GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 1, PAGES 53-56, JANUARY 1987

OBSERVATIONS OF COMET HALLEY AT H_α AND 6300 Å

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Abstract. A small aperture telescope has been used with the Fabry-Perot interferometer at the Arecibo Observatory to make high spectral resolution measurements of Comet Halley emissions at 6562.72 Å (H_α) and 6300.30 Å (O^1D). Observations in March, 1986, are characterized by a highly structured spectral signature at H_α. The H_α spectra imply non-isotropic outflow of hydrogen atoms following dissociation of the parent species. The H_α surface brightness for a 5′.9 field of view centered on the comet head was 59 ± 13 rayleighs (R) on March 12, 1986, decreasing to 25 ± 6 R on March 23 (after correction for atmospheric extinction). Calculation of atomic hydrogen production rates and outflow velocities is not straightforward due to the non-isotropic nature of the atomic hydrogen outflow. The $O(^1D)$ emission at 6300.3 Å was accompanied by a feature at 6300.8 Å that we attribute to NH_2. The brightness of the $O(^1D)$ emission for a 6′ field of view was 260 ± 50 R on March 15 and 17. This brightness decreased by a factor of about 2 when the comet was viewed with a 5′.9 field of view centered 6′ off the comet nucleus (sunward or tailward). The width of the $O(^1D)$ emission line was $3.9 \pm 1.5\ \mathrm{km\,s^{-1}}$ on March 15, and $7.4 \pm 2.2\ \mathrm{km\,s^{-1}}$ on March 17. The $O(^1D)$ spectral line profiles on March 17 were skewed to the red side of line center.

Introduction

High spectral resolution spectra of Comet Halley near 6562.72 Å and 6300.30 Å were obtained by coupling a small telescope to a pressure scanned Fabry-Perot interferometer. The purpose of the experiment was to obtain and analyze line profiles in order to elucidate the dissociation processes that produce hydrogen atoms and excited ^1D oxygen atoms in a cometary atmosphere [Huppler et al., 1975; Scherb, 1981]. All wavelengths reported in this letter are for emissions in dry air, at 15°C and 76 cmHg.

Hydrogen atoms in cometary atmospheres are believed to be produced in one or more of the following ways:

$$H_2O + h\nu \rightarrow OH + H + 1.9\ \mathrm{eV}\ (19, 1\ \mathrm{km\,s^{-1}}) \quad (1)$$

$$OH + h\nu \rightarrow O + H + 0.4\ \mathrm{eV}\ (8.8, 0.5\ \mathrm{km\,s^{-1}}) \quad (2)$$

$$H_3O^+ + e^- \rightarrow H_2O + H + 6.4\ \mathrm{eV}\ (35, 2\ \mathrm{km\,s^{-1}}) \quad (3)$$

$$\rightarrow OH + 2H + 1.2\ \mathrm{eV}\ (11, 0.5\ \mathrm{km\,s^{-1}}) \quad (4)$$

[Mendis et al., 1985] where the velocities are those of the hydrogen atoms and the heavier partner respectively. $O(^1D)$ atoms can be generated by the following processes:

$$H_2O + h\nu \rightarrow H_2 + O(^1D) + 1.9\ \mathrm{eV} \quad (5)$$

$$O_2 + h\nu \rightarrow O(^3P) + O(^1D) + 1.3\ \mathrm{eV} \quad (6)$$

$$CO_2 + h\nu \rightarrow CO + O(^1D) + 5.5\ \mathrm{eV} \quad (7)$$

[Mendis et al., 1985]. The excess energy shown for the photolytic processes is appropriate for photodissociation by solar Lyman-α radiation.

It was expected that the observations would show symmetric Doppler shifted lines, where the shift would be that appropriate for the motion of the comet relative to the earth. Analysis of the velocity broadened line profiles would then reveal the relative importance of such processes as (1) to (7). In fact, the observations show many peaks in the neighborhood of H_α. Some of these peaks may be emissions from H_2O^+, but most appear to be due to resonance fluorescence of hydrogen atoms that are moving in beams at high velocity within a few hundred thousand kilometers of the nucleus. Most of the hydrogen atoms produced appear to be in these beams.

Instrumentation

Light from the comet was collected by a 40.6 cm Newtonian telescope on an equatorial mount at the Arecibo Observatory. The light was transmitted through a fiber optic cable to a single etalon interferometer. The interferometer scanned in wavelength by varying the pressure of SF_6 gas between the etalon plates. The free spectral range of the interferometer was 1.96 Å (89.43 $\mathrm{km\,s^{-1}}$) at H_α and 1.80 Å (85.85 $\mathrm{km\,s^{-1}}$) at 6300 Å. The spectral resolution was 8.9 $\mathrm{km\,s^{-1}}$ (0.195 Å) at H_α and 8.6 $\mathrm{km\,s^{-1}}$ (0.180 Å) at 6300.3 Å. Light from the interferometer passed through an aperture to a lens that collimated it through an interference filter. The light was then focused onto the cathode of a photomultiplier detector. The H_α filter is a three cavity device that has a square transmission profile 6.8 Å wide with a maximum transmission of about 0.6 at H_α. The 6300 Å filter is a two cavity filter with a 3.2 Å band-pass and transmission of 0.5. Thus configured, the interferometer passed 3.47 spectral orders at H_α and 1.77 spectral orders at 6300.3 Å. The transmission of the filters was tested before and after observation throughout the range of sensitivity of the phototube. At all wavelengths the transmission was found to be more than three orders of magnitude below that attained in the maximum of the filter pass band.

The tracking accuracy of the telescope was 1 – 2 arcsec min^{-1}. A 3.17 mm fiber optic cable placed at the prime focus of the telescope has a field of view of 5′.9, equivalent to about 2×10^5 km at Comet Halley in March, 1986. Absolute intensity calibration was obtained by observing identical sources with the interferometer and with a tilting filter photometer that had been calibrated with a ^{14}C standard brightness source [Kerr et al., 1986]. These calibrations were confirmed with a tungsten lamp calibration. The sensitivities of the interferometer-telescope system were 0.175 ± 0.05 $\mathrm{counts\,s^{-1}\,R^{-1}}$ at H_α and 0.104 ± 0.03 $\mathrm{counts\,s^{-1}\,R^{-1}}$ at 6300.3 Å. The interferometer itself has been used and cal-

Paper number 6L6396.
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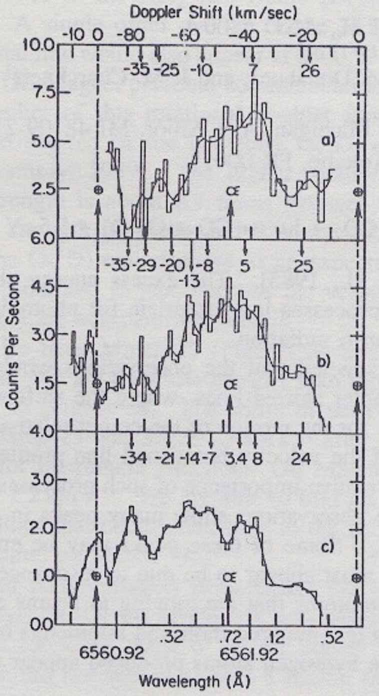

Fig. 1. Three head centered H_α scans using a 5′.9 field of view. The Doppler shift and wavelength scales on the upper and lower abscissas are for the earth reference frame. The vertical dashed lines define one free spectral range of the interferometer. The H_α earth rest position is denoted by an arrow pointed upward from the lower abscissa with the earth symbol above it. Upward pointing arrows with a comet symbol at the top indicate the expected position of cometary H_α. The arrows pointed downward from the top abscissa of each panel indicate locations of identified peaks, and the numbers below these arrows are the velocity shifts relative to the comet along the earth-comet axis in km s^{-1}. Negative velocity is toward the earth. a) March 12, 9.54 UT. Three scans have been added, for an effective 21 s integration period (I.P.) per point. b) March 18, 8.59 UT. Five summed scans, 50 s I.P. c) March 23, 8.87 UT. Four summed scans, 40 s I.P. The data in this scan has been smoothed using a three point running average. In each panel, the lowest count rate along the scan has been subtracted from each data point.

ibrated extensively for geocoronal observations at Arecibo [Kerr et al., 1986].

Observations And Analysis

Observations were attempted in January, March and April, 1986. Only March observations will be discussed here. Problems with instrumentation and weather hindered observations in January, and the analysis of the April data is not yet complete. Many H_α spectra were obtained on March 12, 18, 21 and 23; $O(^1D)$ emissions were observed on March 15 and 17.

The H_α Spectral Region

Examples of H_α spectra are shown in Figures 1 and 2. The most striking aspects of the H_α profiles are that they are by no means symmetric about the position of the expected comet line center, marked with the comet symbol in the figures, and that there are a number of distinct maxima in the spectra. Some of the maxima are shifted by as much as 35 km s^{-1} from the center of the line in the rest frame of the comet.

We have conducted a careful search for instrument artifacts, first of all by rechecking the transmission of the filter. As we have already noted, this test shows that it is extremely improbable that strong emission lines in distant wavelength regions are being transmitted at higher order through the system. However, OH, H_2O^+, and NH_2 emit within the instrument band-pass near H_α.

There are no emission features corresponding to the positions of cometary Meinel OH (6-1) P branch lines that should appear +6.2 Å and -9.1 Å removed from H_α. Terrestrial OH emissions were never observed when the instrument was directed away from the comet; they are not within the band-pass of the filter anyway.

From Figures 1 and 2 it appears that the favored values of velocity components in the comet rest frame are about -9, -15, -21 and -35 km s^{-1} toward the earth, and 4 and 25 km s^{-1} away from the earth. The positions of the H_2O^+ P branch (0,7,0) $1_{01} - 2_{22}$ doublet correspond to 4 and 18 km s^{-1} away from the earth [Lew, 1976]. The positions of the H_2O^+ R branch (0,7,0) $4_{23} - 3_{13}$ doublet correspond to -10 and -31 km s^{-1} toward the earth, allowing a second order overlap of the low wavelength doublet [Lew, 1976]. The absence of an emission feature at 18 km s^{-1} away from the earth implies that H_2O^+ emissions cannot be responsible for the observed peaks at -10, -31, and 4 km s^{-1}. Without the 18 km s^{-1} feature, the second member of the doublet (4 km s^{-1}) should not

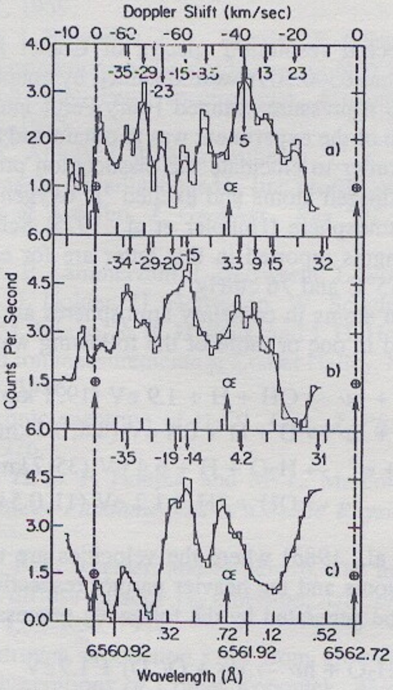

Fig. 2. The same as Figure 1 for three observation geometries on March 21. Each panel represents a single scan, with 10 s I.P. per point. a) 8.71 UT, head centerd 11′.8 field of view. b) 9.18 UT, 5′.9 field of view centered 3′ sunward of the comet nucleus. c) 8.96 UT, 5′.9 field of view centered 6′ sunward of the comet nucleus.

TABLE 1. Halley Surface Brightness

Date	Geometry	[1]Absolute Brightness (R)	[2]Comet Elevation (°)	[3]Adjusted Brightness (R)
		H_α (6562.72 Å)		
Mar. 12	head centered	42 ± 9	23.0	59 ± 13
Mar. 18	head centered	33 ± 9	17.3	52 ± 15
Mar. 21	head centered	[4]18 ± 9[5]	19.7	28 ± 14
	3′ sunward	19 ± 10[5]	24.7	26 ± 13
	6′ sunward	28 ± 14[5]	26.9	37 ± 19
Mar. 23	head centered	18 ± 4	25.4	25 ± 6
		$O(^1D)$ (6300.30 Å)		
Mar. 15	head centered	156 ± 32	16.2	261 ± 53
	6′ sunward	86 ± 34	22.3	124 ± 49
	6′ tailward	134 ± 48[5]	24.5	186 ± 66
Mar. 17	head centered	185 ± 20	23.6	260 ± 28
		NH_2 (6300.79 Å)		
Mar. 15	head centered	69 ± 24	17.8	110 ± 38
	6′ sunward	71 ± 21	28.0	94 ± 28
	6′ tailward	128 ± 58[5]	25.3	175 ± 79
Mar. 17	head centered	77 ± 21	23.6	108 ± 29

[1]errors are root mean square values of the averaged scans
[2]average elevation of the included scans
[3]atmospheric extinction correction, Scherb [1981]
[4]based on 11′.8 field of view, others are 5′.9
[5]based on single scan, error bar is estimated

be present, and the higher energy ($4_{23} - 3_{13}$) doublet should also not be present. On the other hand, the emission features at 13 and 15 km s^{-1} in Figures 2b and 2c respectively are possibly detections of the 18 km s^{-1} H_2O^+ emission. If so, then four of the spectral peaks may be due to H_2O^+. Since the doublets should have nearly equal strengths [Lew, 1976], and the 18 km s^{-1} feature is usually absent, we conclude that H_2O^+ is probably not responsible for the observed spectral features. It is certain the H_2O^+ emissions are not responsible for all the observed spectral features at H_α.

The rotational spectrum of NH_2 also has emission lines near H_α due to P branch (0,8,0) $5_{32} - 6_{42}$ and (0,10,0) $6_{15} - 7_{25}$ electronic transitions. The nearest NH_2 emissions to the observed spectral maxima occur at 2 km s^{-1} toward the earth in comet rest frame and 19.5 km s^{-1} away from the earth [Dressler and Ramsay, 1959].

We have concluded that the H_2O^+ and NH_2 spectra cannot account for the observed cometary spectra, and that the spectral features observed are primarily H_α emitted by hydrogen atoms after they have absorbed solar Lyman-β radiation.

In principle, the effects seen in Figures 1 and 2 could result if parent species had the average outflow velocity components in the earth-comet direction that are indicated in the figures, and if they were confined to fairly narrow beams. These velocity components of some tens of kilometers per second would imply that parent species, whose mass is of the order of 20 amu, would have kinetic energies of many tens of electron volts. No feasible mechanism could accelerate parent species to such high energies. Thus, most of the hydrogen atoms produced within a few hundred thousand kilometers of the comet must be confined to jets after they have been generated. We conclude that the Doppler shifts are associated with directed motion of the hydrogen atoms and not the parent species. We can offer no plausible suggestion for a collimating mechanism, although it must operate near or above the exobse, which is located about thirty thousand kilometers from the nucleus. This constraint applies since collimation well below the exobase would be smeared out by collisons. Furthermore, the lifetime against production of atomic hydrogen by (1) is about 10^5 s [*Mendis et al.*, 1985], so that most atomic hydrogen would be produced near the exobase, following ouflow of H_2O at about 0.9 km s^{-1} [*Krankowsky et al.*, 1986]. The high velocities would be imparted by processes (1) – (4). The spectral width of the individual peaks would be due to the spread in speeds of the hydrogen atoms produced in the dissociation process and the angular spread of the collimated beam.

The measured H_α surface brightness for four dates in March, 1986 are listed in Table 1. The brightness is determined by the amplitude of a Gaussian function fit to the data using the method of nonlinear least squares. The correction for atmospheric extinction of the cometary emission has been estimated by interpolating the values given by Scherb [1981]. The H_α brightness decreased by a factor of about 2 between March 12 and March 23.

The 6300.3 Å *Spectral Region*

Figure 3 shows spectra of the 6300.3 Å region. The principal emission feature occurs at the expected location for cometary $O(^1D)$ at 6299.304 Å – a shift of about 0.96 Å from the earth rest position. The second emission peak 0.49 Å toward the red is probably the NH_2 (0,8,0) $4_{14} - 4_{04}$ line that

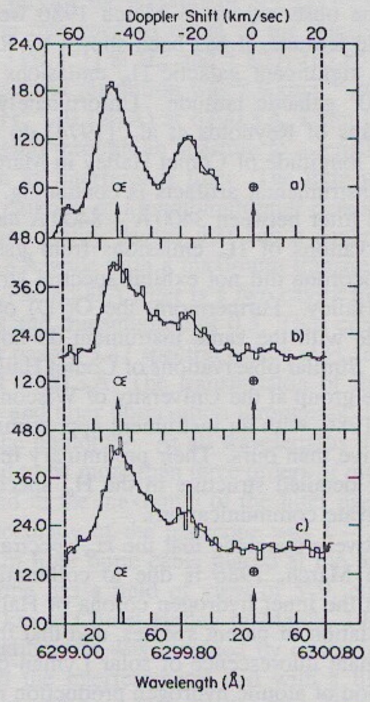

Fig. 3. Similar to Figures 1 and 2, but for the 6300 Å spectral region. Each scan is head centered with a 5′.9 field of view. a) March 15, 8.70 UT. Two summed scans, 16 s I.P. The data has been smoothed and the lowest count rate subtracted from each point. b) March 17, 8.59 UT. Single scan, 10 s I.P. c) March 17, 9.31 UT. Single scan, 10 s I.P.

occurs at 6300.79 Å in the NH_2 rest frame [Dressler and Ramsay, 1959]. A single order overlap of the NH_2 (0,8,0) $3_{13} - 3_{03}$ rotational line would also appear at 6300.79 Å in the NH_2 rest frame (K. Magee, personal communication, 1986). The second member of this rotational doublet should also appear 0.61 Å to the red of the cometary $O(^1D)$ emission [Dressler and Ramsay, 1959]. The higher rotational level emission line strength is about 2.7 times stronger than the lower level line strength [Dressler and Ramsay, 1959]. No large shifts in the $O(^1D)$ emission are to be expected, even if the atoms are confined to jets, because the velocities for processes (5) – (7) are comparatively small.

The line profiles from March 17 (Figures 3b and 3c) are skewed to the red, and are therefore broader than those measured on March 15 (Figure 3a). The width of the cometary $O(^1D)$ line on March 15 was $3.9 \pm 1.5\,\mathrm{km\,s^{-1}}$ after removal of the Fabry-Perot instrument function. On March 17 the width was $7.4 \pm 2.2\,\mathrm{km\,s^{-1}}$. We are able to find no NH_2 or H_2O^+ emission lines that could contribute to the $O(^1D)$ line asymmetry measured on March 17.

The $O(^1D)$ and NH_2 emission brightnesses are listed in Table 1. Although the $O(^1D)$ brightness was smaller by a factor of about 2 for scans made 6′ off the comet nucleus, the NH_2 emission did not appear to have a similar decrease.

Conclusion

The suggestion that the spectral structure of the H_α region may be due to collimation of atomic hydrogen near the Halley exobase is subject to several caveats. First, there may be species emitting near H_α other than H, OH, H_2O^+, and NH_2. Second, there may be some contribution from galactic H_α. Although the observations in March 1986 were made near -25° galactic latitude, it has been shown by Reynolds et al. [1974] that significant galactic H_α emissions are measureable to ±30° galactic latitude. Unfortunately, the galactic isophote maps of Reynolds et al. [1974] do not extend to the galactic longitude of Comet Halley in March, 1986. The search for instrumental artifacts is continuing. Leaks in the interference filter between 3400 Å – 8400 Å have been ruled out. Observations of H_α emissions from gaseous nebulae and the geocorona did not exhibit spectral structure similar to that of Halley. Furthermore, the $O(^1D)$ observations of Halley made with the same instrument do not indicate any difficulties. Similar observations of Comet Halley at H_α were made by the group at the University of Wisconsin in January and April, 1986, with an instrument approximately 20 times more sensitive than ours. Their preliminary results show no evidence of detailed structure in the H_α spectral region (F. Roesler, private communication).

We tentatively conclude that the H_α spectral structure we observed in March, 1986 is due to collimation of atomic hydrogen in the inner hydrogen corona of Halley, following photodissociation of parent species, and that the emission is due to resonant fluorescence of solar Lyman-β radiation. If so, calculation of atomic hydrogen production rates, using an assumption of isotropic outflow of atomic hydrogen from the cometary nucleus, is invalid.

At 6300 Å the $O(^1D)$ emission feature is a strong component of the Halley spectrum. Emission from NH_2 is also evident in this spectral region.

Perhaps the strongest conclusion we can make is that a relatively simple instrumental configuration, employing a commercially available telescope, is capable of returning valuable information regarding the processes that produce hydrogen atoms and $O(^1D)$ atoms in a cometary atmosphere. The prospect for similar observations of other comets, which typically provide short periods for experimental preparation, is improved.

Acknowledgements. The authors thank G. Hernandez for calibrating the interference filters after the observations. It is a pleasure to acknowledge the critical review and discussion of our data provided by F. Roesler, F. Scherb, R. Reynold, K. Magee, and J. Harlander at the University of Wisconsin. We are also grateful for the opportunity to review the experimental results of that group prior to publication. Thanks are due the Arecibo Observatory staff in general and D. Campbell in particular for their support of this experiment. This unusual application of the Arecibo Airglow Facility required equally unusual extensions of their responsibilities. The two-body ephemeris generator program used to determine relative earth-comet velocities was written by D. Yeomans and provided for us by R. Wimberly. This research was supported in part by grant NSG-7404 from the NASA/Planetary Atmospheres program, NASA grant NAS2-12314, and NSF grants ATM-8520653 and ATM-8419730. The Arecibo Observatory is operated by Cornell University under contract with the National Science Foundation.

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(Received October 6, 1986;
revised November 18, 1986;
accepted November 20, 1986.)