Extended Atmospheres of Outer Planet Satellites and Comets

William H. Smyth

and

Michael R. Combi

Atmospheric and Environmental Research, Inc.
840 Memorial Drive
Cambridge, MA 02139-3794

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16. Abstract

Significant accomplishements in the second year of this three-year project in the area of model analysis of the extended atmospheres of outer planet satellites and comets are discussed herein. Primary emphasis in this year was placed upon cometary atmospheres because of the return of Comet P/Halley. As part of our collaborative effort with A.I.F. Stewart, observations of the hydrogen coma of Comet P/Giacobini-Zinner obtained from the Pioneer Venus Orbiter ultraviolet spectrometer (PVOUVS) were successfully analyzed at AER and are reported. In addition, significant pre-modeling and post-modeling activities to support and analyze the PVOUVS observations of Comet P/Halley successfully acquired in late 1985 and early 1986 are also discussed. Progress in model preparation for third-year analysis of the Voyager UVS Lyman-α brightness distribution emitted by hydrogen atoms in the Saturn system is also summarized.

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I. INTRODUCTION

The research goals of this project are to provide physical insight into the nature of the extended gaseous atmospheres of both outer planet satellites and comets. For the outer planets, research efforts are focused upon understanding the large circumplanetary atomic hydrogen distribution in the Saturn system, both in terms of its neutral sources (which include the satellite Titan) and its role as a plasma source for the planetary magnetosphere. For comets, the emphasis is to understand the basic chemical composition of the nucleus and its interaction with the sun and solar wind through study of the composition and spatial structure of its extended cometary hydrogen, oxygen and carbon atmospheres.

To understand the circumplanetary atomic hydrogen in the Saturn system, the strategy adopted has been to model carefully the spatial structure of the hydrogen torus of Titan (the expected dominant source of H atoms) and compare it with the Voyager UVS data for the hydrogen Lyman-α emissions. To achieve this objective, a collaborative effort has been established with D.E. Shemansky to provide optimally prepared Voyager UVS Lyman-α data for this comparison. The Titan hydrogen torus model at AER has also been improved to include the spatial lifetime of H atoms in the planetary magnetosphere by incorporating the best available Voyager PLS electron and ion data. This model-data comparison will not only determine the Titan source but will also provide a means of identifying and assessing the relative importance of other possible non-Titan hydrogen sources (i.e., the icy satellites, the planetary rings, and the planetary atmosphere).

The basic chemical composition of the comet nucleus, which is too small to be seen and is furthermore obscured from view by the gas and dust coma, will be investigated by studying the observed nature of the very-extended atmospheres of the comet. For this strategy (which is widely adopted) to be successful, however, it is vital to have a model for the cometary atmosphere that accurately contains all the relevant physical interactions that occur in the sun/solar wind environment for the so-called parent molecules that are ejected from the nucleus. Recognizing this requirement, a very general particle trajectory model (PTM) has been developed at AER. In this project, this model is being utilized to analyze the density and UV emissions of extended cometary hydrogen, oxygen, and carbon atmospheres. To test and further utilize these models, a collaborative effort with A.I.F. Stewart has been established to analyze cometary H, C, and O emissions obtained by the ultraviolet spectrometer of the Pioneer Venus Orbiter for Comets P/Encke, P/Giacobini-Zinner, and P/Halley.

The discussion of second year progress and achievements is divided into two parts: the hydrogen distribution in the Saturn system and cometary atmospheres. Primary emphasis has been focused upon cometary atmospheres because of the return of Comet P/Halley and also because information required to adequately describe the lifetime of hydrogen atoms in the circumplanetary space of Saturn has been more difficult to obtain than originally envisioned.

II. Hydrogen Distribution in the Saturn System

1. Overview

The three-year plan for our research in the Saturn system is summarized in Table 1. Because of the major emphasis placed on the cometary portion of the project, the initiation of second year objectives for the Saturn system has been largely postponed until the third year. A further factor aiding this postponement has been the difficulty in acquiring an adequate description for the lifetime of hydrogen atoms in the circumplanetary space of Saturn. Progress in describing the lifetime of H atoms near Saturn is discussed below.

2. Hydrogen Lifetime in the Saturn System

The four relevant loss processes for atomic hydrogen in the Saturnian system are summarized in Table 2. The first two processes require a spatial description of the plasma properties in the planetary magnetosphere and also in the solar wind beyond the magnetosphere. The plasma description for the solar wind is readily available. The plasma description for the magnetosphere is more difficult to specify because it must be determined from limited analysis of data acquired by the Plasma Science (PLS) experiment on the Voyager 1 and Voyager 2 spacecrafts during their encounters with the planet (12 November 1980 and 26 August 1981, respectively). The third loss process of Table 2, photoionization, is easily evaluated. The fourth process, elastic collision with atomic hydrogen in the instellar medium, was identified last year by this project. Evaluation of this loss rate requires the determination of low-velocity cross-sectional information currently unavailable. This cross-sectional information is being calculated by Shemansky (1986) as part of his collaborative involvement with this project.

To construct a plasma description for the planetary magnetosphere, PLS data acquired by the Voyager spacecrafts have been utilized. The PLS data is divided into the reduction and analysis of electron data (being performed at the Goddard Space Flight Center, primarily by E.C. Sittler) and ion data (being performed at the Massachusetts Institute of Technology, primarily by J.D. Richardson). Earlier adopted descriptions of the spatial plasma properties by this project were developed by Sittler and were based upon his hot/cold component analysis of the electron data in which very simple

TABLE 1

SATURN SYSTEM: THREE-YEAR PLAN FOR MODELING ANALYSIS

Subject	First Year	Second Year	Third Year
(1) Titan Torus	Continue to refine plasma information in the life-time description. Obtain properly sorted Voyager 1 Lyman α data. Perform preliminary model calculations.	Perform exploratory model calculations with various exospheric escape parameters. Analyze the Lyman α data and determine the source rate and spatial distribution of hydrogen from Titan.	Perform a complete analysis of the Lyman α data and extract relevant information to describe the escape and magnetospheric interaction of H atoms from Titan and other important neutral sources.
(2) Non-Titan Satellite and Ring Sources	--	Identify possible non-Titan sources of H atoms from the above analysis. Develop suitable models to investigate the properties of these sources.	Determine for these neutral sources the spatial character and magnitude of their plasma input rates.
(3) Planetary Source	--	Use the collaborative effort with Shemansky and the above analysis to assess the importance of a planetary source	

Table 2

LOSS PROCESSES FOR ATOMIC HYDROGEN IN THE SATURNIAN SYSTEM

1. $$H + \left\{ \begin{matrix} e \quad (\text{cold}) \\ e \quad (\text{hot}) \end{matrix} \right\} \longrightarrow H^+ + 2e$$

2. $$H + \left\{ \begin{matrix} H^+ \\ O^+ \\ N^+ \end{matrix} \right\} \longrightarrow H^+ + \left\{ \begin{matrix} H \\ O \\ N \end{matrix} \right\}$$

3. $$H + h\nu \longrightarrow H^+ + e$$

4. $$\underset{\substack{\text{ISM} \\ (\sim 20 \text{ km sec}^{-1})}}{H} + \underset{\substack{\text{TORUS} \\ (\text{slow})}}{H} \longrightarrow \underset{\substack{\text{ISM} \\ (\text{fast})}}{H} + \underset{\substack{\text{TORUS} \\ (\text{fast})}}{H}$$

assumptions were made regarding the temperature and relative abundance of light (H^+) and heavy (N^+ and/or O^+) ions. Very recently, an analysis of part of the PLS ion data was completed and published by Richardson (1986) in which these ion properties are deduced. Effort in this third quarter was expended to combine the separate electron and ion information determined from the PLS data along the spacecraft trajectory and develop a more consistent three-dimensional description for the plasma properties in the magnetosphere. To achieve this goal, magnetic tapes containing the best electron and ion information were obtained from PLS team members.

Comparison of electron and ion densities deduced from the PLS data along the inbound and outbound trajectory of Voyager 1 spacecraft indicated a consistent imbalance in charge neutrality of about a factor of two, with the electron density deduced from the ion data being greater. This difference is not understood, but it may occur because of instrumental effects or spacecraft charging. Initially, this imbalance in charge neutrality has been rectified in our description by adding more cold electrons to the electron population. The electron/ion description so developed for the Voyager 1 inbound data has then been properly projected down to the magnetic symmetry plane. The lifetime of H atoms in this symmetry plane, calculated for the first two processes of Table 2, is shown in Figure 1 and compared with an earlier lifetime description developed by Sittler and based upon outbound Voyager 1 data. Beyond 12 Saturn radii, the new lifetime is lower by a factor of two or more than the earlier adopted lifetime. Inside 12 Saturn radii, the new lifetime departs even more from the earlier results. The differences in the old and new lifetimes depend not only upon the improved ion descriptions but also upon asymmetries in the inbound and outbound data. Further effort in the third year will be required to improve this lifetime information. A three-dimensional lifetime description for H atoms in the planetary magnetosphere will then be incorporated in the Titan torus hydrogen model, and the model will then be used to analyze the Voyager UVS Lyman-α data for the Saturn system.

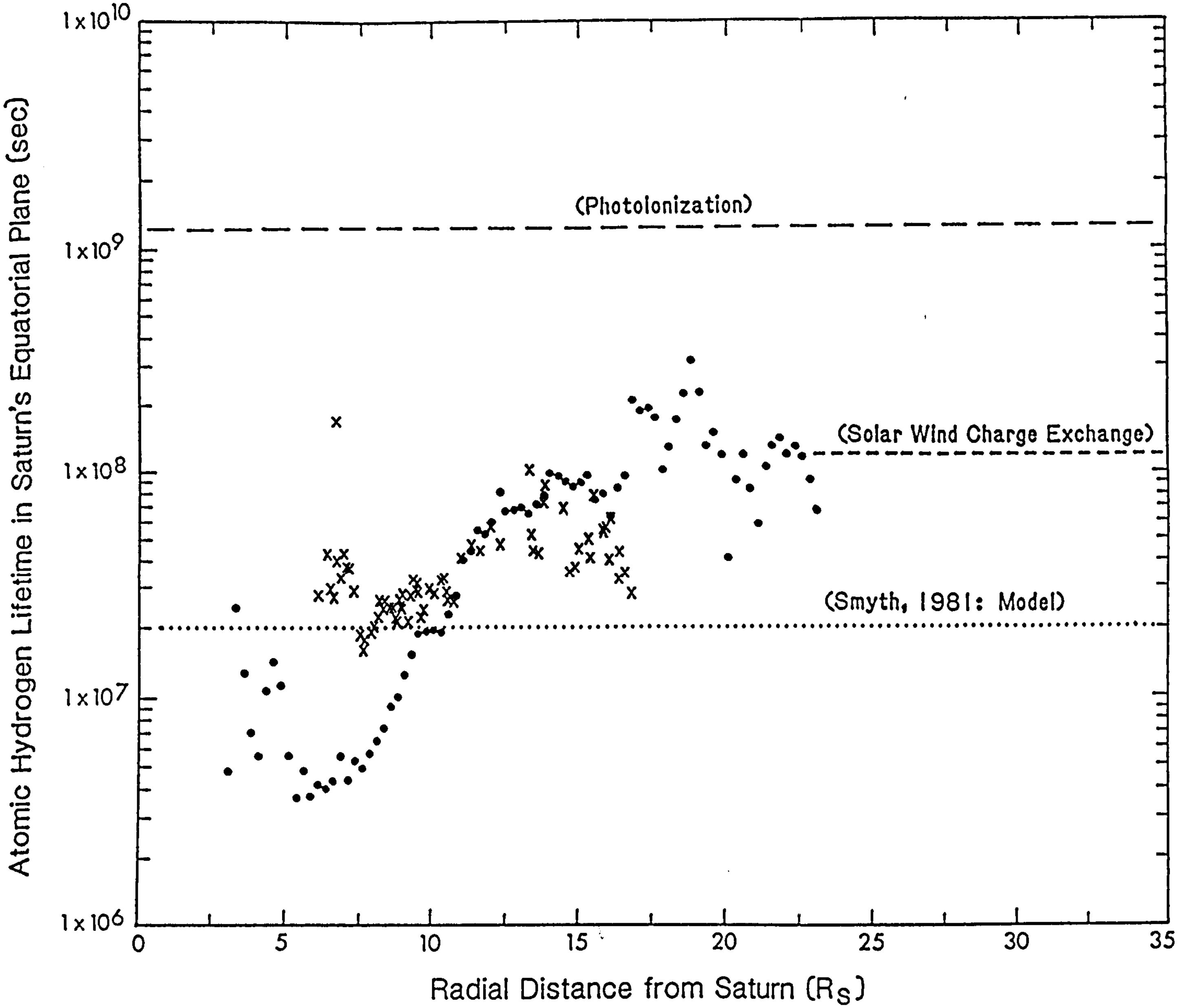

Figure 1

Lifetime of H Atoms in Saturn's Equatorial Plane. The most recently determined lifetime deduced using the plasma ion information of Richardson (1986) is indicated by the "x" symbol and compared with earlier project-adopted H lifetime in the magnetosphere (•), the simple pre-Voyager lifetime assumed by Smyth (1981), and the photoionization and solar wind exchange lifetimes. See text for discussion.

III. COMETARY ATMOSPHERES

1. Overview

The three-year plan for our research in cometary atmospheres is summarized in Table 3. In the first year, models for the hydrogen, carbon and oxygen comae were developed. In addition, model calculations for hydrogen and oxygen comae of Comet P/Encke appropriate to the Pioneer Venus Orbiter Ultraviolet Spectrometer (PVOUVS) measurements acquired on 14 and 15 April 1984 by A.I.F. Stewart, and also preliminary model calculations for the carbon coma observations of Comet Kohoutek acquired much earlier by Opal and Carruthers (1977) were performed in the first year (see the 1985 Annual Report). As an outgrowth of the Comet P/Encke observations, a collaborative program was established with A.I.F. Stewart to analyze hydrogen data for Comet P/Giacobini-Zinner and H, O, C and OH data for Comet P/Halley to be acquired by the PVOUVS in the second project year.

In light of the significant progress accomplished in the first project year (see Table 3), efforts in the second project year were focused in three main areas: (1) analysis of PVOUVS hydrogen coma data for Comet P/Giacobini-Zinner where the effects of a time-variable solar wind and UV flux were also included, (2) performance of preliminary supporting model calculations and initial modeling analysis for PVOUVS observations of Comet P/Halley, and (3) generalization of the hydrogen comae model to include collisions of non-thermally produced H atoms with slower and heavier outflow species (H_2O, OH, O) and, in addition, testing the model with Comet Kohoutek observational data as preparation for analysis of the PVOUVS data for Comet P/Halley. Second year progress in these three main areas is summarized below.

2. Analysis of Comet P/Giacobini-Zinner Observations

The PVOUVS observations of Comet P/Giacobini-Zinner at 1216 Å (hydrogen Lyman-α) were acquired on 11 September 1985 by A.I.F. Stewart. These observations were initially analyzed in the first quarter (see the first quarter progress report) using our particle-trajectory model (PTM) for hydrogen coma based upon production of H atoms by photodissociation of H_2O and OH. The model analysis implied a water production rate of 2.3×10^{28} H_2O molecules sec^{-1} at the time of the observation. This value was bracketed by

TABLE 3

COMETARY ATMOSPHERES: THREE-YEAR PLAN FOR MODELING ANALYSIS

Subject	First Year	Second Year	Third Year
Hydrogen	Perform detailed model calculations for currently available data to test the model assumptions and numerical input parameters (branching ratios, velocity dispersion, etc.) Perform exploratory model calculations to investigate the effects of the variable solar UV flux on photochemical reaction rates, radiation pressure acceleration, and fluorescence excitation		Apply the models developed and refined in the first two years to new data for a <u>self-consistent</u> study of the relative roles of H, C, and O as observed in the extended atmosphere, and their ultimate sources in the cometary nucleus.
Carbon and Oxygen	Develop basic models	Perform initial model calculations for currently available data. Investigate the roles of likely molecular sources for cometary C and O.	
General	Identify and acquire new observational data.		

the OH production rate of P/Giacobini-Zinner obtained by 18 cm radio observations by Bockelee-Morvan et al. (1985) in August (1.8×10^{28} molecules sec^{-1}) and October (2.9×10^{28} molecules sec^{-1}). A paper summarizing the PVOUVS observations and their analysis was presented in October at the AAS/DPS meeting (Stewart, Combi, and Smyth 1985).

In the second project quarter, further model analysis to describe the actual time dependent development of the hydrogen coma of Comet P/Giacobini-Zinner was undertaken (see the second quarter progress report). This was possible since the PTM provides a completely general and time dependent framework for studying the full range of spatial and temporal processes important in shaping the observed extended coma and can be appropriately implemented with little increase in the length of the model computation. The time dependent solar wind density, temperature, and bulk velocity as measured by the ICE Solar Wind Experiment during the build-up time for the observed hydrogen coma were incorporated in calculating the expected hydrogen lifetime. The sink for hydrogen atoms in the extended coma is a combination of photoionization, charge exchange with solar wind protons, and impact ionization by solar wind electrons. The lifetime of H atoms was shown to vary by more than one order of magnitude (2×10^{5} to 3.5×10^{6} sec) during the 42-day period preceding the observation and exhibited a time-average value of 1.9×10^{6} sec, which is about the original canonical value adopted by Keller and Meier (1976). The time dependent solar Lyman-α flux as measured by the Solar Mesospheric Explorer (SME) satellite for the same time period was also incorporated in the model to properly determine the Lyman-α photon solar resonance scattering of cometary hydrogen atoms that both makes them visible and accelerates them anti-sunward through momentum transfer. A reasonable fit to the observations was achieved for a water production rate of 2.2×10^{28} sec^{-1}. This production rate differed only slightly from that obtained from the initial analysis because the hydrogen lifetime assumed there was very similar to its actual value during the several days preceding the observation. The PVOUVS observations and our hydrogen coma analysis of Comet P/Giacobini-Zinner were published in Geophysical Research Letters (Combi, Stewart, and Smyth 1986) and a reprint of this paper is included in the appendix of this report.

3. Analysis Program for Observations of Comet P/Halley

The 1985/1986 observational program for Comet P/Halley was conducted by Dr. Stewart during the second and third quarters of this project year using the ultraviolet spectrometer of the Pioneer Venus Orbiter. This observing program has been very successful and has acquired a rich set of observations that are summarized in Table 4. As noted there, early pre-perihelion observations were made between 28 December 1985 and 7 January 1986. Additional observations began again on 30 January (10 days pre-perihelion) and continued until 7 March (26 days post-perihelion). The data set contains a large and consistent number of observations for cometary H, O, C and OH over this time period and provides exactly the information required to undertake the self-consistent studies defined by the third-year objectives of this project (see Table 3). Most of the data will provide radial brightness scans across the comet, but some of the hydrogen data (see Table 4) were taken so as to construct Lyman-α images. Some of the hydrogen data were reduced in the fourth quarter and made available to AER for analysis. Carbon, oxygen and OH data will be reduced after the hydrogen data are completed and made available to AER in the third project year for analysis. A model calculation fitting one of the observed hydrogen radial brightness scans is shown in Figure 2 and results in a water production rate of 1.4×10^{30} molecules sec^{-1} on 4 February 1986, just 5 days before perihelion when the comet made its closest approach to Venus of 0.27 AU.

Prior to receiving data for the hydrogen coma of Comet P/Halley in the fourth quarter, PTM computations to support PVOUVS observations of this comet at 1216 Å (hydrogen Lyman-α) were performed in the second quarter. These computations provided a best-guess expected hydrogen coma as it was to be viewed by the PVOUVS on February 2, 1986 and were based upon a water production rate of 1×10^{30} molecules sec^{-1}. This PTM result is shown in Figure 3. To investigate any observable effects on the H coma owing to outbursts or irregular vaporization of H_2O from the nucleus, an outburst model computation was also performed. The four-day time evolution of a one-day outburst for this same date is shown in Figure 4 as integrated through the trapezoidal instrument slit function of the PVOUVS. The H_2O production rate for the outburst is equal to the baseline level adopted in the model results in Figure 3 and would have to be added to this background level established by the normal vaporization rate. The day-to-day coverage available to PVOUVS should provide the time coverage necessary to study such time dependent effects with the PTM if present in Comet P/Halley.

TABLE 4

COMET P/HALLEY OBSERVATIONS FROM THE PIONEER VENUS ORBITER

	Date of Observation	Total Daily Observing Time (hr)	Observing Time per Species (hr)				
			H	O	C	OH	OTHER
1985	28 December	15	8	7	–	–	–
	29 December	15	7	8	–	–	–
	30 December	16	6	1	9	–	–
	31 December	16	5	3	–	8	–
1986	1 January	13	9	–	4	–	–
	2 January	20	4	15	1	–	–
	3 January	16	4	4	8	–	–
	4 January	15	4	3	–	8	–
	5 January	14	4	10	–	–	–
	6 January	14	7	–	7	–	–
	7 January	7	3	4	–	–	–
	30 January	3	3	–	–	–	–
	31 January	16	10	2	2	2	–
	1 February	11	5	2	2	2	–
	2 February*	18	18	–	–	–	–
	3 February*	19	19	–	–	–	–
	4 February*	19	13	1	2	1	2
	5 February*	19	17	–	–	–	2
	6 February*	19	17	–	–	–	2
	7 February	15	9	1	1	1	3
	8 February	11	7	2	2	–	–
	9 February†	16	8	2	2	2	2
	10 February	11	8	1	2	–	–
	11 February	16	9	1	2	1	3
	12 February	16	9	1	6	–	–
	13 February	19	12	6	1	–	–
	14 February	15	10	5	–	–	–
	15 February*	20	20	–	–	–	–
	16 February	16	10	4	2	–	–
	17 February	16	9	3	2	2	–
	18 February	18	11	2	2	3	–
	19 February	12	9	1	2	–	–
	20 February	19	12	2	2	2	1
	21 February	20	13	2	2	2	1
	22 February	16	13	1	1	1	–
	23 February	19	13	2	2	2	–
	24 February	19	13	2	2	2	–
	25 February	21	14	3	2	2	–
	26 February	14	6	3	3	2	–
	27 February	19	11	2	3	3	–
	28 February	22	14	3	2	3	–
	1 March	18	12	2	2	2	–
	2 March	19	11	3	2	3	–
	3 March	21	13	2	3	3	–
	4 March	21	13	3	2	3	–
	5 March	15	8	2	2	3	–
	6 March	20	12	3	2	3	–
	7 March	2	–	1	1	–	–

*Image data acquired on these days for hydrogen

†Perihelion

PIONEER VENUS OBSERVATIONS OF LYMAN-α IN COMET P/HALLEY

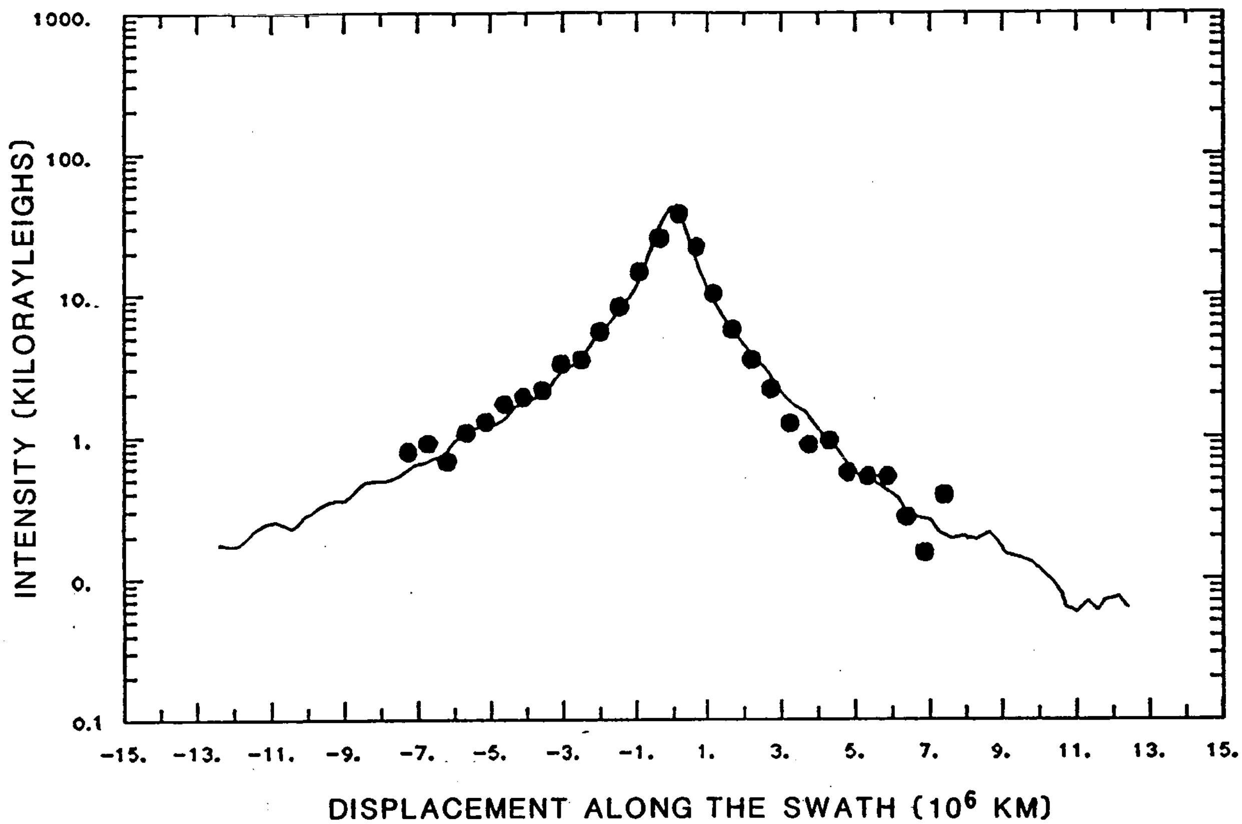

Figure 2. Model Analysis of Pioneer Venus Lyman-α Observations of Comet P/Halley

The points are a nucleus-crossing swath across the coma of Comet Halley recorded by the Pioneer Venus Orbiter UV spectrometer on 4 February 1986. The line shows the PTM analysis as corrected for optical depth effects near the nucleus. We find a production rate of 1.4×10^{30} s^{-1} for water on that day and a hydrogen lifetime of 2×10^6 s, reduced to 1 AU.

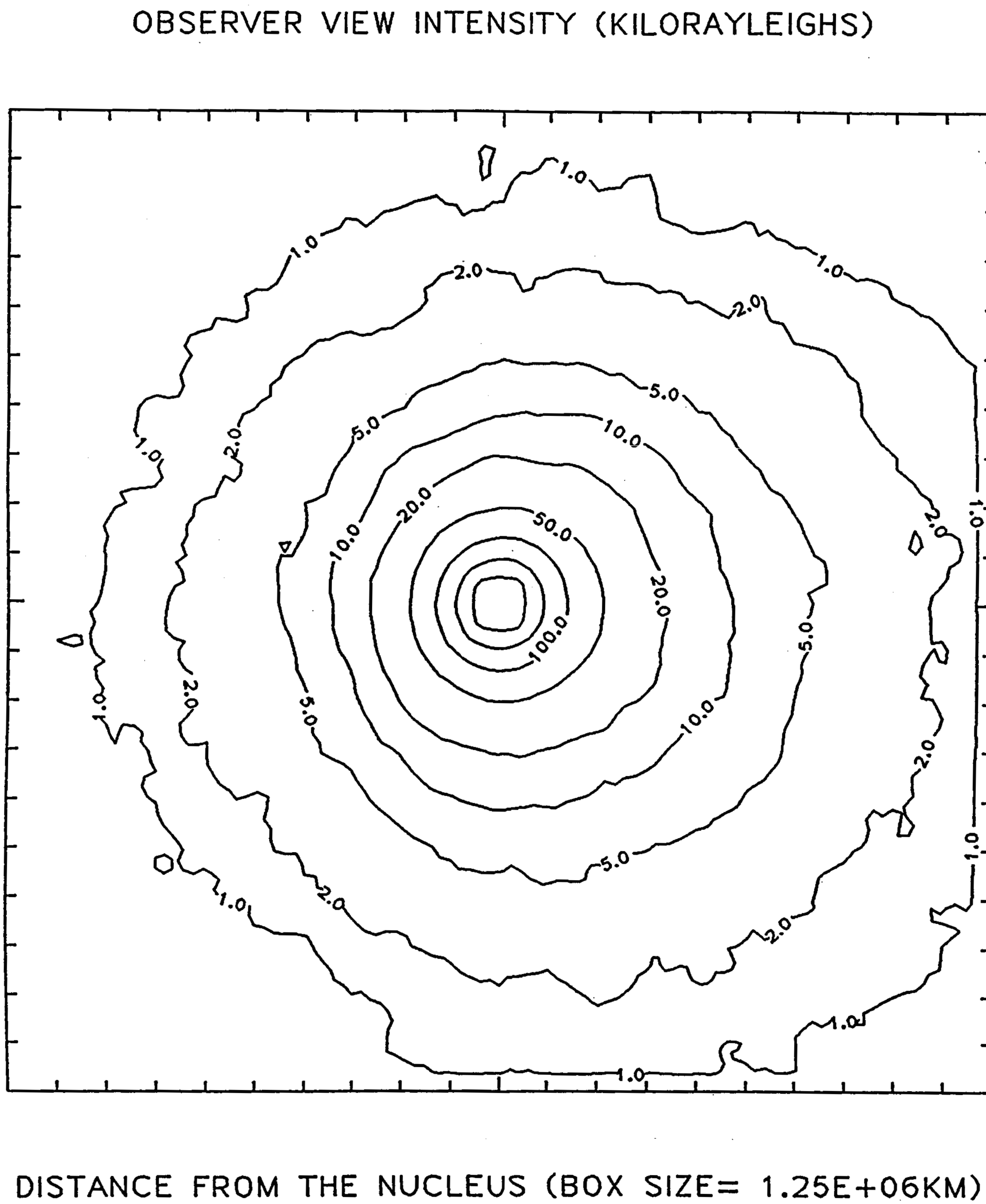

Figure 3. Modeled Image of the Hydrogen Coma of Comet P/Halley

The 1216 Å resonance scattered brightness of the hydrogen coma calculated using the PTM is shown in kiloRayleighs for the viewing geometry of the Pioneer Venus Orbiter on February 2, 1986. The sun is to the left. See text for details.

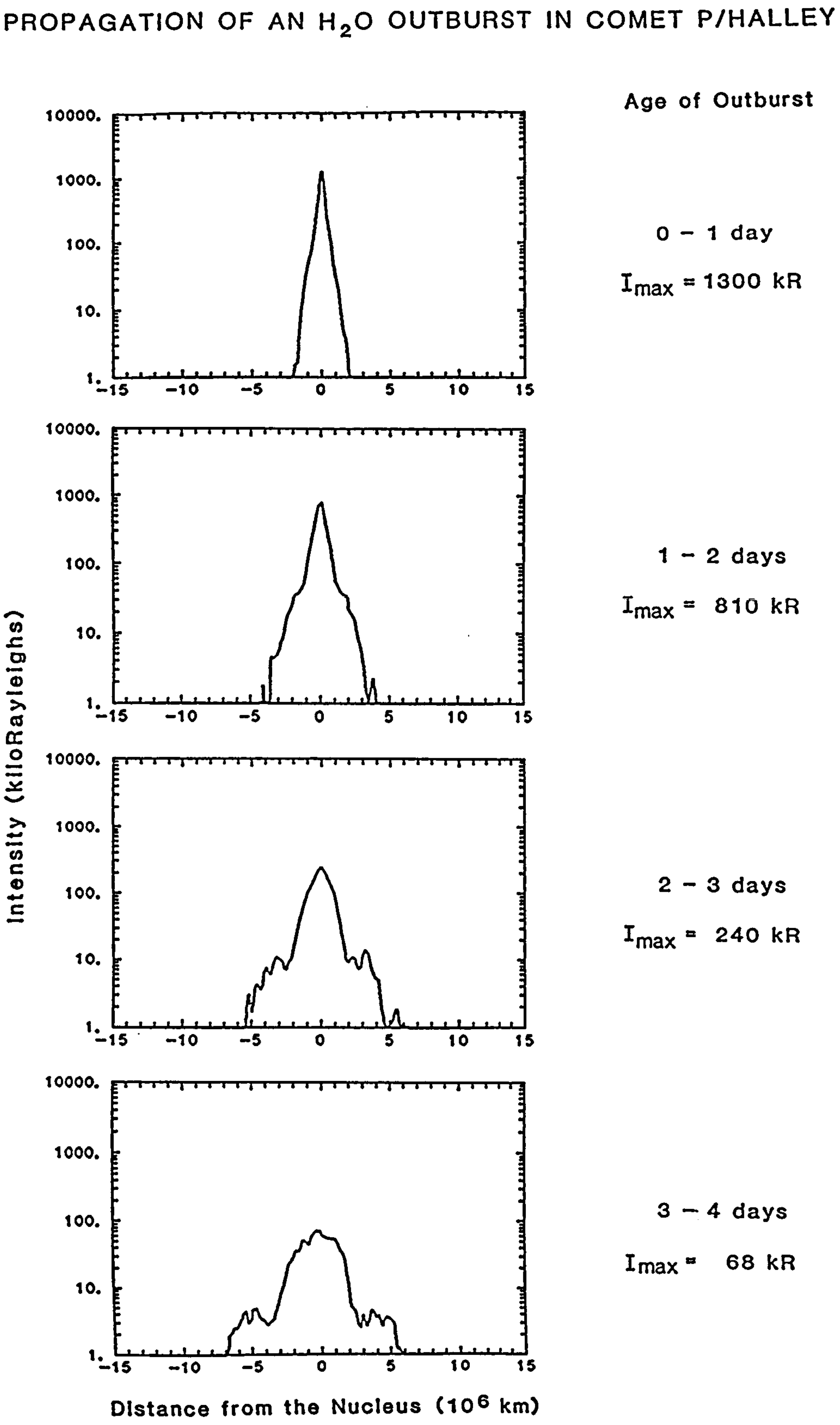

Figure 4. Propagation of an H_2O Outburst in Comet P/Halley

The one-dimensional spatial brightness profile of the one-day outburst is simulated as it would be seen through the instrument slit of the Pioneer Venus Orbiter ultraviolet spectrometer. The profile and its maximum intensity are shown from top to bottom at the end of 1, 2, 3 and 4 days. See text for further discussion.

4. Generalization of the Hydrogen Coma Model

The PTM for cometary hydrogen has been generalized in the third year to include elastic collisions between the non-thermal (~20 km sec^{-1} and 8 km sec^{-1}) hydrogen atoms (produced by photodissociation of H_2O and OH) and the heavy molecules and atoms (H_2O, OH, O) that flow radially outward from the nucleus at a speed of ~1 km sec^{-1}. Such collisions are thought to be important for comets with large H_2O production rates and smaller perihelion distances such as Comet Kohoutek and possibly Comet P/Halley. For Comet Kohoutek, the best analysis of Lyman-α images (Meier et al. 1976) using the model of Keller and Meier (1976) suggested that, after dissociation, (partial) thermalization of the hydrogen atoms by collisions with the heavy molecules plays an important role in determining the spatial morphology of the cometary atmosphere.

To investigate the importance of this H atom thermalization in cometary atmospheres, preliminary PTM calculations have been performed which explicitly include these collisions. Application of the model to a Lyman-α image of Comet Kohoutek (8 January 1974) reported by Meier et al. (1976) was initiated in the third quarter to test this idea further. For a water production rate of 4×10^{29} molecules sec^{-1}, the result of one such model calculation is shown in Figure 5 and successfully confirms this idea. In the third project year, the PTM analysis of additional Lyman-α images for Comet Kohoutek to be pursued will further examine and develop this idea. These model calculations will be included in a PTM documentation paper (Combi and Smyth 1986) to be completed during the third project year. Once the hydrogen data for Comet Kohoutek are understood, the carbon and oxygen data simultaneously acquired for this comet will also be analyzed with the PTM.

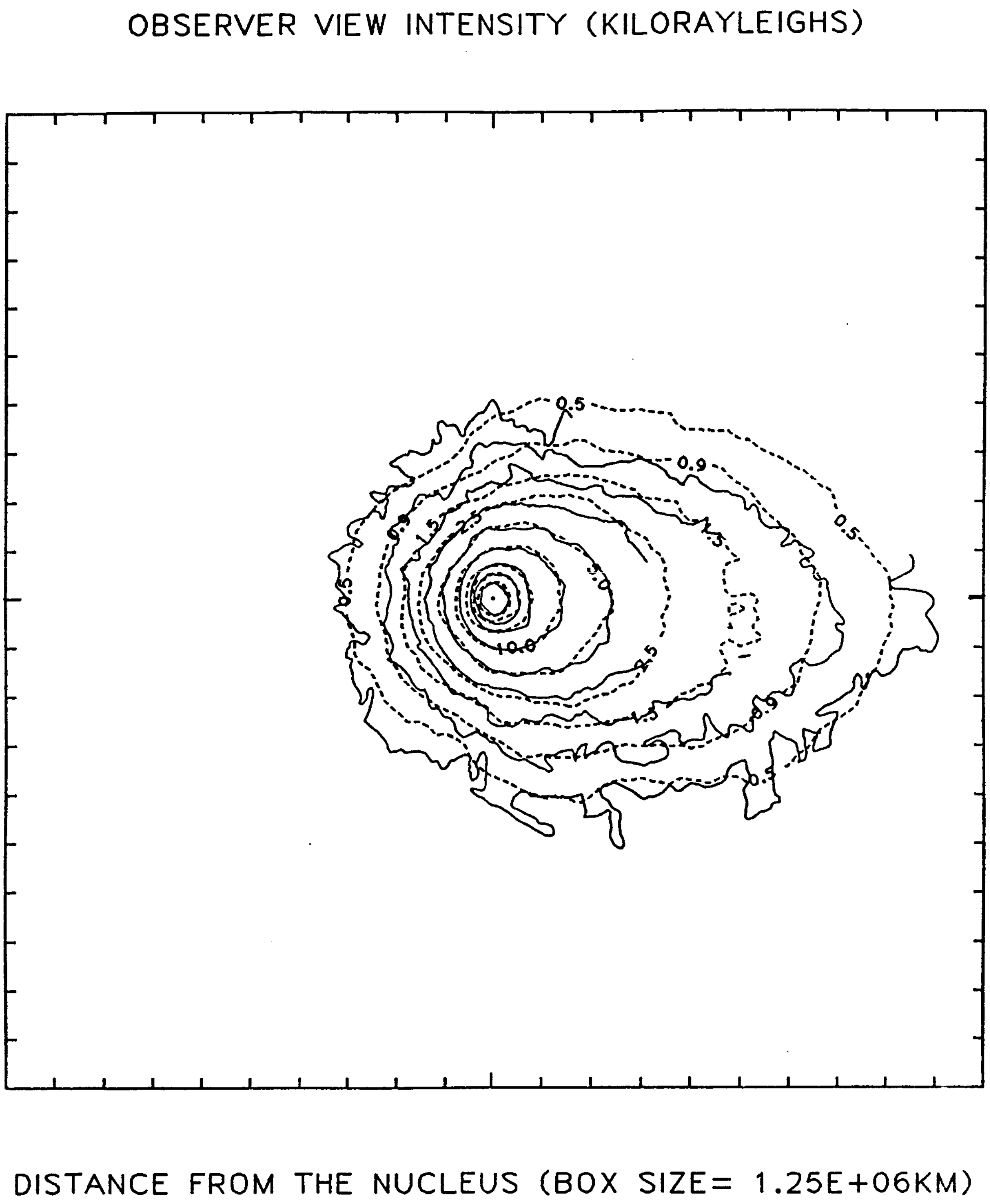

Figure 5. Comparison of the Observed Lyman-α Cloud of Comet Kohoutek with Collisional PTM Results

The observations of Comet Kohoutek were made by Meier et al. (1976) on 8 January 1974 when the comet was 0.434 AU from the sun. The three-dimensional model is fully time dependent and includes the explicit calculation of the partial thermalization of newly produced H atoms by multiple collisions with the background gas.

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V. APPENDIX

Pioneer Venus Lyman-α Observations of Comet P/Giacobini-Zinner and the Life Expectancy of Cometary Hydrogen

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PIONEER VENUS LYMAN-α OBSERVATIONS OF COMET P/GIACOBINI-ZINNER AND THE LIFE EXPECTANCY OF COMETARY HYDROGEN

M. R. Combi[1], A. I. F. Stewart[2], and W. H. Smyth[1]

Abstract. Pioneer Venus observed the hydrogen coma of Comet P/Giacobini-Zinner on 11 September 1985 during the ICE fly-by. Analysis of these data with a time-dependent 3-D particle-trajectory model implies a water production rate of 2.2×10^{28} s^{-1} on that day. The model includes the irregular variations in the H lifetime and the H Lyman-α fluorescence rate determined from simultaneous measurements of the solar wind by ICE and of the solar UV by SME, respectively. The H lifetime varied from 2×10^5 to 3×10^6 s during the 42 days preceding the observation.

Introduction

Observations of the spatially extended hydrogen comae of comets are important because neutral hydrogen is the most abundant of the observed constituents in comets. There is also significant quantitative evidence that hydrogen is produced through the photodissociation of water [Keller and Lillie 1974, Festou et al. 1979], which is thus believed to be the dominant parent gas that controls the vaporization of the icy-conglomerate nuclei of most comets [Delsemme 1982]. In short period comets like P/Giacobini-Zinner, water likely accounts for more than 98% of the total gas production [A'Hearn 1982]. Even in new comets like West (1976 VI) water is still the dominant species with possibly CO or CO_2 amounting to 20-40% of the total [Feldman 1978].

Monitoring the cometary hydrogen cloud and calculating with the aid of models the hydrogen (water) production rate are also important for allied studies of cometary phenomena. The size-scale and strength of the general plasma interaction between the solar wind and the outflowing cometary ions are determined largely by the total gas production rate of the comet, as are the initial velocity and particle size distributions for the refractory material present in the observed dust tail.

We report here the results of a continuing effort to observe comets with the Pioneer Venus Orbiter Ultraviolet Spectrometer (PVOUVS). We began with the first post-perihelion observations during the 1984 apparition of Comet P/Encke [Combi et al. 1984] and continue at least through the perihelion period observations of Comet P/Halley in February and early March 1986.

[1]Atmospheric and Environmental Research, Inc., Cambridge, MA.

[2]Laboratory for Atmospheric & Space Physics and Department of Astrophysical, Planetary & Atmospheric Sciences, University of Colorado.

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Observations

The Pioneer Venus Orbiter is in an eccentric (2000 x 66000 km), 24-hour orbit around Venus. The inclination is 105° and the latitude of periapsis is 8° N [Colin 1980]. The spacecraft is spin-stabilized with a spin period of 13.514 sec. The University of Colorado's Orbiter Ultraviolet Spectrometer (OUVS) [Stewart 1980] is mounted with its line of sight offset 60° from the spin axis. During one spin of the spacecraft, the OUVS entrance slit (1.38° by 0.14°) traces a swath 1.38° wide along a cone of 60° half-angle.

A scan of the hydrogen coma of Comet P/Giacobini-Zinner in Lyman-α was made on 11 September 1985 during the ICE spacecraft fly-through of the tail. The coma was sampled every 0.36° along the swath and the total integration time for the observation was 9.4 hours. The path of the swath cut through the coma from northeast to southwest at an angle of 46.577° from the comet-sun line on the sky plane. The OUVS has a spectral resolution of 13 Å. During acquisition of data from the comet, it was set to the position closest to the wavelength of Lyman-α (121.6 nm). Its sensitivity to Lyman-α is 130 counts/sec/kiloRayleigh.

The data show emissions from the comet, interplanetary hydrogen, and Venus' hydrogen corona. The non-cometary signals (260 Rayleighs) were removed by subtraction. Absorption of the extra-Venusian signals by hydrogen atoms in the planetary corona was insignificant, and the interplanetary signal in the neighborhood of the comet was estimated by interpolation. Figure 1 shows the measurements along the swath with the Venusian and interplanetary contributions already subtracted. The large signal at ~6×10^6 km toward the sunward (right) side of the nucleus is likely to be spurious, as a shorter integration taken later the same day shows no evidence of such an anomaly.

Model Description

To analyze these data, we have employed the particle-trajectory model (PTM) [Combi and Smyth 1985]. Two other major modeling efforts have been set forth to date for this purpose by Keller and co-workers [Keller and Meier 1976] and Festou and co-workers [Festou et al. 1979]. Keller and co-workers developed point source cometary hydrogen models which use the "syndyname" method to approximate the relative trajectories of an atom and the nucleus in the extended coma (10^5 - 10^7 km). Festou et al. used a steady state one-dimensional vectorial model to describe more realistically the source region in their analysis of the inner coma ($\lesssim 10^4$ km) Lyman-α profiles of Comet Kobayashi-Berger-Milon (1975 IX).

The PTM calculates the atom trajectories in an arbitrarily large spatial domain, by explicit integration of the equations of motion, and describes the spatially extended source region

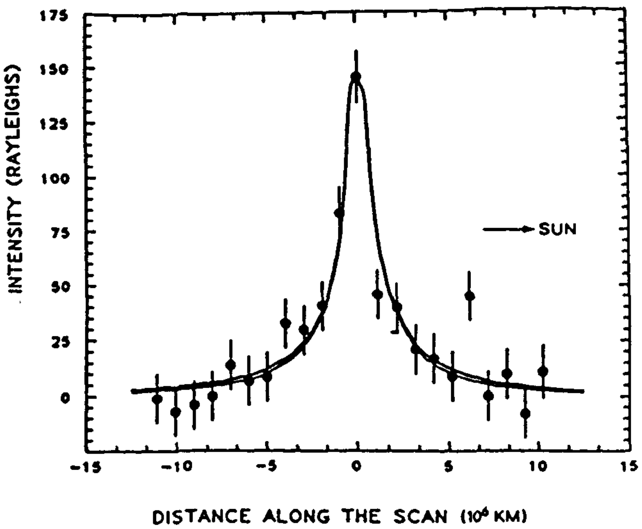

Fig. 1. Pioneer Venus Hydrogen Lyman-α Observations of Comet P/Giacobini-Zinner. The slit averaged intensities (points) are shown in comparison with two sets of model results; Model A is the thin (lower) line, Model B is the heavy (upper) line. The error bars indicate the statistical uncertainties in the observations.

($<10^5$ km) with a complete generalization of the Monte Carlo method developed by Combi and Delsemme [1980], which provides the starting times, locations and velocities for the non-thermal photodissociated H atoms. This generalization includes the complete heliocentric distance and velocity (doppler) dependence for photochemical lifetimes of H_2O and OH [Schleicher and A'Hearn 1983, van Dishoeck and Dalgarno 1984].

The source production rate of H_2O was assumed to vary as the inverse cube of the heliocentric distance as is appropriate for water vaporization at heliocentric distances $\gtrsim 1$ AU. However, since the comet's heliocentric distance did not change very much during the build-up time of the hydrogen coma, the model is not very sensitive to this assumption. The outflow velocity for the H_2O molecules was taken to be 0.58 $r_H^{-1/2}$ km s^{-1} [Delsemme 1982] and the lifetime for H_2O appropriate to the quiet sun conditions was 8.2×10^4 s at 1 AU [Festou 1981]. The velocity distributions for the H and OH fragments upon photodissociation of H_2O were taken from Festou [1981] with an update to the branching ratio for the Lyman-α dissociation branch (Slanger 1982, private communication). An H velocity from OH dissociation of 8 km s^{-1} was adopted.

The variable radiation pressure acceleration and the instantaneous emission rate for H atoms was calculated for the shape of the solar disc averaged Lyman-α profile [Lemaire et al. 1978] and for the overall solar Lyman-α flux from simultaneous Solar Mesospheric Explorer (SME) observations (Rottman 1986, private communication). Past modeling efforts [e.g., Keller and Meier 1976] have tied together a single value for the solar Lyman-α flux appropriate both for the instantaneous fluorescence rate at the time of the observation which sets the absolute abundance calibration, and that for the radiation pressure acceleration which determines the atoms' kinematics and causes most of the spatial distortion of the hydrogen coma along the comet-sun line.

The hydrogen atom lifetime has usually been modeled by choosing a nominal value at 1 AU (due mainly to charge exchange with solar wind protons) and scaling it as the square of the heliocentric distance (~1/particle flux). The canonical value of 2×10^6 s [Keller and Meier 1976] was questioned in our previous analysis of PVOUVS observations of Comet P/Encke [Combi et al. 1984] where a value of 9.4×10^5 s best explained the observations and was also shown to be consistent with mean solar wind conditions if one included the combined effects of charge exchange, electron impact ionization and photoionization.

The generality of the PTM has enabled us for the first time to model the impact of irregular time variations in both the solar Lyman-α flux and the hydrogen atom lifetime on the coma.

Solar Wind and Solar Lyman-α Data

We have obtained 12-hour averages of the solar wind density, bulk flow velocity, and electron temperature for in situ observations near the same heliocentric longitude and latitude as the comet from the ICE Solar Wind Plasma Experiment (Bame and Zwickl 1985, private communication). The data cover a 42-day period ending on the observation day of 11 September 1985, which is more than adequate to generate the entire observable hydrogen coma. We have also obtained the daily averages of the solar Lyman-α flux as measured by SME during the same time period (Rottman 1986, private communication). Since the earth was ~27.5° ahead of both the comet and the ICE spacecraft in heliocentric longitude we have made a 2 day correction to the time scale of the SME data to account for solar rotation.

The total hydrogen lifetime results from three processes: charge exchange with solar wind protons, solar wind electron impact ionization, and photoionization by extreme ultraviolet solar photons. Charge exchange is the dominant process and has been calculated from collision cross section data [Fite et al. 1960]. The charge exchange cross section in square Angstrom units in the range of speeds of 200-700 km s^{-1} appropriate for the solar wind can be expressed as $\sigma = 291.47\, v^{(-0.4419)}$, where v is the relative speed in km s^{-1}. The electron impact ionization rate coefficient is a function of temperature and was calculated from the expression of Shemansky (1984, private communication). The charge exchange rate is also proportional to the solar wind proton flux and the electron impact ionization rate is proportional to the electron density. The photoionization rate at 1 AU of 7.3×10^{-8} s^{-1} for quiet sun conditions was adopted from the value of Huebner and Carpenter [1979].

Figure 2 shows the solar wind data, the hydrogen lifetime, and the daily averages of the solar Lyman-α flux, for the entire 42 day period ending on the observation date.

Analysis and Discussion

The numerical results in Figure 2 show significant irregular variations in the hydrogen atom lifetime and smaller variations in the Lyman-α fluorescence rate. Variations in UV

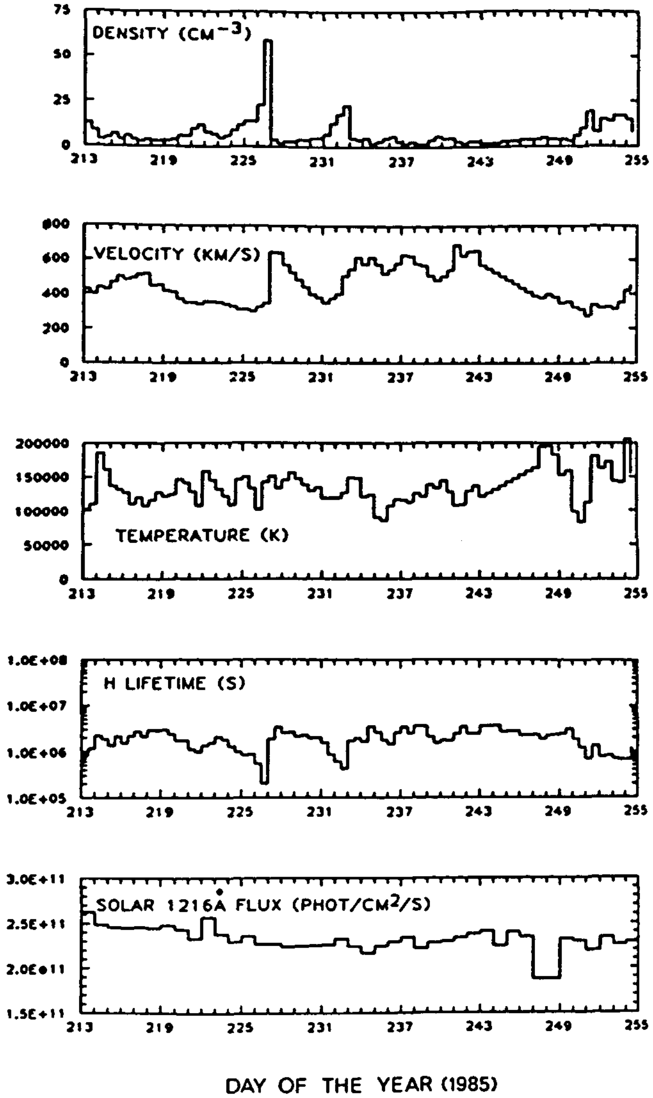

Fig. 2. Irregular Variations in the Solar Wind, the Hydrogen Lifetime and the Solar Lyman-α flux. Shown are the SME and ICE solar data as viewed from the comet during a 42 day period ending on September 11, 1985 (day 254). Plots from the top down are (1) solar wind density, (2) velocity and (3) temperature, (4) the hydrogen atom lifetime for charge exchange, electron impact and photoionization, and (5) the solar Lyman-α flux. Three minor gaps in the solar wind data have been filled by linear interpolation. The ICE data are as measured at 1.03 AU; the SME data and hydrogen lifetime are at 1 AU.

fluorescence rates had been forewarned in the early days of space observations of comets [Feldman et al. 1976], thus these results should come as no real surprise. The hydrogen lifetime (reduced to 1 AU) ranges from 7-10 x 10^5 s during the several days immediately preceding the observation. This is the period covered by the portion of the H coma best observed by PVOUVS, and is consistent with our previously determined value of 9.4 x 10^5 s [Combi et al. 1984]. The 42-day average value is surprisingly 1.9 x 10^6 s or about the original canonical value [Keller and Meier 1976]. Most importantly, the lifetime varied significantly from the average value, ranging from 2 x 10^5 to 3.5 x 10^6 seconds. Departures from the average lasted for extended periods of several days which are generally long enough to have observable effects on the coma.

A model similar to the one used for Comet P/Encke [Combi et al. 1984] was first applied to the Comet P/Giacobini-Zinner data and is shown as the thin line in Figure 1 [Stewart et al. 1985]. For this model the hydrogen lifetime was taken to be 9.4 x 10^5 seconds at 1 AU and was assumed to vary as the square of the heliocentric distance (hereafter referred to as Model A). A reasonable fit was achieved for a water production rate of 2.3 x 10^{28} per second. In hindsight we can now see that this lifetime was in fact appropriate for the inner 5 x 10^6 km of the coma as evidenced by the calculated lifetime (Figure 2) during the last five days before the observation.

The heavy line in Figure 1 shows the result of using the actual irregular variations in both the hydrogen lifetime and the Lyman-α fluorescence in the PTM (hereafter referred to as Model B). The inner part of the hydrogen coma is fitted equally well by the two curves. However, the comet's activity level and thus its Lyman-α brightness were low enough that an adequate signal-to-noise needed to record the more distant regions of the coma was not attainable with reasonable integration times. Had the good signal-to-noise data extended to farther distances from the nucleus, we would have been easily able to distinguish between the models; this would be the case for a comet as active as P/Halley at 1 AU. The difference is better illustrated in Figure 3 which shows the two modeled two-dimensional sky plane images. As expected, the inner parts of the images are nearly identical out to the 20 Rayleigh level since the constant lifetime (9.4 x 10^5 s) in Model A is roughly the same as the varying values in Model B. The 5-10 Rayleigh level in Model B extends farther from the nucleus than does that for Model A. This results from the fact that, during the 5 to 20 day period

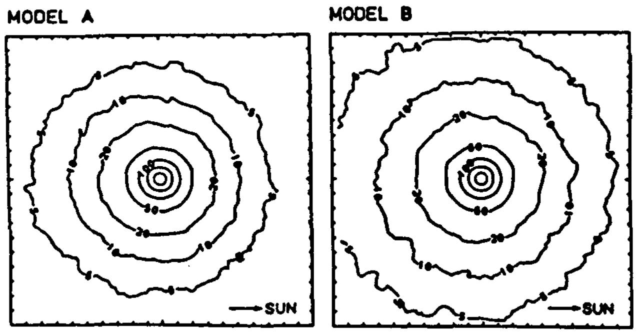

Fig. 3. Modeled Images of the Hydrogen Coma of Comet P/Giacobini-Zinner. Model A is the PTM result for the straightforward heliocentric distance and velocity scaling of the values at 1 AU of the hydrogen atom lifetime and Lyman-α fluorescence rate. Model B includes the actual hydrogen atom lifetime and Lyman-α fluorescence rate as determined from the measured irregular variations in the solar wind (ICE) and the solar Lyman-α flux (SME). Adjacent tick marks are separated by 1.25 x 10^6 km.

prior to the September 11 observation, the calculated hydrogen lifetime was more than a factor of two larger than the value during the 0 to 5 day period, which was appropriate for the observed inner part of the coma and used as the constant value in Model A.

The differences due to variations in the solar Lyman-α flux did not make themselves evident in this comparison. This is due to the fact that the solar radiation pressure-induced distortion at 1 AU is small, and 0-20% variations in a small effect will not be apparent. The constant Lyman-α flux assumed in Model A was within a few percent of that measured for the actual observation time. This difference yields the best fit water production rate, 2.2×10^{28} s^{-1}, for Model B. For a comet closer to the sun, the distortion will be much larger and 20% variations which last for a few days should be distinguishable.

Comparisons of our H observations with concurrent OH observations imply similar water production rates. International Ultraviolet Explorer observations on September 11 (A'Hearn 1986, private communication) yield a range of model dependent OH (water) production rates. Haser models A and B and the vectorial model [Weaver et al. 1981] yield values of 5.4×10^{28}, 2.7×10^{28} and 3.2×10^{28} s^{-1}, respectively. Radio observations [Bockelée-Morvan et al. 1985, Schloerb and Claussen 1985] using a Monte Carlo model find OH production rates in the range of $2\text{-}3 \times 10^{28}$ s^{-1} in September. All calculations of production rates are necessarily model dependent. The vectorial analysis of the IUE data, the Monte Carlo model for the radio data and our PTM results for the Pioneer Venus data all implicitly assume the lifetimes and velocities associated with water photodissociation. Their mutual consistency is encouraging.

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M. R. Combi and W. H. Smyth, Atmospheric and Environmental Research, Inc., 840 Memorial Drive, Cambridge, MA 02139-3758.

A. I. F. Stewart, Laboratory for Atmospheric and Space Physics and Department of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado, Campus Box 392, Boulder, CO 80309-0392

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