(NASA-CR-183157) EXTENDED ATMOSPHERES OF OUTER PLANET SATELLITES AND COMETS Final Report, 1 Aug. 1984 - 31 Aug. 1988 (Atmospheric and Environmental Research) 28 p CSCL 03B G3/91

N88-30572

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ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.
CAMBRIDGE, MASSACHUSETTS

Extended Atmospheres
of Outer Planet Satellites and Comets

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August 1988

Final Report for Period
August 1, 1984 - August 31, 1988

Prepared for
NASA Headquarters

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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 overall strategy has been to model 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 allow the Titan source to be quantified 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 used to analyze the density and UV emissions of extended cometary hydrogen, oxygen and carbon atmospheres. For this purpose, a collaborative effort with A.I.F. Stewart has been established to provide cometary H, C, and O emission data obtained by the ultravoilet spectrometer of the Pioneer Venus Orbiter for Comets P/Encke, P/Giacobini-Zinner, and P/Halley.

The discussion of third year progress and achievements is emphasized in this final report, with a brief overview summary of first and second year efforts provided for completeness. A more thorough discussion of the accomplishments in the first and second year of this project is contained in the 1985 and 1986 annual reports.

II. HYDROGEN DISTRIBUTION IN THE SATURN SYSTEM

1. Overview

The initial three-year plan for this project in the Saturn system is summarized in Table 1. Although the basic strategy has remained the same, cometary emphasis because of the return of P/Halley and a discovery of significant amounts of new Voyager data for the circumplanetary distribution of hydrogen at Saturn have altered the implementation of this plan as summarized below.

In the first year, scheduled objectives were achieved for refining the lifetime description of hydrogen atoms in the magnetosphere and for evaluating and partially processing Voyager UVS data for the Lyman-α emission. A new lifetime process for hydrogen involving collisional loss with H atoms of the interstellar medium was identified. Preliminary model calculations were performed to determine the best procedure for including the long lifetimes of hydrogen atoms.

In the second project year, efforts to have been expended on Saturn system research were largely postponed until the third year. This was because of the major emphasis placed on cometary activities with the return of Comet P/Halley and because of difficulties in acquiring adequate self-consistent plasma information from the Voyager PLS instrument from which to calculate the hydrogen atom lifetime in the planetary magnetosphere.

In the third year, the program outlined in Table 1 was resumed. The primary development, however, has been centered about the discovery by D.E. Shemansky in our collaborative effort of a significant amount of new Lyman-α data for hydrogen in the old Voyager UVS data tapes. This discovery, which is discussed below, has established the basis for a whole new set of studies and suggests that both Titan's hydrogen torus and Saturn's hydrogen corona play a major role in the circumplanetary distribution of hydrogen. The new studies have provided the basis for research that is to be undertaken in a new NASA-sponsored project that logically continues the efforts initiated here.

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 lifetime 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	

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 interstellar 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 for hydrogen atoms is being calculated by Shemansky as part of his collaborative involvement with this ongoing 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). As noted in the second year annual report, significant discrepancies exist between the Voyager PLS electron and ion data for the magnetosphere. In addition, large and likely unrealistic differences exist between the amount of plasma inferred on L-shells in the inbound and outbound path of the Voyager spacecraft. To properly address these issues, E.C. Sittler has agreed to work with J.D. Richardson and publish a paper resolving these matters. Prior to this publication, their results will be available to the continuation of this project in which modeling analysis will be undertaken for the complete set of Lyman-α emission data for the Saturn system obtained by the UVS instrument of the Voyager 1 and 2 spacecrafts during their 1980 and 1981 encounters with the planet.

Table 2

LOSS PROCESSES FOR ATOMIC HYDROGEN IN THE SATURNIAN SYSTEM

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

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

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

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

3. Voyager UVS Data for Atomic Hydrogen

Voyager measurements published to date for the hydrogen Lyman-α distribution in the Saturn system are for radial-scan data obtained in the Voyager 1 pre-encounter period (Broadfoot et al. 1981) and vertical-scan data obtained in the Voyager 2 pre-encounter period (Sandel et al. 1982). As part of a collaborative effort with this project, D.E. Shemansky has prepared additional Voyager data for our modeling analysis. In the second project year, significantly improved radial scan data were identified and reduced by Shemansky for the Voyager 2 pre-encounter period. Additional data of lesser quality were also examined in hopes of constructing a complete image of the Lyman-α distribution. In this period, a search of the magnetic tapes containing all pertinent UVS data of Voyager 1 and Voyager 2 was undertaken. The search has uncovered a significant amount of new data that had <u>not</u> previously been reduced. In fact, this new data set is approximately 2.5 times larger than the old data set that was already reduced and published by the UVS team. A summary of the older published data and newly reduced data is given in Table 3.

There are a number of interesting aspects of the new data in Table 3 that deserve discussion. The most spectacular is that from the Voyager 1 post-encounter data from which an <u>image</u> of the H Lyman-α emission has been constructed at a viewing angle of ~25° to the orbit plane of Titan. A preliminary version of this image is shown in Figure 1. The image indicates that the brightness distribution is <u>not</u> cylindrically symmetric as expected for a Titan torus alone (Smyth 1981; Hilton and Hunten 1988). The brightness distribution between Saturn and Titan's orbit has a minimum at pre-dawn and a maximum in the vicinity of the dusk terminator line suggesting an asymmetric dayside hydrogen source for a large electroglow-driven planetary corona. In the less corona-dominated portion of the circumplanetary hydrogen, the presence of the Titan hydrogen torus can be distinctly identified. The image data are discussed in detail by Shemansky and Hall (1988). In addition to these data, the newly reduced Voyager 2 pre-encounter data provide the <u>best</u> one-dimensional data in the orbit plane. Combining the earlier published data and new data in the

Table 3

Voyager Spacecraft Data Available for Research on the Atomic Hydrogen Distribution in the Saturn System

Voyager 1 pre-encounter data

- Published Data: 14 days of one-dimensional scan data nearly parallel to the satellite orbit plane have been reported in the V1 30 day science report (Science 212, 201-211, 1981). These data were obtained at a range of ~ 2 x 10^7 km from Jupiter.

- New Data: Additional data of similar nature is available but the quality is uncertain. The reduction process should be repeated to include the additional data.

Voyager 1 post-encounter data

- Published Data: none

- New Data: Observations were obtained in mosaic scans across the system. All the data have been reduced for the first time in the past few months of 1987. The Voyager 1 post encounter trajectory is out of the solar system plane, and the data are obtained at an angle of ~25° to the orbit plane of Titan. An image of the system in H Lyman-α emission has been constructed but is not yet published. The data in this image were obtained over the period 1980 DOY 324-343 (6-25 days post encounter) at spacecraft planet ranges of 0.83 x 10^7 - 0.33 x 10^8 km. The integration time of the data set is 126 hours. Titan moves ~1.25 orbits during the 20 day observing period.

Voyager 2 pre-encounter data

- Published Data: Observations of one-dimensional scan data approximately normal to the satellite orbit plane were published in the V2 30 day science report (Science 215, 548-553, 1982).

- New Data: All usable observations for one-dimensional scan data approximately parallel to the satellite orbit plan have been reduced for the first time. The data were obtained in 1981 DOY 180-186, at ranges of 0.54 x 10^8 - 0.49 x 10^8 km. The integration time for this data set is 88 hours. These observations provide the best one-dimensional data in the orbit plane of Titan that were obtained by the Voyager spacecrafts.

Voyager 2 post-encounter data

- Post-encounter sequences were not obtained because of the lockup of the scan platform drive.

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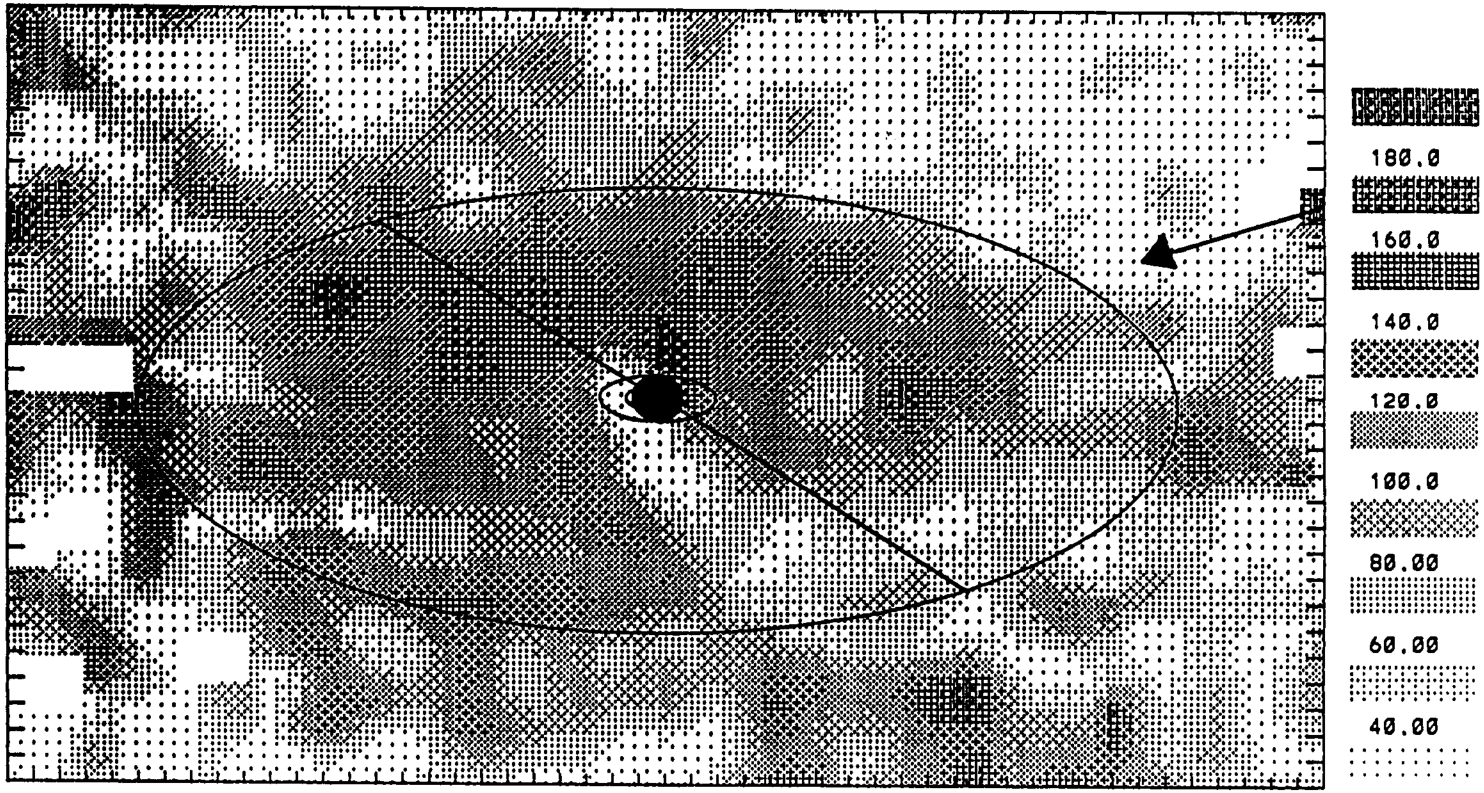

Figure 1

Lyman-α Image for Hydrogen in the Saturn System

(see page 15 for legend)

LEGEND

Figure 1. Density plot of the Saturn system in H Ly α emission obtained from Voyager 1 UVS mosaic scans of the system in the period, 1980 DOY 324-343 (6-25 days post encounter). Spacecraft-planet range 0.83×10^7 - 3.3×10^7 km. The total integration time for the observations was 126 h. The pixel size is 1 R_J x 1 R_J perpendicular to the spacecraft-planet line, 1 R_J x 2.4 R_J projected onto the satellite orbital plane. The zenith angle of the spacecraft is 65°. The data is shown after subtraction of the LISM background calculated with the aid of a model, and weak stellar sources which appear in three locations approximately along the right side of the major axis of the Titan orbital ellipse drawn on the figure. The bright spot at the right ansa is due to imperfect correction for one of the stellar sources. The location of the sun-planet line is indicated in the upper right sector. The planet is drawn to size on the figure with the superposed mean size and orientation of the Voyager UVS field of view. A small sunlit crescent affects the signal on the right side of the planet. The data has been smoothed in a 3 x 3 pixel area, weighted by integration time, in a 1,2,1; 2,4,2; 1,2,1 pattern. The brightness scale in Rayleighs is given on the figure. The depression in signal in a rectangular area oriented parallel to the length of the slit at the position of the planet is caused by occultation of the LISM signal by the planet. The darkside of the planet would otherwise be of the same order of brightness as the coronal hydrogen. Bright areas toward the periphery and in some locations in the vicinity of Titan's orbit on the left side lose their significance because of low signal to noise ratios.

analysis of the H distribution with an appropriately developed model for the planetary corona and the Titan hydrogen torus model should provide a most interesting study. Preliminary modeling activities regarding the new data were initiated near the end of this project. The study of these data will be undertaken at AER in a new NASA funded continuation project for this research.

III. COMETARY ATMOSPHERES

1. Overview

The three-year plan for this project in the area of cometary atmospheres is summarized in Table 4. The project has been very successful in meeting these objectives and has made significant advances in understanding the physics and interrelationships in the structure and dynamics of the inner and extended comae of comets.

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 (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 4), 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 the 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. Our analysis of the hydrogen coma data for Comet P/Giacobini-Zinner was published in Geophysical Research Letters (Combi, Stewart and Smyth 1986). The preliminary supporting model calculations for observation of Comet P/Halley are discussed in the 1986

TABLE 4

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 self-consistent 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.		

Annual Report. Generalization of the hydrogen comae model to include collisions and the role of collisional thermalization are discussed below.

In the third project year, the two main areas of endeavor have been (1) assessment and preliminary analysis of the PVOUVS data for Comet P/Halley, and (2) completion of the hydrogen model including collisions and its successful employment in understanding the role of collisional thermalization in the spatial morphology of the Lyman-α coma of comets. These two main areas are discussed below.

2. Data and Preliminary Analysis for Comet P/Halley

Coma data for Comet P/Halley were obtained by the 1985/1986 observational program conducted by Dr. A.I.F. Stewart during the second project year using the ultraviolet spectrometer of the Pioneer Venus Orbiter. This program acquired a rich set of observations that are summarized in Table 5. 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). There is a large and consistent data set for cometary H, O, C and OH over this time period. For atomic hydrogen, most of the data provide radial brightness scans across the coma, but some of the H data (see Table 5) were taken so as to construct Lyman-α images. For the O, C and OH comae, the data provide radial brightness scans which contain useful signal to noise information, but only within a few pixels of the nucleus. The O, C and OH data are therefore valuable for determining the relative abundance of these species near the nucleus. Modeling studies of the spatial structure of the coma can therefore be undertaken only for hydrogen.

Reduction of the H coma data by Dr. Stewart has been slower than initially anticipated because of two main factors: (1) uncertainties in the spacecraft pointing, and (2) uncertainties in the removal of the interplanetary Lyman-α background emission which is very spatially non-uniform. A preliminary discussion of the H, O and C data has been given by Stewart (1987).

TABLE 5

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

PVOUVS Lyman-α data for Comet P/Halley for 7 days in the December 1985 - March 1986 period have been received to date from Dr. Stewart for preliminary analysis. The background Lyman-α emission from these scan data has been only approximately removed. The scan data on each date that includes the nucleus have been selected for modeling analysis. Seven scans were thus constructed and fit by the Particle Trajectory Model (PTM). The scan on 9 February 1986 and its model fit are shown in Figure 2. The observing dates for the seven scans and their H_2O production rate as determined by the model fits are summarized in Table 6. A complete analysis of the Lyman-α scan and image PVOUVS data for hydrogen will be undertaken in a new project that will continue this research work.

3. The Role of Collisional Thermalization in the Coma

The particle trajectory model (PTM) for cometary hydrogen was generalized in the second year to include elastic collisions between non-thermal (~8 km sec^{-1}, ~20 km sec^{-1}, and ~30 km sec) 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. For comets with large production rates and small perihelion distances such as Comet Kohoutek and possibly Comet P/Halley, these collisional processes in the inner coma have been shown to be important in determining the velocity dispersion and hence spatial distribution of H atoms observed in Lyman-α emission of the outer coma.

A paper entitled "The Role of Hydrogen Thermalization in Shaping the Lyman-α Coma", which briefly discussed the physics of the inner coma and its effect on the outer H coma, was presented (in poster format) at the "Symposium on the Diversity and Similarity of Comets" (6-9 April 1987, Brussels, Belgium). This paper was also published by ESA (Combi and Smyth 1987).

The PTM used in the above paper is but one of a more general class of models for cometary gases. Addressing this larger subject, a major model documentation paper entitled "Monte Carlo Particle Trajectory Models for Neutral Cometary Gases. I. Models and Equations" and a companion paper entitled "Monte Carlo Particle Trajectory Models for Neutral Gases. II.

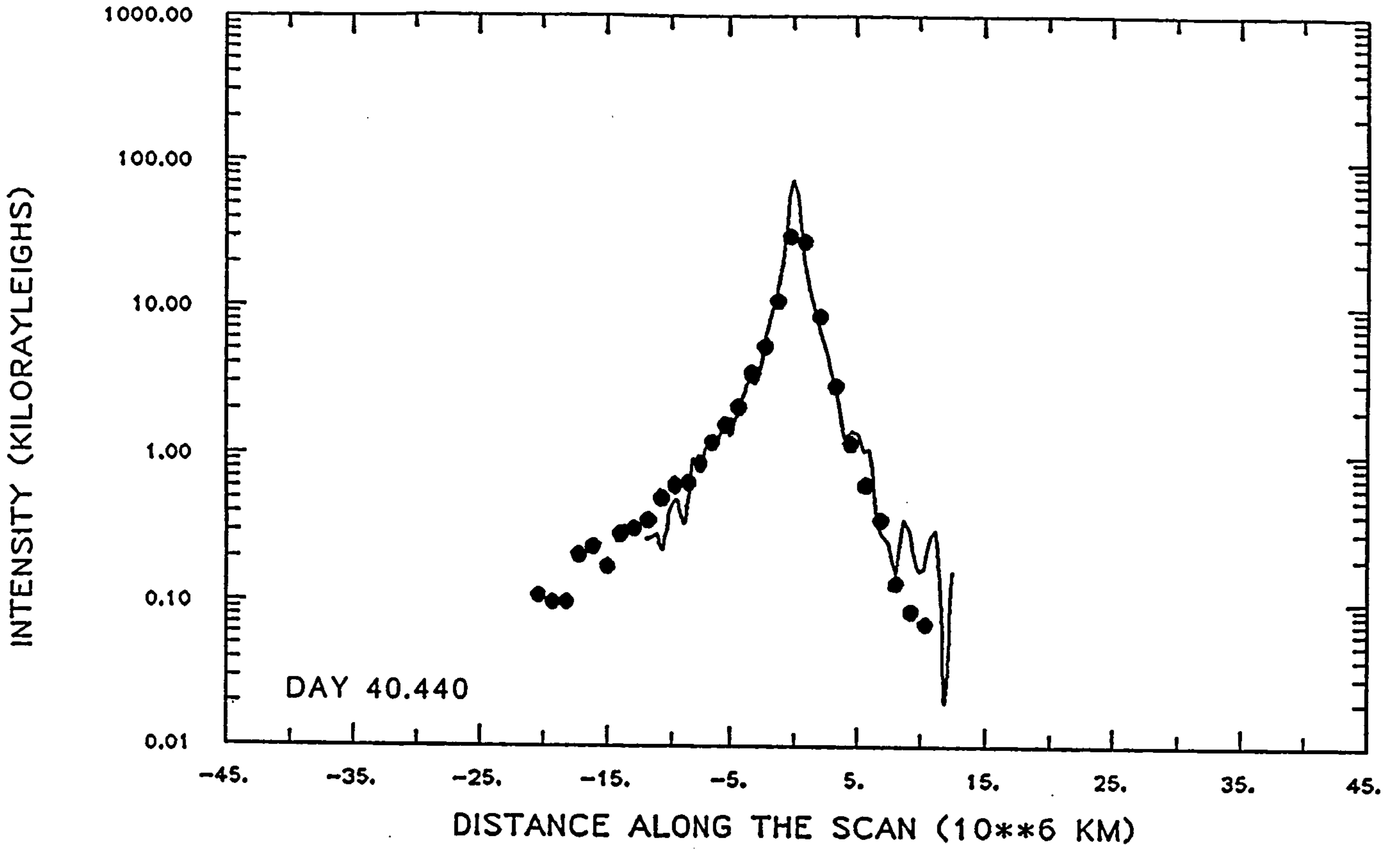

Figure 2
Model Analysis of Pioneer Venus Lyman-α Observations of Comet P/Halley

The points are a nucleus-crossing swath across the coma of Comet Halley recorded by the Pioneer Venus Orbiter UV spectrometer on 9 February 1986. The line shows the PTM analysis. The water production rate is 1.74 x 10^{30} s^{-1} on that day.

Table 6

WATER PRODUCTION RATE FOR COMET P/HALLEY FROM PIONEER VENUS ORBITER

Date of Observation	Heliocentric Distance (AU)	H_2O Production Rate (10^{30} molecules sec^{-1})
1985 30 December	1.022	0.41
1986 1 February	0.614	1.37
4 February	0.598	1.40
9 February	0.587	1.74
13 February	0.594	1.65
18 February	0.620	1.61
7 March	0.802	1.02

Spatial Morphology of the Lyman-α Coma" have been completed and published (Combi and Smyth, 1988 a,b). Both papers are included in the Appendix of this report. The first paper documents this new class of Monte Carlo particle trajectory models which are based upon physical processes of atoms and molecules in the coma. This model provides a new level of realism in predicting the spatial distribution of observed species in cometary comae and in exploring the basic physics of the transition zone between true fluid-flow and free molecular flow. The second paper successfully applies the general model of the former paper to simulate the hydrogen Lyman-α image for Comet Kohoutek and includes near perihelion one image representing an extreme case for collisional thermalization. The success of the model in this application is particularly noteworthy.

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V. APPENDIX

A. Monte Carlo Particle-Trajectory Models for Neutral Cometary Gases. I. Models and Equations

B. Monte Carlo Particle-Trajectory Models for Neutral Cometary Gases. II. The Spatial Morphology of the Lyman-Alpha Coma

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Extended Atmospheres of Outer Planet Satellites and Comets

5. Report Date
August 1988

6. Performing Organization Code

7. Author(s)
William H. Smyth and Michael R. Combi

8. Performing Organization Report No.

9. Performing Organization Name and Address
Atmospheric and Environmental Research, Inc.
840 Memorial Drive
Cambridge, MA 02139-3794

10. Work Unit No.

11. Contract or Grant No.
NASW-3966

12. Sponsoring Agency Name and Address
NASA Headquarters
Headquarters Contract Division
Washington, DC 20546

13. Type of Report and Period Covered
Final Report
8/1/84-8/31/88

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In the third year of this three-year project, research accomplishments are discussed and related to the overall objective. In the area of the distribution of hydrogen in the Saturn system, new Voyager UVS data have been discovered and are discussed. The data suggest that both Titan's hydrogen torus and Saturn's hydrogen corona play a major role in the circumplanetary gas source. Modeling analysis of this new data establishes a strong basis for continuing studies to be undertaken in a new NASA-sponsored project. In the area of the cometary atmospheres, observational data for H, O, C and OH acquired with the Pioneer Venus Orbiter are evaluated and preliminary modeling analysis for some of the hydrogen Lyman-a data is presented. In addition, the importance of collisional thermalization in spatial properties and structure of the inner and extended comae of comets has been demonstrated using the recently developed particle trajectory model. The successful simulation by this model of the hydrogen Lyman-a image for Comet Kohoutek near perihelion, an extreme case for collisional thermalization, is particularly noteworthy.

17. Key Words (Selected by Author(s))
satellites
comets

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
26

22. Price*

---

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.