Reports

Analysis of the Pioneer-Venus Lyman-α Image of the Hydrogen Coma of Comet P/Halley

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Comet Halley passed within 0.27 astronomical unit of Venus on 4 February 1986, 5 days before perihelion. This provided a unique opportunity to observe the comet's coma with the ultraviolet spectrometer orbiting the planet aboard the Pioneer Venus Orbiter spacecraft when the coma was otherwise obscured from Earth's view by the sun's glare. More than 9000 data points acquired systematically over the 5-day period from 2 to 6 February were combined to construct an excellent Lyman-α image of the hydrogen coma. The Lyman-α image was successfully reproduced with a comprehensive physical model, thereby verifying and documenting the underlying chemical kinetics and dynamics of the hydrogen coma.

WATER MOLECULES, THE DOMINANT volatile constituent sublimated from the surfaces of comets by solar heating, undergo multistep photodissociative reactions that liberate fast H atoms (*1–3*). For an active comet such as Halley, a collision-dominated zone develops around the nucleus. Within this zone, the fast atoms are thermalized or partly thermalized before escaping into the outer collision-free region where they form an enormous H coma, tens of millions of kilometers across. The shape of this coma depends on the interplay between the velocity distribution of the atoms, solar gravity, the antisolar acceleration produced by radiation pressure on the atoms, and (at large distance) the lifetime of the H atoms in the solar-wind environment. A satisfactory explanation of the detailed shape of the H coma of comet Kohoutek (*4*) was not achieved until a model incorporating a physical, unparameterized description of the collision zone was developed (*5–7*). Halley's H coma, which was imaged three times in 1216 Å ultraviolet (Lyman-α) light during its 1986 apparition, provides a second comet with a higher gas production rate and a much larger perihelion distance to test the physical picture noted above. We have analyzed the first of these images, obtained from the Pioneer Venus Orbiter Ultraviolet Spectrometer (PVOUVS) (*8*) a few days before perihelion, and have verified that the detailed physics and photochemistry incorporated in the model provide an excellent match to the image. The PVOUVS image was obtained during a period when the comet's conjunction with the sun rendered measurements from Earth extremely difficult. The other two images were obtained from sounding rockets some weeks after perihelion (*9*).

Observations of solar resonance–excited species in the comae of comet P/Halley by PVOUVS were obtained daily from 28 December 1985 through 7 March 1986, except for the period 7 to 30 January 1986 when Venus's superior conjunction interrupted the downlink to Earth. A description of the spacecraft and observing procedures and a presentation of the one-dimensional intensity scan data for the H, O, and C comae were reported by Stewart (*10*). The observing geometry over the 5-day period from 2 to 6 February, which provided this excellent out-of-the-plane Lyman-α image of the asymmetric hydrogen coma for PVOUVS but not for Earth, is illustrated in Fig. 1. Also shown in Fig. 1 is a simplified diagram of the spin-stabilized Pioneer Venus Orbiter showing that the optical axis of the ultraviolet spectrometer is fixed at about 60° from the spin axis and hence traces out a cone in the sky plane with each rotation of the spacecraft (approximately once every 13.5 s). The spacecraft spin axis, and hence the spectrometer field-of-view scan line across the sky, was held fixed for the 5-day imaging period. The comet's motion in the sky then carried its coma across this scan line, thereby mapping a two-dimensional region about the comet. Each scan line is composed of up to 128 samples along the portion of the complete cone sampling the coma and corresponds to a swath 1.4° wide through the coma. Typically 50 to 100 separate scan lines were added to improve the signal-to-noise ratio of each sample (or data point) along the scan.

Three possible sources contribute to the measured Lyman-α intensity at each data point: the comet, the Venus H corona, and the interplanetary background. The contribution from the Venus corona is negligible because observations of the comet were not made when the orbiter was near periapsis. The spatially dependent interplanetary background originates from the resonance scattering of solar Lyman-α photons by interstellar H atoms streaming through the solar system. The background contribution to each of the data points, which we determined using the interstellar hydrogen model of Ajello (*11*), was subtracted. We then constructed the cometary Lyman-α intensity image by spatially sorting the corrected data points (*12*). The resulting contour plot of the image is shown in Fig. 2. Superimposed over the contour map are dots marking the location of the over 9000 data points.

We analyzed the Lyman-α image using an updated version (*7*) of the fully time-dependent three-dimensional Monte Carlo particle trajectory model (MCPTM) of Combi and Smyth (*5, 6*). This model has

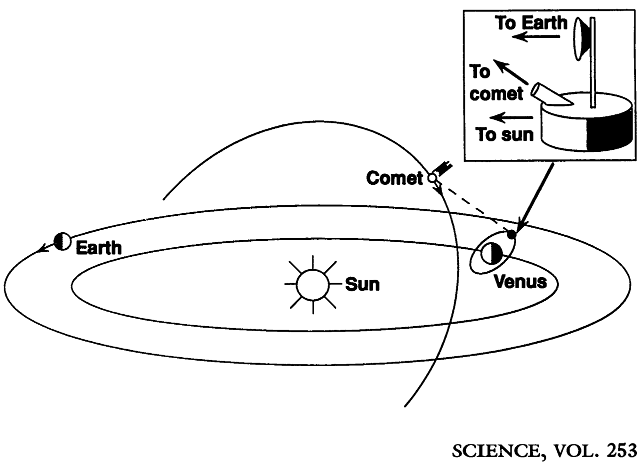

Fig. 1. Observing geometry of the Pioneer Venus Orbiter for comet P/Halley near perihelion. The relative positions to the sun of Earth, Venus, the comet, and the spacecraft on their orbits are shown. On 4 February 1986, the observational midpoint of the Lyman-α image data, the phase angle of the comet was 108°. The close-up of the Orbiter illustrates its spin-stabilized platform on which the ultraviolet spectrometer is located.

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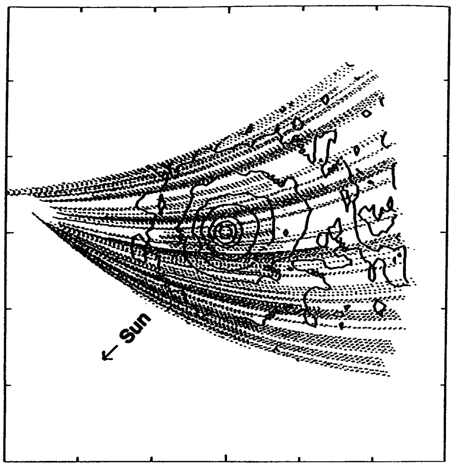

Fig. 2. Pioneer Venus Orbiter ultraviolet spectrometer image of comet Halley. A contour plot of the hydrogen Lyman-α emission from comet Halley, as seen by the PVOUVS during the period 2 to 6 February 1986, is shown with the contour levels in kilorayleighs of 0.2, 0.5, 1, 2, 5, 10, and 20. The tick marks on the circumscribed box are separated by 10×10^6 km. The map was constructed from over 9000 spin-scan data points, the locations of which are denoted by dots.

already been used successfully for analyzing PVOUVS observations of comets P/Giacobini-Zinner (*13*) and the published rocket observations (*4*) of comet Kohoutek (*6*). Whereas other earlier models used a parameterized atom velocity distribution to reproduce the shape of the H coma (*4*), this model predicts this distribution (and hence the coma shape) through its explicit description of the photolysis of water and the collision zone. Our treatment also allows for the effects of multiple scattering of Lyman-α photons in the inner coma, by means of a plane-parallel radiative transfer calculation (*14*). The Lyman-α flux for the sun in the model was taken from observations by the Solar Mesosphere Explorer corrected for solar rotation to the comet's heliocentric longitude. The time-dependent and spherically symmetric inner coma description used for the model was taken from a set of coupled dusty gas–dynamic and MCPTM calculations (7), which self-consistently explained most aspects of the heliocentric distance dependence of the outflow speed of the coma as inferred from widely varied sets of observations of the comet. In this inner coma description, the water production rate has been assumed to be 80% of the total gas production rate to account for species other than water (*15*).

In the H coma MCPTM, the remaining adjustable parameter is the H lifetime. This lifetime in the interplanetary environment is determined by three processes: charge exchange with solar-wind protons (by far the most important), photoionization by solar ultraviolet photons, and electron impact ionization by solar-wind electrons (*13*). There was no continuous monitoring of the solar-wind conditions in the space surrounding comet Halley except for the brief time before and after the spacecraft flybys. To compensate for this factor, we have collected much of the solar-wind data taken by the ISEE-3 (International Sun-Earth Explorer) and IMP-8 (Interplanetary Monitoring Platform) satellites (*16*) during this period and find an average lifetime for H atoms during the month of January of 2×10^6 s at 1 astronomical unit (AU).

The first model calculation of the two-dimensional Lyman-α image in Fig. 2 reproduced the innermost coma very well, but in portions of the outer coma below about 0.2 kR the modeled intensity fell below the observed level. This could be caused by (i) an underestimation of the H lifetime in the model, (ii) a radical increase in select portions of the actual time-dependent gas production rate not included in the model, or (iii) an underestimation of the Lyman-α background correction in the data.

Increasing the H lifetime even to an unrealistically large value of 3×10^6 s or more (reduced to 1 AU) increased the amount of H in the model at large distances from the nucleus and improved the fit to the image out to the 0.1- to 0.2-kR level. Beyond this distance, however, in the model the Lyman-α intensity again fell below the observed brightness. Of course, increasing the gas production rate during the period about 2 to 4 weeks before 4 February could reproduce the image at large cometocentric distances. However, the type of time variability required was severely at odds with the significant amount of excellent data used to determine the dependence of the gas production rate on the heliocentric distance (7). The effects of short-term variations in the water production rate are readily seen in the inner coma (*10*), but at the greater distances involved here they are strongly averaged by the wide dispersion of "ages" of atoms observed along a given line of sight. Only long-term changes are relevant.

A detailed examination of the radial profile of the image data in Fig. 2 (already corrected for the assumed interplanetary background), however, revealed that the inferred comet signal became independent of distance from the nucleus at large distances, a nonphysical result. This indicated that the background brightness initially assumed had to be larger by about 0.069 kR (that is, about 20%). With this larger interplanetary background, the new comet image can be well understood, even down to the 0.05-kR level. Furthermore, the image now makes physical sense (independent of the model) and agrees with the model using the H lifetime of 2×10^6 s at 1 AU. The corrected Lyman-α image and its comparison with the MCPTM calculation are shown in Fig. 3.

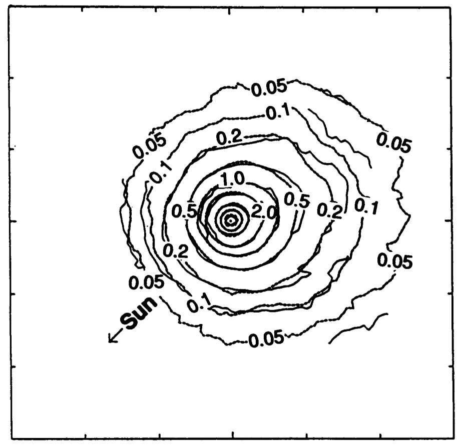

Fig. 3. The MCPTM analysis of the PVOUVS Lyman-α image. The isophote contours from PVOUVS observation (solid line), where an additional uniform background of 0.0692 kR has been subtracted, are compared with the best MCPTM result (dashed lines) which implies values of 2×10^6 s for the H lifetime (reduced to 1 AU) and 1.55×10^{30} s^{-1} for the water production rate during the period 2 to 6 February when the data were taken. The tick marks on the circumscribed box are separated by 10×10^6 km. Comparable models for the beginning and end of the 5-day period showed that the projected view of the comet did not change significantly and that the midpoint-time model was appropriate. The comet was essentially viewed from directly below its orbit plane, and the main temporal change, which was the rotation of the comet-sun line in the sky, had already been removed by the map sorting procedure.

The larger Lyman-α background in the comet image raises some interesting questions for other PVOUVS measurements, which are also directed toward improving the interstellar H model of Ajello (*11*) used here as an initial background correction. This model derived a best fit to a data set acquired over a period of 10 weeks, assuming that the interstellar H was uniformly illuminated by solar Lyman-α radiation throughout. One idea that is being pursued to understand this 20% increase is that the solar output at the Lyman-α wavelength has a longitudinal variability large enough so that the interstellar H and cometary H, which are at different heliocentric longitudes, may actually be subject to significantly different intensities for solar resonance scattering. Further work is required to evaluate the merit of this and other ideas.

The best fit of the model to the PVOUVS image in Fig. 3 implies a water production rate of 1.55×10^{30} s^{-1} during the midpoint of the observation. This production rate is ~30% higher than that published in the first

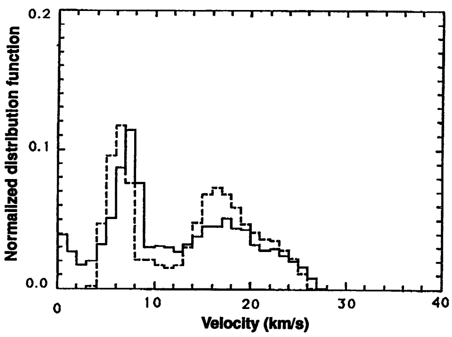

Fig. 4. Velocity distribution function for H atoms leaving the inner coma of comet Halley. The dashed line shows the distribution of velocities of H atoms as initially produced by photodissociation. The solid line shows the actual distribution function for atoms leaving the inner coma after partial collisional thermalization. Thermalization reduces the 20 km/s region and populates the region of low speeds (0 to 4 km/s), which initially contains no atoms.

analysis of these data (*10*), which was based only on the inner region of the coma and did not take into account the optical thickness of the inner coma to solar Lyman-α radiation. The MCPTM analysis of the entire extended image shows that the model (corrected for the optical thickness that occurs only in the inner coma) self-consistently reproduces the two-dimensional shape and gradient of the whole observable inner and outer coma. This result implies that the entire PVOUVS Lyman-α data set should be reevaluated, because all of the production rates determined from the Lyman-α data are likely to be systematically too low, at least where the derived production rates are large. The agreement of the model and data in Fig. 3 is most gratifying in that it both verifies and documents the advantage and value of using the physical model. Together with the analysis of comet Kohoutek (*6*), this analysis represents the second major and successful application of the full H MCPTM for a comet for which the gas production rate is sufficiently large that significant collisional thermalization occurs in the inner coma. Figure 4 shows the distribution in phase space of the velocities of H atoms leaving the inner coma as they are initially produced by photodissociation and after they are partially collisionally thermalized. The MCPTM naturally produces the correct number of low-speed H atoms that are required to explain the shape of the coma. This obviates the need for using a parameterized velocity distribution in the model (*4*).

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Allerød–Younger Dryas Lake Temperatures from Midge Fossils in Atlantic Canada

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Remains of freshwater midges are abundant in lake sediments, and their species distributions are closely related to the surface-water temperature of lakes; their distributions thus provide a powerful tool for paleoclimatology. The distribution of species in a core from Splan Pond in Atlantic Canada indicates that there were abrupt transitions in late-glacial temperatures between warm and cold states. The transitions are correlative with the well-known warm Allerød and cold Younger Dryas events in Europe. These data thus confirm the inference from palynological data that these events affected regions on both sides of the Atlantic.

The Allerød–Younger Dryas event, a reversion from the relatively warm climate of the Allerød before 11 ka (thousand years ago) to the much cooler conditions of the Younger Dryas between approximately 11 and 10 ka, is well documented in Europe (*1*). The occurrence of late-glacial temperature fluctuations in Atlantic Canada that are correlative with the European event has been suggested on the basis of palynological and lithological evidence (*2–4*). In Atlantic Canada, from 11 to 10 ka, deposition of organic-rich sediments was interrupted by reversion to mineral deposition in many lakes (*3*). Pollen evidence is interpreted as indicating a reversion to more open vegetation at this time in response to a colder climate (*3*). Nevertheless, other independent records are needed to confirm this interpretation. Although evidence is accumulating for the occurrence of these events in North America outside Atlantic Canada, the evidence is still weak and widely scattered (*5–9*). We therefore used a newly developed technique, weighted averaging calibration of fossil midges to temperature (*10*), to study paleotemperatures in a lake in Canada in which palynological data have indicated that these events occurred.

Two sediment cores with nearly identical stratigraphy were removed from Splan Pond (45°15′15″N, 67°19′50″W), New Brunswick, Canada; this lake [also called Basswood Road Lake (*2, 3, 11*)] is less than 30 km from the coast, near the international border with the United States. The first core (MS 68-27) was sampled for lithostratigraphy and palynostratigraphy (*11*). To evaluate independently the presence of a late-glacial climatic oscillation, we analyzed sediments from the second Splan Pond core (MS 78-3) for fossil aquatic midges. Midge fossils (Diptera: Chironomidae, Ceratopogonidae, and Chaoboridae) were isolated, identified, and enumerated (*10, 12*) from 13 levels in the Splan Pond core [spanning the intervals Mott *et al.* (*3*) believed to represent the Allerød and Younger Dryas].

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