

On the Spectrum of Comet Bradfield 1980*t*

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Summary. Twenty spectra of Comet Bradfield 1980*t* have been obtained in the period January 8–16, 1981, using the 122 and 182 cm Asiago telescopes. Three photographs have also been taken on January 8 with the 90 cm Schmidt telescope.

192 neutral and 41 plasma lines (CO^+ , CO_2^+ , NH^+ , CH^+ , and H_2O^+) have been identified in the coma and in the tail of the comet. A new cometary ion, H_2S^+ , could be present. The wavelengths of 26 unidentified lines in the coma coincide with transitions of neutral CO.

The first certain identification of the CO-Triplet system ($d^3\Delta \rightarrow a^3\Pi$) is reported.

Another important result achieved is the determination of absolute fluxes of 86 lines in the range 5850–9100 Å, using a Reticon 512 detector.

Key words: Comets – Comet Bradfield 1980*t* – near infrared spectroscopy

Introduction

Spectroscopic data of the near infrared part of the spectrum of cometary comas are very rare.

Recent observations of Comet Bradfield 1979*L* indicated the presence of the (3–0) Phillips band system of C_2 (Cosmovici and Ortolani, 1980) and permitted the measurement of the CN near-infrared (1–0) band and the determination of the 3–1/2–0 and 1–0/2–0 ratios of this molecule (Danks and Dennefeld, 1981).

Unfortunately, absolute fluxes of the near infrared bands of CN and C_2 were not available up to now and the knowledge of these fluxes is very important for comparison with the well known CN (0,0) violet and C_2 Swan bands.

Therefore, in order to obtain a better insight in the red and near infrared spectrum of the cometary coma, we used our new Reticon 512 system which permits not only the identification of the cometary features in the range 5850–9100 Å but also the determination of the absolute fluxes of all the present lines.

At the same time a detailed analysis of the spectra was carried out in order to identify possible new features on the basis of new laboratory data on molecular transitions.

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The Observations

Comet Bradfield 1980*t* was discovered on Dec. 17.7 UT at $M=6$ in the southern hemisphere. Because it was in conjunction with the sun, it was invisible at its brightest magnitude ($M \sim 2.5$) in late December. We were able to start the observations on Jan. 8.7 at $M=4.8$ and continue till Jan. 16.7 at $M=7.1$ (see Table 1).

Three photographs taken in Jan. 8.7 (Fig. 1) show a plasma-rich comet with a visible extension of the tail of about $5 \cdot 10^6$ km. The dust contribution to the tail is very low as observed by using a RG 1 red filter.

16 spectra were taken on the 122 cm telescope using the prism spectrograph coupled with an S20 image tube. The exposure times were varied between 3 and 25 min. The dispersions on the plate are: 50 Å/mm at 4200 Å, 100 Å/mm at 5000 Å, 200 Å/mm at 6100 Å, and 350 Å/mm at 7200 Å.

15 spectra were taken setting the slit in the central part of the coma radial to the tail. The dimensions of the slit were chosen between $750 \times 28,000 (\text{km})^2$ and $850 \times 49,000 (\text{km})^2$ around the central part of the coma (Fig. 2).

Plate No. 13913 was taken setting the $1360 \times 45,400 (\text{km})^2$ field of view perpendicular to the radius vector of the tail at a distance of 10^5 km from the center of the coma. From the 200 measured lines (Table 2) 28 could not be identified up to now on the basis of available tables. Table 2 represents a summary of all lines present in the 16 prism-spectra.

Three spectra were obtained with the Reticon 512 spectrophotometer of the 182-cm telescope the evenings of Jan. 14 and 15, 1981.

On both dates the spectra were taken with the slit oriented E–W, 32" long and 3" wide ($26,100 \times 2450 \text{ km}^2$), centered on the bright nuclear condensation. The area of comet detected by the spectrophotometer was therefore approximately $100 (\text{arcsec})^2 = 2.35 \cdot 10^{-9}$ sterad. The spectra of Jan. 14 were obtained with the 600 g/mm grating rotated in order to cover the spectral region $\lambda\lambda 6100\text{--}9100 \text{ Å}$, with a resolution of 5.85 Å/diode. The following evening, the 1200 g/mm grating was used so that the region 5850–7380 was observed with a resolution of 2.93 Å/diode.

The standard procedure for Reticon observations, which are entirely computer-controlled, consists of two exposures, one on the object, followed by an equally long exposure on the adjacent sky; between the two exposures, the object is moved off the slit by tilting a transparent plate in front of the spectrograph. However, this movement was not sufficient to exit from the extended coma of the comet, so that the telescope was moved in Dec. by some 0.5° south of the coma.

Table 1. Data of observations

No.	Date (Jan. 81) UT	Telescope	Instrument	Plate no. Type exp. time in min	<i>M</i>	Δ km 10 ⁶	<i>r</i> km 10 ⁶
1– 4	8.7	122 cm	Prism-Spectrogr. + S 20	13861-4 103 <i>a-O</i> 3; 6; 12; 3	4.3	134.25	60
5	8.7	Schmidt (90 cm)	Camera	10781 103- <i>a-D</i> + <i>GG</i> 14 10	4.3	134.25	60
6	8.7	Schmidt (90 cm)	Camera	10782 103- <i>a-D</i> + <i>GG</i> 14 5	4.3	134.25	60
7	8.7	Schmidt (90 cm)	Camera	10792 INsens. + <i>RG</i> 1 20	4.3	134.25	60
8	11.7	182 cm	Grating-Spectro- graph B&C (600 + ITT)	1948 103- <i>a-D</i> 5	5.4	150.9	70.5
9–11	14.7	122 cm	Prism-Spectrogr. + S 20	13908-10 103- <i>a-O</i> 3; 5; 10	4.9	168.15	81.3
12–13	14.7	182 cm	Grating-Spectro- graph B&C (600 + Reticon 512)	– – 1	4.9	168.15	81.3
14–17	15.7	122 cm	Prism-Spectrogr. + S 20	13911-13 103- <i>a-O</i> 5; 15; 6	5.1	173.7	84.9
	15.7	182 cm	Grating-Spectro- graph (1200 + Reticon 512)	– – 1	5.1	173.7	84.9
18–23	16.7	122 cm	Prism-Spectrogr. + S 20	13925-27 13932-36 103- <i>a-O</i> 5; 10; 15; 15; 25; 25	5.1	179.4	88.35

Δ = Geocentric distance
r = Heliocentric distance
M = Total magnitude

Because of the low elevation of the comet (Zenith distance $\approx 70^\circ$) which prevented the observation of nearby standard stars, only α And could be used as calibration star.

In order to reduce the error in the continuum determination, a polynomial of low degree, best-fitting the instrumental continuum, was removed from the raw data; the effect is the artificial horizontal “continuum” present in Fig. 3a and b.

The rest of the image processing followed the usual way which includes wavelength calibration and linear filtering of the noise.

Figure 3a shows the corrected spectrum obtained Jan. 14 at UT 17^h15^m, with 1 min exposure time. The spectrum obtained with higher resolution the following night at UT 16^h38^m is shown in Fig. 3b.

The identification of the lines and the absolute fluxes of the most relevant features are given in Tables 3 and 4. There are some features in Table 4 and Fig. 3b which have no counterpart in Table 3 and Fig. 3a. If the reason would be the fact that the two spectra were taken during two different nights under different experimental conditions and that the position of the slit on the comet was not exactly the same, one should observe the disappearance of all features of a particular chemical species. The disappearance of some but not all features of a single species indicate that between the 24 h of observation on January 14 and 15 some physical changes have occurred in the Comet. This is confirmed by different observations in this period. “Several observers in USA and Belgium reported a more than twofold increase

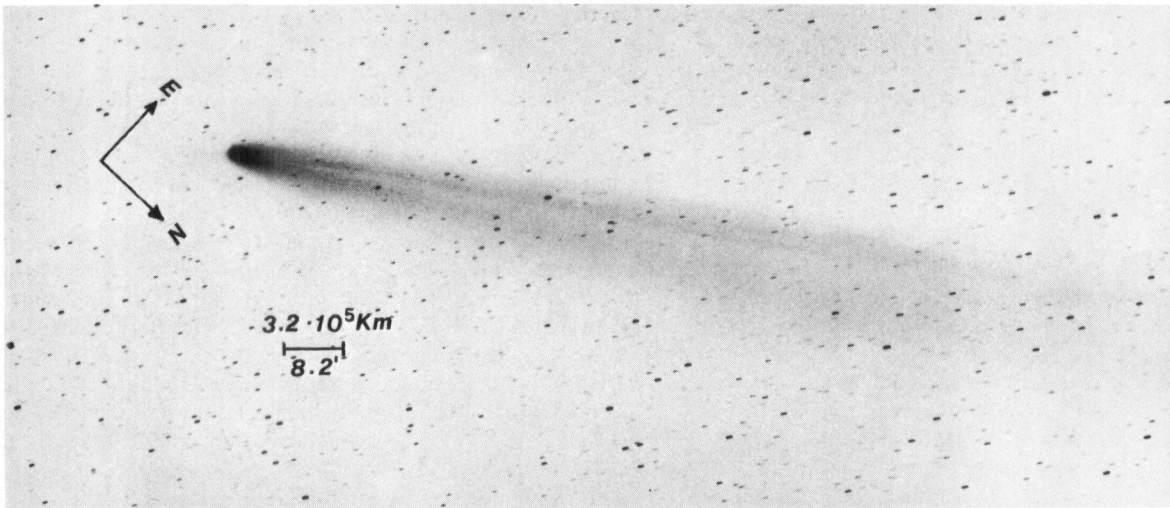


Fig. 1a. Photograph taken with the 90 cm Schmidt telescope with 10 min exposure time (plate 10781), on Jan. 8, 1981 (see Table 1). The visible part of the plasma tail is about $5.6 \cdot 10^{-6}$ km long

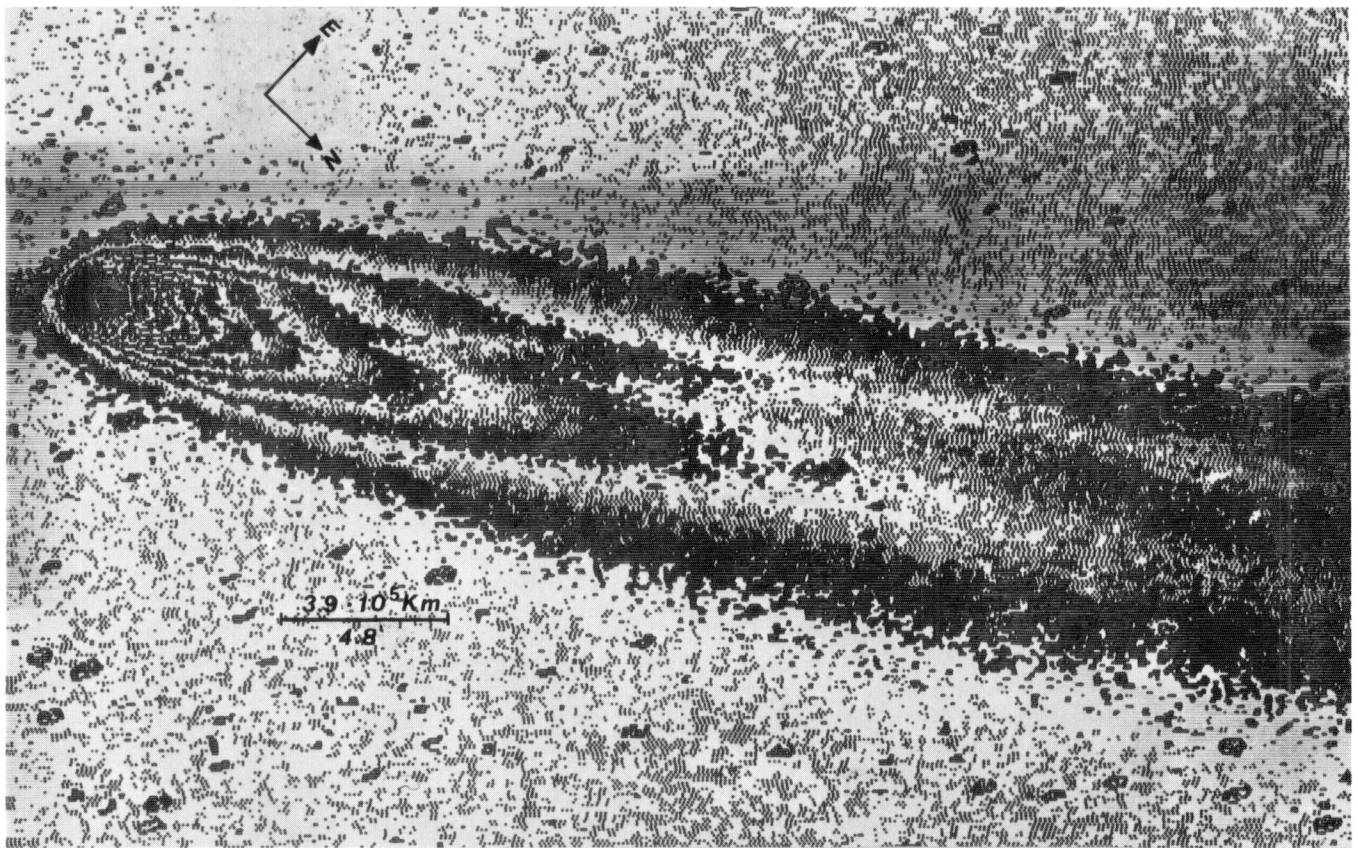


Fig. 1b. Isodensitometry of the same plate. The morphology of the Comet and the evolution of a double structure in the plasma tail is here visualized

in the comet's overall brightness. The outburst was short-lived, and within a few days the magnitude had returned to the previous level. Possibly this sudden alteration in brightness heralded a disruption in the comet's nucleus" (Bortle, 1981).

A more detailed analysis is therefore necessary on the plates taken with the prism-spectrograph in the period 13–15 January in order to state the same anomalies observed in the reticon spectra.

The error in the flux determination is about 50% due to the bad observational conditions. The relative intensities of the lines are known with better precision, typically $\pm 10\%$. The flux in the continuum is about $2 \cdot 10^{-14}$ erg/s cm² Å (arcs)², or $8.5 \cdot 10^{-14}$ erg/s cm² Å sterad. This value can be considered approximately the same for the entire range of observed wavelengths within the error. This result is in good agreement with that of Danks and

Dennefeld (1981) who found a decrease of a factor 1.3 between 6100 and 10,000 Å for Bradfield 1979*l*. The fluxes given in Tables 3 and 4 are calculated at the peaks and not under the area of the line or band, because of the low resolution.

Results

A. The Prism-spectrograph Spectra

The usual cometary molecular bands are present in the coma, and ions appear already at a distance of 20,000 km from the nuclear region.

H_2O^+ (9-0, 8-0, 7-0, 6-0, 5-0) bands and lines are identified with much higher certainty than in the plasma-poor Comet Bradfield 1979 L (Cosmovici and Ortolani, 1980).

A new cometary ion, H_2S^+ could be present at 4421, 4509, and 4756 Å (Duxbury et al., 1972). The other transitions in this region are all blended by other molecules.

Herbig (1976) suggested to search for this ion since it has a extensive electronic system in the blue-violet. Furthermore, H_2S is a well known constituent of interstellar dark clouds and microwave observations of neutral H_2S at 1.4 mm in a future bright comet should be taken into account.

The presence of Fe I at 5207, 5329, 5369, and 5428 Å is doubtful since, as pointed out by Marsden (1974), Fe I lines appear in Comets with $r \sim 0.1$ A.U.

The Fe I multiplet between 5269 and 5428 Å was very strong in Comet 1882 II which was observed at $r \sim 0.008$ A.U. Greenstein and Arpigny (1962) detected the feature at 5269 Å in Comet Mrkos (1957*d*) which had the same r as Comet Bradfield 1980*t*, but their identification is uncertain.

The [O I] redlines are of cometary origin as confirmed by the Reticon-spectrum which permitted a precise sky-subtraction. The green line at 5577 Å if present, is weak and cannot be resolved from the strong 5585 Å C_2 -line.

Also the D-lines of Na could be discriminated from the sky with the Reticon system.

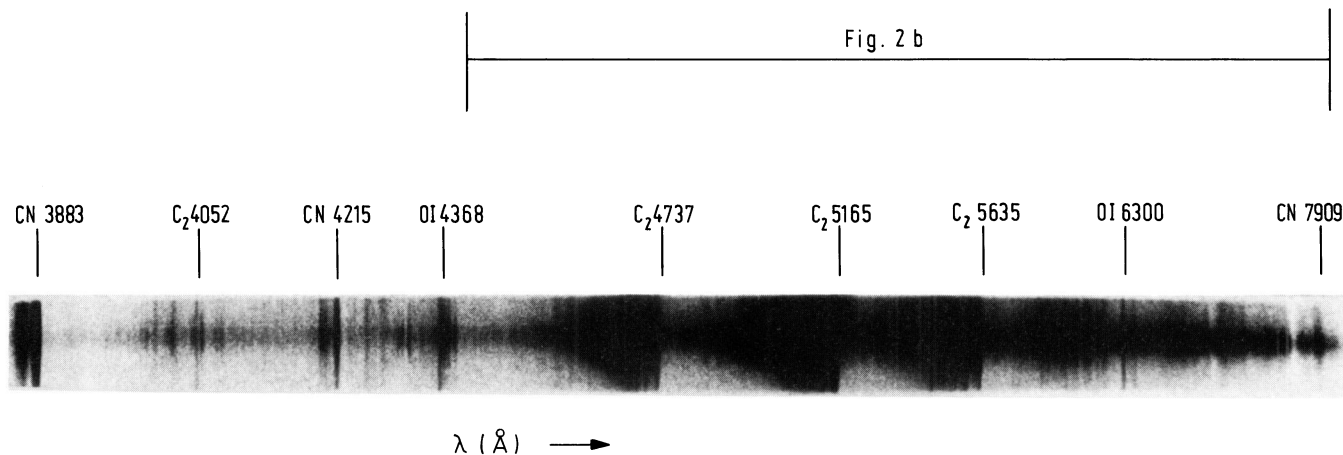


Fig. 2a. Spectra of the Comet taken with the 122 cm telescope, on Jan. 15, 1981. Plate 13911, 5 min exposure time. The slit was oriented radial to the tail and centered on the nuclear region, covering a field of $1360 \times 45,400 \text{ km}^2$

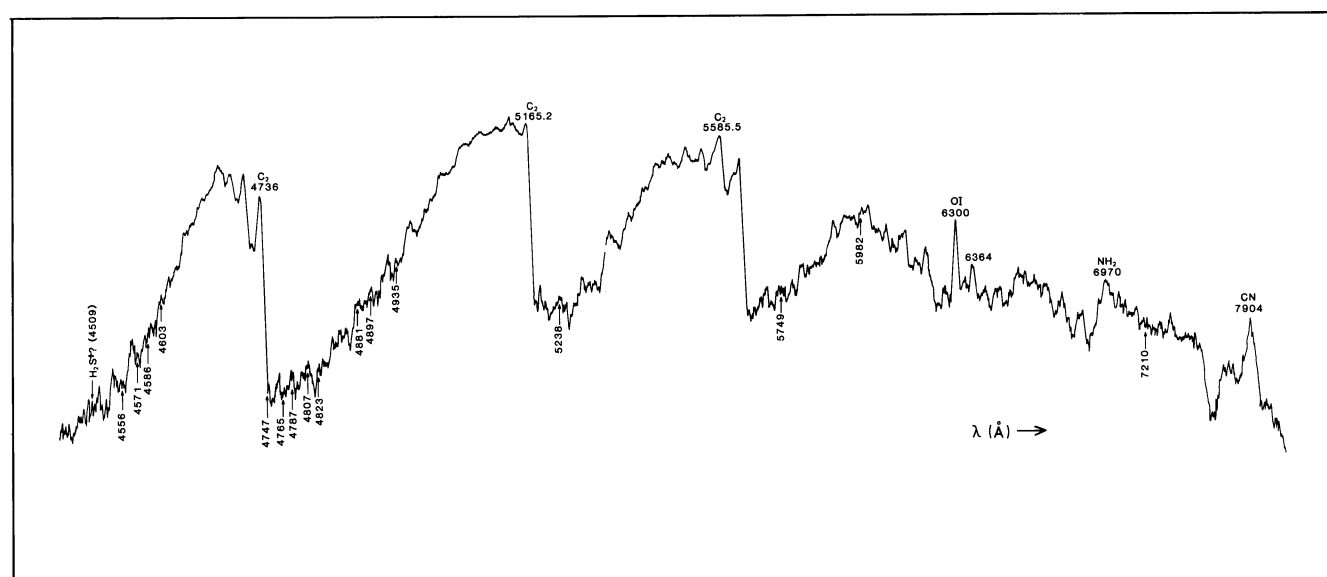


Fig. 2b. Microphotometer plot of Fig. 2a between 4500 and 8000 Å. The arrows indicate the position of CO lines (see Table 2)

Table 2. Observed lines (Prism-Spectrograph-Spectra). The laboratory values are taken from: Greenstein and Arpigny (1962), Davis and Phillips (1963), Pearse and Gaydon (1976), Phillips (1948), Phillips and Davis (1968), Swings and Haser (1956), Wehinger et al. (1974), Woszczyk (1962), Dressler and Ramsay (1959), Duxbury et al. (1972), Krupenie (1966)

$\lambda(\text{\AA}) \pm 2 \text{\AA}$ observed	Suggested identification	Laboratory $\lambda(\text{\AA})$
3882	CN (0-0)	3883.48
3896	CH (0-0)	3897.2
3904	CH (0-0)	3902.6
3912	N_2^+ (0-0) + CN (0-0)	3913.7 + 3909.5
3916	CH (0-0) + C_3	3914.5
3928	C_3	3925.9
3931	C_3	3935.8
3940	CH (0-0)	3943.82
3946	CH (0-0)	3944.18
3949	$\text{C}_3 + \text{CO}^+$ (0-0)	3949.1 + 3951.3
3954	$\text{C}_3 + \text{CH}^+$ (1-0) + CO^+ (0-0)	3954.0 + 3954.4 + 3953.6
3966	CH^+ (3-1) + C_3	3967.1 + 3965.9
3976	CH^+ (0-0)	3977.7
3985	CO^+ (0-0) + OH^+ (0-1) + C_3	3983 + 3983.1
3987	C_3	3987.2
3995	$\text{C}_3 + \text{CO}^+$ (3-0)	3992.6 – 3997.5 + 3997.3
4002	$\text{C}_3 + \text{CO}^+$ (3-0)	4002.2 + 4001.5
4014	$\text{C}_3 + \text{CO}^+$ (3-0) + H_2S^+ ?	4013.2 + 4017.7 + 4012.0
4021	$\text{C}_3 + \text{CO}^+$ (3-0) + CH (1-1)	4018.3 + 4019.7 + 4025.3
4034	C_3	4033.2
4045	C_3	4043.6
4052	C_3	4051.6
4061	CH (1-1)	4059.5
4068	$\text{C}_3 + \text{CO}_2^+$	4068.4 + 4070.7
4075	C_3	4074.4
4084	C_3	4084.8
4091	C_3	4090.0
4101	$\text{C}_3 + \text{C}_2$ (0-1)	4099.5 + 4102.3
4109	$\text{C}_3 + \text{CO}_2^+$	4109.4 + 4107.9
4119	CO_2^+	4120.8
4124	$\text{C}_3 + \text{CO}^+$ (4-1)	4124.4 + 4124
4129	CN (1-2)	4130.14
4132		
4139	$\text{C}_3 + \text{CO}_2^+$	4137.8 + 4137.6
4142	CO^+ (4-1)	4140.0
4147	CN (2-3)	4147.2
4154	CH (0-0)	4153.39
4160	$\text{CO}_2^+ + \text{CN}$ (2-3)	4159.5 + 4160.25
4163	CH (0-0) + CN (1-2)	4162.66
4169–73	CH^+ (2-1) + H_2S^+ ?	4171.1 + 4172.5
4180	CN (1-2)	4179.58
4184	CN (1-2)	4184.0
4193	CN (0-1)	4193.0
4198	CN (0-1) + CO (11-0)	4197.0 + 4198.9
4215	CN (0-1) + CO (11-0)	4214.7 + 4213.7
4223	CH^+ (0-0) + CO (11-0)	4225.3 + 4227.2
4231	CH^+ (0-0) + CO^+ (0-1) + N_2^+ (1-2)	4231.0 + 4231.6
4234	CO^+ (0-1)	4236.2
4238	CH^+ (0-0) + CN (0-1)	4238.5 + 4239.0
4247	CO^+ (2-0)	4248.9
4249	CH (0-0)	4249.49
4252	CO^+ (2-0)	4252.0
4254	CH^+ (0-0)	4254.4
4258	CH (0-0)	4258.48
4270	CO^+ (2-0)	4272.0
4280	CH (0-0) + N_2^+	4281.0 + 4278.1

Table 2 (continued)

$\lambda(\text{\AA}) \pm 2 \text{\AA}$ observed	Suggested identification	Laboratory $\lambda(\text{\AA})$
4292	CH (0-0)	4291.7
4298	CH (0-0)	4297.3
4304	CH (0-0)	4303.9
4313	CH (0-0) + NH ⁺ (1-0)	4313.2 + 4312.7
4323	CH (2-2)	4323.5
4331	CH (0-0)	4329.3
4335	CH (0-0) + OH + H ₂ S ⁺ ?	4334.2 + 4336.6 + 4336.4
4348	CH (0-0) + NH ⁺ (0-0)	4348 + 4348.5
4359	Hg (NS)	4358
4368	O I (NS)	4368
4373	C ₂ (3-1) + CO (10-0)	4371.1 + 4374.0
4380	C ₂ (2-0)	4380.9
4400	CO ⁺ (3-1)	4403.3
4412		
4422	H ₂ S ⁺ ?	4421.3
4431	CH ⁺ (1-1)	4433.8
4436	CO (---)	4437
4442	CO (---)	4445.5
4456	CO (---)	4454.6
4466	H ₂ O ⁺ (0-14-0) + CO (15-3)	4468.82 + 4462.9
4470	H ₂ O ⁺ (0-14-0)	4469.36
4477	CO (15-3)	4478.8
4490	CO (13-2)	4488.4
4499	CH (1-2) + CO (15-3)	4495.5 + 4494.4
4503	NH (0-0) + CN (5-7) + CO (13-2)	4502.0 + 4502.2 + 4505.5
4509	H ₂ S ⁺ ?	4508.64
4512		
4518	CO ⁺ (4-2) + CO (13-2)	4518.0 + 4520.7
4530		
4540	CO ⁺ (1-0) + CO (11-1)	4539.4 + 4541.0
4544	CO ⁺ (1-0)	4543.8
4554	CO (11-1)	4556.5
4565	CO ⁺ (1-0)	4565.8
4573	CO (9-0)	4571.0
4584	CN (0-2)	4585.9
4588	CO (9-0)	4586.4
4591		
4597		
4604	CO (9-0)	4602.6
4613	CN (0-2) + H ₂ S ⁺ ?	4612.9 + 4616.9
4629	NH ⁺ (0-0)	4628.9
4639		
4647	CO (14-3)	4646.7
4662	CO (14-3)	4664
4680	CO (14-3)	4680.3
4696		
4713	Swan { C ₂ (5-4) (6-5) (4-3) (3-2) (2-1) (1-0)	4678.6 – 4737.1
4727		
4735		
4745	CO (10-1)	4747.5
4758	H ₂ S ⁺ ?	4755.7
4766	CO (10-1)	4764.8
4781		
4783		
4790	{ CO (8-0)	4787.3
4806		
4822		
4828	CO (8-0) + H ₂ S ⁺ ?	4823.5 + 4818.5

Table 2 (continued)

$\lambda(\text{\AA}) \pm 2 \text{\AA}$ observed	Suggested identification	Laboratory $\lambda(\text{\AA})$
4842		
4848		
4854		
4864	CO ⁺ (3–2)	4865.8
4877	CO ⁺ (0–0) + CH	4879.5 + 4877.37
4883	CO (13–3)	4880.8
4891		
4900	CO (11–2)	4897.5
4913	CO ⁺ (0–0)	4910.9
4925	NH ₂ (0, 13, 0)	4925.47
4938	CO (11–2)	4935.5
4956	NH ₂ (0, 13, 0)	4954.41
4960	CO (9–1) + H ₂ S ⁺ ?	4959.0 + 4962.4
4988		
4994	C₂ (0–0) Swan	
5011		
5046		
5079		
5109		
5129		
5165		5165.2
5200	NH ₂ (0, 12, 0)	5199.41
5209	Fe I ?	5207
5237	CO (8–1)	5238.4
5250		
5280		
5293		
5301		
5328	NH ₂ (0, 12, 0) + CO (6–0) + Fe I ?	5327.59 + 5330.5 + 5329
5340		
5370	Fe I ?	5369
5408	NH ₂ (0, 7, 0)	5409.09
5429	Fe I ? + CO (---) + NH ₂ (0, 11, 0)	5428 + 5428.3 + 5428.6
5444	NH ₂ (0, 7, 0)	5442.81
5461	Hg (NS) Swan	5460.7
5502		5501.9
5541		5541.1 + 5540.7
5586		5585.5
5636		5635.5
5670		5670.5
5682	NH ₂ (0, 10, 0)	5682.24
5696	NH ₂ (0, 10, 0)	5696
5741	NH ₂ (0, 10, 0)	5741.28
5746	CO (11–1) ? A	5746.0
5754	NH ₂ (0, 10, 0)	5752.57
5769	Hg (NS) + CO (11–1) ? A	5769.3 + 5769.7
5790	Hg (NS)	5790.7
5801	H ₂ O ⁺ (0–9–0)	5799.78
5816	H ₂ O ⁺ (0–9–0)	5814.66
5852	NH ₂ (0, 10, 0)	5852.57
5893	Na I	5890 + 5896
5928	H ₂ O ⁺ (0–9–0)	5927.55
5960	NH ₂ (0, 9, 0)	5960.97
5984	CO (4–0)	5982.0
5997	NH ₂ (0, 9, 0)	5994.85, 95.01
6054		
6077	NH ₂ (0, 9, 0)	6077.32
6099	NH ₂ (0, 9, 0)	6098.37

Table 2 (continued)

$\lambda(\text{\AA}) \pm 2 \text{\AA}$ observed	Suggested identification	Laboratory $\lambda(\text{\AA})$
6109	NH ₂ (0, 9, 0)	6110.02
6120	C ₂ (1-3) + NH ₂ (0, 9, 0)	6122.1 + 6121.12
6152–6160	H ₂ O ⁺ (0–8–0)	6158.64, 58.86
6188	CO ⁺ (0–2) + C ₂ (0–2)	6189.4 + 6191.3
6230	OH (NS)	6233.7
6258	OH (NS) + NH ₂ (0, 9, 0)	6256.0 + 6257.67
6300	[O I] + NH ₂ (0, 8, 0)	6300.0 + 6300.08, 00.79, 00.91
6335	NH ₂ (0, 8, 0) + CN (5–1)	6334.51 + 6332.2
6364	[O I] + CO (11–2) A	6363.9 + 6366.9
6420	OH (NS)	6421.2
6464	OH (NS) + CO (3–0)	6463.8 + 6464.6
6484–7 6531 6568 6575 6595 6648 6663 6686 6762 6827 6857 6970 7040 7077 7147 7188 7207 7227 7244 7285 7350 7438 7457 7469 7500 7521 7688–7701 7727 7766 7905	H ₂ O ⁺ (0, 7, 0)	6524.92 – 6599.53
	OH (NS)	6665.0
	H ₂ O ⁺ (0, 7, 0)	6686.56, 85.51
	OH (NS)	6828.9
	OH (NS) ?	6861.7
	H ₂ O ⁺ (0–6–0)	6970.14, 73.71
	H ₂ O ⁺ (0–6–0)	7040.65, 37.89
	CO (6–0) A + (3–1)	7210.4 + (7200)
	CO (6–0) A + (3–1)	7229.0 + 7231.3
	CN (5–2)	7289.0
	NH ₂ (0, 5, 0)	7350.0
	CN (6–3)	7438.4
	H ₂ O ⁺ (0–5–0)	7467.76
	CO (1–0) ?	(7502.1)
	CN (6–3)	7518.64 – 7521.55
	CN (6–3)	7690.56 – 7697.06
	C ₂ (3–0)	7727.56
	C ₂ (3–0)	7767.4
	C ₂ (4–1) + CN (2–0)	7907.7 + 7908.6

Only the CO lines with A belong to the Asundi system

B. On the Possible Identification of CO

Neutral Carbon Monoxide has been observed in Comet West 1975n at 1510 Å by means of a UV-rocket experiment (Feldman and Brune, 1976). The presence of the Cameron bands in the spectrum of the same comet is not sure (Smith et al., 1980). Search for CO in the radio- and in the IR-range at 2.6 mm (Ulrich and Conklin, 1974) and 4.7 μ resp. (Wollman et al., 1974) was not successful.

CO has, like N₂, a high vaporization rate; therefore it could be a major constituent only in a new Comet and because of its volatility would be almost entirely lost after repeated passages around the Sun.

Herbig (1976) suggests that the nuclei of CO-rich comets represent material that was withdrawn from the parent gas at a time when that gas was hotter than about 550 K. Herbig also points out that a CO-rich comet would be correspondingly H₂O-poor. Our Reticon results do not confirm this hypothesis (see Tables 3 and 4).

Feldman and Brune (1976) conclude from their measurements that CO must be abundant close to the nucleus, implying that it is a primary constituent of the Comet. From the presence of a large number of C-atoms in the ¹D state they conclude that dissociative recombination is important near the cometary nucleus and that CO must originate in the nucleus, not as the product of CO₂ dissociation. This model has been acknowledged by A'Hearn and

Feldman (1980), from more accurate observations of Comet Bradfield 1979 I, to not explain the observations near the nucleus in subsequent comets. In this paper is pointed out that CO cannot produce as much atomic carbon as is observed. The additional source of carbon is at present not known.

The bands of CO most commonly encountered in laboratory are (Pearse and Gaydon, 1976; Krupenie, 1966):

1. the Ångström system between 6620 and 4124 Å ($B^1\Sigma \rightarrow A^1\Pi$)
2. the Herzberg system between 5706 and 3681 Å ($C^1\Sigma \rightarrow A^1\Pi$)
3. the 3rd positive and 5 *B* bands between 2833 and 3699, 2665, and 3825 Å resp. ($b^3\Sigma \rightarrow a^3\Pi$)
4. the 3 *A* bands between 2711 and 2296 Å ($c^3\Sigma \rightarrow a^3\Pi$)
5. the 4th positive system between 2800 and 2006 Å ($A^1\Pi \rightarrow X^1\Sigma$)
6. the Cameron bands between 2575 and 1989 Å ($a^3\Pi \rightarrow X^1\Sigma$)
7. the Triplet bands between 6465 and 4011 Å ($d^3\Delta \rightarrow a^3\Pi$)
8. the Asundi bands between 8592 and 5749 Å ($a'^3\Sigma^+ \rightarrow a^3\Pi$).

The bands 5–8 should be observable in cometary spectra. The electronic levels involved are singlet and triplet.

Biermann (1976) investigated the high-dispersion spectra of Comet Mrkos (1957V) taken by Greenstein and remeasured by Woszczyk (1962) where many unidentified lines are present in order to state the possibility of CO-identification. The results of this investigation strongly favor the identification of the triplet transitions of CO, but the numbers do not seem to be large enough to rely entirely on the argument of a small statistical probability (0.2%) that the presence of the observed bands is merely due to chance.

Biermann suggests a further investigation of the rotational structure of the CO bands for the triplet system and further detailed observations of cometary UV and visible spectra.

It is clear, as pointed out by Biermann (1976) that not all the transitions observed in laboratory have a sufficient probability to be detected in comets. Because of the diluted sunlight, only resonance transitions or transitions arising from metastable levels have a chance to be detected.

Fluorescence excitation, leading to one of the higher triplet levels, from the ground state is so unlikely that other mechanisms such dissociative recombination of CO_2^+ (or other parent ion like HCO^+) or collisional excitation from the ground state of CO which would require high electron densities and temperatures, have to be considered.

Preliminary theoretical calculations on possible parent molecules of CO and production rates were presented by Cosmovici et al. (1982).

As we can see from Tables 5 and 6 and from comparison with Franck-Condon factors (McCallum et al., 1972) the identification of the Asundi band system can be deemed rather uncertain, but the number of coincidences is much larger in the case of the triplet system, and the presence of these emissions can be established much more convincingly (Cosmovici et al., 1982).

The fact that CO emission lines were not detected before even in brighter comets leads to the conclusion that the Asiago observations are related to an exceptional event as pointed out above. It is possible that during the outburst large amounts of CO or its parent molecule were released from inside the nucleus.

A support to this hypothesis by UV-observations (IUE satellite) is unfortunately not available. Thus only future high resolution observations of bright comets and cometary outbursts will be able to confirm the presence of visual emission of CO in cometary spectra.

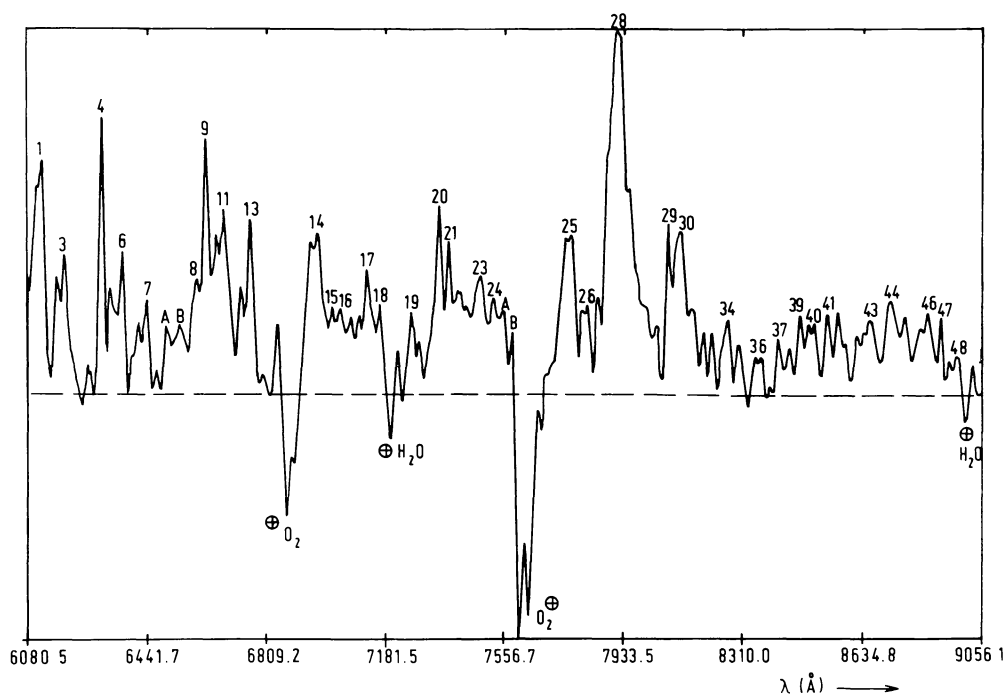


Fig. 3a. Reticon spectrum with 6 Å resolution taken on Jan. 15, 1981. The identification is given in Table 3. The dotted line represents the continuum obtained as described in the text. The absolute fluxes for the most interesting lines are given also in Table 3. The fluxes for the other lines can be easily drawn from the height above the continuum ($F \approx 9 \cdot 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1}$)

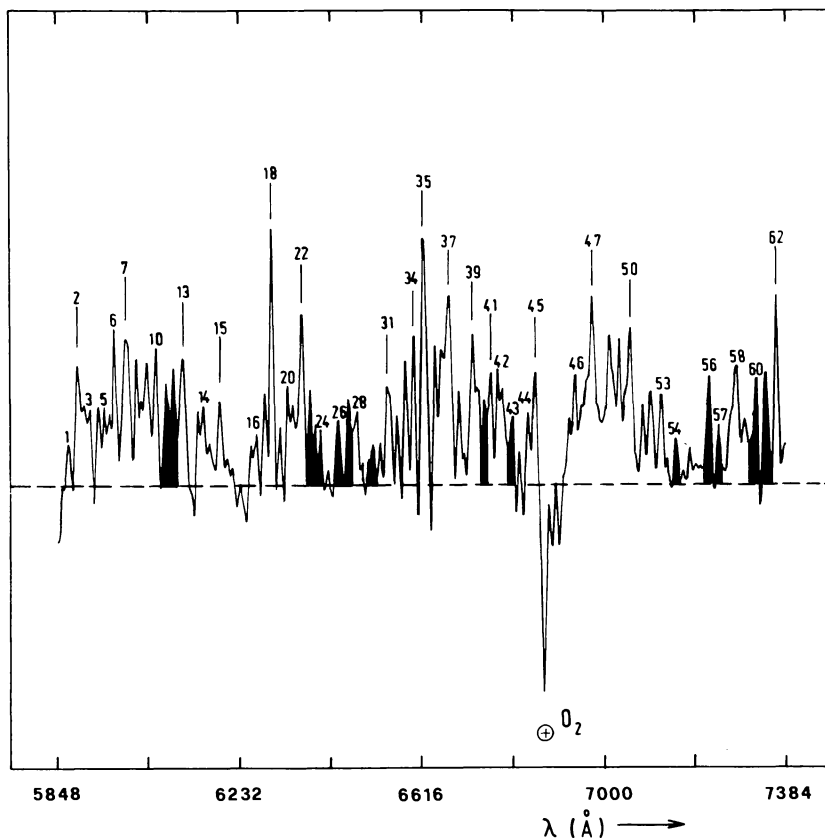


Fig. 3b. Reticon spectrum with 3 Å resolution. Identification and fluxes of the most relevant lines are given in Table 4. Black lines are CO features. Continuum as in a

C. Reticon Spectra

As already pointed out, the great advantage of using a Reticon system is the possibility of determining absolute fluxes of astrophysical lines.

We could identify in the two spectra of Fig. 3a and b, 86 lines (see Tables 3 and 4) and give their absolute fluxes. Danks and Dennefeld (1981) have also used a Reticon detector in the range 6100–11,000 Å for observations of Comet Bradfield 1979 I, but they omitted to measure absolute fluxes. Because of the lower magnitude of this comet, they could not either detect single molecular lines by using a higher resolution grating, despite an integration 15 times greater than ours.

The most important results from our spectra are the identification and the flux determination of the red H_2O^+ bands (9–0, 8–0, 7–0, 6–0, 5–0) up to 7468 Å, of cometary Na I, of CO up to 7229 Å and of the Phillips bands of C_2 .

Fifty H_2O^+ -lines from (10–0) to (5–0) were identified in Comet Kohoutek by Wehinger et al. (1974) on the basis of high resolution spectra and the (8–0), (7–0), (6–0) bands were also observed by Cosmovici and Ortolani (1980) in the plasma-poor Comet Bradfield 1979 I. The absolute fluxes and the relative intensity of the 14 H_2O^+ -lines observed in our Reticon spectra permit a first comparison in the near infrared with the strengths of other atomic and molecular species.

The UV-observations of Comet West 1975 n (Feldman and Brune, 1976) have shown that the CO production rate was about one third of the H_2O production rate.

The column density ratio $N(\text{H}_2\text{O}^+)/N(\text{CO}^+)$ which is very important for modeling purposes, was measured only in Comet Kohoutek (Wickoff and Wehinger, 1976).

A detailed study of the production rates on the basis of our fluxes is the object of a quantitative forthcoming paper.

H_α at 6563 Å cannot be separated from the H_2O^+ (7–0)-band (see Tables 2 and 4). But the contribution of H_2O^+ emission is probably much less than one-half of the measured H_α emission in the area of the cometary coma (Lanzerotti et al., 1976).

The identification of the Phillips system of C_2 which was rather difficult and uncertain in Comet Bradfield (1979 I) (Cosmovici and Ortolani, 1980), is somewhat better here, since emission features can be associated with five bands of this system.

These are rather weak, however, and it can be concluded that the intensity ratio Phillips/Swan is very small.

Theoretical calculations of the fluorescence of C_2 (A'Hearn, 1978, and references therein) imply that the (3–0)-sequence should have an intensity only 1/4 that of the (2–0)-sequence, whereas the here determined experimental values as well as the values shown in the spectrum of Danks and Dennefeld (1981) are comparable in the two sequences.

Also the spectrum shown by Cosmovici and Ortolani (1980) supports this experimental evidence.

The here derived ratio $R(3-1)/R(2-0) = 0.45 \pm 0.05$ of the red CN-lines is the same as for Comet Bradfield 1979 I (Danks and Dennefeld, 1981), but this ratio cannot be compared to previous determinations for Comet Kohoutek or West because of the much higher error given by the authors and determined with different experimental techniques. The ratio of the O I forbidden line at 6300 Å to the strongest CN-lines is in Comet Bradfield 1979 I (Danks and Dennefeld, 1981) about twice that in Bradfield 1980 t.

It is not clear why the 6364 O I-line is anomalously strong in our spectra in comparison to the blended 6300 O I

($I(6300)/(6364) \simeq 1.5$). In Comet Bradfield 1979 I this ratio was about 2.6 (Danks and Dennefeld, 1981; Cosmovici and Ortolani, 1980).

A possible contamination with CO (11–2) of the Asundi bands at 6367 Å should not be excluded since this line is as strong as the other Asundi lines detected (see Tables 3 and 6).

The permitted line at 8446.5 Å cannot be separated from the CN (4–2)-band at our resolution. Its flux was calculated to be 0.8 to 2.0 times the H_α -flux (Byard and Newsom, 1974), i.e. considering the computations of Lanzerotti et al. (1976), the 8446 Å O I-line would have a flux between 0.5 and $1.9 \cdot 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1}$ (the flux of the peak 38, Table 3 and Fig. 3a, at 8447 Å is $\sim (0.4 \pm 0.2) \cdot 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1}$). Thus, if these values are correct, its observation may be feasible with a Fabry-Pérot high-resolution spectrophotometer operating in this wavelength-range (Cosmovici et al., 1979).

In Table 7 our values for some molecules are compared with those obtained at other wavelengths. The CN-values in the 8500 Å range are about 12 times lower than the calculated ones, whereas our continuum is about 50 times weaker than a predicted dust continuum.

It should be pointed out that the laboratory molecular wavelengths given in the tables indicate sometimes a single rotational line which is the closest to the observed wavelength. The purpose was only to simplify the identification of the species. Of course, because of the low resolution, we are not able to discriminate between very close different rotational lines.

Above 7000 Å the spectrum is particularly complex since the molecular emissions, often relatively large, are the result of an agglomeration of several C_2 - and CN-groups.

In order to avoid misunderstanding it should also be pointed out that the C_2 -bands at $\lambda \leq 7800 \text{ Å}$ belong to the Swan- and those at $\lambda \geq 7800 \text{ Å}$ to the Phillips-system.

Table 3. Reticon-spectrum between 6080 and 9056 Å (resolution 6 Å) from Fig. 3a. Laboratory values as in Table 2

Line no (Fig. 3a)	λ (Å) $\pm 2 \text{ Å}$	Suggested identification	Laboratory λ (Å)	F ($\text{erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1}$) 10^{-3}
1	6116	C_2 (1–3) + NH_2 (0, 9, 0)	6122. + 6121.12	2.1
2	6161	H_2O^+ (0, 8, 0)	6158.64, 58.86	1.1
3	6186	C_2 (0–2) + CO^+ (0–2)	6191.3 + 6189.4	
4	6300	[O I] + NH_2 (0, 8, 0)	6300.0 + 6300.08, 00.79, 00.91	2.6
5	6330	NH_2 (0, 8, 0) + CN (5–1)	6334.51 + 6332.2	
6	6364	[O I] + CO (11–2)	6363.9 + 6366.9	1.3
7	6439	CO (3–0)	6433.1	
7A	6503	CN (6–2)	6502.4	
7B	6544	H_2O^+ (0, 7, 0)	6541.48, 41.85	
8	6596	H_2O^+ (0, 7, 0) + C_2 (3–6)	6595.05, 93.54 + 99.1	
9	6619	NH_2 (0, 7, 0)	6618–6620	2.4
11	6676	C_2 (2–5)	6675.9	
12	6730			
13	6760			
14	6970	H_2O^+ (0, 6, 0)	6970.14, 73.71	1.5
15	7017			
16	7040	H_2O^+ (0, 6, 0)	7040.65, 37.89	
17	7122			
18	7163	NH_2 ?	7163.8, 65.4, 66.2	
19	7262	CN (5–2) + CO (3–1)	7259.1 + (7270 $\pm$ 2)	
20	7349	NH_2 (0, 5, 0)	7350.0	1.8
21	7380	NH_2 (0, 5, 0)	7376.2 + 77.6, 78.3	
22	7415	NH_2 (0, 5, 0)	7414.9	
23	7480	CN (6–3)	7479.97 – 83.2	
24	7521	CN (6–3)	7518.64 – 21.55	
24A	7556	CN (6–3)	7552.79 – 7556.27	
24B	7586	CN (6–3)	7583.05 – 7590.77	
25	7763	C_2 (3–0) NH_2 (0, 4, 0)	7764.0	
26	7814		7767.4 – 7813.14	1.5
27	7852	CN (2–0) + C_2 (6–11) ?	7850.2 + 7852.5	
28	7904	CN (2–0) + C_2 (4–1)	7908.6 + 7907.7	3.3
29	8070	CN (3–1)	8067.1	1.6
30	8108	C_2 (5–2) } overlapped	8108.2	1.5
31	8146	C_2 (5–2)		
32	8182		8143.13 – 8210.0	
33	8205			
34	8259	CN (4–2) + NH_2 ?	8250 – 8270 + 8255 – 64	
35	8294	CN (4–2)	8294.8	
36	8353	CN (4–2)	8352.43 – 56.35	
37	8418	CN (4–2)	8414.23 – 8420.51	

Table 3 (continued)

Line no (Fig. 3a).	λ (Å) ± 2 Å	Suggested identification	Laboratory λ (Å)	F (erg cm ⁻² s ⁻¹ sterad ⁻¹) 10 ⁻³
38	8447	CN (4-2)+OI ?	8445.28 – 8454.15 + 8446.5	0.4
39	8483	CN (5-3)	8484.75	0.7
40	8518	CN (5-3)	8518.07 – 8520.69	
41	8571	CN (5-3)	8568.47 – 8572.14	
42	8604	CN (5-3)	8602.48 – 8605.67	
43	8707	CN (6-4)	8709.2	
44	8766	C ₂ (2-0)	8750 – 8780	0.9
45	8811	C ₂ (2-0)	8809.38 – 8930.18	
46	8886			
47	8929			
48	8979	C ₂ (3-1)	8980.5	

Table 4. Reticon-spectrum between 5850 and 7350 Å (resolution 3 Å) from Fig. 3b. Laboratory values as in Table 2

Line no. (Fig. 3b)	λ (Å) ± 2 Å	Suggested identification	λ (Laboratory)	F 10 ⁻³ (erg s ⁻¹ cm ⁻² sterad ⁻¹)
1	5871	H ₂ O ⁺ (0, 9, 0)	5871.01; 69.71	1.2
2	5891	Na I	5890 + 5896	
3	5916	H ₂ O ⁺ (0, 9, 0)	5917.29; 13.38	
4	5936			
5	5949			
6	5971			
7	5995	NH ₂ (0, 9, 0)	5994.95; 95.01	1.5
8	6015	CO (4-0) T + NH ₂ (0, 9, 0)	6010.5 + 6020	1.2
9	6038	CO (4-0) T + NH ₂ (0, 9, 0)	6037.0 + 6034	
10	6054			
11	6077	NH ₂ (0, 9, 0)	6077.32	
12	6098	NH ₂ (0, 9, 0)	6098.37	
13	6121	NH ₂ (0, 9, 0) + C ₂ (1-3)	6121.12 + 6122.1	
14	6158	H ₂ O ⁺ (0, 8, 0)	6158.64; 58.86	
15	6190	CO ⁺ (0-2) + C ₂ (0-2)	6189.4 + 6191.3	
16	6265			
17	6286	NH ₂ (0, 8, 0)	6286.14; 88.06; 88.76	2.6
18	6300	[OI] + NH ₂ (0, 8, 0)	6300.0 + 6300.08; 00.79; 00.91	
19	6318	CO (8-3) T	6319.8	
20	6334	NH ₂ (0, 8, 0) + CN (5-1)	6334.51 + 6332.2	
21	6345	NH ₂ (0, 8, 0)	6345.27; 45.43	
22	6364	[OI] + CO (11-2) A	6363.9 + 6366.9	1.7
23	6384	CO (8-3) T	6383.1	
24	6403	CO (3-0) T	6401.0	
25	6418			
26	6439	CO (3-0) T	6433.1	
27	6464	CO (3-0) T	6464.6	
28	6478	C ₂ (5-8) + CN (6-2) ?	6481.8 + 6478.4 ?	
29	6512	CO (9-1) A	6513.5	
30	6526	H ₂ O ⁺ (0, 7, 0)	6525.24; 24.92	
31	6541	H ₂ O ⁺ (0, 7, 0)	6541.48; 41.85	
32	6561	H ₂ O ⁺ (0, 7, 0)	6562.7	
33	6579	H ₂ O ⁺ (0, 7, 0)	6576.77; 77.26; 77.66	
34	6595	H ₂ O ⁺ (0, 7, 0) + C ₂ (3-6)	6595.05; 93.54 + 99.1	
35	6619	NH ₂ (0, 7, 0)	6618 – 6620	2.4
36	6643			
37	6671	H ₂ O ⁺ (0, 7, 0) + C ₂ (2-5)	6671.14; 71.38; 71.69 + 75.9	
38	6689	H ₂ O ⁺ (0, 7, 0)	6686.56; 85.51	

Table 4 (continued)

Line no. (Fig. 3b)	λ (Å) ± 2 Å	Suggested identification	λ (Laboratory)	$F 10^{-3}$ (erg s $^{-1}$ cm $^{-2}$ sterad $^{-1}$)
39	6718	H ₂ O ⁺ (0, 7, 0)	6715.49; 14.65	
40	6740			
41	6760			
42	6772			
43	6802	CO (10–2) A	6804.0	
44	6837			
45	6851			
46	6936			
47	6971	H ₂ O ⁺ (0, 6, 0)	6970.14; 73.71	1.9
48	7006	H ₂ O ⁺ (---)	7003.94	
49	7017			
50	7040	H ₂ O ⁺ (0, 6, 0)	7040.65; 37.89	
51	7070	H ₂ O ⁺ (0, 6, 0)	7069.5; 7041	
52	7084	C ₂ (6–10) + CN (4–1)	7083.2 + 7089.0	
53	7108	CN (4–1)	7107.0	
54	7136	CO (11–3) A	7134.0	
56	7208	CO (6–0) A + T (3–1)	7210.4 + (7200)	1.1
57	7228	CO (6–0) A + T (3–1)	7229.0 + 7231.3	
58	7265	CN (5–2) + T (3–1)	7259.1 + 7270 $\pm$ 2 Å	
59	7285	CN (5–2)	7289.0	
60	7310	CO (9–2) A	7314.0	
61	7334	CO (9–2) A	7337.0	
62	7350	NH ₂ (0, 5, 0)	7350.0	1.9

A = Asundi

T = Triplet

Table 5. Band heads of the $d^3\Delta \rightarrow a^3\Pi$ CO-Triplet system (Krupenie, 1966) and observed lines

λ (Å)	I	$v'-v''$	λ (Å) observed	Blended by
(7502.1)?			(7500)?	
7515	–	1–0		CN (6–3)
(7483)				CN (6–3)
7270			7265	
(7231.3)	–	3–1	(7228)	CO (6–0) Asundi
(7200)			(7208)	
6964.3				H ₂ O ⁺ (0, 6, 0)
6925.2	–	2–0		O ₂ Atm
6901				O ₂ Atm
6736			6740?	
6703	–	4–1		
6669			(6671)	NH ₂ (0, 7, 0) + C ₂ (2–5)
6464.6			6464	
6433.1	10	3–0	6439 ?	
6401.0			6403	
6383.1			6384	
6348.7	1	8–3		
6319.8			6318	
6037.0			6038	NH ₂
6010.5	8	4–0	6015 ?	NH ₂
5982			5984	
5670.5			5670	
5647.6	6	5–0		
5624				C ₂ (Swan)

Table 5 (continued)

λ (Å)	I	$v'-v''$	λ (Å) observed	Blended by
5554.1				(Swan)
5532.5	5	7–1		(Swan)
5508				(Swan)
5351.2			5340 ?	
5330.5	5	6–0	5328	NH ₂ (0, 12, 0)
5308			5301 ?	
5258.3			5250 ?	
5238.4	5	8–1	5237	
5216			5209 ?	
5070.9			5079 ?	C ₂ (Swan)
5052.7	8	7–0	5046 ?	(Swan)
5033				(Swan)
4996.9			4994	C ₂ (Swan)
4979.0	6	9–1		(Swan)
4959.0			4960	
4935.5			4938	NH ₂ (0, 13, 0)
4917.2	2	11–2		C ₂ (Swan)
4897.5			4900	(Swan)
4880.8			4883	C ₂ (Swan)
4869.3	–	13–3		
–				
4823.5			4822	
4806.7	8	8–0	4806	
4787			4790	

Table 5 (continued)

λ (Å)	I	$v'-v''$	λ (Å) observed	Blended by
4764.8	5	10-1	4766	C ₂ (Swan)
4747.5			4745	
4729.1				
4716.6	-	12-2		(Swan)
4702				(Swan)
4678				(Swan)
4680.3	-	14-3	4680	
4664			4662	
4646.7			4647	
4602.6	7	9-0	4604	
4586.4			4588	
4571			4573	
4556.5	5	11-1	4554	CO ⁺ (1-0)
4541.0			(4540)	
4524.0				
4520.7	-	13-2	(4518)	CO ⁺ (4-2)
4505.5			(4503)	
4488.4			4490	
4494.4	-	15-3	4499	CH (1-2)
4478.8			4477	
4462.9			4466	
4454.5	1	-	4456	H ₂ O ⁺ (0, 14, 0)
4445.5			4442	
4437			4436	

The wavelengths of the (4-1) band are not tabulated by Krupenie and were calculated on the basis of the given molecular constants

Table 6. Band heads of the $a'^3\Sigma^+ \rightarrow a^3\Pi$ CO-Asundi system (Krupenie, 1966) and observed lines

λ (Å)	I	$v'-v''$	λ (Å) observed	Blended by
8281.0	-	6-1		
-	-			
-	-			
8222.5	-	5-0		
7888.0	-			
-	-			
7833.9	-	7-1		CN (6-3)
7598.0	-			
7574	-			
7552.5	-	9-2		
7359.0	-			
7337	-		7334	
7314.0	-		7310	

Table 6 (continued)

λ (Å)	I	$v'-v''$	λ (Å) observed	Blended by
7257.0	-	6-0		CO (3-1) Triplet
-	-			
7229	-		(7228)	
7210.4	-		7208	
7158	-	11-3		
-	-			
7134	-		7136	
7116.5	-	8-1		H ₂ O ⁺ (-)
-	-			
7007	-		(7006)	
6988	-	10-2		
6841.5	-			
6820	-			
6804.0	-		6802	
6726.3	-	7-0		
6704	-			
6685.7	-		(6686)	
6551.0	-	9-1		H ₂ O ⁺ (0, 7, 0)
6530	-		(6531)	
6513.5	-		6512	
6445.3	-	16-5		
6405.0	-			
6397	-	11-2		
6366.9	-		(6364)	
6275.0	-	8-0		NH ₂ (0, 9, 0)
6257.8	6		(6258)	
6244.7	-			
6159.5	5	15-4		H ₂ O ⁺ (0, 8, 0)
6135.0	-			
6127.5	-			
6119.0	6	10-1	(6120)	C ₂ (1-3) + NH ₂ (0, 9, 0)
6105.2	-			

Table 6 (continued)

λ (Å)	I	$v'-v''$	λ (Å) observed	Blended by
5888.7	—	9–0	(5852)	NaI
—	—			
5876.2	5			H ₂ O ⁺ (0, 9, 0)
5869.4	—			
5855.8	—	16–4	(5816)	NH ₂ (0, 10, 0)
—	—			
5836.5	—			
—	5			
—	—	11–1	(5769)	H ₂ O ⁺ (0, 9, 0)
5812.8	—			
5779.6	—			
5773.5	—			
5769.7	5	5746	5746	Hg (NS)
5761	—			
5746.0	—			

Table 7. Typical flux values for representative cometary molecules

Molecule	λ (Å)	F (erg s ⁻¹ cm ⁻² sterad ⁻¹)
CN	3883	1.0 10 ⁻¹ – 6.0 10 ⁻³
C ₃	4057	1.4 10 ⁻² – 5.5 10 ⁻³
C ₂	4732	1.0 10 ⁻² – 8.0 10 ⁻³
C ₂	5165	1.2 10 ⁻¹ – 6.2 10 ⁻³
Continuum	5200	1.1 10 ⁻² – 3.2 10 ⁻³
C ₂	5634	1.8 10 ⁻² – 8.0 10 ⁻³
CN	8500–8700	8.2 10 ⁻³ – 5.5 10 ⁻⁵ (calculated ^a)
Dust	8500–8700	4.1 10 ⁻² (calculated ^a)
H ₂	8748	3.9 10 ⁻³ (calculated ^a)
<i>Our values</i>		
Continuum	8000–9000	8.5 10 ⁻⁴
C ₂	7767	1.5 10 ⁻³
CN	7909	3.4 10 ⁻³
CN	8067	1.6 10 ⁻³
C ₂	8108	1.5 10 ⁻³
CN	8483	0.7 10 ⁻³
C ₂	8750	0.9 10 ⁻³
CN	9198	11.5 10 ⁻³ [from the Danks and Dennefeld ratio (1–0)/ (2–0) = 3.38]

^a Michel et al. (1976)

Conclusions

The bright Comet Bradfield 1980 t has shown a very interesting and wide spectrum of atomic, molecular, and ionic species.

We were able to identify about 200 features, to give absolute fluxes for the lines present between 5850 and 9050 Å and to state the presence of new species.

At least 226 unidentified lines belong to neutral Carbon Monoxide. A first detection of H₂S⁺ was also considered.

The fact that CO emission lines were not detected before in the visible part of the spectrum leads to the conclusion that our observations are related to an exceptional outburst.

From the determined fluxes further theoretical studies on particular interesting species can be carried out.

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