

# High-Resolution Spectra of the 6300-Å Region of Comet P/Halley

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A series of high resolution spectra of the 6300-Å region of Comet P/Halley were taken with the echelle/reticon system on the 61-in. telescope at the Harvard-Smithsonian Oak Ridge Observatory from 23 October 1985 through 5 January 1986. Relative contributions of various rotational lines within the (0,8,0) band of NH<sub>2</sub> and of the cometary and airglow contributions of O(<sup>1</sup>D) were clearly spectrally separated. Measurements were taken both centered on the nucleus as well as offset by various displacements in different directions. A number of important implications have resulted from the analysis of these data. (1) The relative fluxes of different rotational members of the NH<sub>2</sub> (0,8,0) band vary not only from day-to-day, as previously reported, but also with radial distance within the coma. Indications are that the vib-rotational structure of the band could be useful as a diagnostic for coma temperatures and/or outflow kinematics. (2) Deviations from circular symmetry were negligible for NH<sub>2</sub> but detectable for O(<sup>1</sup>D), having only a small (0-10%) average sunward asymmetry. (3) The inner radial brightness distribution for O(<sup>1</sup>D) is consistent with its production from the photodissociation of its parent (H<sub>2</sub>O). (4) The inner radial brightness distributions for NH<sub>2</sub> were reasonably consistent with previously published results found for Halley and other comets. (5) Some inconsistencies were found in the comparison of the cometary NH<sub>2</sub> line wavelengths with the standard laboratory values. © 1991

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cometary OH (van Dishoeck and Dalgarno 1984, Magee-Sauer *et al.* 1989) in the outer coma. Understanding both the absolute abundance and the spatial distribution of NH<sub>2</sub> in comets is important because of its likely production from photodissociating parent ammonia molecules. The relative abundance of cometary ammonia is an important indicator of the cosmochemistry associated with the conditions in the early solar nebula where cometary nuclei were formed (Delsemme 1982). The difficulty in studying these emissions arises from the fact that most cometary observations are made with low to medium spectral resolution where all three emissions are blended into a single broad feature.

The terrestrial O(<sup>1</sup>D) airglow emission is usually separated from the cometary emissions by recording the spectrum of a region of the nearby sky and subtracting its intensity contribution from the blend. In the case of long-slit spectra this can sometimes be accomplished by taking the contribution to the spectrum at the far end of the slit as a measure of the sky (Delsemme and Combi 1979, Fink and Johnson 1984). At low to medium resolution the separation of the NH<sub>2</sub> and O(<sup>1</sup>D) is more difficult. Spinrad (1982) and Delsemme and Combi (1983) have shown that the NH<sub>2</sub> contributions in the region between the 6300 and the 6364 Å blend (also of O(<sup>1</sup>D) and NH<sub>2</sub>) might be scaled to yield an estimate of the 6300 Å NH<sub>2</sub> emission.

Sufficiently high spectral resolution can effectively eliminate the problem altogether by enabling all of the various features to be separated spectrally. Arpigny and co-workers have most recently published a set of high resolution coudé and coudé-echelle spectra of the 6300-Å regions of comets Kohoutek (1973 XII), Bradfield (1974 III), Kobayashi-Berger-Milon (1975 IX), West (1976 VI), and Halley (Arpigny *et al.* 1987). In their work the relative contributions of a number of sets of individual rotational lines of the NH<sub>2</sub> (0,8,0) band were compared with one

## I. INTRODUCTION

The 6300-Å region of the spectra of comets is important to study yet difficult to interpret. The spectrum in this region is dominated by the emissions from three principle sources: terrestrial airglow O(<sup>1</sup>D), cometary O(<sup>1</sup>D), and many members of the (0,8,0) band of cometary NH<sub>2</sub>. The emission of cometary O(<sup>1</sup>D) is important because its source is found in the photodissociation of cometary parent water molecules (Biermann and Trefftz 1964, Festou and Feldman 1981) in the inner coma (<10<sup>5</sup> km) and of

another. They found significant variations in the relative strengths of the NH<sub>2</sub> emissions in the (0,8,0) band both from comet-to-comet and from day-to-day. This variation contributes an additional uncertainty to the estimate of the NH<sub>2</sub> emission at 6300 Å from the measured contribution at 6334 Å. They found that the ratio of the NH<sub>2</sub> contribution at 6300 Å to that at 6334 Å varied by more than a factor of 3 for different comets on different days. Their spectral resolution corresponded to a spectral element size of approximately 0.15 Å. The problem is exacerbated in Halley because of the relatively high abundance of NH<sub>2</sub> compared with other comets, but is usually overcome by averaging a numbers of features near 6334 and 6300 Å having mixed upper vib-rotational levels (Fink, private communication).

In this paper we present the results of the analysis of a set of high-resolution spectra of the 6300-Å region of Comet Halley taken with the echelle/reticon system on the 61-inch telescope at the Harvard-Smithsonian Oak Ridge Observatory. These spectra were recorded not only centered on the nucleus but also at various displacements from and around the nucleus. From these observations we have studied the identifications of and the variations of relative intensity between the various members of the (0,8,0) band. The variations were measured not only from day-to-day but also from one location in the coma to another. Results concerning the circular symmetry of the coma as well as limited information regarding the radial brightness profiles of NH<sub>2</sub> and O(<sup>1</sup>D) are also presented.

## II. OBSERVATIONS

The observations of Comet P/Halley were taken during the preperihelion period from 23 October 1985 through 6 January 1986 using the linear reticon array with the echelle spectrograph on the 61-inch Wyeth telescope at the Harvard-Smithsonian Oak Ridge Observatory in Harvard, Massachusetts (Latham 1985). At 6300 Å we obtain an approximate spectral resolving power of better than 65,000 or spectral resolution element somewhat less than 0.1 Å. The entrance slit to the spectrograph projected a rectangle on the sky with its length running along the north-south line which was 6 by 1.5 arcsec. Table I provides a summary of all the individual 6300-Å region scans. As can be seen in the table, spectra were recorded not only with the spectrograph slit centered on the nucleus but also with the slit displaced in different directions and by different amounts. The comet and slit were monitored with the guide TV camera at the focal plane. The slit location with respect to the nucleus was determined by the observer's judgment of the center of brightness of the comet and the known scale of the TV image.

All of the spectra have been "flat-fielded" using a broadband continuum source. Data reduction followed

TABLE I  
Oak Ridge Observatory Reticon/Echelle Spectra of the  
6300-Å Region of Comet P/Halley

Date	UT	Expt (s)	Description	Air mass	b/d <sup>a</sup>	b/c <sup>a</sup>
10/23/85 <sup>b</sup>	02:15:21	600	Nucleus	1.114		
	02:29:55	600	Nucleus	1.091	1.20	0.70
12/4/85	20:24:28	866	Nucleus	1.226	1.10	0.64
	20:32:33	360	12" East	1.238	0.92	0.53
	20:37:55	300	6" East	1.246	1.00	0.58
	20:43:18	300	12" West	1.256	0.90	0.52
	20:48:45	300	6" West	1.266	1.03	0.60
	20:55:37	300	12" South	1.280	0.75	0.44
	21:01:17	300	6" South	1.293	0.91	0.53
	21:08:03	360	12" North	1.310	1.10	0.64
	21:31:58	300	6" North	1.325	0.76	0.44
	21:39:58	480	24" East	1.373	0.97	0.56
12/07/85	17:42:47	600	Nucleus	1.247	1.09	0.63
12/08/85	19:06:03	300	Nucleus	1.243	1.10	0.64
	19:11:49	600	40" East	1.239	0.92	0.53
	19:22:34	600	40" West	1.248	0.95	0.53
	19:34:32	600	20" East	1.263	0.81	0.47
	19:50:02	600	20" S, 40" East	1.287	1.23	0.71
	20:06:23	600	10" S, 40" East	1.318	1.03	0.60
	20:18:10	600	10" N, 40" East	1.346	1.21	0.70
	20:29:42	600	20" N, 40" East	1.378	1.09	0.63
	20:43:48	600	20" West	1.423	0.98	0.57
	20:55:35	600	20" South	1.467	0.93	0.54
12/29/85	17:23:44	600	Nucleus	1.590	1.31	0.76
	17:36:20	600	36" West	1.642	1.21	0.70
	17:48:22	600	72" West	1.699	1.54	0.89
	18:06:01	600	36" East	1.801	1.11	0.64
	18:20:20	600	72" East	1.903	1.57	0.91
	18:41:12	600	72" E, 36" North	2.089	1.68	0.97
01/05/85	17:31:53	300	Nucleus	1.948	1.23	0.71
	17:45:45	600	27" East	2.069	1.45	0.84
	17:57:32	600	27" South	2.191	1.38	0.80
	18:05:01	360	Nucleus	2.281	1.19	0.69
	18:16:24	600	27" West	2.437	1.31	0.76
	18:27:51	600	27" North	2.625	1.60	0.93

<sup>a</sup> The results for 23 October were summed before ratios were calculated.

<sup>b</sup> Ratio of NH<sub>2</sub> b/d and b/c features. (See text for details.)

the procedures described by Wyatt (1985). Although no formal absolute calibrations were made for the spectra, relative fluxes can and have been derived between spectra taken on the same night. Standard air mass corrections have been used for this purpose, and the consistency of the results between spectra is taken as a validity of our approach. Typically the air mass did not change much between spectra and the differences between corrections from spectrum to spectrum on one night were small. See Table II for information about observational geometry.

Integrated line fluxes were calculated for various fea-

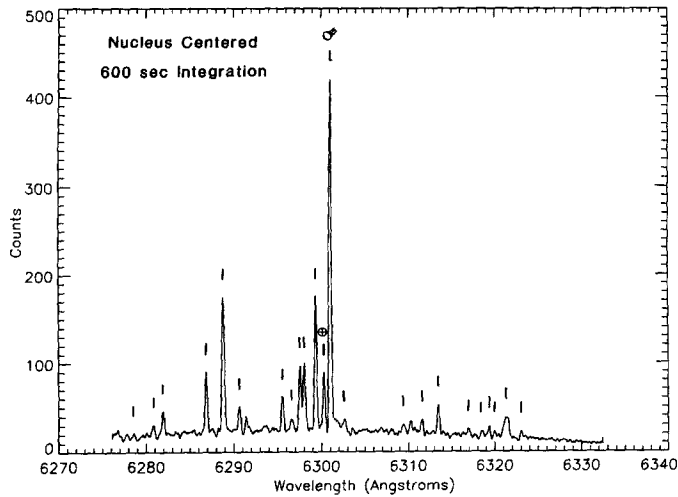


FIG. 1. Echelle-Reticon scan of the 6300-Å region of the spectrum of Comet P/Halley. The many features of the (0,8,0) band of  $\text{NH}_2$  are marked with a short vertical line and the  $\text{O}(^1\text{D})$  lines from airglow and the comet are indicated with a  $\oplus$  and a  $\ominus$ , respectively.

tures and groups of features as will be presented later in this paper. The spectral resolving power is so high that the contribution to each spectral pixel from the dust-scattered solar continuum is very small as compared with any of the emission lines. This is even the case in the nucleus-centered spectra where the relative continuum contribution is the largest. The choice of the appropriate continuum level is not at all critical as it amounts to no more than a few percent of the line flux even for the strong lines or groups of lines for which relative line fluxes are presented in this paper. A smooth continuum was estimated from a few regions spaced across the spectrum which were free of emission line contributions. Changing the procedure had little effect on the relative line fluxes anyway.

Figure 1 shows an example of one of the nucleus-centered scans taken on 29 December 1985. The  $\text{O}(^1\text{D})$  lines from both the airglow and the comet are indicated, as well as are the positions of numerous members of the  $\text{NH}_2$  (0,8,0) band. The counts scale on the ordinate represents an arbitrary flux scale and not true counts in a statistical sense because of the air mass correction and the flat-fielding procedure employed.

### III. RESULTS

#### Identification of Spectral Features in the 6300-Å Region

Twenty-one members or blends of members of the  $\text{NH}_2$  (0,8,0) band have been identified using the laboratory wavelengths and identifications of Dressler and Ramsey (1959) and Woszczyk (1962). All of the features' wave-

TABLE II  
Observational Geometry for the Oak Ridge Observatory  
Echelle/Reticon Spectra

Date	$r$ (AU)	$\dot{r}$ (km/sec)	$\Delta$ (AU)	$\dot{\Delta}$ (km/sec)	$\beta$ ( $^\circ$ )
10/23/85	2.05	-23.94	1.34	-53.19	24.4
12/4/85	1.44	-26.25	0.66	+17.40	36.0
12/7/85	1.39	-26.39	0.69	+23.14	41.3
12/8/85	1.36	-26.48	0.72	+26.22	44.3
12/29/85	1.04	-26.62	1.12	+34.31	54.1
1/5/86	0.93	-25.96	1.25	+31.55	50.9

Note.  $r$ , heliocentric distance in AU;  $\dot{r}$ , heliocentric velocity in km/sec;  $\Delta$ , geocentric distance in AU;  $\dot{\Delta}$ , geocentric velocity in km/sec;  $\beta$ , Earth-comet-Sun angle in degrees.

lengths and laboratory identifications are listed in Table III along with the comet and airglow  $\text{O}(^1\text{D})$  lines. In several cases Woszczyk provided the wavelengths of a line attributed to  $\text{NH}_2$  but no transition identification is given. These are denoted in the table with the entry W62 in the identification column.

Because these spectra are of such a high resolution, note that two moderately strong lines, which have been associated by observers (e.g., Magee-Sauer *et al.* 1989) with the  $^R Q_{0,N}$  branch from lower resolution spectra are actually found to be members of the  $^P R_{2,N-2}$  branch. These are the cometary features at wavelengths of 6294.86 and 6295.90 Å. In addition to those features listed, there is evidence of the presence of some very weak lines very near the cometary  $\text{O}(^1\text{D})$  lines which are members of the  $^R Q_{0,N}$  branch.

#### Relative Fluxes within the $\text{NH}_2$ (0,8,0) Band

Arpigny *et al.* (1987) compared the fluxes of several groups of  $\text{NH}_2$  lines with each other. Of particular note was the comparison of the  $\text{NH}_2$  contributions to the emission in the immediate vicinity of 6300 Å with that in the vicinity of 6334 Å. As mentioned earlier, the flux at 6334 Å has been used by low to medium resolution observers to assess the flux contribution of  $\text{NH}_2$  at 6300 Å. The reticon/echelle scan centered on 6300 Å does not extend quite far enough to the red to cover the strong  $\text{NH}_2$  lines at 6333 and 6336 Å in question which Arpigny *et al.* designated as feature "c" in their notation. However, the groups of features between 6285 and 6293 Å and 6295 and 6302 Å, which they designate as features "d" and "b," respectively, as well as the oxygen line, designated as "a" are all present in our spectra. Arpigny (private communication) reports that the "d" features, which appear both in our spectra and theirs, and the "c" features at 6334 Å which appear only in theirs originate from the same upper rotational levels. In fact their results for the d/c ratio, not published but reported to us privately, show



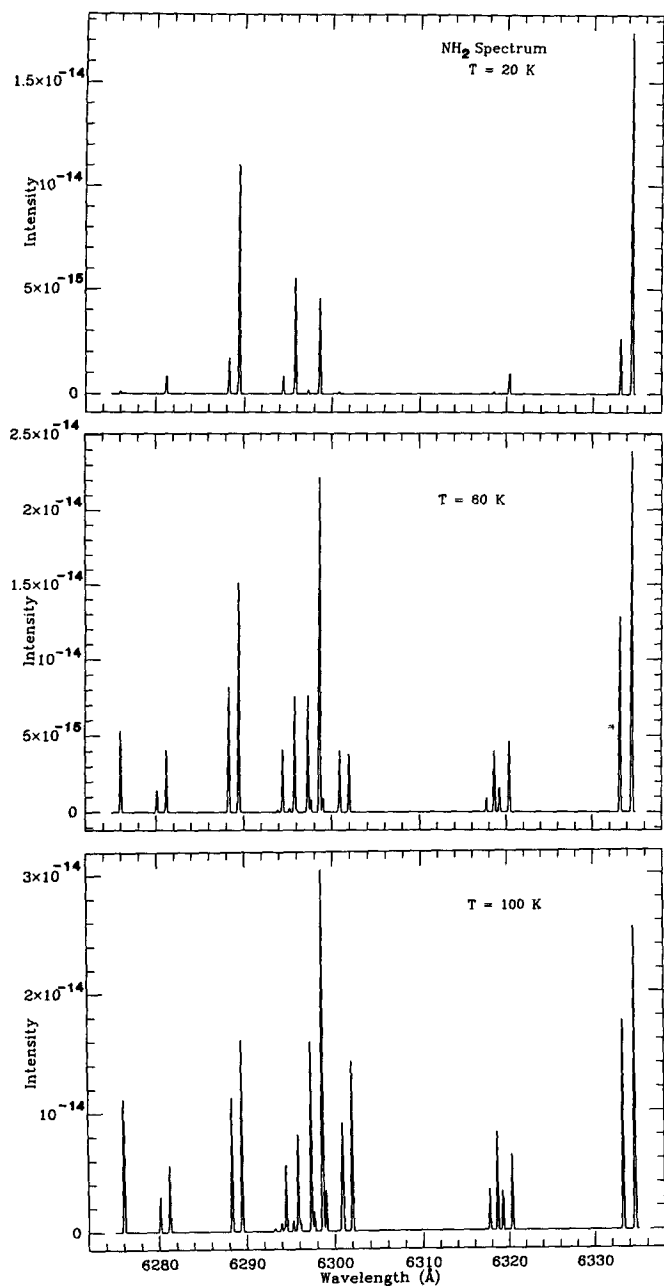


FIG. 3. Calculated fluorescence spectra of the  $\text{NH}_2(0,8,0)$  band. The simple fluorescence spectrum of the  $\text{NH}_2(0,8,0)$  band calculated by Wyckoff (private communication) for rotational temperatures of 20, 60, and 200 K. The spectrum at 60 K gives the best overall match to the observed spectra.

temperatures one might expect to occur in the coma. The calculation is a very simple calculation since it assumes only a flat continuum excitation source, rather than a true solar spectrum. All of the observed spectra seem to agree best with a temperature near 50–60 K. Wyckoff (private communication) reported that most of the spectra pub-

lished by Arpigny *et al.* (1987) were best matched by the calculated spectrum at 35 K. The differences we find between various observed spectra are still smaller than those between the observed and these simple synthetic spectra so it is not yet possible to do any kind of detailed spectral model analysis. There are important points to be made. The rotational temperatures implied are definitely of the magnitude both found in the coma observationally (Bockelée-Morvan and Crovisier 1987; Weaver *et al.* 1987) and expected theoretically (Combi 1989). There are measurable differences in the rotational structure which are indicative of and consistent with differences either in rotational temperature or in the relative outflow speed in different parts of the coma. For a number of reasons we favor the variation in rotational temperature. Therefore, careful modeling of observed spectra of the  $\text{NH}_2$  band structure as a function of distance from the nucleus could provide an important diagnostic tool for the remote sensing of temperatures in the comae of comets.

#### Circular Symmetry of the Coma

In addition to the relative contributions of  $\text{NH}_2$  and  $\text{O}(^1\text{D})$  features, these data also provide information regarding the circular symmetry of the coma as well as some limited information of the radial brightness distribution. The offset spectra taken at the same distance from the nucleus but in different directions serve as an indication of the circularity of the isophotes which says something about the sphericity of the coma, or at least of the  $\text{NH}_2$  and  $\text{O}(^1\text{D})$  in the coma. For the December and January data, where the offset observations were made, the sunward direction was West to West-Southwest of the nucleus. The important and unique value in these data is that the oxygen observations are clearly spectrally uncontaminated. In nearly all other types of spatially resolved observations (medium resolution long-slit spectra and narrow-band CCD images), the  $\text{NH}_2$  and  $\text{O}(^1\text{D})$  contributions have to be separated using the Spinrad (1982) method which the results of Arpigny *et al.* (1987) and those presented here indicate may not always be reliable.

The importance of the unambiguous observations of  $\text{O}(^1\text{D})$  especially cannot be understated. It is now well accepted that the emission of these photons (6300 and 6364 Å) results from a forbidden transition of oxygen atoms produced in the  $^1\text{D}$  state upon photodissociation of the parent molecule. The atom then undergoes a spin-forbidden decay to the ground  $^3\text{P}$  state after a lifetime of roughly 100 sec. The emission of these photons thus provides a direct trace of the distribution of the parent molecule. In the inner coma ( $<10^3$  km) the principal source of these atoms is the photodissociation of water. In the outer coma the principal source is the photodissociation of OH (van Dishoeck and Dalgarno 1984, Magee-

Sauer *et al.* 1989). The spatial region covered by our observations is clearly the inner water source. A further complication in the very innermost coma is that the  $^1\text{D}$  state can be collisionally quenched before the photon emission. This however is generally too close to the nucleus to be observable for comet–Earth distances which are at least a few tenths of an AU (Festou and Feldman 1981).

Table IV lists the integrated line fluxes in arbitrary units of the  $\text{O}(^1\text{D})$  and  $\text{NH}_2$  emissions in all of the offset spectra. The  $\text{NH}_2$  values are the sums of the b and d features. The main apparent departure from circularity, which can be seen by a quick examination of the table, is that the north and south displacements are generally larger than the east and west values. The differences are particularly noticeable for the smallest displacements. This effect however is only due to the fact that when a rectangular slit is oriented with its longer dimension along the north–south direction, it samples distances both closer to and farther from the nucleus than the displacement of the center, whereas when the same slit is displaced to the east or west it samples distances only greater than or equal to the nominal center position. Therefore corresponding points to the north and south are always brighter than those to the east and west. For the  $\text{O}(^1\text{D})$  emission which approximately follows a  $1/r$  dependence, this slit function can be simply integrated and accounts very well for all of the differences between north–south and east–west.

The more important asymmetry would be a sunward to anti-sunward one which would be indicative of any preferential sunward ejection of material which has been reported by a number of investigators. The most dramatic asymmetries were seen in the dust distribution in the Giotto Multicolor camera (Keller *et al.* 1987), however it is well understood both observationally and theoretically that the dust collisionally decouples from the gas in the inner coma (Combi 1989).

Asymmetries have been reported both in the spatial and velocity distributions of coma gases. Net sunward doppler shifts of up to a  $0.3 \text{ km sec}^{-1}$  have been seen in radio and infrared observations of parent and daughter species in the coma (Larson *et al.* 1986, Schloerb *et al.* 1987; Tacconi-Garman 1989). Various instruments on the VEGA spacecraft also reported asymmetric distributions in gas density through comparison of inbound and outbound data, for example, with TKS by Krasnopolvsky *et al.* (1987), and with NGE by Hsieh *et al.* (1987).

In the data presented here similar asymmetries would show themselves as east/west brightness differences. An examination of the west to east brightness ratio from the  $\text{NH}_2$  and  $\text{O}(^1\text{D})$  observations yields some interesting results. We find an average for the sunward to anti-sunward ratio of 1.04 for  $\text{O}(^1\text{D})$ , which represents the water distribution, and 0.99 for  $\text{NH}_2$ . The values show corresponding

TABLE III  
Spectral Features in the 6300-Å Region

$\lambda_{\text{air}}$ (comet) <sup>a</sup>	$\lambda_{\text{air}}$ (lab) <sup>b</sup>	Identification <sup>c</sup>	
6277.89	6277.88 6278.14	$^{\text{P}}\text{P}_{1,\text{N}-1}$	$4_{04}-5_{14}$ (0,11,0)
6280.09	6280.11	$^{\text{R}}\text{R}_{0,\text{N}}$	$2_{11}-1_{01}$
6281.20	6281.20	$^{\text{R}}\text{R}_{0,\text{N}}$	$1_{10}-0_{00}$
6286.13	6286.14	$^{\text{R}}\text{R}_{0,\text{N}}$	$1_{10}-0_{00}$
6288.06	6288.05	W62 <sup>d</sup>	
6289.93	6289.97	W62	
6294.86	6294.45 6294.82	$^{\text{P}}\text{R}_{2,\text{N}-2}$	$4_{13}-3_{21}$
6295.90	6295.83 6296.08	W62 $^{\text{P}}\text{R}_{2,\text{N}-2}$	$3_{12}-2_{20}$
6296.89	6296.85	W62	
6297.31	6297.32	$^{\text{R}}\text{Q}_{0,\text{N}}$	$2_{12}-2_{02}$
6298.60	6298.62	$^{\text{R}}\text{Q}_{0,\text{N}}$	$2_{12}-2_{03}$
6300.30	6300.30	$\text{O}(^1\text{D})$ airglow <sup>e</sup>	
6300.28	6300.30	$\text{O}(^1\text{D})$ comet	
6301.91	6301.86 6301.97	W62	
6308.70	6308.71	W62	
6310.80	6310.78	W62	
6312.74	6312.71	W62	
6316.22	6316.06	W62	
6317.81	6317.72	$^{\text{P}}\text{Q}_{2,\text{N}-1}$	$2_{11}-2_{21}$
6318.63	6318.63	$^{\text{P}}\text{Q}_{2,\text{N}-1}$	$2_{11}-2_{21}$
6319.26	6319.25	$^{\text{P}}\text{Q}_{2,\text{N}-2}$	$2_{12}-2_{20}$
6320.59	6320.59 6320.76	$^{\text{P}}\text{Q}_{2,\text{N}-1}$	$3_{12}-3_{22}$
6322.34	6322.33	$^{\text{P}}\text{Q}_{2,\text{N}-1}$	$3_{12}-3_{22}$

<sup>a</sup> Rest wavelength in air of cometary spectrum feature in Angstrom units.

<sup>b</sup> Laboratory wavelength in air in Angstrom units.

<sup>c</sup> Line identifications for  $\text{NH}_2$  are from Dressler and Ramsey (1959) and/or Woszczyk (1962). Except for the feature at 6277.89, all  $\text{NH}_2$  lines are members of the (0,8,0) band.

<sup>d</sup> W62 signifies lines attributed to  $\text{NH}_2$  by Woszczyk (1962) with no specified transition designation.

<sup>e</sup> Rest wavelengths in air of  $\text{O}(^1\text{D})$  line.

statistical deviations taking all of the ratios as a group (to average out the point to point scatter) of 0.04 and 0.06. These are  $3 \sigma$  in the means of the distributions. It is worth noting that even though for  $\text{O}(^1\text{D})$  where the asymmetry is of the order of the uncertainty that in every individual case the west to east ratio is always greater than one. Therefore we feel there is a small consistent sunward bias

to the water distribution. The fact that the  $\text{NH}_2$  distribution is not asymmetric may be due to the fact that it is a daughter species. Even if its parent (presumably  $\text{NH}_3$ ) were 4% asymmetric, the vectorial ejection of the  $\text{NH}_2$  should generally isotropize the distribution.

The fact that we do not see some of the dramatic asymmetries reported in the coma of Halley's comet is not surprising if we are careful to compare only with observations made during the preperihelion period. The OH radio observations are the best long-term observations with which to compare since they cover both the pre- and postperihelion periods. Tacconi-Garman (1989) has analyzed the observed OH doppler line profiles determined from 18-cm radio observations using a model parameterized with an anisotropy parameter (AP). The parameter has a value of zero if the coma is spherical and a positive value if the coma is skewed sunward. Whereas he finds substantial sunward offsets for observations of Halley, especially in the period of March and April 1986 when most of the other observations were taken, his December 1985 and January 1986 values are  $(0.25 \pm 0.18)$  and  $(0.02 \pm 0.12)$ . Therefore, we should expect to find a nearly spherical distribution throughout the period covered by our observations. It is also noteworthy to mention here that Tacconi-Garman also found significant asymmetries in Halley and other comets at certain times with values for AP greater than unity; but few negative values were found.

#### Radial Brightness Distributions of $\text{O}(\text{}^1\text{D})$ and $\text{NH}_2$

Since the individual observations in different directions show at most only a small departure from circularity, we have constructed average radial brightness distributions for  $\text{O}(\text{}^1\text{D})$  and  $\text{NH}_2$  by averaging over different directions. The radial profiles are shown in Figs. 4a–4c. The  $\text{NH}_2$  profiles were constructed again from the sums of b and d features. The horizontal error bars were derived from the sums of the range of distances covered by the slit, and an estimate of the uncertainty in pointing accuracy relative to the location of the photonucleus. For the data from December 4 and 8 there were enough widely separated points to attempt a crude model analysis for both species. For the December 29 data there were only enough points to verify the approximate  $1/r$  distribution for  $\text{O}(\text{}^1\text{D})$  expected.

The  $\text{O}(\text{}^1\text{D})$  profiles for December 4, and 8, and 29 are consistent with the expected  $1/r$  distribution. During early December the comet's heliocentric distance was about 1.4 AU, which would place the water photodissociation scale length at about  $1.6 \times 10^5$  km. Given the limited spatial extent of the observed profile it is impossible to distinguish a profile with this lifetime from one from an infinite lifetime.

TABLE IV  
Circular Symmetry of the Coma of Comet Halley

Offset (arcsec)	North	East	South	West
<b>4 December 1985</b>				
<b><math>\text{O}(\text{}^1\text{D})</math></b>				
6	868.1	694.4	919.4	713.0
12	540.1	473.9	530.9	517.7
24		273.4		
<b><math>\text{NH}_2</math></b>				
6	1257.7	1093.9	1248.4	1087.3
12	895.4	871.9	937.7	755.4
24		503.2		
<b>8 December 1985</b>				
<b><math>\text{O}(\text{}^1\text{D})</math></b>				
20		284.5	282.0	318.6
40		188.8		162.8
10,40	155.3		159.1	
20,40			127.3	
<b><math>\text{NH}_2</math></b>				
20		625.2	621.1	642.9
40		339.4		283.1
10,40	305.1		329.3	
20,40			240.3	
<b>29 December 1985</b>				
<b><math>\text{O}(\text{}^1\text{D})</math></b>				
36		195.5		207.0
72		116.9		82.42
<b><math>\text{NH}_2</math></b>				
36		432.6		404.0
72		260.0		129.2
<b>5 January 1986</b>				
<b><math>\text{O}(\text{}^1\text{D})</math></b>				
27	345.8	285.7	332.4	307.8
<b><math>\text{NH}_2</math></b>				
27	539.5	578.7	569.7	550.7

In the few  $\text{NH}_2$  brightness profiles which have been published in the literature and analyzed, the parent and daughter scale lengths were found to be nearly the same (Delsemme and Combi 1983; Johnson *et al.* 1984; Konno and Wyckoff 1988), or to differ by as much as a factor of 50% (Wyckoff *et al.* 1988). Given this fact it is possible to force-fit a Haser model in which both scale lengths are the same, even for our sparse profiles for December 4 and 8. The best fit equal-scale-length Haser models are shown as the dashed curved lines in Figs. 4a and 4b. The scale lengths determined for those two profiles are  $(3.7 \pm 1.3) \times 10^4$  and  $(2.6 \pm 0.7) \times 10^4$  km, respectively. When reduced to 1 AU (assuming they vary as the square of the heliocentric distance) they are consistent with the average of the parent and daughter values at 1 AU of 1.1 and  $1.6 \times 10^4$  for Comet Halley (Wyckoff *et al.* 1988), the equal parent and daughter values reported by Delsemme and Combi (1983) for Comet Kohoutek at 0.465 AU of  $6.9 \times$

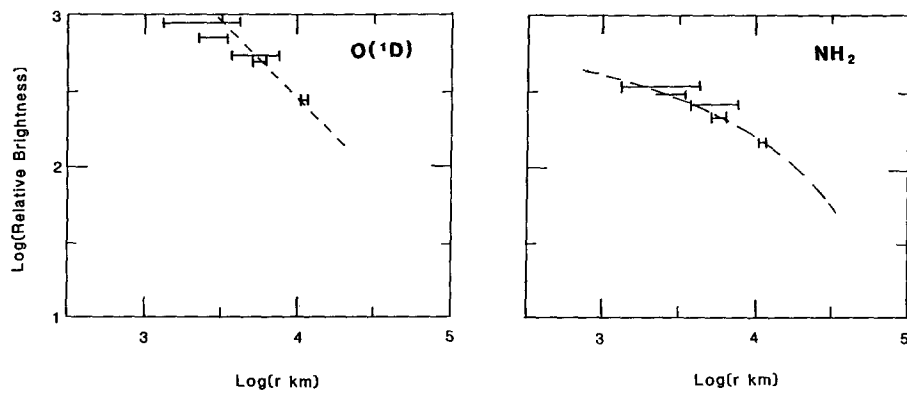


FIG. 4a.  $O(^1D)$  and  $NH_2$  radial brightness profiles in Comet Halley on 4 December 1985. The brightness values are plotted as error bars whose radial range corresponds to the sum of the slit coverage and the slit location uncertainty. The dashed line on the  $O(^1D)$  profile corresponds to a best-fit  $1/r$  profile which is expected for the distance range covered. The dashed line on the  $NH_2$  profile corresponds to a best-fit equal-scale-length Haser model where the scale length =  $(3.7 \pm 1.3) \times 10^4$  km.

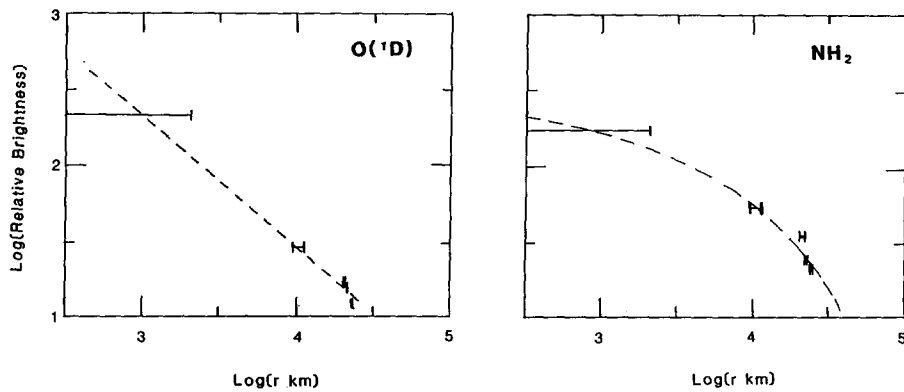


FIG. 4b.  $O(^1D)$  and  $NH_2$  radial brightness profiles in Comet Halley on 8 December 1985. The best-fit equal-scale-length Haser model for  $NH_2$  corresponds to a scale length of  $(2.6 \pm 0.7) \times 10^4$  km. Refer to Fig. 4a for other details.

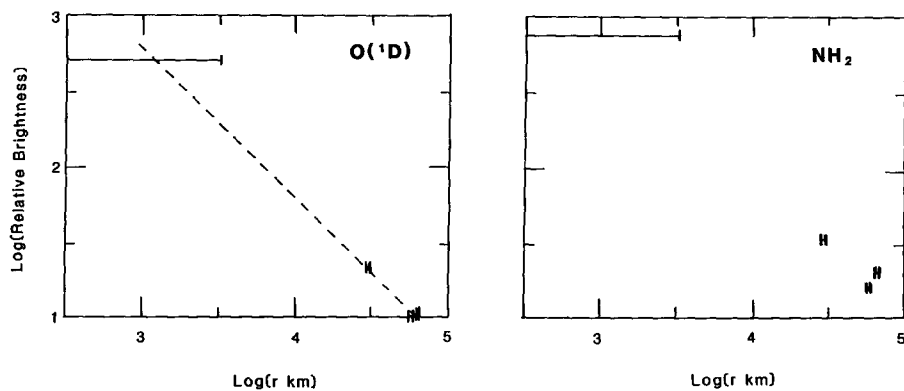


FIG. 4c.  $O(^1D)$  and  $NH_2$  radial brightness profiles in Comet Halley on 29 December 1985. No equal-scale-length Haser model for  $NH_2$  was possible. Refer to Fig. 4a for other details.



$10^3$  km and the Monte Carlo velocities and lifetimes found by Konno and Wyckoff (1988). It should be stressed that our profiles do not constrain the parent and daughter scale lengths to be equal.

#### IV. SUMMARY AND CONCLUSIONS

We have presented the results of the analysis of a set of high-resolution echelle spectra of the 6300-Å region of Comet P/Halley taken during the preperihelion period.

1. The identifications of numerous members of the NH<sub>2</sub> (0,8,0) band were found and some discrepancies in the literature corrected.

2. The relative intensity of sets of features within the (0,8,0) band have been shown to vary over time, as previously reported by Arpigny *et al.* (1987), although our results for a more limited set of data showed a smaller range variation than they reported. In late October 1985 and from early December 1985 to early January 1986 the ratio of the 6300-Å contribution of NH<sub>2</sub> to that at 6334 Å varied between 0.63 and 0.70.

3. A new result, which shows that the rotational structure within the (0,8,0) band changes with radial distance from the nucleus within the coma, has also been found. Therefore, a more sophisticated spectral analysis (than attempted here) in combination with similar or better high resolution spectra could yield a new method for remote sensing of temperatures within the coma. This variation of rotational structure also could introduce further uncertainty to the process of separation of the spatial distributions of O(<sup>1</sup>D) and NH<sub>2</sub> in low to medium resolution spectra. The NH<sub>2</sub> 6300 to 6334 Å ratio varied from an average of 0.66 near the nucleus up to 0.90 at a few tens of thousands of kilometers.

4. The O(<sup>1</sup>D) distribution, which is a tracer of the primary water distribution shows a small sunward bias (0–10%) from spherical symmetry. The NH<sub>2</sub> distribution showed no sunward bias; it should however become isotropicized somewhat by the vectorial ejection of the radicals upon their production by the photodissociation of the parent.

5. The O(<sup>1</sup>D) distribution is consistent with the  $1/r$  water distribution expected in the inner coma. Simple equal-scale-length Haser models for the radial profiles of the NH<sub>2</sub> yield values in the range found by other observers for separate parent and daughter values.

The ability to observe the 6300 Å line from ground-based telescopes provides an important monitor of the abundance and spatial distribution of water in comets. The very high spectral resolution results presented here (and by others) show that the separation of the NH<sub>2</sub> and O(<sup>1</sup>D) contributions can be done to some degree of uncertainty. The ratio of the NH<sub>2</sub> contribution at 6300 Å and to that at 6334 Å in fact can vary somewhat from day

to day, comet to comet, and from location to location within the coma. Caution should be taken when estimating uncertainties both in O(<sup>1</sup>D) production rates from nucleus-centered observations and in spatial profiles of O(<sup>1</sup>D). Whenever possible high spectral resolution observations should be used as a check on the scaling of one NH<sub>2</sub> feature to another.

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