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HIGH-RESOLUTION STUDIES OF [O I] AND NH_2 LINE EMISSIONS AT 6300 Å IN HALLEY'S COMET*

C. DEBI PRASAD, T. CHANDRASEKHAR, J. N. DESAI, AND N. M. ASHOK
Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India

AND

K. R. SIVARAMAN AND R. RAJMOHAN
Indian Institute of Astrophysics, Bangalore 560 034, India

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ABSTRACT

Comet Halley was observed with a high-resolution Fabry-Perot spectrometer ($\lambda/\delta\lambda \sim 4 \times 10^4$) in the wavelengths [O I] and NH_2 (0-8-0) in the neighborhood of 6300 Å during 1986 April 13–15. The [O I] line and NH_2 rotational lines were spectrally well separated by the interferometer. The profile analysis shows the profiles of [O I] and NH_2 to be symmetric with the linewidths ~ 3.5–3 km s^{-1}. The ratio (NH_2 λ6298.6 (2_{12}–2_{02}))/[O I] is ~ 0.5. Observations were also attempted in Hα, but no clear signal was detectable above the noise within the field of view (50″) of the instrument. Upper limits consistent with other results are derived for Hα. This paper discusses the observations briefly followed by details of the analysis and the results.

Key words: comet Halley–high-resolution line profiles–Fabry-Perot–NH_2 and [O I]

I. Introduction

At the time of closest approach to Earth of comet Halley in April 1986 a high-resolution piezoelectrically-controlled scanning Fabry-Perot (FP) spectrometer was coupled with a 1-m telescope to observe some of the optical-emission lines of the coma. The experiment was initially aimed at studying the spatial distribution of hydrogen and oxygen atoms and their velocity fields through high spatial and spectral resolution observations of Hα λ6563 and [O I] λ6300 emissions and, hence, the formation and dynamics of these atoms in the cometary atmosphere. However, the faintness of the line emissions did not permit the study of spatial distributions. Even in the inner coma Hα was barely detectable; [O I] λ6300 emission, however, was well observed and spectrally well separated from its NH_2 blending at our resolution $\lambda/\delta\lambda \sim 4 \times 10^4$. This paper details these observations.

II. Instrumentation and Observation

Figure 1 shows the schematic layout of the spectrometer. The FP spectrometer is used in a classical configuration. A fixed focal-plane aperture corresponding to 50″ on the sky was used throughout the observations. Light collected by the 1-m telescope (*f*/13 optics) was brought to a focus at the entrance aperture and then collimated by a lens, passed through the FP and filter before being imaged by the camera lens onto the exit aperture plane and thence by a Fabry lens onto a cooled photomultiplier detection system. By changing the spacing in the Fabry-Perot minutely by a piezoelectric servocontrol system, it was possible to scan the wavelength through several interference orders of the Fabry-Perot etalon. The details of the piezoelectric system, its advantages over conventional pressure-scanned FP systems, and other instrumental details are given elsewhere (Chandrasekhar *et al.* 1988).

The free spectral range of the spectrometer was 4.342 Å at 6563 Å and 4.001 Å at 6300 Å corresponding to a 496 μm spacer value. A number of laser scans taken during the observations serve as the spectral calibration of the instrument for Hα and [O I]. Figure 2 shows a scan of the He-Ne laser line at 6328 Å with the interferometer. Bandpass interference filters of 5 Å width (FWHM) were used at 6563 Å and 6300 Å with ~ 40% transmission.

The field of view of 50″ corresponds to ~ 15,000 km at the time of observation. The guiding errors during the observation were well within the seeing limit ~ 2″–3″. The flux calibration at Hα was obtained by observing the trapezium region of the Orion nebula (M 42) with the same aperture. Table I gives the cometary parameters during our observations.

III. Cometary Spectra of [O I] and NH_2 Near 6300 Å

A. *[O I]*

Forbidden [O I] at the 6300 Å (^1D–^3P) line in cometary

*Observations were taken at Vainu Bappu Observatory, Kavalur, India.

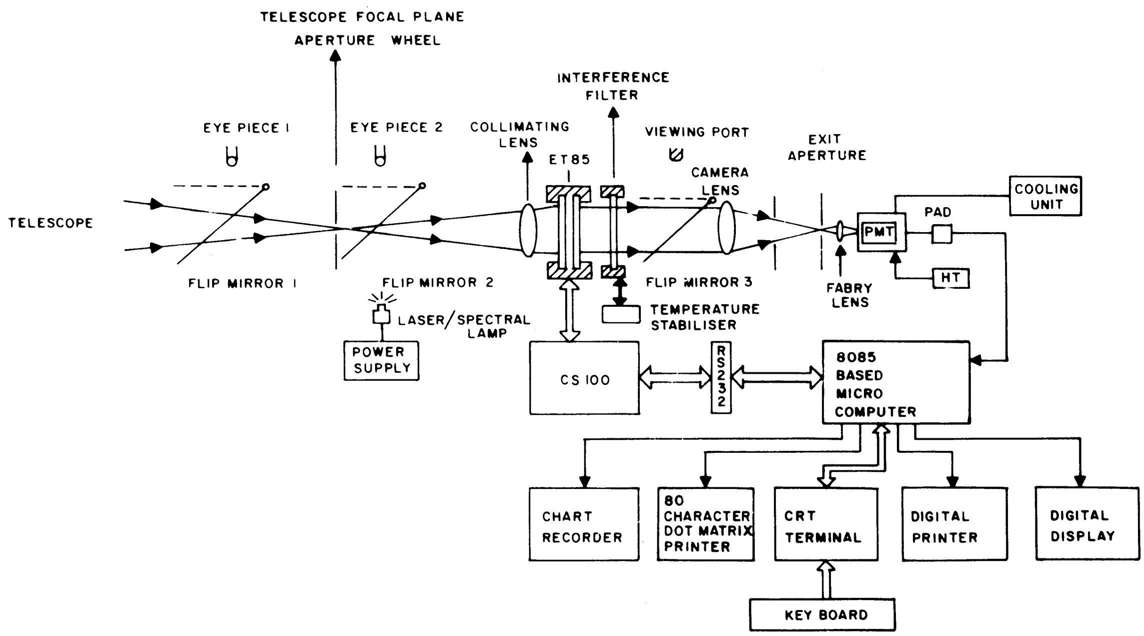

FIG. 1–Schematic layout of the piezoelectric Fabry-Perot spectrometer and associated electronics.

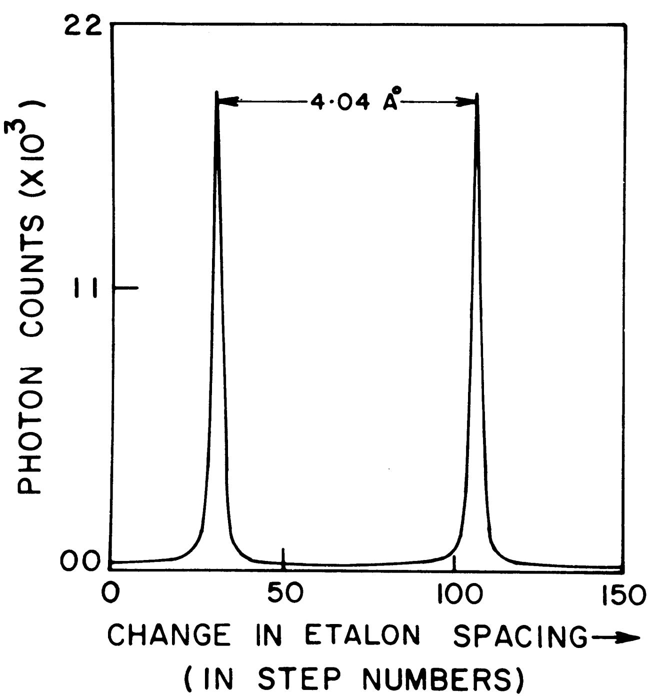

FIG. 2–A scan of the He-Ne laser line at λ 6328 Å with the piezoelectric Fabry-Perot spectrometer. The width of the profile which is the instrumental broadening is 0.14 Å.

spectra was first established by Swings and Greenstein (1958) with the high-resolution spectra of comet Mrkos and later in comet Seki. Subsequently, reexamination of several low-dispersion spectra of comets by Swings (1962) established the presence of cometary [O I] lines on many occasions.

TABLE I

Cometary Parameters During Observations

Date	Δ AU	$\dot{\Delta}$ km/s	R AU	$\dot{R}$ Km/s
10.4.86	0.42	0.03	1.32	26.51
13.4.86	0.42	13.35	1.36	26.47
14.4.86	0.43	17.59	1.38	26.43
15.4.86	0.44	21.94	1.39	26.38

Δ and R are geocentric and heliocentric distances respectively.

It is well known that these forbidden lines cannot be produced by the fluorescence mechanism because of the low-transition probabilities involved. Since collisional excitation is also inadequate for explaining the observed line emissions, these lines are presumed to arise due to the photodissociation of some parent molecule in an excited singlet state (^1D) from which it decays to the ground state (^3P). O (^1D) states can be generated by the following processes:

$$H_2O + h\nu \rightarrow H_2 + O(^1D) + 1.9\,\text{eV}$$
$$O_2 + h\nu \rightarrow O(^3P) + O(^1D) + 1.3\,\text{eV}$$
$$CO_2 + h\nu \rightarrow CO + O(^1D) + 5.5\,\text{eV}\ .$$

The O (^1D) doublet state emits radiation at 6300.304 Å and 6363.87 Å with the transition probabilities of 5.1 ×

10^{-3} s^{-1} and 1.64×10^{-3} s^{-1}, respectively. It is observed that the strength of the 6363.87 Å line is ~ 30% of the 6300.304 Å line because of the quenching processes involved in the cometary atmosphere. However, the details of the quenching processes are not known.

In the low-resolution spectra [O I] emission detection is always limited by NH_2 blending. The use of high-resolution spectroscopic techniques in recent days could overcome the blending problem and also separate the emission from terrestrial airglow effects. The high-resolution [O I] observations made earlier with FP spectrometers are summarized in Table II. Figure 3 shows the variation of [O I] 6300 Å emission as a function of heliocentric distance for several comets.

B. *NH_2*

The NH_2 spectrum arises due to excitation from the asymmetric ground state to a linear state, followed by the deexcitation to the ground state through "vibronic" transitions. The absorption spectrum of the NH_2 free radical was first observed in the laboratory during flash-photolysis experiments with ammonia (Herzberg and Ramsay 1952) and hydrazine (Ramsay 1953). The laboratory spectrum is extremely rich and has been rather thoroughly studied by Dressler and Ramsay (1959). Table III gives details of the NH_2 band emission near 6300 Å.

In the cometary atmosphere these molecules are supposed to be formed by fragmentation of ammonia molecules NH_3 or hydrazine N_2H_4 (Greenstein and Arpigny 1962). However, Robinson and McCarty (1959) have noted that NH_2 can be easily synthesized from N and H in low-pressure discharges and they point out that this might provide another possible interpretation of the production of NH_2 in even so rarefied a gas cloud as a comet. The detection of this molecule in comets was originally interesting as evidence of the presence of triatomic molecules in comets.

The NH_2 spectrum in comets shows a series of bands over the entire optical spectrum corresponding to successive levels of bending vibration decaying to the ground vibrational state. The relative strength of different vibrational bands appears qualitatively to be controlled by the solar flux available for fluorescence. The NH_2 observations made earlier are summarized in Table IV.

C. *Hydrogen Alpha*

In the cometary atmosphere Hα 6563 Å is produced by the 2-photon decay of hydrogen which has been excited by solar Lyman-β radiation. It was first observed in comet Kohoutek by Huppler, Scherb, and Trauger (1975). The Lyman-α 1216 Å and ground-based observations show that the velocity of atomic hydrogen in the comet atmosphere is much higher than the thermal velocity. The excess velocity of these atoms is mostly attributed to the dissociation processes producing the hydrogen atom. The hydrogen atoms in the cometary atmosphere can be pro-

TABLE II

[O I] 6300 Å Observations of Comets with Fabry-Perot

Comet	Heliocentric distance (R) in AU	Instrument	Comments	Reference
Kohoutek	0.65-1.08	Field of view = 4" Resolution = 40,000	1. Flux = 200±100 R at 0.7 AU 2. Flux decreases as $R^{-4.2}$ (Fig.3) 3. Line width 2.7 km/s, wider than telluric emission. 4. Surface brightness of the coma follows a power law r^{-2} (r = cometocentric distance)	Huppler et al.(1975)
Halley	1.98	Field of view = 14' Resolution = 30,000-200,000	Cometary line width 3·05±0.11 km/s. Telluric line width 1.6±0.1 km/s.	Roesler et al. (1985)
	0.83-2	Field of view ≃ 7'	Flux varies as $R^{-0.4}$ (Fig.3)	Scherb et al. (1985)
	0.89	Field of view ≃ 5.9' Resolution: 30,000	1. Flux ≃ 260 R 2. The surface brightness show a decrease of flux by a factor of 2 at 6' away from the head. 3. Line widths 3.9±1.5 km/s at 0.92 AU 7.4±2.2 km/s at 0.94 AU	Kerr et al. (1987)
	1.35	Field of view ≃ 50" Resolution: 45,000	1. Flux = 150±40 R 2. Line width: 3.5 km/s.	Present work

duced by the photodissociation of several water-group molecules. The reactions responsible for producing the H atom in comets are discussed in greater detail by Festou (1981). The velocities acquired due to the photolytic processes would normally decide the shape and shift of the Hα line profile.

The Hα observations made earlier are summarized in Table V and Figure 4. The low mean outflow velocity of

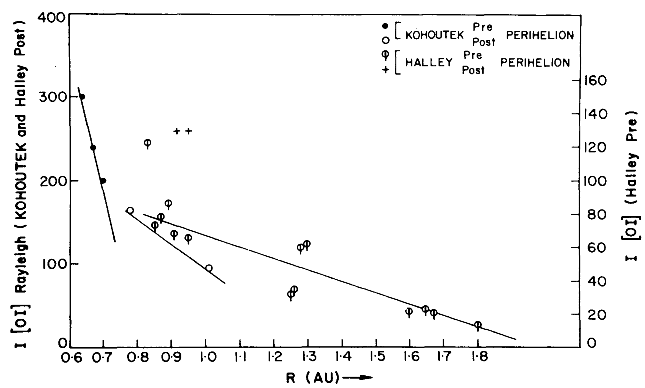

FIG. 3–[O I] intensity variation with heliocentric distance in comets.

comet Austin (Shih *et al.* 1984) and the multicomponent spectra of comet Halley (Kerr *et al.* 1987) need further discussion. The analysis of Lα images (Meier *et al.* 1976) also showed a significant enhancement of a low-velocity component (4 km s^{-1}) when comet Kohoutek was at R = 0.18 AU. These enhancements at low outflow velocities are interpreted as the result of increasing thermalization of hydrogen atoms by collisions with the cooler heavy molecules in the vicinity of the cometary nucleus. The multicomponent spectra observed by Kerr *et al.* are attributed to the hydrogen atoms produced within a few hundred-thousand kilometers of the comet which are confined to jets after their production. However, no plausible mechanism for the collimation is suggested.

During the three nights of observation repeated scans were taken over the Hα region. A careful analysis involving coadding the different scans has not revealed any detectable signal at Hα from the comet above the noise level. From the minimum detectability of the instrument we conclude that the Hα intensity from the coma (within 15,000 km from the nucleus) is 30 Rayleighs. The estimated flux of Hα at 1.35 AU found by extrapolating the value by Kerr *et al.* is ~ 12 Rayleighs. Our results are

TABLE III

Theoretical and Observed NH_2 (0-8-0) Transition

Transition[1]	λ (Å) Theoretical	λ (Å)[2] Observed	Intensity[3] in Rayleigh	NH_2/[OI]
1_{11} - 1_{01}	6294.45			
	6295.83			
2_{12} - 2_{02}	6297.32			
	6298.62	6298.604	75 ± 50	0.5
3_{13} - 3_{03}	6298.98	6299.004	78 ± 50	0.52
	6300.91			
4_{14} - 4_{04}	6300.78			
	6301.96			
5_{15} - 5_{05}	6300.91			
	6300.85			
6_{16} - 6_{06}	6299.52			
	6300.08			
[OI]	6300.304		150 ± 40	

1. Notation from Dressler and Ramsay (1959).
2. Observed wavelengths are in agreement with Arpigny et al. (1986).
3. Intensity is corrected for filter transmission.

TABLE IV

NH_2 Observations of Comets

Comet	Heliocentric distance R (AU)	Comments	Reference
Kohoutek	0.37	1. NH_2 cloud extends to 0.74×10^4 km in coma. 2. NH_2 is concentrated more towards the nucleus compared to C_2. 3. NH_2 emission increases markedly with C_2 as R increases.	A'Hearn (1975)
Halley	0.87 - 1.04	1. Flux on head with 5.6' aperture ≃ 110 R, 6' sunward≃175 R, 6' antisunward≃175 R.	Kerr et al. (1987)
	0.77	1. line width 2.4 ± 0.2 km/s	Roesler et al. (1985)

TABLE V

Hα Observations of Comets

Comet	Heliocentric distance R (AU)	Instrument	Comments	Reference
Kohoutek	.62- .94	FOV 2'	1. Mean outflow velocity 7.8 ± 0.2 km/s 2. Hα flux varies as (preperihelion)$\sim R^{-0.23}$ (postperihelion)$\sim R^{-0.46}$ (fig.7)	Huppler et al. (1975)
Austin	0.644-0.678	FOV 25'	1. Mean outflow velocity 4.8±1.2 km/s 2. Flux variation follows $R^{-0.01}$ (fig.7) (see text).	P.Shih et al. (1984)
Halley	.87-1.04	FOV 5.9'	1. Multivelocity component spectra showing the maximum radial velocity component to be ≃35 km/s. 2. Flux decreases by a factor of 2 between 0.8 AU and 1.04 AU of heliocentric distance. 3. Flux was considerably higher in 6' sunward side compared to the head.	Kerr et al. (1987)
"	.83-1.72		1. Outflow velocity components of 14.2±3.5 km/s and 2.6±1.5 km/s 2. Flux varies as $\sim R^{-0.16}$ (fig.7).	F.Scherb et al. (1985)
"	1.35	FOV	Flux does not exceed ∿30 R	Present work.

therefore consistent with the earlier observations. Further, no strong H_2O^+ emission feature within the filter bandwidth of Hα could be detected, implying a similar flux limitation for H_2O^+ in the near-nucleus region.

In light of our photographic Fabry-Perot results from Mount Abu, India (Debi Prasad *et al.* 1988) wherein, on a particular day following a special event, strong Hα emission is seen, it is concluded in retrospect that Hα observations on future comets must be strongly pursued, but with a flexibility of increasing the field of view while employing

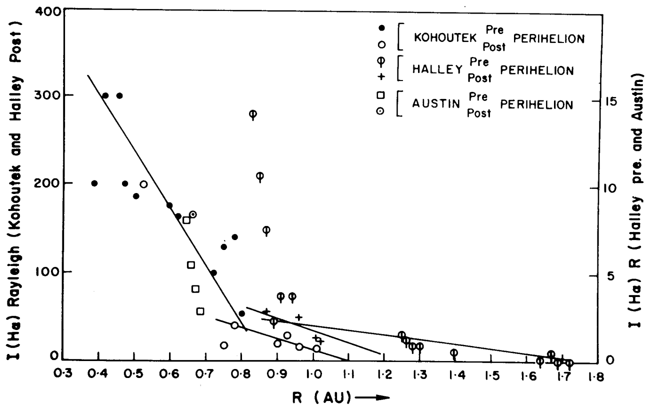

FIG. 4–Hα intensity variation with heliocentric distance in comets.

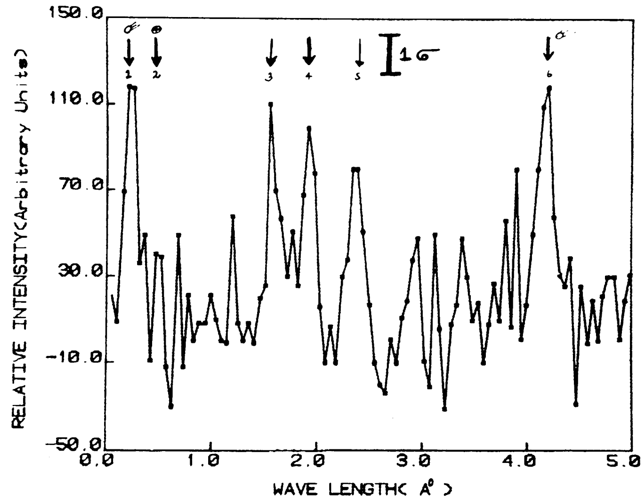

FIG. 5–Cometary [O I] 6300 Å and NH_2 lines, obtained using the spectrometer on 1986 April 13. Features: (1) cometary [O I] 6300 Å, (2) expected position of airglow [O I] emission, (3) NH_2 6299.004 Å, (4) NH_2 6298.6 Å, (5) unidentified, and (6) next order of cometary [O I] 6300 Å.

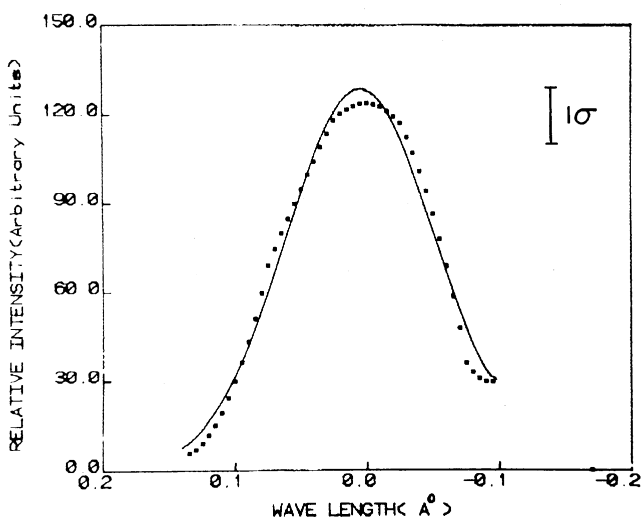

FIG. 6–[O I] line profile. The solid line is a least-squares-fit Gaussian.

techniques for improving S/N (which is discussed later) if the signal is found to be weak.

IV. Results and Discussion

A. *[O I] Results*

Figure 5 is a spectral scan of about one free spectral range taken at 6300 Å with the field of view centered on the nucleus. The principal features marked 1 and 6 separated by 4.001 Å (one free spectral range at 6300 Å) are identified as the two adjacent orders of cometary 6300.304 Å emission. The other features 3 and 4 are attributed to NH_2 (0-8-0) band emission. Figure 6 shows the O (^1D) line profile observed and a best-fit Gaussian superposed. The Gaussian linewidth after correction for instrumental broadening (0.14 Å) corresponds to 3.5 km s^{-1}. The result is in agreement with that of Huppler *et al.* (1975) who had studied comet Kohoutek using PEPSIOS. They had derived a half width of ~ 3 km s^{-1} for the [O I] line suggesting a systematic coma-expansion rate of ~ 1.5 km s^{-1}. The symmetric profile indicates the isotropic flow of the oxygen atoms.

The airglow emission at 6300 Å was not detected above the noise level of the detector within our 50″ field of view. Since our observations were taken near local midnight when the telluric emission is minimum (Ramachandra Rao 1971) assuming the airglow flux to be ~ 40 Rayleighs, we estimate the cometary O (^1D) flux to be > 150 ± 40 Rayleighs. This estimation agrees with the instrumental flux calibration on the Orion nebula on the same day. This value is also consistent with the value expected at a heliocentric distance of ~ 1.35 AU by extrapolating the results of Kerr *et al.* (1987).

B. *NH_2 Results*

The wavelengths calculated for the features marked 3 and 4 in Figure 5 with reference to feature 1 (6300.304 Å) agree well with two of the rotational lines of the NH_2 (0-8-0) band. However, feature 5 remains unidentified within the errors of estimation, as it cannot be attributed to any of the NH_2 lines of the (0-8-0) band. Table III lists the observed NH_2 lines and expected lines if all rotational levels were populated (Dressler and Ramsay 1959). The observed relative intensities were corrected for the varying transmission of the filter across its 5 Å bandwidth. We obtain the ratio NH_2 λ6298.62/[O I] λ6300.303 of ~ 0.5. The value obtained by Arpigny *et al.* (1986) at about the same time is ~ 0.3. Considering the variation of this ratio with the filter-transmission characteristics induced by temperature changes, we do not consider the difference in the values to be significant. As pointed out by Arpigny *et al.* a careful study of spatial variation of the NH_2 lines of the (0-8-0) band, well resolved from the [O I] 6300.304 Å line over the extent of the emission coma, remains to be carried out. The profiles were also fitted with equivalent Gaussian profiles. Figures 7a and 7b show the NH_2 line

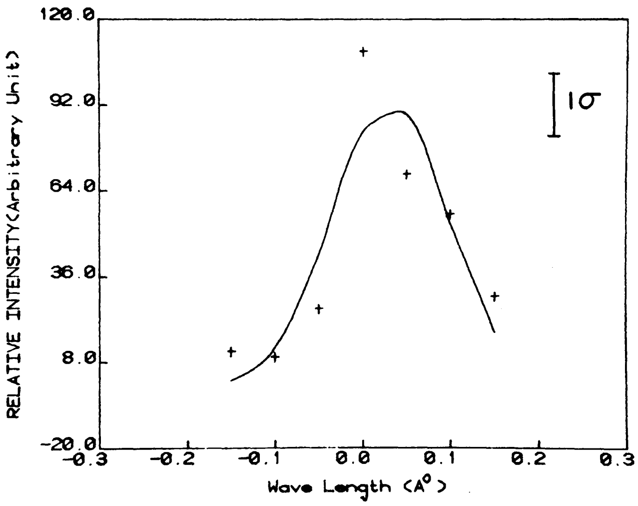

FIG. 7(a)–NH_2 (3_{13}–3_{03}) 6299.004 Å line profile. The solid line is a least-squares-fit Gaussian.

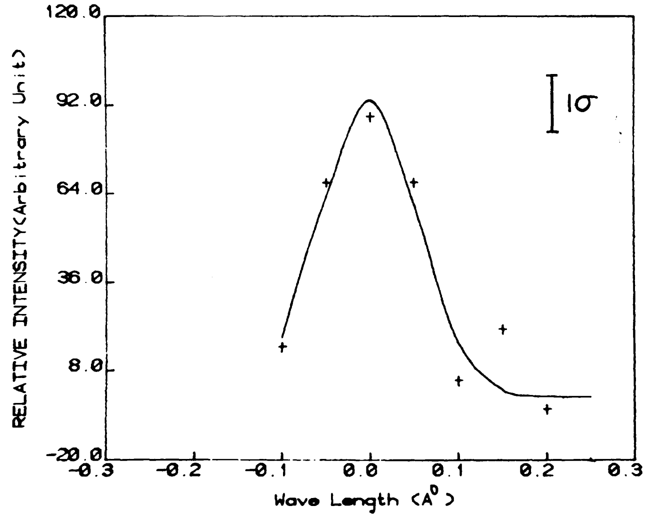

FIG. 7(b)–NH_2 (2_{12}–2_{02}) 6298.6 Å line profile. The solid line is a least-squares-fit Gaussian.

profiles observed, and the best-fit Gaussian linewidth after correction for instrumental broadening (0.14 Å) corresponds to ~ 3 km s^{-1} which is in good agreement with the results of Roesler *et al.* (1986). Table IV summarizes the results. Table VI gives the ratio of NH_2 6298.6/[O I] for several comets.

C. *Improvements in S/N*

If one compares the line-profile observations made by the single-etalon FP spectrometer (Kerr *et al.* 1987) with those made by tandem systems (Roesler *et al.* 1986), it is clear that the tandem systems give much better signal-to-noise ratio due to their superior rejection of the continuum intensity over a wider wavelength band. However, this is achieved at the cost of a large reduction in overall system transmission and greater complexity of instrumentation. Also, it should be noted that, for a source like a comet with large spatial variation of brightness, the major contribution to the deterioration of *S/N* comes from the scintillation noise in the continuum, associated with sky-transparency fluctuations and residual guiding errors.

The performance of a single-etalon system in this re-

TABLE VI

The Ratio of NH_2 (2_{12} - 2_{02}) of Comets

Comet	Field of view	R AU	$\dot{R}$ km/s	NH_2 6298.62/[OI] (2_{12} - 2_{02})	Authors
Halley	0.9'	1.28	-26.66	0.53	F.I.Roesler
	7'	0.77	-23.06	0.3	"
	2"x20"	1.25	+26.7	0.3	Arpigny C.
	50"	1.35	+26.51	0.5	Present work
Mrkos	3"	0.58	+12.00	0.1	Greenstein
Kohoutek	3"	0.34-0.63		0.2	Kohoutek
Wilson	2"x20"	1.22	-5	0.28	Arpigny C.

spect can probably be greatly improved by adoption of a modification first proposed (and subsequently used) by one of us in connection with detection of line emission from lithium vapor trails released in the upper atmosphere during the daytime (Desai, Anandarao, and Raghavarao 1979). Essentially, in this scheme, modulating masks placed in the Fabry-Perot fringe plane allow the photodetector to look at, alternately, the flux at the wavelength of the line and in the adjacent continuum with the same bandwidth and from the same portion of sky, and to record the difference. Scanning in λ allows one to record the line profile as a derivative spectrum, i.e.,

$$dI/d\lambda \text{ vs. } \lambda \ .$$

To apply the scheme to detect line profiles on a source like a comet some modifications would be needed, viz.:

1. Use of the FP in telecentric mode with rather large f ratio ($\sim f/100$) rather than the classical use in a collimated beam. This is to ensure that variation of brightness over the source has no effect (Meaburn 1976).

2. Use of up-down counting controlled by electronic gates, synchronized with a stepped scan in λ, to permit adjustable integration time.

An instrument based on the above considerations is under fabrication.

V. Conclusion

A sophisticated piezoelectric Fabry-Perot spectrometer was developed for emission-line profile studies of [O I] λ6300 and Hα lines. The instrumental resolution was ~ 0.14 Å.

1. The cometary [O I] emission at ~ 6300.304 Å was readily detected and NH_2 emission of the (0-8-0) band was spectrally well separated from it.

(a) The estimated intensity of [O I] on 1986 April 13 ($r = 1.36$ AU, $\Delta = 0.42$ AU) was 150 ± 40 Rayleighs.

(b) The ratio

$$\frac{\text{(0-8-0), } NH_2\ 2_{12}\text{–}2_{02}\ 6298.6\ \text{Å}}{\text{[O I] } 6300\ \text{Å}}$$

integrated over the 50″ aperture was found to be 0.5. The NH_2 profile linewidths are ~ 3 km s^{-1}.

(c) The [O I] line profile was symmetric and a Gaussian fit yielded a width (FWHM) of ~ 3 km s^{-1}.

2. The cometary Balmer emission of hydrogen at 6563 Å was barely detectable. An upper limit based on the instrumental sensitivity yields a value of 30 Rayleighs.

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