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HIGH SPECTRAL RESOLUTION FABRY-PEROT INTERFEROMETER MEASUREMENTS OF COMET HALLEY AT H-ALPHA AND 6300 Å

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ABSTRACT

A 40.6 cm Newtonian telescope has been interfaced to the Fabry-Perot interferometer at the Arecibo Observatory to make high spectral resolution measurements of Comet Halley emissions at 6562.72 Å (H-alpha) and 6300.3 Å (OI). In March 1986 the H-alpha surface brightness for a 5'.9 field of view centered on the comet nucleus decreased from 39±7.8 rayleighs on 12 March to 16±3.8 rayleighs on 23 March. The atomic hydrogen production rate on 12 March 1986 was 1.62±0.5 x 10^{30} s^{-1}, and on 23 March 1986 it was 6.76±2.3 x 10^{29} s^{-1}. Using spectral resolution of 0.196 Å, we found the atomic hydrogen outflow velocity to be approximately 7.9±1.0 km s^{-1}. In general, the H-alpha spectra are highly structured, and indicative of a multiple component atomic hydrogen velocity distribution. An isotropic outflow of atomic hydrogen at various velocities is not adequate to explain the spectra measured at H-alpha. The 6300.3 Å emission of O(1D) had a surface brightness of 81±16 rayleighs on 15 March 1986, and 95±11 rayleighs on 17 March 1986. After adjustment for atmospheric extinction, the implied O(1D) production rate on 15 March is 6.44±3.0 x 10^{28} s^{-1}, and the production rate on 17 March is 5.66±2.7 x 10^{28} s^{-1}. These spectra included a feature at 6300.8 Å that we attribute to NH_2. The brightness of this emission feature was 37±11 rayleighs on 15 March.

INTRODUCTION

Prior to the 1985 - 1986 apparition of Comet Halley, the most extensively studied comet was Comet Kohoutek (1973f). During the Kohoutek apparition it was demonstrated that cometary hydrogen coronae could be studied at H-alpha from ground based facilities /1,2/. Using a dual etalon Fabry-Perot interferometer coupled to the McMath solar telescope at Kitt Peak, Arizona, extremely useful data concerning the production rates and outflow velocities of atomic hydrogen and O(1D) were obtained by Huppler et al. /2/. These ground based observations had the advantage of high spectral resolution, allowing the distinction of cometary emission features from terrestrial features due to the earth-comet Doppler shift.

The production of atomic hydrogen from parent molecules (e.g. H_2O or OH) in cometary atmospheres is likely to result in a multi-component hydrogen velocity distribution. Three hydrogen outflow velocity components have been inferred from previous Lyman-alpha observations of Comets Bennett, Kohoutek, and West /3,4/, for example. Thus, high resolution observations of the H-alpha emission can provide important information regarding the photochemistry of parent molecules in cometary atmospheres. This paper presents preliminary results of an experiment similar to that conducted by Huppler et al. /2/ using more modest resources. The ability to make high spectral resolution measurements of cometary coronae with a commercially available telescope is due primarily to advances in detector, interference filter, and fiber optic technology.

INSTRUMENTATION

Light from Comet Halley is gathered by a 40.6 cm Newtonian telescope on a German equatorial mount. The light is passed via fiber optic cable to the plates of a single etalon Fabry-Perot interferometer. Light exiting the fiber optic cable expands and is collimated by a lens in order to fill the 14 cm effective etalon diameter. The focal length of the telescope is 183 cm, and the scale is 0.532 mm (arc min)$^{-1}$. The tracking accuracy is approximately 5 arc sec min^{-1}. A 3.17 mm fiber optic cable placed at prime focus of the telescope provides a field of view of 5'.9, equivalent to approximately 2 x 10^5 km at the distance of Comet Halley in March 1986.

The Fabry-Perot is pressure scanned using SF_6 gas. The etalon plate spacing is 0.11 cm, giving a free spectral range of 1.96 Å (89.43 km s^{-1}) at H-alpha and 1.80 Å (85.85 km s^{-1})

at 6300 Å. Absolute intensity calibration is achieved by cross calibration with a tilting filter photometer, which is calibrated with a ^{14}C standard brightness source /5/. The Fabry-Perot sensitivity at H-alpha and 6300.3 Å is 0.20 counts s^{-1} rayleigh^{-1} plus or minus about 25%. The calibration has been confirmed with a tungsten lamp at both wavelengths, and by observations of bright nebulae at H-alpha /6/. The earth rest frame H-alpha line center position is determined with a hydrogen discharge lamp, and the 6300.3 Å line center is found by observations of the terrestrial airglow during twilight periods in the zenith.

OBSERVATIONS AND ANALYSIS

The H-alpha Emission

Figure 1 shows three scans of the H-alpha spectrum. The top panel is the result of summing three fringes, with integration time of 21 s per point. Most of the background has been removed by subtracting the lowest count rate from each point. The middle panel of Figure 1 shows the result for three summed scans where the data have been smoothed with a three point running average and normalized to the peak count rate. The top and middle panels of Figure 1 are observations made with a 5'.9 field of view centered on the comet head. The bottom panel shows a measurement made with the same field of view centered 6'.0 sunward of the comet head.

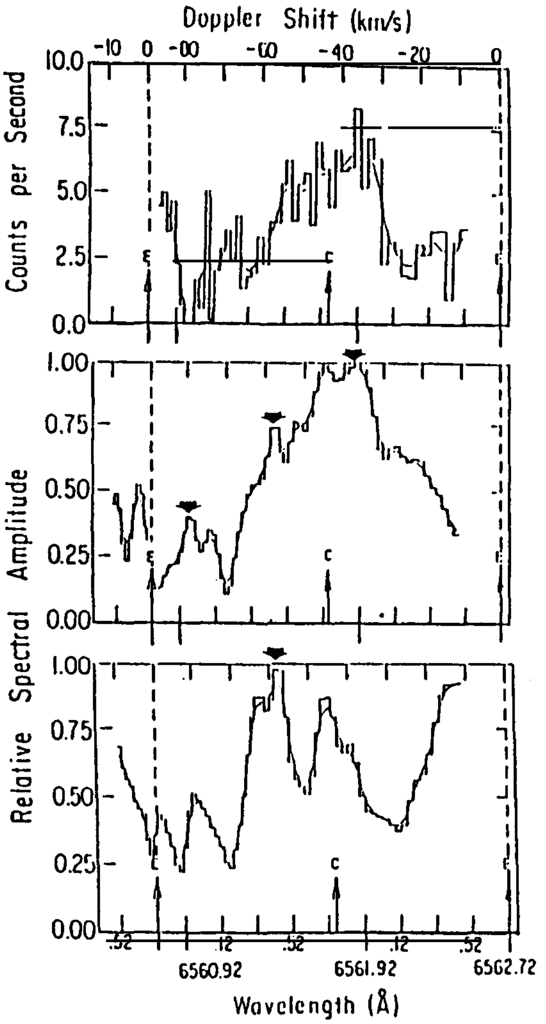

Fig. 1. Three typical examples of H-alpha spectra. The vertical dashed lines define one free spectral range. The H-alpha earth rest position is denoted by an arrow with an "E" at the top. The cometary rest H-alpha position is denoted by the arrow with a "C" at the top. Top panel: 12 March 9.54 UT, head centered. Middle panel: 18 March 8.55 UT, head centered. Bottom panel: 21 March 8.95 UT, 6'.0 sunward of comet nucleus. Each spectrum was measured using a 5'.9 field of view, and required a total integration period of about 21 m. The broad arrows indicate spectral features that are discussed in the text.

On the basis of previous cometary research, H-alpha spectral profiles similar to the middle panel of Figure 1 might be expected. Following isotropic outflow of a parent molecule, photodissociation produces atomic hydrogen with discrete and randomly directed velocities. Two examples are dissociation of H_2O and OH, which produce atomic hydrogen with velocities of 19 km s^{-1} and 8.8 km s^{-1} repectively /7/. Dissociative recombination of H_3O^+ also results in atomic hydrogen with excess kinetic energy. Atmomic H from this process can be produced with velocities of 35 km s^{-1} or 11 km s^{-1}, depending upon dissociation products /7/. The spectral line profile measured by the Fabry-Perot has a full width at half maximum determined by the combined effects of the outflow velocity of the parent molecule and the velocities acquired by the hydrogen atoms in the dissociative process. For a multiple component outflow velocity, the H-alpha profile will be broadened by an amount characteristic of each velocity component, and the actual shape of the profile depends on the relative populations of each velocity compnent.

In the middle panel of Figure 1, the shoulders 15 km s^{-1} on each side of the cometary H-alpha position appear to show a symmetric broadening of the H-alpha line profile, suggesting an atomic H population with an outflow velocity of about 35 km s^{-1} (after removal of the instrument function). The broad shoulders on the profile appear to be imposed upon a narrower emission feature centered at the wavelength of cometary H-alpha, indicative of a lower velocity component.

There are, however, features in Figure 1 that cannot be explained by an isotropic outflow of atomic H. These are shown in the middle panel with broad arrows at -38, -60, and -80 km s^{-1} from the earth rest position. Negative doppler shift velocities indicate populations of atomic H moving toward the earth. There are four possible explanations for these features. They are:

(A) The parent molecules of atomic H are moving in bulk away from the cometary nucleus non-isotropically and at high speed.
(B) Atomic H derived from dissociation of parent species and consequently moving at high velocities are collimated, presumably confined to beams with the collimation occurring near the nucleus.
(C) Emissions are present near H-alpha that are not due to atomic hydrogen.
(D) Instrumental artifacts are producing these features.

If the features are produced by mechanism (A), they imply non-isotropic outflows of parent species moving with velocity components 7, -15, and -35 km s^{-1} along the comet-earth axis. It is difficult to conceive of a mechanism adequate to accelerate the parent molecules to the required velocities. If the parent species is an ion, a non-isotropic outflow can be expected since the ions will be swept tailward prior to production of atomic H by dissociative recombination. However, in March 1986 Halley's tail was directed away from the earth, and H-alpha emissions from atomic H produced by tailward streaming parents should be shifted toward the red (positive velocity) from the cometary rest position. Two of the spectral features in question are shifted to the blue, so an ion parent explanation cannot account for them.

If the emission features are associated with fast H atoms produced near the nucleus and collimated into beams (process B), the implied velocity components again are 7, -15, and -35 km s^{-1} along the comet-earth axis. Velocity dispersion would reflect averaging over the solid angle of the beam and the velocity spread of the atoms.

Other species that emit near H-alpha are H_2O^+ and OH. There are no emission features in our spectra at the cometary OH positions (H-alpha +6.2 Å and -9.1 Å), and it is difficult to excite these OH(6-1) P branch Meinel transitions in a cometary atmosphere anyway. Terrestrial OH is not detected in observations made away from the comet. Furthermore, the H-alpha interference filter has a 6.9 Å bandpass, and the instrument therefore passes 3.5 orders, or 6562.72± 3.43 Å. The terrestrial OH emissions are not able to enter the instrument bandpass. H_2O^+ emissions a 6562.8 and 6562.67 Å have been identified in spectra of Comet Kohoutek /8,1/. These ion features should be shifted to the red from the cometary H-alpha position however, and if they are responsible for the blue shifted features overlapping orders of the Fabry-Perot bandpass must be present. The required tailward velocity of H_2O^+ in March 1986 to produce the features to the blue of cometary H-alpha is greater than 120 km s^{-1}, allowing overlapping orders.

We are currently testing elements of the Fabry-Perot for possible sources of artifacts. The interference filter has been recalibrated, and no light leaks were found from 5500 Å - 8300 Å. Transmission in this region was found to be three orders of magnitude below the peak transmission everywhere.

Several H-alpha scans were made with the field of view centered sunward of the comet nucleus, where ion populations are expected to be small. The bottom panel of Figure 1 shows an H-alpha scan using sunward viewing geometry. The sunward scans still contain features near -60 km s^{-1} (broad arrow) and -80 km s^{-1} from the earth rest position. Some structure on the red side of cometary H-alpha appears to diminish when this geometry is used however. The persistence of the spectral features on the blue side of coemtary H-alpha in sunward scans argues against an ion source for these features.

Atomic hydrogen production rates. We have used the formulation of Huppler et al. /2/ to calculate atomic hydrogen production rates. This requires the determination of H outflow velocities. We have used spectra like that shown at the bottom of Figure 1 for this measurement. The width of the feature at cometary H-alpha in this figure is 7.9±1.0 km s^{-1}. Using this value and a g-factor of 5.4 x 10^{-7} s^{-1}, the production rates of atomic H in March 1986 are shown in Table 1. The brightness values listed in this table are not adjusted for extinction, but the production rates Q_H are. Atmospheric extinction has been estimated by interpolating the values of Scherb /6/. The error bars for Q_H are estimated based on the determination of outflow velocity, the g-factor, and the root mean square variation of the calculated values each night. The root mean square (RMS) variation is roughly 25% of the reported error bar in each case. The brightness errors are RMS values for the observations.

TABLE 1 Atomic Hydrogen Production Rates

Date	Brightness (rayleighs)	Production Rate (s^{-1})
12 March 1986	38.6 ± 7.8	1.62 ± 0.5 x 10^{30}
18 March	28.3 ± 8.0	1.39 ± 0.4 x 10^{30}
21 March	18.9 ± 3.9	1.15 ± 0.4 x 10^{30}
23 March	16.2 ± 3.8	6.76 ± 2.3 x 10^{29}

The 6300 Å Emission

Figure 2 shows two unprocessed spectra of the 6300 Å region. Each scan used 10 s integration time per point. There is a strong feature at the expected position of cometary 6300.3 Å, the O(1D) emission. (The cometary doppler shift relative to earth rest in March 1986 was approximately 45 km s^{-1} /9/.) The O(1D) feature is asymmetric, with a red tail. There is a second emission feature 0.49 Å to the red of the O(1D) feature as well.

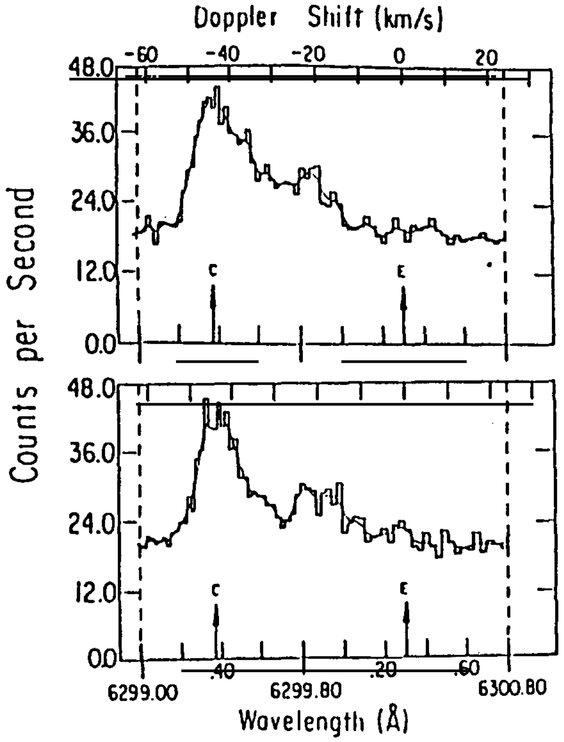

Fig. 2. Two examples of the 6300 Å spectrum from 17 March 1986 using a 5'.9 field of view. Labeling is similar to that used in Figure 1. Top panel: 8.59 UT. Bottom panel: 9.07 UT. Both scans are centered on the comet nucleus, and required about 13 minutes of total integration time.

We have identified the second emission feature at 6300.79 Å as the $NH_2(0,8,0)$ 4_{14} - 4_{04} line /10/. The red tail of the O(1D) line may also be due to an NH_2 emission line at 6300.33 Å /11/. However, a feature at this position would not appear as a red tail with the spectral resolution that we used, unless the NH_2 has an outflow velocity different from that of O(1D). The width of the O(1D) feature implies an O(1D) outflow velocity of 7.4±2.2 km s^{-1} on 17 March. Observations on 15 March resulted in spectra with less red side asymmetry, and the outflow velocity on this date was found to be 3.9±1.5 km s^{-1} for head centered scans. Scans 3'.0 sunward and tailward on the same date indicated outflow velocities of 5.7±2.0 and 2.6±0.9 km s^{-1}. The emission brightness at 6300.3 Å on 15 March was about 45% lower in the sunward direction than for head centered scans. Similar viewing geometry tailward produced brightnesses that were reduced 15% from the head centered scans.

Table 2 lists the O(1D) and NH_2 absolute brightnesses at 6300.3 Å and 6300.79 Å respectively. The O(1D) production rates in Table 2 have been calculated assuming one photon is emitted by each O(1D) atom in the field of view. This calculation ignores quenching, and assumes that emission occurs before the outflowing atom departs the field of view. This is a reasonable assumption in view of the measured outflow velocities and the size of the field of view. Atmospheric extinction has been estimated in the same manner as used for the H-alpha calculations prior to the calculation of O(1D) production rates.

TABLE 2 Results of the 6300 Å Observations

Date	Brightness (rayleighs) O(1D)	 NH_2	O(1D) production Rate (s^{-1})
15 March 1986	81 ± 16	37 ± 11	6.4 ± 3.0 z 10^{28}
17 March	95 ± 11	40 ± 10	5.7 ± 2.7 x 10^{28}

CONCLUSION

The spectra of Comet Halley at H-alpha in March 1986 provide atomic H production rates that are similar to those predicted by the model of Meier and Keller /4/. However, the calculation of these production rates is hampered by difficulty in determining the H outflow velocity from the highly structured H-alpha spectra. Until we have completed a rigorous search for instrumental artifacts, we are not prepared to speculate further on the cause of these H-alpha emission features, or on the location of possible H_2O^+ features in the spectra. The spectra at 6300 Å show a strong feature due to O(1D) and a second prominant feature probably due to NH_2. A red tail on the O(1D) feature may also be due to NH_2.

The most important result of this experiment has been the establishment of a technique to retrieve high spectral resolution observations of cometary atmospheres with a relatively simple instrumental design. This will allow observations of this type to be made in the future with short advance notice, an important consideration for cometary observations.

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