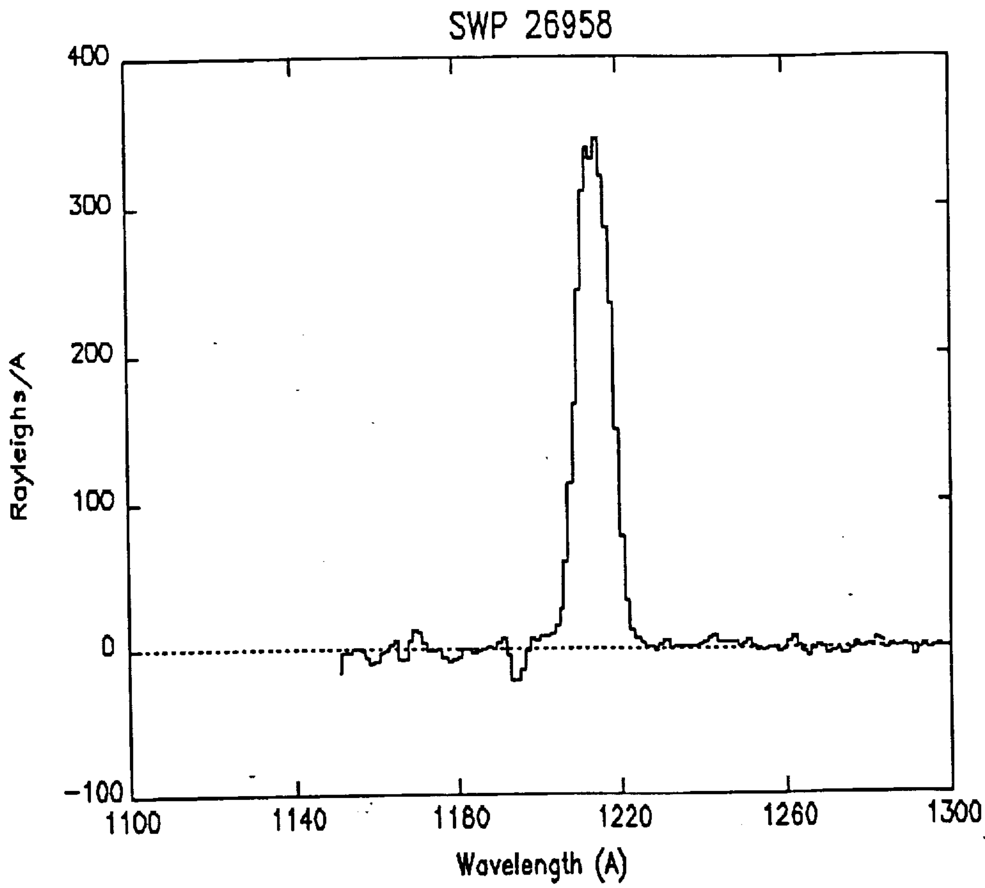

Figure 1. The Spectrum of the Lyman-α Region of Comet Halley recorded using the IUE large aperture centered on the nucleus on 20 October 1985.

The only important work in the area of understanding the multiple scattering of Lyman-α radiation in a cometary coma was done by Keller (1973). In his model the flow field of the H atoms was considered to consist of a purely radial outflow field having a single-component Maxwellian velocity distribution. The method employed was a Monte Carlo photon scattering simulation. Although this model in the later 3-component form could reproduce the wide field images, the results of Combi and Smyth (1988b) clearly indicate that the true velocity distribution function for H atoms is far from purely radial in the inner coma where optical depth effects are important. Furthermore, this is exactly the region where the H atoms are being produced so the produced so the point source approximation also fails. Therefore, although Keller's model could account for the magnitude of the Lyman-α brightness level it produced an overexaggerated asphericity about the comet-sun line because of the unrealistic pure radial outflow.

A final problem in understanding the emission of Lyman-α from a comet is to know the Lyman-α flux from the sun. The solar Lyman-α line is on the order of 1 Å wide, which is very broad as compared with the portion of the line seen by a comet at some point in its orbit (< 0.2 Å). To complicate the situation, a typical comet is in a highly elliptical orbit that causes the radiation scattered by the cometary H atoms to be Doppler shifted by as much as another $\pm$ 0.2 Å from the center of the line. The integrated line flux is known to vary on long time scales with the 11-year solar cycle and on short time scales with solar rotation. The solar line profile shows a self-absorption in the center that has been measured (Lemaire et al. 1978) but there has been considerable controversy over whether the shape of the line changes with the integrated flux.

Direct solar observations have indicated that the line-center flux may vary more than integrated flux based on a reconstruction of a full solar disk spectrum from a number of smaller scale observations (Lean 1987). However, years of spacecraft observations of the interstellar medium both by Pioneer Venus (Ajello et al. 1987) and Voyager (Shemansky and Judge 1982; Shemansky 1991) are consistent with little or no variation of the ratio of the line-center to integrated flux. Comparisons of comet observations of H Lyman-α and OH at 3090 Å, which are both produced (mostly) from water, with Solar Mesospheric Explorer (SME) measurements of the integrated solar flux could provide yet another test.

Progress for Work in this Project

In work performed under the NASA Astrophysics Data Program we have already developed the modeling tools necessary for analyzing the Lyman-α observations of comets. Furthermore, we have verified their validity on the IUE data obtained in the comet Giacobini-Zinner campaign (Combi and Feldman 1992) and have just completed a similar analysis on the comet Halley campaign data. The modeling tools consist of two models that have been successfully interfaced: the H coma MCPTM (Combi and Smyth 1988a) and a spherical radiative transfer code (adapted from Anderson and Hord 1977).

The hydrogen coma model is the culmination of two parallel modeling efforts that were necessary to understand the distribution of H atoms. A hybrid dusty-gasdynamic/Monte Carlo model was developed in order to describe the basic dynamics (outflow speed, density and temperature) of a water-dominated inner coma out to 10^5 km from the nucleus (Combi 1987; Combi and Smyth 1988a). A semi-kinetic treatment was necessary because the principal heating mechanism in the inner coma is the thermalization of the hot (2 eV) H atoms produced in the primary photodissociation of water. However, molecular densities become small enough by 1000-10000 km from the nucleus so that collisions between individual atoms and molecules become less frequent. Furthermore, because of the large mass difference between water molecules and H atoms, many single collisions are required before H atoms become thermalized and heat the coma. A Monte Carlo model was used to assess this heating efficiency and was run iteratively with a hydrodynamic model for calculating the basic dynamics of the inner coma. The basic dynamics predicted by the model have been used since then to understand various Doppler resolved observations of comet Halley (Combi 1989). Finally, the hydrogen coma model then uses the description of the inner coma generated by the gasdynamics/Monte Carlo model in order to accurately produce the full distribution of H atoms in the coma in both space density and velocity distribution. In the most general case the model performs a fully time-dependent description of the production rate and three-dimensional trajectory calculations for the H atoms that include the effects of individual solar orbits and the irregular variations of the solar radiation pressure acceleration.

Large numerical simulations such as these Monte Carlo models are used in applications where enough of the details of the physics and chemistry of the atmosphere are believed to be understood and where the simple parametrized models are clearly found to be inadequate. One gains the capability of treating complex processes and geometries but one also loses to some degree the certainty of uniqueness that is provided only apparently by simpler models. The last 25 years' worth of comet coma modeling has clearly demonstrated that the simple models such as the fountain model, the Haser model, and even subsequent and moderately complicated parametrized models are clearly inadequate for use in analyzing many comet observations. So, although they may provide an apparently unique fit, the underlying assumptions of the models are not physically correct. Our models have in the last few years been applied successfully to various types of data including images, spatial profiles, and high resolution radio and interferometric line profiles for several species. So despite their lack of formal mathematical uniqueness, the details are based on sound physical principles, laboratory measurements and have already been tested on many complementary sets of observational data.

In order to calculate the scattering of solar Lyman-α photons in the H coma and determine the brightness distribution about the nucleus we have adopted the spherical radiative transfer model of Anderson and Hord (1977) which was originally developed for the planetary corona problem but has since been adapted to treat the H coma problem (Bishop 1990). The radiative transfer model requires the density profile and average kinetic temperature of H atoms in the coma, the solar radiation flux per unit wavelength at the Doppler shift of the comet, and the sun-comet-earth angle as physical input parameters. Recently, we have demonstrated success in combining the model for the distribution of H in the coma of a comet with the spherical radiative transfer model for the IUE

H Lyman-α observations of comet P/Giacobini-Zinner during the 1985 apparition. We have found that the observed brightnesses of H Lyman-α imply the same water production rates in the coma as were determined from IUE observations of OH (McFadden et al. 1987). Furthermore, the observations were made with the IUE aperture located both centered on the nucleus and offset by a number of displacements from 7000 to 42000 km from the nucleus. The combination of the H coma and radiative transfer models accounted for both the absolute brightness as well as the spatial distribution of brightness in the inner coma. The H coma model therefore now has been shown to accurately portray the distribution of H from a few thousand out to several times 10^7 km from the nucleus.The results of the Giacobini-Zinner analysis have been recently published in Icarus. A reprint of the paper (Combi and Feldman 1992) is attached in an appendix to this report. The paper goes into considerably more depth concerning the data and the models than is reasonable to do again in this report. We have finished a similar analysis of the IUE Halley campaign data using the same procedures. A publication of those results is in preparation. Table I shows a list of the nucleus-centered observations of Halley at Lyman-α.

When a comet observation is made from Earth orbit the Lyman-α emission from the large envelope in the geocorona is also detected. Its signal is normally on the order of 500 to 2000 Rayleighs. When the comet's brightness is not large it is necessary to have a coincident measurment of the geocorona from a nearby direction since it is not easily predictable, varying both with direction and with solar Lyman-α flux. Table II gives a list of the geocorona observations made during the Halley campaign. When the comet was bright a value of 1000 Rayleighs provides a good estimate.

Even though the geocorona background observations were taken in many cases within an hour or two of the comet observation and offset by usually 2 degrees from the comets location, it is still required that a model be used to reproject the line of sight through the geocorona back or forward to the exact time and location of the line of sight through the comet. In order to do this we have used a program developed by the UV group at Johns Hopkins University and provided to us by Dr. Melissa McGrath. In a few cases and with some success we used this model along with the day-to-day variations of the solar lyman-a flux determined from the SME satellite (and corrected for solar rotation) to project a measured geocorona background a few days on either side of a comet observation. In a few cases however when the comet was at a large zenith angle, i.e. too close to the limb of the earth, the geocorona becomes very large and very difficult even for the model to project. This turned out to be the case for the June 25 observation, which although there was a geocorona observation less than 2 hours later, was not usable.

In addition to the nucleus-centered observations of Halley there were both a number of serendipitous observations taken during nucleus-centered LWP exposures which are offset by 64 arc seconds as well as two placed offsets. We are using these to examine the spatial distribution in

Table I. H Lyman-α Nucleus-Centered Observations of Comet Halley

Date	Spectrum	Start (UT)	Exp (s)	Total (Rayleighs)
Sep 22	SWP26700	1:38:00	3600	1587
Oct 19	SWP26956	16:18:01	14400	2617 (SAT)
Oct 20	SWP26958	2:43:13	2700	3615
Nov 4	SWP27033	21:40:59	11100	3458 (SAT)
Dec 2	SWP27209	14:36:10	7020	6506 (SAT)
Dec 3	SWP27212	2:29:21	300	12280
Dec 16	SWP27287	11:18:55	600	29260
Dec 25	SWP27378	2:50:39	120	38180
Dec 26	SWP27382	0:35:42	240	35790
Dec 29	SWP27409	2:07:23	240	44140
Dec 30	SWP27423	16:03:28	90	44967
Dec 31	SWP27429	10:53:13	180	55950
Mar 9	SWP27885	17:57:02	90	99467
Mar 18	SWP27946	23:00:15	90	58947
Mar 23	SWP28008	21:14:57	120	46700
Mar 25	SWP28014	1:59:00	60	48540
Mar 31	SWP28073	23:02:13	120	42750
Apr 4	SWP28099	23:45:12	300	39580
Apr 10	SWP29135	0:01:00	300	34730
Apr 29	SWP28240	20:37:00	600	17260
May 12	SWP28296	20:45:00	600	12870
May 16	SWP28317	0:23:08	600	9980
May 19	SWP28343	20:07:00	600	11740
May 31	SWP28409	16:47:17	900	6894
Jun 8	SWP28458	23:13:26	900	4361
Jun 9	SWP28459	4:05:08	1800	4759
Jun 12	SWP28478	15:58:29	1800	4022
Jun 25	SWP28541	7:17:14	1800	4654

(SAT) means an overexposed spectrum is indicated.

Table II. H Lyman-α Geocorona Background Observations

Date	Spectrum	Start (UT)	Exp (seconds)	Total (Rayleighs)
Sep 22	SWP26701	3:33:00	3600	772.8
Oct 20	SWP27959	4:05:00	2700	980.0
Dec 2	SWP27206	9:54:35	600	4123
Dec 3	SWP27213	4:20:49	1200	1256
Mar 23	SWP28009	22:50:36	120	2368
May 19	SWP28344	22:08:00	900	1052
Jun 25	SWP28542	8:40:49	1800	2114

Table III. H Lyman-α Offset Observations of Comet Halley

Date	Spectrum	Offset (arc seconds)	Start (UT)	Exp (seconds)	Total (Rayleighs)
Sep 21	SWP26697	64.6	19:16:04	1200	1321
Sep 21	SWP26698	64.6	20:41:39	1200	1427
Sep 21	SWP26699	64.6	22:16:47	3600	1806
Oct 20	SWP26957	64.6	0:40:26	3600	1735
Nov 5	SWP27034	68.5	6:27:39	720	2535
Dec 2	SWP27207	42.6	11:39:32	600	4123
May 16	SWP28318	64.6	1:19:26	1500	4562

the inner coma. Such analyses of the comet Giacobini-Zinner data (see Combi and Feldman 1992 attached) indicated that the model provided quite a good representation of the spatial distribution out to a few time 10^4 km. Our preliminary analysis of the Halley data shows a similar agreement. The offset observations are summarized in Table III.

Halley varies from being minimally optically thick at the largest heliocentric distances (2.5 AU)--even less than comet Giacobini-Zinner--to being very optically thick at the smallest heliocentric distances (0.88 AU). A preliminary summary of those results are listed in Table IV.

Table IV. Water Production Rates in Comet Halley from IUE Observations of OH and H

Date 1985-6	r (AU)	Δ (AU)	B(Lyman-α) (Rayleighs)	log Q(OH) (s^{-1})	log Q(H) (s^{-1})
			pre-perihelion 1985		
Sep 22	2.46	2.33	1587	28.400	28.425
Oct 20	2.09	1.43	3615	28.743	29.012
Dec 3	1.45	0.65	12280	28.987	28.974
Dec 16	1.25	0.84	29260		29.139
Dec 25	1.13	1.00	38180	29.582	29.505
Dec 26	1.11	1.02	35790	29.348	29.334
Dec 29	1.05	1.10	44140	29.476	29.371
Dec 30	1.03	1.14	44967	29.572	29.327
Dec 31	1.02	1.16	55950	29.555	29.448
			post-perihelion 1986		
Mar 9	0.84	1.06	99467	29.818	29.730
Mar 18	0.98	0.84	58947	29.642	29.687
Mar 23	1.04	0.73	46700	29.382	29.259
Mar 25	1.07	0.69	48540	29.728	29.659
Mar 31	1.18	0.53	42750	29.649	29.479
Apr 4	1.24	0.46	39580	29.332	29.522
Apr 10	1.32	0.42	34730	29.367	29.339
Apr 29	1.62	0.77	17260	29.134	29.420
May 12	1.81	1.18	12870	29.334	29.496
May 16	1.85	1.28	9980	29.340	29.402

In Figure 2 we compare the water production rates calculated using the combination of the H coma and radiative transfer models with a reanalysis of the published IUE observations of OH (Feldman, et al. 1987). The agreement is quite encouraging even though the H coma was highly optically thick at the comet's most active time. The OH observations were analyzed using the same hybrid dusty-gasdynamic/Monte Carlo model as for the H observations. The OH results are from a paper by Combi, Bos and Smyth (1993) which is scheduled for publication in the May 10 issue of the Astrophysical Journal, where it is compared and contrasted with the standard vectorial model analysis that assumes a constant outflow speed of 1 km/s for the outflowing water molecules.

It is quite clear that analyzing H Lyman-α and OH observations taken with the same instrument and using physically realistic models which are completely self-consistent has resulted in tremendous progress in our ability to determine water production rates in comets. Such self-consistent modeling is most important in comparing both observations made at a range of different heliocentric distances and observations of different comets. The apparent success we have demonstrated in analyzing the IUE observations of H and OH in comets provides further justification for many of the details included in our simulation of the full phase space distribution of matter in the coma and in our new spherical radiative transfer code for the calculation of multiple scattering of sloar Lyman-α radiation throughout the coma, even when it is very optically thick.

Future Work

We hope to continue this effort and have just submitted a proposal for a small 3-year effort to the Astrophysics Data Program. We plan to analyze a significant sample of the H Lyman-α IUE observations of over 30 comets made since the beginning of operation of the satellite in 1978. Our objectives are to (1) determine the H production rates and compare with those of OH, (2) study the spatial distribution of H in the innermost coma, and (3) study the variations in water photochemistry in comets and the solar Lyman-α line profile over the solar cycle using the combined H and OH observations. The basic task is to study the abundance and distribution of H atoms in many comets and compare with the established base of OH observations using the H coma MCPTM and the spherical radiative transfer model. In addition to analyzing the H data, some of the OH data will need to be reanalyzed with the a self-consistent set of vectorial or hybrid dusty-gasdynamic/Monte Carlo models. The analysis will include both nucleus-centered and spatially offset observations. Also to be examined is spatial resolution seen within the large aperture for some bright comets.

Several investigators have studied the dissociation process of water, including the overall rate and the various branching ratios (Huebner and Carpenter 1979; Festou 1981). Oppenheimer and

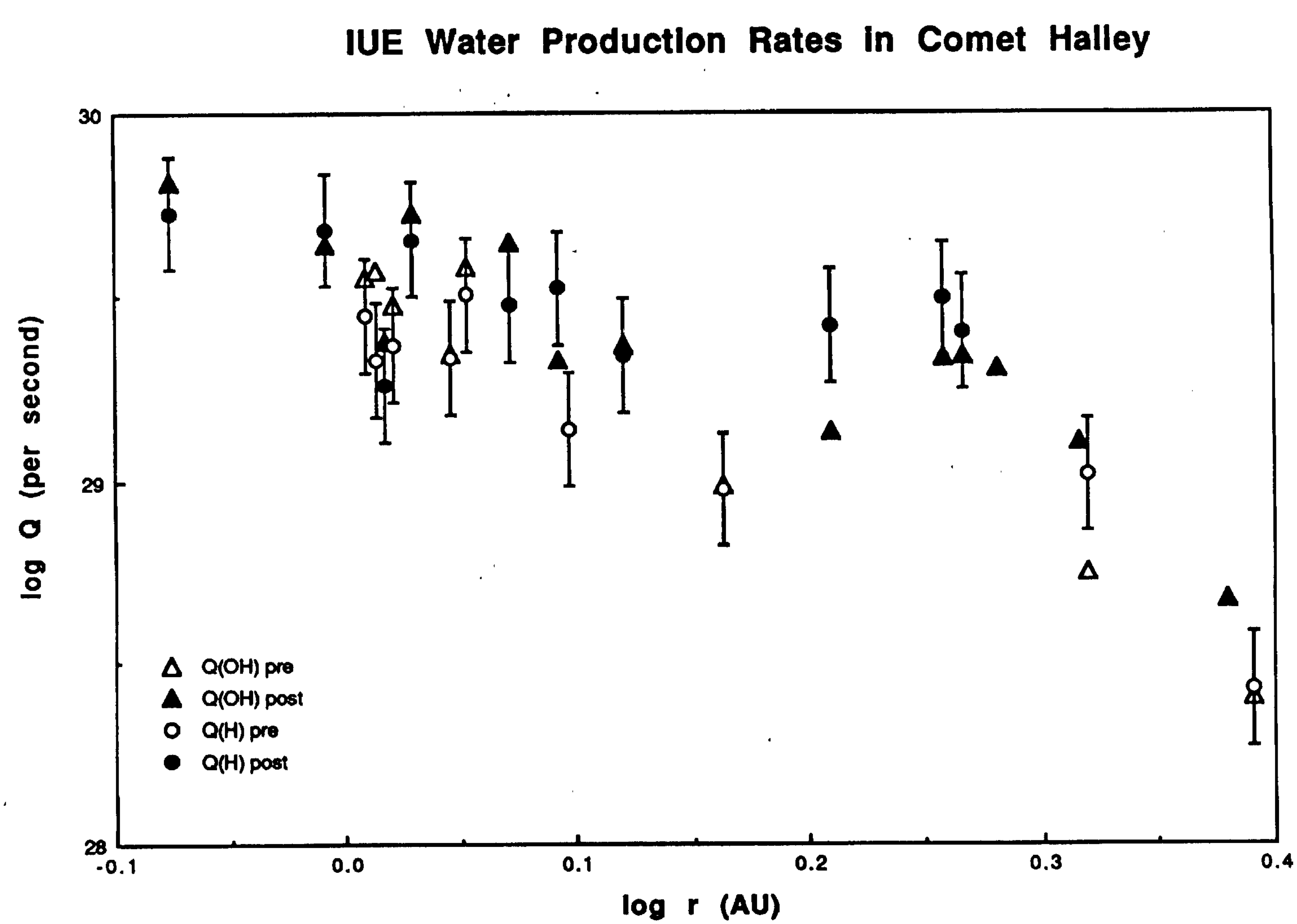

Figure 2. Water production rates determined by self-consistent analyses of H (circles) and OH (triangles) from IUE observations of comet P/Halley. The filled symbols are postperihelion and the open symbols preperihelion. The error bars are fairly uniform owing to the large relative importance of the optical depth uncertainty at small heliocentric distance but the large relative uncertainty of the geocoronal sky background subtraction at large heliocenric distance. The OH results are from Combi, Bos and Smyth(1993).

Downey (1980) also noted the importance of the variation of solar Lyman-α to the dissociation of water, and concluded that the overall rate could vary by up to a factor of two with solar activity. In addition, the ratios between the ionization, the H + OH, the H_2 + $O(^1D)$ and 2H + O dissociation branches should also vary with solar activity. Because of this the water lifetime used both in the reduction of OH observations and the H observations should also vary over the solar cycle. We can test this variation by comparing the observations and resultant water production rates between solar minimum and solar maximum, and varying or not varying the lifetimes in the model. It is not clear to what extent the relative H and OH abundances as seen by IUE near the nucleus are effected by varying the water lifetime. It is clear that the absolute abundances of each should be effected. Observations offset from the nucleus and the spatial distribution within the IUE large aperture will be the most helpful in this regard (such as we have already analyzed for the quite-sun conditions present at comet P/Giacobini-Zinner in 1985), since the spatial distribution of a species is dependent upon the photodissociation lifetimes of both the parent and the species itself.

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IUE Observations of H Lyman-α in Comet P/Giacobini-Zinner

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Comet P/Giacobini-Zinner (1985 XIII) was observed during the flyby of the International Cometary Explorer (ICE) satellite and during the 3 preceding months by the International Ultraviolet Explorer (IUE) satellite. Models for the hydrogen abundance and spatial distribution, which were previously used to reproduce the observed spatial distribution of the wide-field Lyman-α comae of Comets Kohoutek and Halley measured by rocket and spacecraft borne instruments, have now been successfully applied to these IUE observations. Vectorial models, which implicitly assume production of cometary OH by dissociation of water molecules, have been routinely used to infer global water production rates from various nucleus-centered IUE observations of comets. However, because of modeling complexities, a large base of Lyman-α observations has not generally been analyzed. One of these modeling complexities is that often the H atom column densities are high enough so that the coma is optically thick to solar Lyman-α radiation which cannot be treated by the standard optically thin models (Haser, vectorial, or Monte Carlo). A spherical radiative transfer model, adapted for application to the H coma, has been used to analyze the IUE observations. This analysis yields water production rates in very good agreement with those calculated from vectorial model analysis of OH observations. The H model makes essentially the same physical assumptions as the vectorial model for OH except for optical density. A further interesting aspect of this dataset is that various offset observations of the Lyman-α brightness were made on August 12, and September 10 and 11, 1985, at sampling distances of 7,500 to 41,000 km. This is much higher spatial resolution than is typically available from the usual rocket-borne cameras which have made most of the wide-field measurements of the H distribution in comets. The same H model, in combination with the radiative transfer calculation, also reproduces the observed spatial distribution of H in the inner coma. © 1992 Academic Press, Inc.

I. INTRODUCTION

The production rate of water in comets has been determined from various observations. The most recent is direct observation of fluorescence of the vibrational transition at 2.7 μm (Weaver, Mumma, and Larson 1987, Moroz *et al.* 1987). More typically, it has been inferred indirectly by observation of one of its photodissociation products, namely OH, H, or O(^{1}D). All types of observations (even direct) and their analyses are fraught with their own difficulties, ambiguities, and uncertainties. They are all based on model assumptions and uncertain photochemical rates and branching ratios, in addition to the usual problems of calibration and background subtraction of the data themselves.

Although H and OH have been observed in many comets, by many investigators, and with varied types of telescopes and detectors, nearly simultaneous observations made using the same instruments and analyzed using self-consistent models are rare. Among the more than 30 comets observed with the International Ultraviolet Explorer satellite was Comet P/Giacobini-Zinner (1985 XIII). On September 11, 1985, the International Cometary Explorer (ICE) satellite, with a full complement of particle and field instruments, flew across the tail of Giacobini-Zinner. In support of this effort, the IUE satellite in addition to many ground-based telescopes observed the comet in the months before, during, and after the encounter. Ultraviolet spectra of the comet were obtained from June 22

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through October 8, 1985, using the IUE. The results of the water production rates inferred from the OH observations throughout the 3-month period, as well as the spectrum and emission intensities and derived column abundances of several species from the point of closest approach of the ICE spacecraft, were presented by McFadden *et al.* (1987).

Early analyses of observations of water dissociation products on or near the day of the ICE encounter were compared by Combi, Stewart, and Smyth (1986). These data included their own observations of the H Lyman-α coma by the Pioneer Venus UV spectrometer, preliminary versions of radio observations of OH (Bockelée-Morvan *et al.* 1985, Schloerb and Claussen 1985), and preliminary versions of the IUE OH results (A'Hearn 1986, private communication). All water production rate results fell in the range of 2–5 × 10^{28} sec^{-1}; however, there was considerable variation in the models and parameters used at that time. Even the Pioneer Venus result used an earlier version of the Monte Carlo model than was used in the analysis of this paper, based on the Delsemme (1982) velocity law for the water outflow speed, the pre-Crovisier (1989) photodissociation of water, and the old SME calibration.

Since that time the column abundances determined from the nucleus-centered IUE observations of OH throughout the 3-month period have been converted to water production rates using the vectorial model (Festou 1981), which accounts for the distribution of OH as produced by the photodissociation of water (McFadden *et al.* 1987). Furthermore, the water production rates determined in this way for Comet Halley were shown to be in excellent agreement with those determined by direct *in situ* measurements (Feldman *et al.* 1987). However, direct comparison of production rates between observed species (especially other than OH) is unreliable since the production rates depend upon models with uncertain parameters and/or parameterizations. Furthermore, different observers tend to use different models and parameters making direct comparisons of production rates problematic.

Schleicher *et al.* (1987) have described a set of ground-based photometric observations of Comet P/Giacobini-Zinner which included C_2, CN, C_3, NH, and OH. Although OH observations from the ground are very difficult, their results agreed with the secular variation of the comet activity over several months as seen by IUE. They even found agreement with the level of the water-production rate when they accounted for the factor of 1.5 difference between the Haser model analysis of the photometry and the vectorial model analysis of the IUE observations.

Bockelée-Morvan *et al.* (1990) have more recently reexamined the modeling of OH line profiles determined from 18-cm radio observations of nine comets, including five observations of P/Giacobini-Zinner. Although they find that collisional quenching seems to resolve the long-standing differences between radio and UV observations of OH in some cases, especially for Halley, other cases (including Giacobini-Zinner) still show the radio results to imply water production rates which are a factor 1.5 to 2 below the UV results, or sometimes imply very small (0.4–0.5 km sec^{-1}) water outflow velocities which are nominally inconsistent with our ideas about coma thermodynamics. The radio results show a much larger week-to-week variation between August 3–9 and August 10–16 which is different and in the opposite direction from that seen by the IUE between August 6.5 and 12.1. The radio results show a much larger week-to-week variation between August 10–16 and August 18–22, which is also in the opposite direction from that seen in the ground-based observations by Schleicher *et al.* (1987) for all species (not just OH) between August 13 and August 20.

In this paper we present an analysis of Lyman-α observations of Comet P/Giacobini-Zinner made with IUE using the H coma model of Combi and Smith (1988a and b) in combination with a spherical atmosphere Lyman-α radiative transfer code adapted from the method of Anderson and Hord (1977) to the case for a large comet coma (Bishop 1990, private communication). As discussed above, there are often considerable differences between the water production rates calculated from various types of observations of the water dissociation products owing to differences and uncertainties in models, model parameters, observing aperture (beam) size, and instrument calibration, as well as in assessing the relevant excitation mechanisms. We focus the rest of this paper on the comparison of our analysis with water production rates determined from the OH observations by IUE (McFadden *et al.* 1987). The observations were taken with the same instrument and at nearly the same time, both H and OH UV emissions being relatively simple and straightforward solar fluorescences, and the vectorial analysis of the OH observations was reasonably consistent with the Monte Carlo model analysis of the H observations.

II. OBSERVATIONS

The IUE spacecraft, its spectrographs, and the Comet P/Giacobini-Zinner observations were discussed at length by McFadden *et al.* (1987). The measurements of the hydrogen Lyman-α emission were recorded in the short wavelength primary (SWP) SEC vidicon camera which covers the spectral range of 1150–1950 Å. The OH measurements come from the long wavelength primary (LWP) camera. For comet observations the larger entrance aperture (10 × 20 arcsec) was used. Details regarding the standard calibration and reduction have been discussed by Feldman (1983) and Weaver *et al.* (1981) and the overall

TABLE I
IUE Observations of H Lyman-α in Comet P/Giacobini-Zinner

Date (UT)	r (AU)	Δ (AU)	β (degrees)	F (photons $cm^{-2} s^{-1}$)	Brightness
85/06/22.6	1.443	0.931	44.3	1.144×10^{11}	2060
85/07/5.9	1.329	0.811	49.6	1.338×10^{11}	4174
85/08/6.5	1.111	0.576	64.2	2.002×10^{11}	12646
85/08/12.1	1.084	0.543	68.2	2.043×10^{11}	12290
85/09/10.5	1.030	0.470	73.8	2.258×10^{11}	8972
85/09/11.5	1.031	0.472	73.6	2.218×10^{11}	8214

Note. r—heliocentric distance, Δ—geocentric distance, β—sun–comet–Earth angle, F—solar Lyman-α flux at the comet's heliocentric distance and velocity, and B—observed cometary Lyman-α brightness in Rayleighs.

picture in place after 13 years of IUE observations of comets has been recently reviewed by Feldman (1991).

Table I lists the important observational parameters and the observed Lyman-α brightnesses for each of the observations analyzed in this paper. The contribution to the total signal by geocoronal Lyman-α emission, which is typically of order 1 kilorayleigh, has already been subtracted for each observation. Figure 1 shows a sample spectrum of the Lyman-α spectral region. It was taken on September 11, 1985, with the aperture offset by 120 arcsec from the nucleus.

III. THE HYDROGEN COMA AND LYMAN-α RADIATIVE TRANSFER MODELS

The only serious attempt to calculate the effect of optical thickness on the transfer of solar Lyman-α in the coma

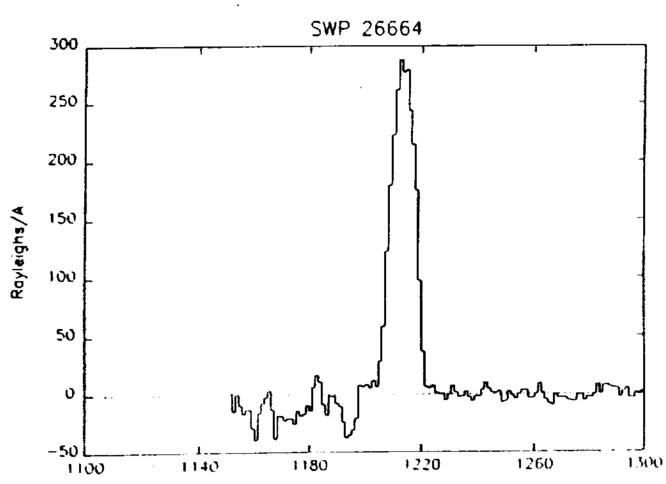

FIG. 1. Spectrum of Comet P/Giacobini-Zinner in the H Lyman-α region on September 11, 1985 at an offset of 120 arcsec from the nucleus.

of a comet was made by Keller (1973). In that paper he presented the results of a Monte Carlo photon-scattering calculation in a modeled hydrogen coma. Any radiative transfer calculation is critically dependent upon the phase space distribution of atoms or molecules in the atmosphere in question. By this we mean the space density and velocity distribution function. Keller's calculation was based upon a purely radially outflowing Maxwellian velocity distribution. Keller and Meier (1976) later used the sum of three Maxwellians for the purpose of explaining the shape of the Lyman-α isophotes in the spatially extended H coma. However, the radiative transfer calculation was never extended to the three-component model. Because of the purely radial outflow, the calculation produced unusual-looking highly asymmetric coma maps.

Combi and Smyth (1988b) later showed that the velocity distribution of H atoms leaving the inner coma could be explicitly modeled using a Monte Carlo model for the H atoms which included the detailed photochemical production of H from H_2O and OH and partial collisional thermalization of the H atoms by collisions with the heavier outflowing coma gases. Although the results of Combi and Smyth demonstrated why the sum of three Maxwellians in the Keller and Meier model can do a credible job of reproducing the isophote shape of the H coma at very large distances from the nucleus (10^6 to several $\times 10^7$ km), they also indicated that the velocity distribution in the inner coma was far from radial. In fact, the initial vectorial (Festou 1981) ejection of H atoms in combination with collisions produces a velocity distribution which has a large isotropic component (8–18 km sec^{-1}) which results from both the vectorial ejection and the few collisions superimposed over a small radial outflow component (1 km sec^{-1}). Gradually, with increasing distance from the nucleus the absence of collisions will cause the velocity distribution to become more radial (with some dispersion); however, at the same time the coma becomes optically thin.

Figure 2 shows the radial and tangential velocity components as calculated in the H coma model for Comet Giacobini-Zinner corresponding to the September 11 observations. The individual H atoms within the spatial region of importance for the IUE observations and where optical depth effects occur (10^3 to 10^5 km from the nucleus) are included. A purely isotropic distribution will have rotation symmetry about a line perpendicular to the velocity plane and through the (0, 0) point. A purely radial velocity model, like the one used by Keller (1973), will have zero tangential component, that is, all atoms would lie along the left edge of the plane in the figure. Although the modeled distribution is not exactly isotropic, it is far more isotropic than radial.

The spherical radiative transfer model of Anderson and Hord (1977) has been used for this analysis having been

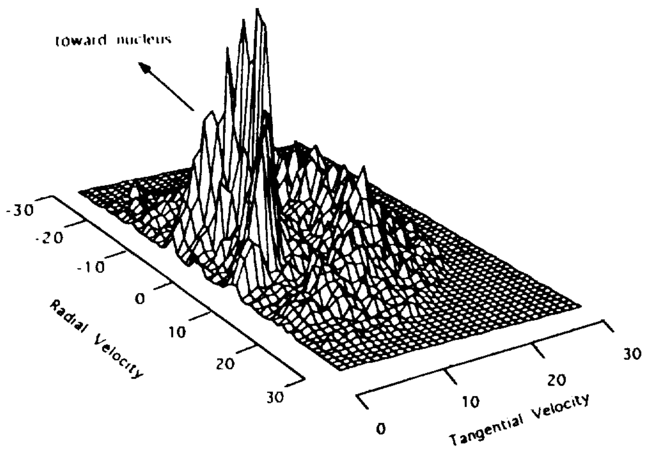

FIG. 2. The velocity distribution function in the inner coma, collected in radial and tangential components, was determined using the H coma model and is shown as a surface plot. The statistics were collected in the volume of importance for the radiative transfer calculation and the IUE observations (a spherical shell from 10^3 to 10^5 km from the nucleus). A distribution which is purely isotropic in velocity angle will have rotation symmetry about a perpendicular line through the (0, 0) point in the velocity plane. A distribution which is purely radial will show no tangential component. It is clear that the modeled distribution is much closer to an isotropic.

adapted from a general geocorona application to that of the cometary coma (Bishop, private communication). Their paper provides a complete mathematical derivation of the method. The adaptation work involved computer code development, e.g., changing the grid dimensions, inputting the coma radial density profile, and setting the order of the basis functions rather than using any alteration of the original mathematical method. Both the corona and cometary models consider the H atmospheres to be spherically symmetric with some radial density distribution and effective temperature. A spherical atmosphere illuminated by the sun produces an emission pattern which is axially symmetric about the line connecting the sun with the origin of the sphere. The Anderson and Hord (1977) model assumes a complete frequency distribution which is reasonable for an atmosphere of moderate optical depth such as a planetary exosphere or as in our adoption of the model for the H coma (Gladstone, private communication). The integral equation for radiative transfer is solved by expanding the source function in terms of a series of basis functions and ultimately inverting a large matrix equation.

For the Lyman-α coma problem the radial distribution of H atoms is taken from the H coma model of Combi and Smyth (1988b). The dusty gasdynamic/Monte Carlo model (Combi 1989) was used to generate the description for the inner coma at different times (heliocentric distances). The relative variation of the time dependent production rate was taken by interpolating between the values set by the water production rates determined from the IUE OH observations (McFadden *et al.* 1987). However, the time dependence in the H coma does not affect the spatial region covered by IUE (effective area = 8.9" by 15.1").

Although the H coma is clearly not spherical on the scale covered by rocket-borne cameras (Meier *et al.* 1976) or the Pioneer Venus UVS observations (Smyth, Combi, and Stewart 1991), especially when the comet is close to the sun, the coma is clearly spherical out to a large fraction of 10 million km. Therefore, for the purpose of understanding the optically thick region (out to a few times 10^5 km at most), the H coma is spherical. The coma density was computed from the H coma model in 50 logarithmically varying shells from 10^2 to 10^7 km. The source function in the radiative transfer code is computed in a grid of the 50 radial bins and 18 angular sectors. This requires the inversion of a 900 × 900 matrix.

The results of the H coma model were also used in order to estimate a value for the average isotropic temperature in the inner coma which is required for using the Anderson and Hord method. In previous work (Combi and Smyth 1988b, Smyth, Combi, and Stewart 1991) the effective velocity distribution of H atoms exiting from the inner coma, $f(v)$, has been presented and discussed. Although at distances of several times 10^7 km these velocities are essentially radial, in the inner coma these same velocities are nearly isotropic in angle. Therefore an effective temperature, T, which is really just a single parameterized measure of the velocity dispersion can be calculated from simple kinetic theory definitions as

$$T = \frac{m}{3k}\frac{\int_0^\infty v^4 f(v)\mathrm{d}v}{\int_0^\infty v^2 f(v)\mathrm{d}v}, \tag{1}$$

where v = isotropic velocity, m = mass of the H atom, and k = Boltzmann constant. Note that the integral in the numerator of Eq. 1 is just the integral over velocity space of the second moment of the distribution function, or the energy, and the denominator is just the normalization, that is the zeroth moment of the distribution function. The integral over the two angular dimensions is identical in both the numerator and denominator and vanishes.

IV. WATER PRODUCTION RATES

Water production rates were determined from the IUE observations of the Lyman-α brightness using the hybrid gasdynamic/Monte Carlo model (Combi and Smyth 1988 a and b; Combi 1989, Smyth, Combi, and Stewart 1991) which has been successful at varifying the physical basis for the velocity distribution of H atoms leaving the inner coma in combination with the Anderson and Hord (1977) radiative transfer model. The velocity distribution of H atoms is formed by the combination of photodissociation of H_2O and OH with partial thermalization of the H atoms through collisions with the ambient coma gas. This model, however, has not before been used to study the abundance and distribution of hydrogen in the inner coma of a comet.

Just as in the cases for the most recent uses of both the extended H coma (Smyth, Combi, and Stewart 1991) and the inner hybrid dusty gasdynamic/Monte Carlo (Combi 1989) parts of the model, the 1 AU values of the relevant parameters for the model include a water photodissociation lifetime of 82,000 sec, an OH lifetime according to the combined results of Schleicher (1983) and van Dishoeck and Dalgarno (1984), a branching ratio of 0.88 for the H + OH branch, and an initial H ejection velocity distribution and photochemical heating from the revised calculations of Crovisier (1989). The standard H lifetime of 2×10^6 sec at 1 AU rather than the time dependent value (Combi, Stewart, and Smyth 1986) is used; however, this is inconsequential for the small aperture IUE observations.

Bockelée-Morvan and Crovisier (1987) state that the radiative cooling rate by water molecules in the cometary coma is a complicated radiative transfer problem involving variation of the density, the collision rate, and the rotational population of the water molecules. More recently Crifo *et al.* (1989) have computed coma models using this new cooling algorithm for the case of Halley near the time of the spacecraft flybys. Comparison of their results with the otherwise comparable pure-gas model of Combi (1989), that includes the cooling rate and the collisional inefficiency approximation of Crovisier (1984) as modified by the escape probability optical depth of Huebner and Keady (1983), shows only a small (few percent) difference in the macroscopic quantities such as outflow speed and temperature even for this high production rate comet. Until a tractable alternative is available, the current method is certainly a better alternative than using either no cooling or the original Shimizu (1976) cooling, both of which are still used in some work. In any case, the effect of cooling (or heating, for that matter) is of less consequence for the low gas production rate of Comet P/Giacobini-Zinner at heliocentric distances >1 AU.

The dusty gasdynamic model (Combi 1989) uses a single average dust size to account for the drag effect of dust on the expanding gas in the inner coma. Crifo (1991) has warned against the use of a single-size dust distribution, favoring the multisize dust distribution models of Gombosi *et al.* (1986), for example. However, for our dusty gasdynamic calculation Combi (1989) had adopted a moderate dust size of 0.65 μm as suggested by Gombosi (1988, private communication) which, contrary to Crifo's warning, does reproduce the same gas temperature and outflow speed, as well as the 0.65-μm dust-particle terminal velocity, as in the multisize distribution results of Gombosi *et al.* Therefore, it is clearly possible to use a single moderate-sized dust particle population to assess the dust–gas interaction reasonably well, if a judicious choice is made for the size of the particles.

For this work we adopt a dust-to-gas mass ratio of 0.3 realizing, however, that it is a very uncertain and ill-defined quantity. A large amount of dust mass in large particles for example would neither show much of a dust coma, nor would it have an important effect on the dusty gas flow. Similarly, a large number of small dust particles would have little effect on the dusty gas flow since the mass is small and furthermore shows little dust coma because of decreasing radiation scattering efficiency. It is the number of grains in the optical size (0.4 to 1.0 μm) that are the most important both for the dusty gas flow and for observing a dusty coma. Fortunately, for a large range of small to moderate dust-to-gas ratios (see for example the discussion by Wallis 1982), the effect on the dynamics is only a weakly varying function of the ratio.

Hodges (1990) has demonstrated the first fully kinetic simulation of a pure-water cometary atmosphere, accounting for five species (H_2O, OH, O, H, and H_2). Such a kinetic simulation must explicitly account for mutual collisions between all species in a careful and rigorous fashion since a study of the details of the evolution of the general irregular (nonthermal) molecule distribution functions in phase space is the object. In that paper Hodges raised objections to the collision process as derived by Combi and Smyth (1988a) which was stated to take advantage of the high speed of the H atoms relative to the slow cold outflow water molecules. Both the collision path length and the redirecting target particle randomization make explicit use of the fast-H approximation and can be directly derived from the basic kinetic theory approach. Even in the inner coma, thermalized H atoms have speeds which are more than four times (from the ratio of the masses) those of the heavy gas molecules. Therefore, although the calculation of Combi and Smyth (1988a) should not be indiscriminately applied to all species in all circumstances, it is only a reasonably good approximation for the purposes employed, i.e., in the analysis of radial profiles of the H coma. This is especially true for the case of Comet P/Giacobini-Zinner which has low gas production rates and heliocentric distances >1 AU.

The radial density distributions from the H coma model were used as input for the radiative transfer model. Three separate models were run for each observation date: one at the nominal water production rate determined from the OH observations (McFadden *et al.* 1987) and one each at 30% higher and lower rates for interpolation. Parameters for the H model are the same as have been published for other comets (Combi and Smyth 1988b, Smyth, Combi, and Stewart 1991) and are the same as (or at least consistent with) the OH vectorial model results. For the model results presented in this paper the simulation was run for 1,000,000 water molecules which produce 2,000,000 H atoms. For a large range of coma conditions the average temperature which characterizes the Doppler velocity distribution for the radiative transfer model was found to always be within a few percent of 14,000 K using the results of the H coma model and Eq. 1. This temperature is in fact indicative of the speeds of up to 18 to 24 km sec^{-1} found in the photodissociation of OH and H_2O (Combi and Smyth 1988b). See also Figure 2 for the detailed velocity distribution.

The radiative transfer model produces a standard output which is the axially symmetric source function. A second step is used which produces the line of sight integration through the coma for a desired grid. For integrating the contribution through the IUE aperture a grid 40 by 20 points in the half-sky plane with 400 km per grid point was produced so that for a typical observation 150–400 grid points contribute to a typical IUE aperture. This minimizes possible statistical and undersampling errors.

In order to interpret the Lyman-α brightness it was necessary to assess the solar Lyman-α flux at the location of the comet. For this purpose we have used the Solar Mesospheric Explorer (SME) data base which provides daily averages of the solar UV spectrum. Since the comet did not "see" exactly the same face of the sun as did SME, which is in earth orbit, it was necessary to correct for solar rotation by accounting for the difference in heliocentric longitude between the earth and the comet. As in past work the shape of the solar Lyman-α profile was taken from the results of Lemaire *et al.* (1978) and was scaled linearly with the measured integrated flux. Since there is considerable uncertainty over whether the solar profile shape varies linearly with the integrated flux, we intend in the future to use the IUE cometary Lyman-α data base as a tool to investigate just this question. For now we continue to assume it is linear; this assumption is helped by the fact that the comet observations were made at roughly the same quiet sun conditions as were the solar observations 10 years earlier.

Table II provides a list of the relevant model parameters and results for the water production rates determined from the nucleus-centered observations. It also provides a comparison with the water production rates determined from the OH observations by McFadden *et al.* (1987). The agreement is amazingly good even though the data correspond to the comet changing heliocentric distance by a factor of 1.4 (or r^2 by a factor of 2) and geocentric distance by nearly a factor of 2 (or Δ^2 by a factor of 4). The various photochemical lifetimes are proportional to r^2 and the aperture area is proportional to Δ^2. This is a wide range over which the model parameters vary (for both H and OH) and still preserves very good agreement. Figure 3 shows a plot of the secular variation of the water production rate as determined by McFadden *et al.* from OH and as determined here from H.

The agreement between the two determinations is quite reasonable. The H observations yield production rates which are on the average about 15% higher than the OH observations. As mentioned above, each "best-fit" water production rate from an H observation was calculated by a logarithmic interpolation between the brightnesses predicted by models with three estimates of the water

TABLE II
Production Rates of Water in Comet P/Giacobini-Zinner

Date (UT)	Days from q	r (AU)	Q (Lyman-α)	Q (OH-3090 Å)
85/06/22.6	−74.7	1.443	2.9×10^{28}	2.8×10^{28}
85/07/5.9	−61.4	1.329	4.6×10^{28}	4.0×10^{28}
85/08/6.5	−29.8	1.111	8.2×10^{28}	7.3×10^{28}
85/08/12.1	−24.2	1.084	7.1×10^{28}	7.0×10^{28}
85/09/10.5	5.3	1.030	4.3×10^{28}	3.2×10^{28}
85/09/11.5	6.3	1.031	3.9×10^{28}	3.2×10^{28}

Note. Days from q—days from perihelion. Q (Lyman-α)—water production rates determined for this paper from the H Lyman-α observations, and Q (OH-3090 Å)—water production rates from the OH observations by McFadden *et al.* (1987).

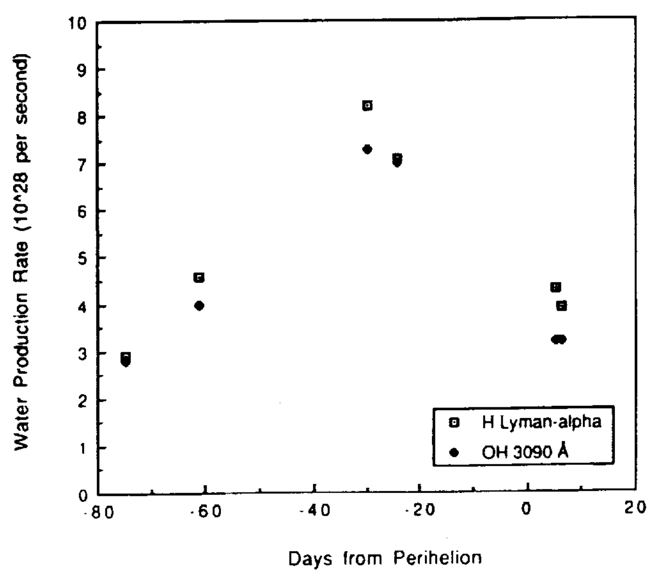

FIG. 3. Comparison of water production rates in Comet P/Giacobini-Zinner determined from the IUE observations of H Lyman-α with those determined by McFadden *et al.* (1987) from the OH observations at 3090 Å. The values are plotted as a function of time from perihelion on September 5.25, 1985.

TABLE III
Spatial Offset Observations of H Lyman-α of Comet P/Giacobini-Zinner

Offset (arcsec)	Observed surface brightness (Rayleighs)	Model brightness[a] (Rayleighs)
	August 12	
66.4"	4416	4825
	September 10	
30"	4885	5359
30"	4990	
	September 11	
22"	5666	4726
120"	2649	2449
120"	2325	

[a] Model brightnesses were derived from the models of the nucleus-centered observations (Table II).

production rate. For half of the observations a separate radiative transfer model was constructed for the best-fit interpolated value and the brightness agreed with the interpolated value to within 0.1%.

V. SPATIAL DISTRIBUTION OF HYDROGEN

On August 12, September 10, and September 11 several SWP observations were made at displacements of 22, 30, 66, and 120 arcsec from the nucleus. The combination of the H coma and radiative transfer models produces a full description of the brightness field so these offset observations can be used to test the spatial variation in the model. Using the best-fit nucleus-centered models for the three dates the various offset brightnesses were calculated. These are compared with the observed brightnesses in Table III.

The radiative transfer model implies a small asphericity along the comet–Sun line as projected on the sky plane which results from a shadow effect on the antisunward side. For Comet Giacobini-Zinner this asymmetry varies from only 10% at 22 arcsec down to negligible values at 120 arcsec for the September 11 observation. Since it is clear that the "scatter" is generally larger than this we present in the table only radially averaged values. It is possible that in future work such asphericity will prove useful and will be investigated; however, for now we consider it at the noise level.

VI. SUMMARY AND CONCLUSIONS

We present in this paper the results of applying a spherical radiative transfer calculation based upon the H coma model previously used to understand the shape of the wide field Lyman-α coma. Although the velocity distribution necessary for producing the shape of the outer coma depends critically upon the physics of the photodissociations and collisions in the inner coma, the results presented in this paper represent the first test of the model for actually looking at the spatial distribution of H atoms in the inner coma itself where they are produced. Total average column optical depths range from less than 0.5 for the largest offset observation to about 4 for the nucleus-centered observations in August. These correspond to "correction factors" over the optically thin values from 3% up to about 70%, that is, the total H columns are up to 70% higher than one would obtain using the optically thin g-factor.

All of the observed offset values agree with the modeled values, which were calibrated on the nucleus-centered observations (Table II), to within about 10% with no evidence of a divergence either up or down with increasing distance from the nucleus. A divergence between model and data with increasing distance would indicate that the modeled spatial distribution (and the corresponding model parameters such as velocities, lifetimes, and branching ratios) would be in error. We interpret this as verification that the model (to within 10%) reproduces the observed spatial distribution of H atoms in the coma from the region very near the nucleus (<3000 km) out to 42,000 km from the nucleus.

Furthermore, the water production rates implied by the set of nucleus-centered observations are consistent with those determined from the comparable vectorial model analysis of OH observations (McFadden *et al.* 1987), the average difference being about 15%. All of the IUE results are furthermore consistent with the overall activity of the comet throughout its apparition as monitored through the photometric observations of Schleicher, Millis, and Birch (1987).

The average 15% difference between the water production rates determined from nearly concurrent observations of H and OH could result from a number of small errors in observation and model analysis. It is very doubtful that one could interpret our results as evidence for additional H-bearing species, especially for Comet Giacobini-Zinner. The results of the photometric study of C_2, C_3, CN, OH, and dust by Schleicher, Millis, and Birch (1987) classify this as a comet which is depleted in all gas species and dust relative to water when compared to other comets. Furthermore, the fact that the water model for H reproduces the correct spatial distribution again points toward self-consistent production of nearly all of the H and OH from water.

The SWP and LWP spectrographs within IUE could have a calibration difference; however, the variation of sensitivity with time has been measured and removed. Minor uncertainties in the model parameters in either the H model or the OH vectorial model could account for the difference. Perhaps the largest uncertainty is in estimating the solar Lyman-α flux illuminating the hydrogen in the comet. There is certainly a contested question regarding how the shape of the solar Lyman-α profile varies with solar activity. There is finally the variation of the integrated solar Lyman-α flux with time and solar rotation. We have attempted to correct for this by accounting for solar rotation. However, the solar Lyman-α flux could have varied in time between when the portion of the sun's surface in question faced the comet and when it was observed from near the earth by SME a few days earlier. There are also calibration uncertainties within the SME measurements themselves.

Enumerating all of these possible sources of uncertainty should not, however, detract from the 15% agreement between the H and OH data which is quite good. The details involved in the production of H and OH have been examined more carefully by more investigators and for a longer time than for any other species or prospective species. The production rates of other species relative to OH or H are likely to be much more poorly determined. Much care has been taken here to ensure that these analyses are as parallel as possible. In addition, we are aided by the fact that all of the data were taken with the same instrument.

In future work we intend to begin to systematically examine the rest of the IUE Lyman-α data set. In addition to analyzing simultaneous H and OH observations in many comets under many conditions, we also hope to use the techniques described in this paper to study the variation of the solar Lyman-α emission over the 13-years' worth of IUE observations of comets which now cover more than one complete solar cycle.

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