THE SPECTRUM OF COMET BESTER (1947k)*

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ABSTRACT

An extensive program of observations, planned in advance, was carried out during the predicted return of Comet Bester in March and April, 1948, as the comet receded from heliocentric distance 0.8 A.U. to 1.55 A.U. The eighteen spectra obtained extend over various parts of the observable region from λ 3070 to λ 8760, most of them from λ 3500 to λ 6800 on grating dispersion. These, together with seventeen direct photographs, provide virtually a continuous record of changes in the comet during the observing period. Since the slit of the spectrograph was oriented along the tail, extending about 4.5 minutes of arc from the nucleus, our spectrograms record the extent of the various molecular bands away from the nucleus.

Based on this material and on observations of other comets, the following topics are discussed:

a) *Variations with heliocentric distance, r.*—In Comet Bester the ratios CN/C_2, λ 4050/CH, λ 4050/CN, λ 4050/C_2 and probably OH/NH all increase regularly with increasing r. No flares or sudden changes in spectrum were observed.

b) *Extent of bands from the nucleus.*—CO^+, N_2^+, λλ 3378, 3509, and 3674 are found exclusively in the tail; CN, C_2, NH, OH, λ 4050, and NH_2 follow in order of decreasing extent from the nucleus.

c) *The far ultraviolet region.*—The ratio OH/NH varies from comet to comet, being somewhat less than unity for Comet Bester, greater than unity for Comet 1941d, and much less for 1947n and 1941c, which are in other respects comparable. In Comet Bester the OH bands have a peculiar rotational distribution, probably due to the fluorescence mechanism.

d) *The photographic regions.*—Twenty lines in the "λ 4050 group" behave in Comet Bester as if they originate from one molecular species.

e) *The red and infrared regions.*—The existence of bands (tentatively identified with the "red system" of CN) at λ 7906 is confirmed, and other bands of the "red system" at shorter wave lengths tentatively identified. A number of other faint maxima between λ 7000 and λ 8700 are noted.

f) *The spectrum of the tail.*—Nine bands of the CO^+ "comet-tail system" are recorded, the (3, 0) band being abnormally strong. Four bands of the "Baldet-Johnson system" of CO^+ are observed. Tentative identifications of the "β system" of NO and the "Schumann-Runge system" of O_2 are noted. The strong emissions at λλ 3378, 3509, and 3674 are identified with CO_2^+, the third ionized molecule to be identified in comet tails.

A summary of identifications and conclusions is given at the end of the paper.

I. INTRODUCTION

When the determination of the orbit of Comet Bester (1947k) indicated that this object would become fairly bright and easily observable after its perihelion passage on February 16, 1948, we decided to plan carefully a program of spectroscopic observations, with the following three aims in view:[1] (*a*) to obtain slit spectrograms of the tail, especially in the ultraviolet region; (*b*) to obtain spectrograms of the head throughout the region from λ 3000 to λ 9000, in sufficient numbers to permit a study of the variations with heliocentric distance; and (*c*) to compare these spectra with those of other comets, especially those observed before perihelion passage.

Very little information is available on the ultraviolet spectrum of comet tails. As far as we know, ultraviolet tail spectra have been obtained only with slitless instruments—e.g., for the following comets: 1907d (Daniel) by J. Evershed,[2] to λ 3580; 1908c (Morehouse) by De la Baume Pluvinel and Baldet,[3] to λ 3269; 1911c (Brooks) by the same

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[1] As this paper goes to press we have received Fehrenbach and Cortès, *Ann. d'ap.*, **12**, 66, 1949, containing a discussion of the spectra of Comets 1947k and 1948g, which, however, duplicates nothing here.

[2] *M.N.*, **68**, 16, 1907.

[3] *C.R.*, **154**, 1286, 1912; Baldet, thesis, p. 36.

observers,[4] to λ 3790; and Halley by Slipher and Lampland,[5] to λ 3585. The only slit spectrograms of comet tails known to us have been taken at the Lick Observatory of 1908c (Morehouse)[6] and of 1911c (Brooks),[7] covering the region from λ 3850 to λ 4800. One fair slit spectrogram of the tail of Comet 1940c (Cunningham) was obtained at the McDonald Observatory but was rather weak. The results of its examination will appear shortly.[8]

Ultraviolet slit spectrograms of comet tails not only may reveal new molecules existing in the tail but may also yield profiles of the known molecular bands, and hence the rotational temperatures of the corresponding molecules. Our understanding of the physical mechanisms at play in comet tails is still so rudimentary that any addition in observational evidence is of importance. It is obvious that only molecules with a very long life can be found in the tails at large distances from the nucleus. There are few molecules known which would be able to live for days or weeks in the field of solar radiation before becoming photo-dissociated or photo-ionized. Actually, new bands found in comet tails may lead physicists to the discovery of "photo-resistant" molecules, in the same way that astronomical observations of CH^+ and CH_2 bands preceded and inspired considerable laboratory work.

While a great deal of qualitative observational information has already been gathered on the heliocentric-distance variations of the absolute and relative intensities of the different bands in comet spectra, there still remains a number of questionable points in the mere description of these phenomena. For example, K. Wurm, in his excellent review of cometary problems,[9] assumes that the ratio CN/C_2 increases as the heliocentric distance, r, decreases, which he bases on Baldet's observations[10] of Comet Brooks (1911c) from $r = 1.42$ to $r = 0.5$, and on van Schewick's[11] photometric investigation of Comet Finsler (1937f). Observations of comets at the McDonald Observatory do not confirm this statement, especially in the case of Comet 1948l.[12] Similarly, Wurm's statements on the behavior of the ratio CH/λ 4050, based mainly on old observations of Comet Brooks, are not confirmed by the recent investigation of Comet 1948l.[12] Such information is required for confirmation of Wurm's theory of "dissociation series."[9]

Within the temporary gaseous atmosphere surrounding the nucleus of a comet and extending into its tail, our usual thermodynamical concepts of temperature and pressure become meaningless. There can be practically no collisional effects, and the problem becomes one of pure photochemistry. If the emission of gas from the nucleus were suddenly interrupted, for instance, the intensity of the CN and C_2 bands would certainly decline and vanish in a few days, the CO^+ bands of the tail after a few weeks. Wurm's theoretical procedure for studying molecular abundances in comets is similar to that followed in discussing a series of radioactive disintegrations. For detailed confirmation of this theory, a longer series of spectra is required than is provided in this paper and more quantitative intensity data than are given here.

Spectroscopic comparisons between different comets, and especially between comets observed before and after perihelion passage, are of great value. As far as we know, no single comet has been described spectroscopically before and after perihelion passage, be-

[4] *C.R.*, **147**, 666, 1908, and **148**, 759, 1909; *Ap. J.*, **34**, 89, 1911; Baldet, thesis, p. 24.

[5] *Lowell Obs. Bull.*, **2**, 3, 1911.

[6] Campbell and Albrecht, *Lick Obs. Bull.*, **5**, 58, 1908; H. D. Curtis, *Lick Obs. Bull.*, **5**, 135, 1909.

[7] W. H. Wright, *Lick Obs. Bull.*, **7**, 8, 1912.

[8] P. Swings and H. Sauvenier, *Bull. Acad. R. Belgium*, **35**, 931, 1949.

[9] *Mitt. Hamburger Sternw.*, **8**, 51, 1943.

[10] Thesis, p. 44.

[11] *Zs. f. Ap.*, **21**, 142, 1942.

[12] P. D. Jose and P. Swings, *Ap. J.*, **111**, 41, 1950.

tween which epochs significant differences are expected in the relative intensities of different bands. M. G. J. Minnaert[13] has treated theoretically the superficial temperature of a sphere with a diameter of 1 km, following the orbit of Halley's comet. In the case of both a stone and an iron nucleus he found that the surface temperature after perihelion passage should for a long time remain higher than before passage. In a recent unpublished investigation, E. Lebon[14] has applied Minnaert's idea to the short-period Comet Encke, with results very similar to those of Minnaert for Comet Halley.

We therefore expect differences in the relative intensities of cometary bands at a given heliocentric distance, before and after perihelion, due to differences in the surface temperature of the nucleus. Other factors, such as the finite life of the molecules, exhaustion of gases, rotation and irregularities of the solids, etc., may further affect these relative band intensities.

Pending spectroscopic observations of the same comet before and after perihelion passage, the best we can do at present is to compare different comets at the same heliocentric distance, some before passage, others after, as in Section III, below. Comparisons between different comets may also help to clarify our ideas regarding the nature, sizes, and distributions of solid particles in the nuclei and the way gases are absorbed and liberated.

The remainder of this paper is divided into seven sections. Each of Sections III–VII presents a pertinent part of the observational results, together with discussion and conclusions. Section VIII is a summary of conclusions.

II. THE OBSERVATIONAL MATERIAL

Comet Bester (1947k) passed perihelion on February 16.433, 1948, the perihelion distance being $q = 0.748$. All our observations were made (by Page) after perihelion. During the observing period the radial velocity of the comet relative to the sun, dr/dt, varied from 17.4 km/sec on March 3 to 24.2 on April 13.[15] The absolute magnitude has been determined by J. Bouška and V. Vanýsek and by P. Ahnert.[16] The value after perihelion was $m_0 = 6.6$, practically the same as that of the two bright comets 1947n ($m_0 = 6.2$) and 1948l ($m_0 = 5.9$). However, these latter two objects had much smaller perihelion distances, which accounts for their temporarily higher brightness than 1947k. Comet Bester definitely has a higher absolute magnitude than Comet Encke ($m_0 = 10.3$ in 1947).

A total of 18 spectra and 17 photographs of Comet Bester was obtained with the 82-inch reflector of the McDonald Observatory, as listed in Table 1.[17] Fourteen of the spectra were obtained at the prime focus with the B spectrograph, a grating instrument with an $f/0.65$ solid Schmidt camera of UV glass,[18] and dispersion about 330 A/mm. The unique characteristics of this instrument made large parts of the present investigation possible. Its unocculted slit length corresponds to about 5 minutes of arc. The telescope was guided with the nucleus at one end of the slit, and the slit was oriented along the tail. The photographs, also taken at the prime focus of the 82-inch telescope, were made primarily to check the direction of the comet tail, which was thin and filamentary during most of the observing period (see Fig. 1). The only practical method of avoiding a

[13] *Proc. Amsterdam*, **50**, 826, 1947.

[14] Thesis, Liége, 1949.

[15] Kindly provided by Dr. L. E. Cunningham in a private communication.

[16] *Bull. Astr. Inst. Czechoslovakia*, **1**, 62, 1949; *A.N.*, **277**, 135, 1949.

[17] A preliminary report of these observations was made to the A.A.S. by Page, *Pub. A.S.P.*, **60**, 249, 1948.

[18] A more complete description of this instrument will soon be published; see also Page, *A.J.*, **54**, 47, 1948.

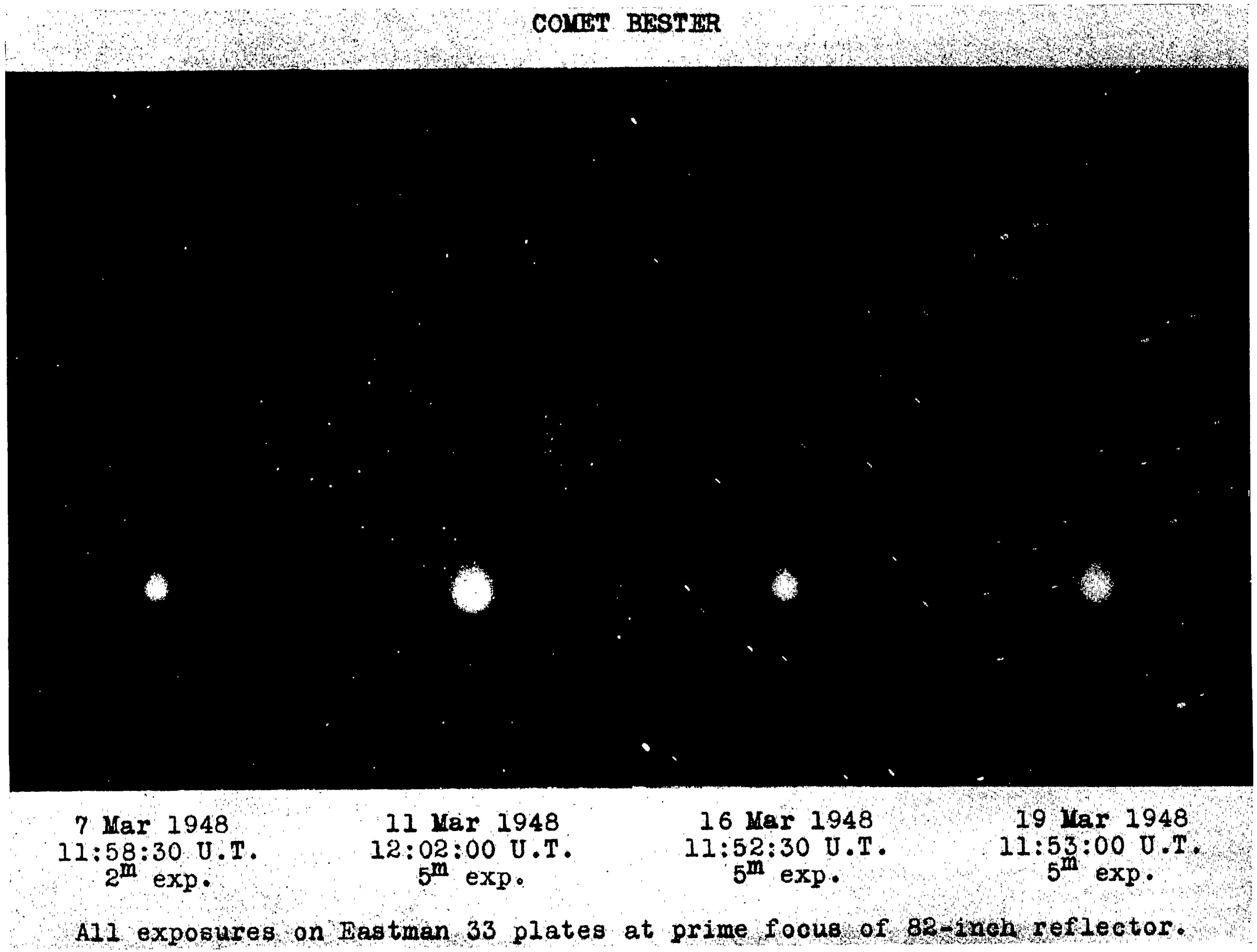

FIG. 1.—Four exposures on Eastman 33 plates at the prime focus of the 82-inch reflector, showing the faint, filamentary, and changing tail of Comet Bester (1947k). Scale of reproduction: 1 mm = 30″.

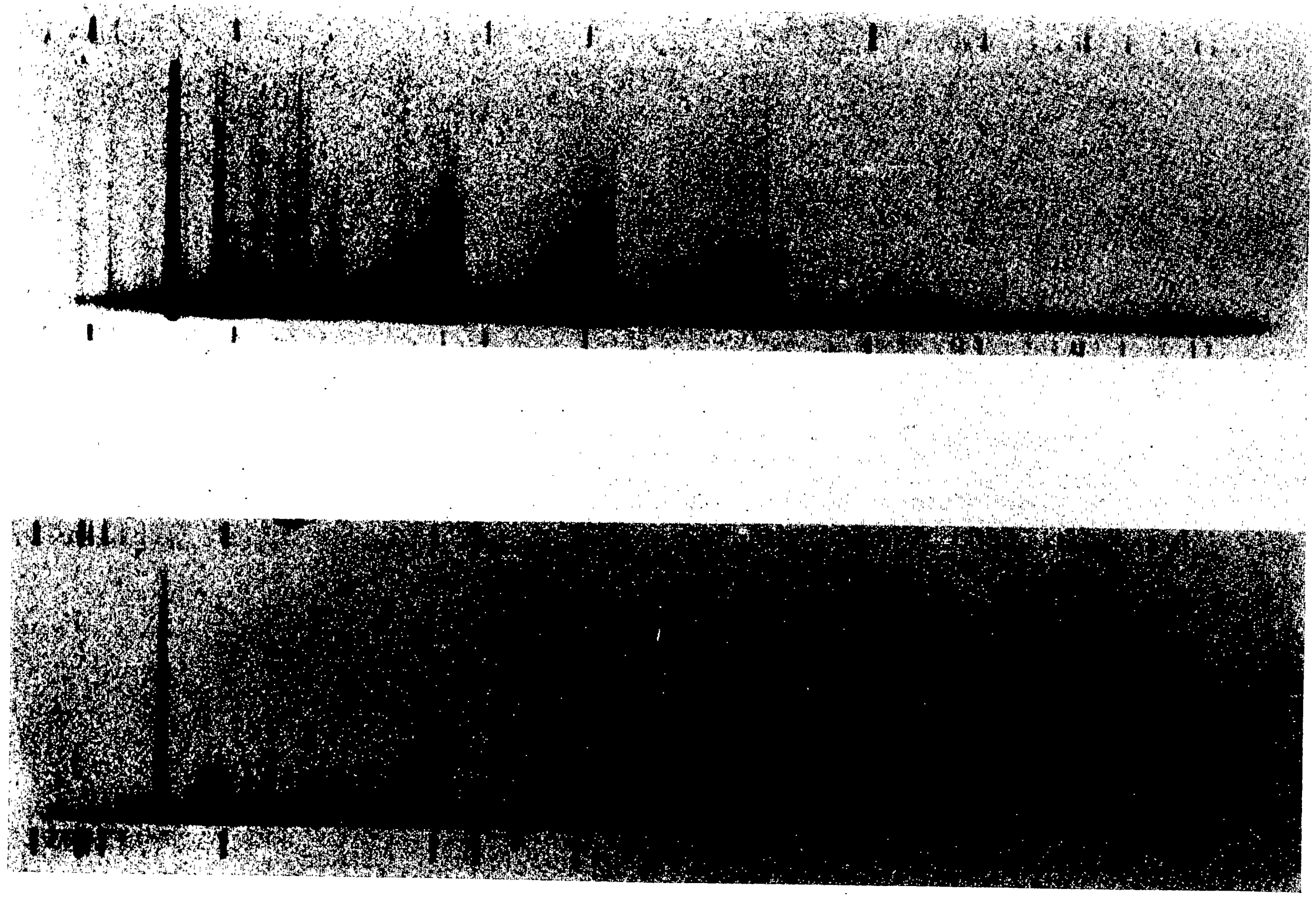

FIG. 2.—Two enlarged spectra of Comet Bester with approximately linear dispersion from λ 3650 to λ 6900 on Eastman 103*a*-F*. The nucleus is near the lower comparison spectrum; the slit is oriented along the tail, with a length corresponding to 280″ in the sky. Upper spectrum (B 133, exp. 50 min.) was taken at $r = 0.86$ A.U.; the lower (B 206, exp. 2 hr.) at $r = 1.30$ A.U. The comparison spectrum is from a cadmium-solder spark and a neon tube.

trailed image of the comet was to set the variable-rate telescope drive and the declination drive for proper guiding beforehand and then to make the exposures without guiding. This pre-setting was generally accomplished during exposures on the spectra, the direct photograph being made immediately thereafter.

For the infrared spectra,[19] a narrow strip of Wratten "*a*" gelatin filter covered a portion of the B spectrograph slit, to eliminate the blue and ultraviolet second-order spectrum. The nucleus of the comet was guided on the edge of this filter, so that the resulting spectrogram shows pure infrared spectrum in the filtered part and the second-order spectrum superimposed on the unfiltered part. The second order of *CN* λ 3883 served as

TABLE 1

COMET BESTER (1947k), ALL PLATES AND FILMS

PLATE OR FILM NO.	1948 DATE U.T.	EXP. (MIN.)	EMULSION	MID-ALT.	SLIT			REGION λλ	*r* (A.U.)	REMARKS
					w (Mm.)	*l* ("Arc)	p.a.			
	Mar.									
B 99	2.51	20	103*a*-F	15°	0.40	290	58°	3500–6500	0.80	Poor focus
B 103	3.49	50	103*a*-F*	10½	.20	103	60	3600–6700	0.81	Excellent def.
PFC 1874	4.50	1	103*a*-F	16½	......	......	.....	(Tail 150″)	0.82	Fair def.
B 115	6.49	30	103*a*-F*	16	.10	290	247	3600–5500	0.83	Good line extension
PFC 1875	6.51	1	103*a*-F	21½	......	......	.....	....	0.83	Trailed
PFC 1876	6.51	1	E 33	22	......	......	.....	(Tail 125″)	0.83	Poor def.
B 121	7.48	30	103*a*-F*	14	.20	290	270	3500–6700	0.84	Fair def.
PFC 1877	7.50	2	E 33	20	......	......	.....	(Tail 640″)	0.84	Fair
B 133	9.48	50	103*a*-F*	17½	.20	290	273	3500–6700	0.86	Excellent def.
PFC 1880	9.50	2	E 33	25	......	......	.....	....	0.86	Trailed
B 136	11.47	45	103*a*-F*	20	.20	290	267	3450–6700	0.88	Good def.
PFC 1884	11.50	2	E 33	27	......	......	.....	(Tail 640″)	0.88	Excellent def.
PFC 1885	11.50	5	E 33	28	......	......	.....	(Tail 2000″)	0.88	Excellent def.
B 151	13.47	75	I-N*	22	.50	290	267	(Nothing)	0.90	*a* filter
B 161	14.48	(45–15)	103*a*-F*	25	.20	290	265	3650–5000	0.92	Weak (clouds)
B 163	15.46	120	I-N*	21	.50	100	270	5800–8800	0.93	*a* filter on ½ of image
B 165	16.45	120	I-N*	21	.50	100	270	5800–8800	0.94	
PFC 1887	16.49	5	E 33	33½	......	......	.....	(Tail 1000″)	0.94	Trailed
PFC 1889	17.49	1.3	E 33	33½	......	......	.....	(Tail 50″)	0.95	Fair def.
B 190	18.46	90	103*a*-O†	29½	.20	290	275	3400–5000	0.96	Excellent def.
PFC 1890	18.50	3	E 33	38½	......	......	.....	(Tail 640″)	0.96	Fair def.
PFC 1891	18.50	1	E 33	39	......	......	.....	(No tail)	0.96	
B 192	19.45	90	103*a*-O†	27	.16	290	270	3400–4400	0.97	Good def.
PFC 1892	19.49	6	E 33	39	......	......	.....	(Tail 460″)	0.97	Good def.
Qf/1 10477	25.42	195	103*a*-O†	31	.013	44	270	3000–3700	1.04	Far UV good
Gf/1 10486	26.45	125	103*a*-O†	41	.013	44	270	3800–5000	1.06	Fair def.
	Apr.									
Gf/1 10559	3.47	45	103*a*-F*	63	.013	44	270	3800–5700	1.16	Excellent def.
B 199	11.46	60	103*a*-F*	59	.20	290	180	3600–6700	1.27	Good def.
PFC 1893	11.49	6	E 33	60	......	......	.....	....	1.27	Poor
B 206	13.41	(120)	103*a*-F*	53	.20	290	296	3460–5600	1.30	(Clouds)
PFC 1894	13.47	5	E 40	56	......	......	.....	....	1.30	Trailed
PFC 1895	13.47	1.1	E 40	56	......	......	.....	....	1.30	Trailed
PFC 1896	14.48	2	E 40	53	......	......	.....	....	1.31	Trailed
PFC 1897	14.48	5	E 40	53	......	......	.....	....	1.31	Trailed
Qf/1 10838	May 1	106	103*a*-F	....	0.013	25	270	3800–6700	1.55	Good def.

* Ammonia hypersensitized.

† Films baked to increase sensitivity.

[19] Obtained as for Comet 1947n. See Swings and Page, *Ap. J.*, **108**, 526, 1948.

a useful wave-length check. The two 2-hour infrared exposures on Eastman I-N* (hypersensitized) film with wide (33 A) slit represent about the limit of detection in the near infrared. The apparition of a brighter comet seems to be the only hope at present for improving these observational results.

Although the films were hypersensitized and pressed against the oiled surface of the solid Schmidt camera, they were all handled as for accurate photographic photometry; calibrating spots were impressed on another part of the same hypersensitized sheet of film, and characteristic curves were derived therefrom. No standardization was attempted. In the ultraviolet and visual regions, band intensities were largely estimated by eye in the eyepiece of the measuring engine. However, microphotometer tracings were made of twelve spectra, and rough intensities were reduced without regard for variation in emulsion sensitivity with wave length. Such "intensity-curves," reduced from tracings of the two infrared spectra, B 163 and B 165, are shown in Figure 3, compared with curves obtained in the same manner for the spectrum of a *CN* discharge tube and the night sky.[20]

Two spectra were obtained with the Cassegrain spectrograph,[21] using the *f*/1 (80-mm) Schmidt camera with dispersion 105 A/mm at λ 4000. Another was made with all-quartz optics, dispersion about 125 A/mm at λ 3300, transmitting to λ 3070. Because of the larger scale at the Cassegrain focus, only a 40″ extent from the nucleus along the comet's tail could be focused on the slit for these three spectrograms.

Thirteen of the spectra were measured carefully for as accurate wave lengths as the small dispersions would allow. Each spectrum was measured twice (by Page), and corrections were made for curvature of the slit image. In some cases independent measures were made by Swings.

In most parts of the observed wave-length region, lines or band heads were measured on two or more spectra. Intercomparison of these independent measures resulted in the elimination of spurious lines, a final "adopted" wave length for each accepted line, and an estimate of the error in wave length, which is about ±2 A. A third characteristic of each line, in addition to wave length and intensity, is its extent from the nucleus, which could be readily measured on these spectra, and was of value in this procedure.

III. VARIATION OF THE MOLECULAR EMISSIONS WITH HELIOCENTRIC DISTANCE

Our series of spectrograms from $r = 0.80$ to $r = 1.55$ reveals a number of conspicuous intensity variations. It is well known that local transitory features in comet heads may have spectra which differ from those of other regions, such differences presumably being due to differences in the size or constitution of solids in the head, and to their motions. However, in the present series there is virtual continuity in the variations of the relative intensities, and it is reasonable to assume that local spectral irregularities and bursts do not play a significant role in the general evolution observed.

There follow short, general descriptions of the best spectrograms:

r = 0.80 and 0.81.—*CN* is much longer than C_2; in the central part of the head, (0, 0) of *CN* has about the same intensity as (0, 0) of C_2; λ 4050 has about the same intensity as (0, 1) of *CN* and (2, 0) of C_2 but is much shorter; λ 4050 is a little stronger than the strongest *CH* line; the strongest NH_2 is conspicuous but very short.

r = 0.83.—*CN* is very much longer than C_2: for example, (0, 1) of *CN*, which is weaker than (1, 0) of C_2 in the nucleus, extends farther out into the head; λ 4050 is definitely more intense than the strongest *CH* but extends similarly in the head; NH_2 is extremely short.

[20] By the courtesy of Dr. J. G. Phillips, who had constructed the *CN* discharge tube at the Yerkes Observatory, and Dr. A. B. Meinel, who made available a tracing of the night-sky spectrum before publication.

[21] Fully described by G. W. Moffitt, *Contr. McDonald Obs.*, No. 1, p. 74, 1936.

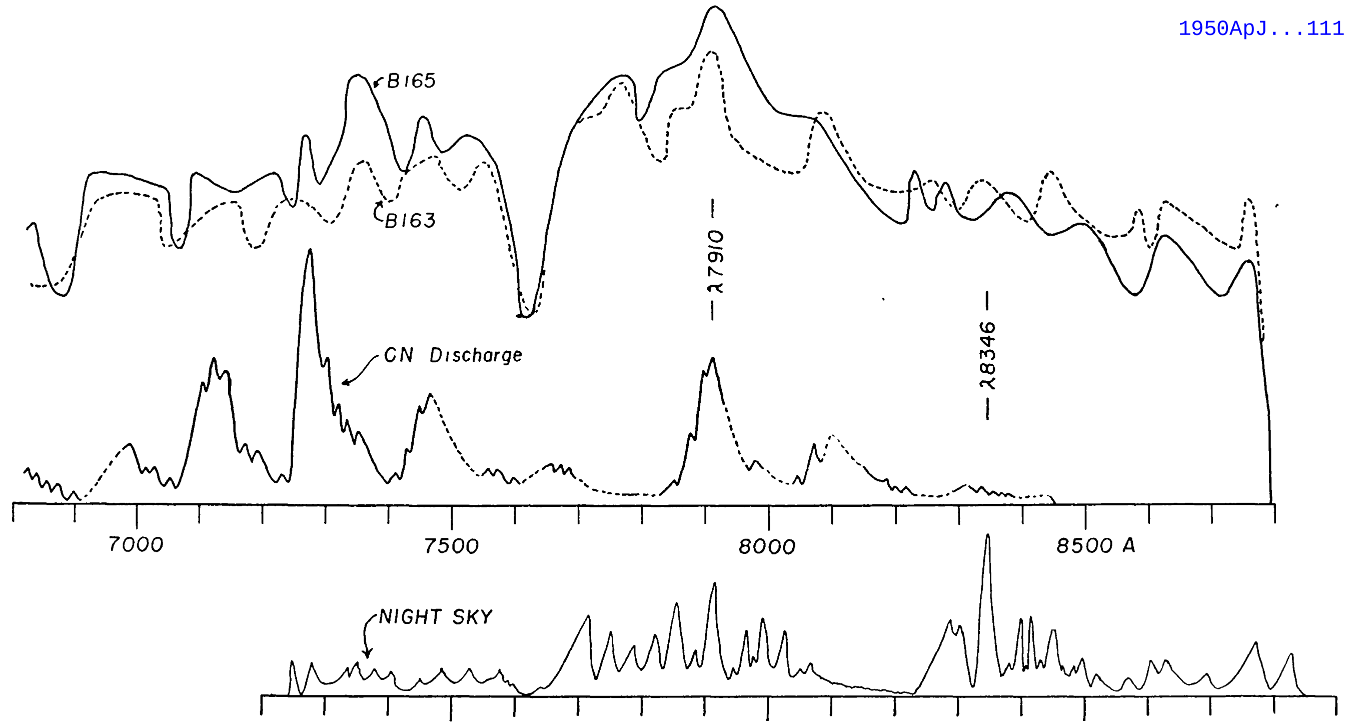

FIG. 3.—Unstandardized "intensity-curves" in the infrared spectrum. Comet Bester (films B 163 and B 165) compared with a *CN* discharge and with the spectrum of the night sky.

r = *0.84 and 0.86.*—Same as for r = 0.83 in the head; NH_2 is conspicuously strong and short (see Fig. 2).

r = *0.88.*—λ 4050 is appreciably stronger than CH; the tail spectrum in the ultraviolet has an appearance quite different from the blue-violet region.

r = *0.92.*—λ 4050 is much stronger than CH; NH_2, CH, and λ 4050 have the same extension in the head; CN is much longer than C_2.

r = *0.96* and *0.97.*—Strong tail bands; λ 4050 is much stronger than CH (see Fig. 5).

r = *1.04.*—The only spectrogram extending to λ 3070. The OH lines extend to shorter distances from the nucleus than NH lines of the same intensity (see Fig. 4).

r = *1.06.*—λ 4050 is very much stronger than CH; CN is stronger relative to C_2 than at r = 0.80.

r = *1.16.*—λ 4050 is much stronger relative to CN, C_2, and especially CH, than at r = 0.83.

r = *1.27.*—The ratio CN/C_2 has increased with r; the ratios λ $4050/CN$, λ $4050/C_2$, and λ $4050/CH$ are still larger than at r = 1.16.

r = *1.30.*—The same evolution continues; NH_2 is still conspicuous but very short; CN is of tremendous length (see Fig. 2).

r = *1.55.*—C_2 has almost disappeared; CH is very weak; CN is long and strong; λ 4050 has the same intensity as (0, 0) of CN in the nucleus, but is extremely short.

Summarizing these observations, as far as they concern the head, we may state:[17] (*a*) The intensity ratios CN/C_2, λ $4050/CH$, λ $4050/CN$, and λ $4050/C_2$ increase regularly with increasing r. (*b*) The bands of CN always extend farther from the nucleus than do those of C_2. (*c*) The lines of NH_2 and of the λ 4050 group are always very short.

Certain of these observed molecules may result from the same parent (e.g., C_2 and CN); others may give rise to another observed radical by photo-dissociation or photo-ionization (e.g., NH_2 to NH, CH to CH^+). The behavior of the intensity ratios of such molecules with heliocentric distance will eventually find interpretation in Wurm's series of photo-dissociations. The theory of such dissociation series is still very limited,[22] owing to lack of knowledge both of the "parent"-molecules and also of the "descendants." For example, we do not know what the immediate parent of the CH radical is, nor are we sure of the relative importance of the photo-dissociation and photo-ionization processes on CH—whether CH gives rise mostly to $C + H$ or to CH^+. Part of our ignorance of the descendants results from lack of information on the intensity of solar radiation in the far ultraviolet. Moreover, the identification of the λ 4050 group is still in doubt; recent laboratory work in Liége, especially by Monfils and Rosen,[23] casts grave doubts on its identification with CH_2.

The variation of absolute intensity of a molecular band as a function of r is connected with the rate of liberation of the parent-molecule at different surface temperatures of solid bodies in the nucleus. This rate itself will depend upon r; will be different for different molecules; and will be influenced by the sizes, shapes, rotations, and relative locations of the solids making up the nucleus. A small pebble will be warmed up more than a big rock; a metallic body will behave differently from a stone; a rotating body will be affected by the solar radiation differently from one always facing the sun; some of the bodies may be shielded from the sun by others. Sudden or irregular spectroscopic variations are presumably due to such interactions between the bodies—for example, to a change in shielding caused by motions.

The qualitative interpretation of the molecular extensions into the head can be under-

[22] R. Collet (thesis, Liége, 1949, unpublished) has tried the following dissociation series: $CH_4 \rightarrow CH_2 + H + H \rightarrow CH + H + (H + H) \rightarrow C + H + H + (H + H)$; $CH_4 \rightarrow CH_2 + H_2 \rightarrow CH + H + H_2$; and $H_2O \rightarrow OH + H \rightarrow O + H + H$. Although most of the physical constants involved are unreliable, the results seem encouraging. In the case of CH and OH, ionization should be included, since CH^+ is observed, and probably also OH^+.

[23] *Nature*, **164**, 713, 1949.

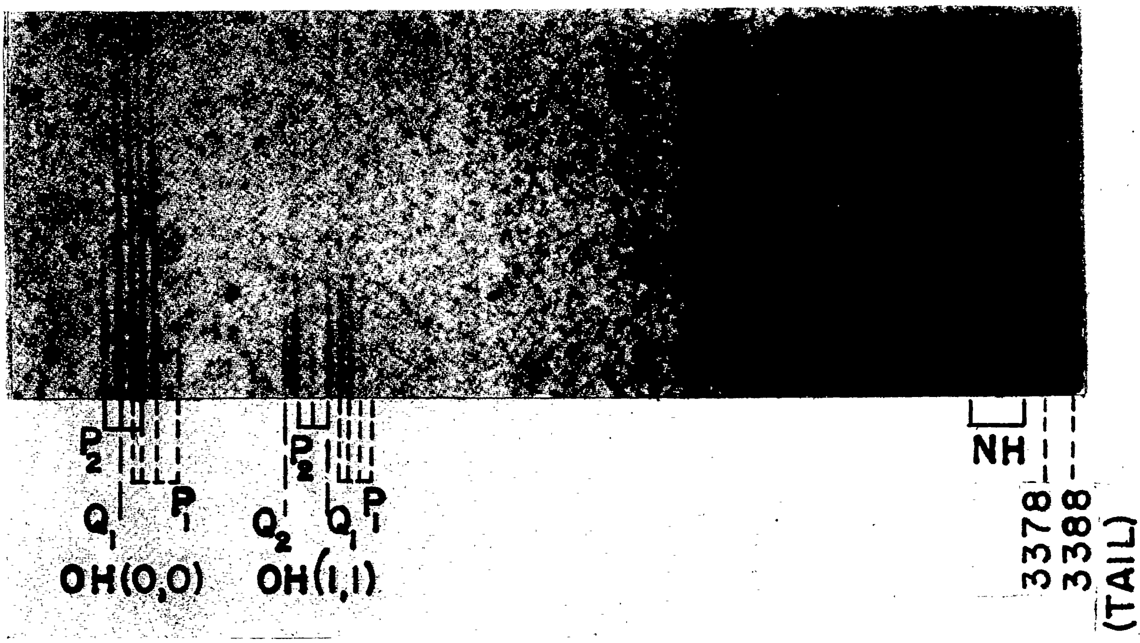

FIG. 4.—Enlargement of the far ultraviolet spectrum of Comet Bester at r = 1.04 A.U. (Qf/1 10477, quartz-prism dispersion on Eastman 103a–O), showing bands of *OH* and *NH*. The nucleus appears near the bottom. The length of the slit corresponds to 40″ in the sky.

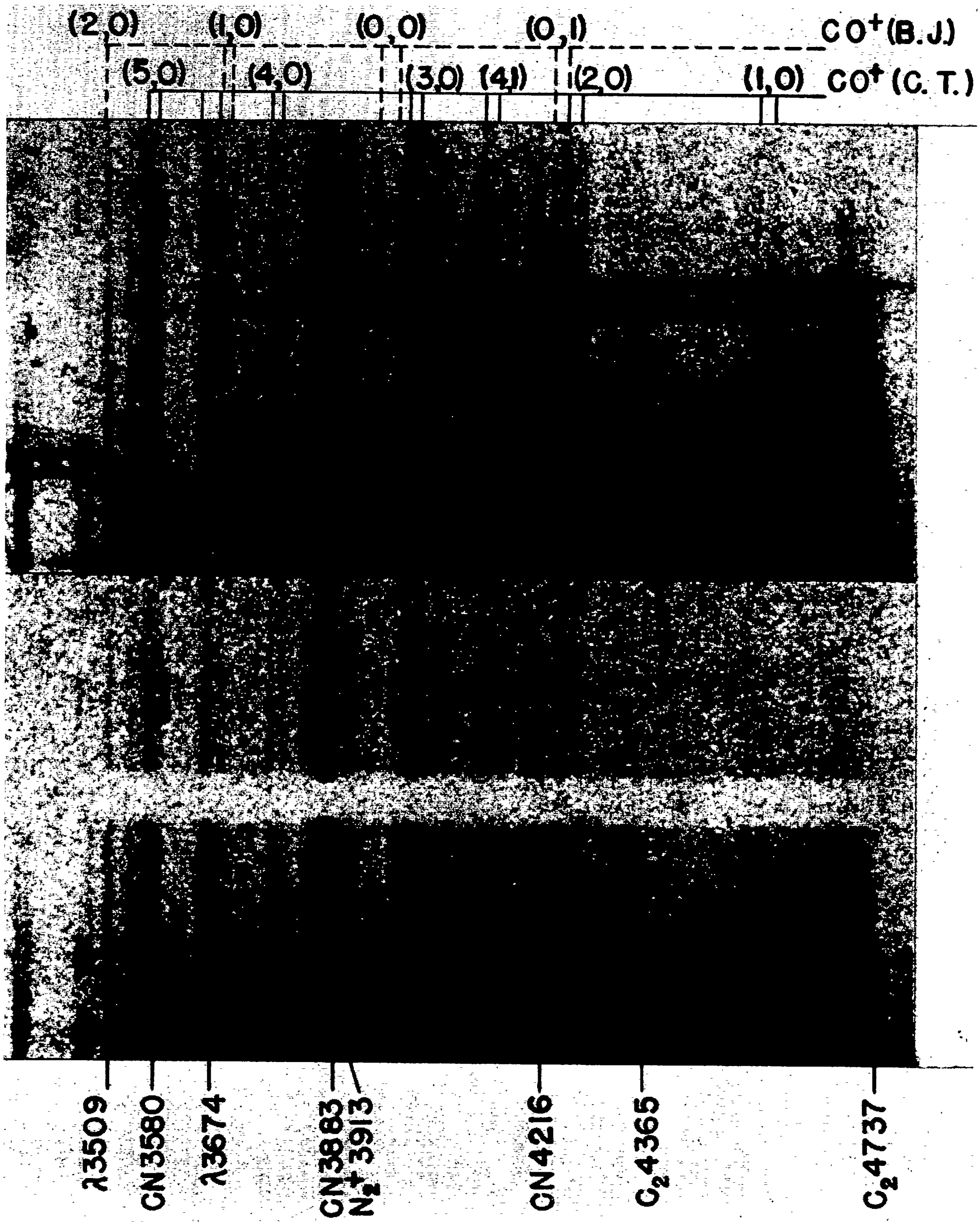

FIG. 5.—The ultraviolet tail spectrum of Comet Bester enlarged from films B 190 and B 193 (linear dispersion, λλ 3650–4800), taken at $r = 0.96$ A.U. (*upper*) and $r = 0.97$ A.U. (*lower*).

stood in terms of the average duration of a molecule and in terms of the velocity it acquires in the photo-dissociation of its parent-molecule. No detailed, numerical discussion will be possible until we know these parent-molecules and the velocities acquired by the observed radicals. We can only say from our observations that the product of average life by mean photo-dissociation velocity must be larger for *CN* than for C_2 and very much larger for *CN* than for *CH*, NH_2, and the molecule responsible for the λ 4050 group. Even this statement may require modification, owing to the distribution of solids in the comet head, a factor which has been considered in an attempt to explain apparently discordant results on the extensions of *OH* and *NH* in different comets.[24]

IV. THE SPECTRUM OF THE HEAD IN THE ULTRAVIOLET

The bands usually observed in the ultraviolet region are the following: (0, 0) and (1, 1) of *OH* at λ 3090 and λ 3135; (0, 0) of *NH* at λ 3350; (1, 0) of *CN* at λ 3590; and possibly (0, 0) of OH^+ at λ 3565. As shown in Figure 4, the *OH* emission appears strongly on the spectrogram obtained at $r = 1.04$, and the structure of the two *OH* bands deserves careful scrutiny.

The (0, 0) band of the $^2\Sigma^+ \rightarrow {}^2\Pi_{inv}$ *system of OH.*—This band reveals a rotational intensity distribution which differs appreciably from previous observations. Table 2 summarizes the wave lengths observed in Comets 1947k (Bester), 1940c (Cunningham), 1941d (Van Gent), and 1942a (Whipple-Bernasconi-Kulin). For Comet Bester the maximum of the P_2 branch is roughly at $J' = 2\frac{1}{2}$ or $K' = 2$; and P_2 ($5\frac{1}{2}$) at λ 3102.10 is probably not present. The maximum of the P_1 branch is at $J' = 1\frac{1}{2}$ or $K' = 2$, and the faintness of P_1 ($4\frac{1}{2}$) relative to P_1 ($5\frac{1}{2}$) can be explained only by assuming that the level $J' = 3\frac{1}{2}$ is underpopulated because of strong solar absorptions at the exciting wave lengths leading to $J' = 3\frac{1}{2}$, account being taken of the radial velocity, *dr/dt*. The Q_1 branch is blended with P_2 ($3\frac{1}{2}$) but definitely contributes to the emission at λ 3090.3,

TABLE 2

(0, 0) BAND OF *OH* IN COMET 1947k AND IN PREVIOUSLY OBSERVED COMETS*

Comet..	1947k		1940c		1941d		1942a		LABORATORY WAVE LENGTHS AND INTENSITIES†			
r......	1.04		1.0		1.25–1.51		1.75 A.U.					
dr/dt....	+22.2		−34.6		−21.8		−14 KM/SEC					
	Int.	λ	Int.	λ	Int.	λ	Int.	λ	λ	G. H.	R	Notation‡
	....	....	2	78.5	1.0	79.0	1–0	78.7	78.43	3	10	$Q_2(1\frac{1}{2})$
	1	3081.5	1	81.6	3	81.7	4	81.9	81.64	2	10	$P_2(1\frac{1}{2})$
	3	3086.3	2	86.3	......	......	1	86.3	86.38	2	8	$P_2(2\frac{1}{2})$
	5n	3090.3	4	90.3	1	90.2	0	89.7	90.46	2	10	$Q_1(\frac{1}{2})$
	....	....	......	....	......	......	......	......	89.85	3	12	$Q_1(1\frac{1}{2}, 2\frac{1}{2})$
	....	....	......	....	......	......	......	......	90.36	2	10	$Q_1(3\frac{1}{2})$
	....	....	......	....	......	......	......	......	91.18	2	10	$P_2(3\frac{1}{2})$
	5	3093.7	1	93.7	2	93.6	2	93.9	93.72	2	4	$P_1(1\frac{1}{2})$
	5	3096.2	3	96.4	......	......	......	......	96.34	2	5	$P_1(2\frac{1}{2})$
	....	....	......	....	......	......	......	......	97.00	2	8	$P_2(4\frac{1}{2})$
	5	3099.6	2	99.4	......	......	0	99.4	99.57	2	.....	$P_1(3\frac{1}{2})$
	0	3103	......	....	......	......	......	......	03.34	2	10	$P_1(4\frac{1}{2})$
	1	3107	......	....	......	......	......	......	07.54	2	8	$P_1(5\frac{1}{2})$

* Sources: 1940c: Swings, Elvey, and Babcock, *Ap. J.*, **94**, 320, 1941; 1941d: Elvey, Swings, and Babcock, *Ap. J.*, **95**, 218, 1942; 1942a: Popper and Swings, *Ap. J.*, **96**, 156, 1942.

† "G. H.": according to Grebe and Holst; "R": observed at the Ryerson Physical Laboratory (Beutler, unpublished).

‡ The J''-values are given in parentheses.

[24] P. Swings, *Ann. d'ap.*, **11**, 124, 1948.

which is broader than P_2 ($2\frac{1}{2}$) or P_1 ($1\frac{1}{2}$). Because of the low population of the level $J' = 3\frac{1}{2}$, as indicated by the faintness of P_1 ($4\frac{1}{2}$), the line Q_1 ($3\frac{1}{2}$) at λ 3090.36 can play only a minor role in the blend. A maximum in the Q_1 branch at $J' = 1\frac{1}{2}$ or $K' = 2$ is not excluded.

The lines observed in Comet Bester are schematized in the level diagram of Figure 6, which omits P_1 ($4\frac{1}{2}$) and P_1 ($5\frac{1}{2}$). Although the R_2 branch near λ 3072 is absent, as in previously observed comets, the laboratory intensities of the R_2 lines are not much weaker than those of P_2. The absence of R_2 in Comet Bester may be due to the absorption of the UV-glass correcting plate of the Schmidt camera in the Cassegrain spectrograph, and possibly also to ozone absorption in this region. Absorption features in the ultraviolet solar spectrum cannot be the reason for the absence of R_2 when P_2 is strong. The same applies to the Q_2 branch at λ 3078, which is not observed in the (0, 0) band. The R_1 branch near λ 3080 is also absent.

The effect of the distribution in population on the different rotational levels is espe-

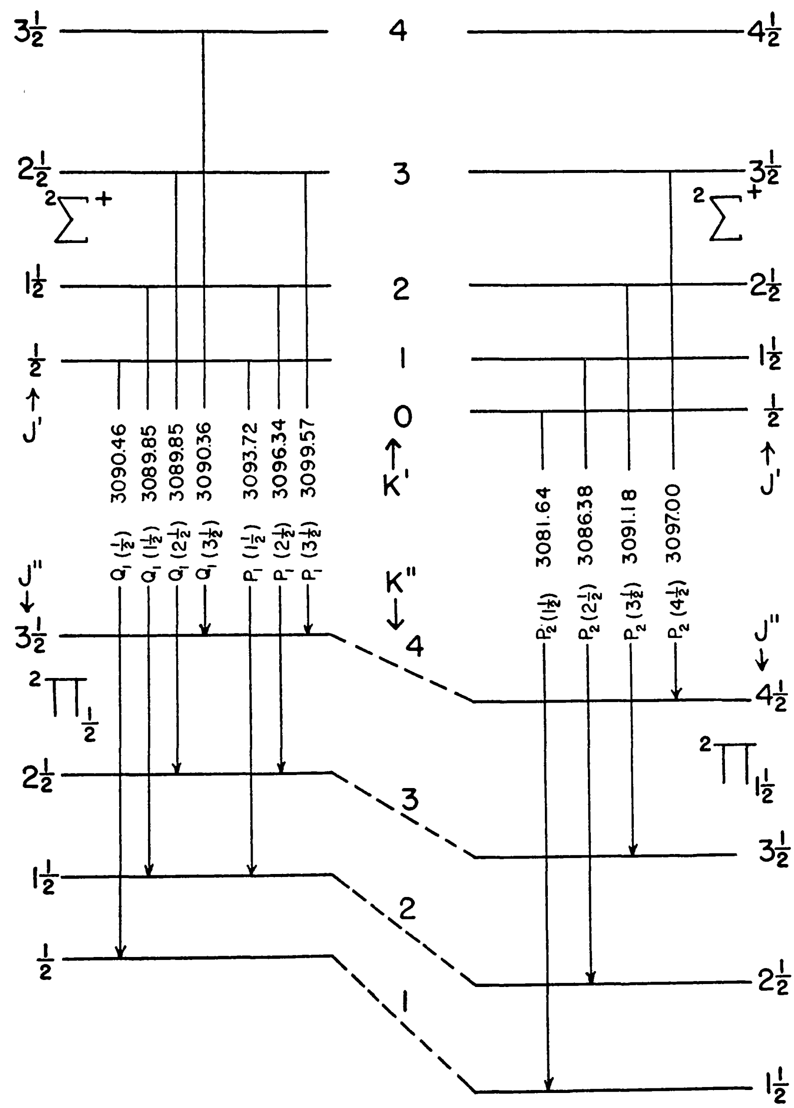

FIG. 6.—Energy levels contributing to the (0, 0) band of OH. The levels $P_1(4\frac{1}{2})$ and $P_1(5\frac{1}{2})$ are omitted

cially apparent in λ 3090. In Comets 1942a and 1941d the observed emission is mainly Q_1 ($\frac{1}{2}$), while in Comets 1947k and 1940c it is a blend of Q_1 ($\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$, $3\frac{1}{2}$) and P_2 ($3\frac{1}{2}$).

Generally speaking, the (0, 0) band corresponds to higher J-values in Comet 1947k than in the spectra of Comet 1940c, which were taken at the same heliocentric distance. Since it is reasonable that the populations in the rotational levels should be determined mainly by the absorption of solar radiation, we assume that the difference in rotational distribution between 1947k and 1940c is due to the different radial velocities, dr/dt being, respectively, +22.2 and −34.6 km/sec. The difference corresponds to a Doppler shift from one comet to the other of 0.6 A at λ 3000, which may, indeed, affect the distributions noticeably. On the other hand, the differences in intensity distribution between 1940c and 1941d or 1942a, which were observed at different heliocentric distances, are

TABLE 3

REGION λλ 3130–3160 IN COMET 1947k

Observed		(1, 1) Band of *OH*		(0, 0) Band of *CH*	
Int.	λ	λ	Notation	λ	Notation
0.1	3131.6	31.45	$R_1(3\frac{1}{2})$		
2	3135.0	34.56	$Q_2(1\frac{1}{2})$	35.6	$R_2(2)$
		36.17	$Q_2(2\frac{1}{2})$	36.2	$R_1(2)$
		33.98	$R_1(2\frac{1}{2})$		
3	3137.9	37.74	$P_2(1\frac{1}{2})$	37.4	$R_2(1)$
		37.03	$R_1(1\frac{1}{2})$	39.1	$R_1(1)$
		37.88	$Q_2(3\frac{1}{2})$		
0	3140.6	40.75	$R_1(\frac{1}{2})$		
1	3142.9	42.49	$P_2(2\frac{1}{2})$	42.9	$Q_2(1)$
3	3147.5	47.44	$P_2(3\frac{1}{2})$	47.5	$P_1(1)$
		47.3	$Q_1(\frac{1}{2})$	46.5	$P_2(1)$
		46.58	$Q_1(1\frac{1}{2})$		
		47.26	$Q_1(2\frac{1}{2})$		
		48.41	$Q_1(3\frac{1}{2})$		
2	3150.5	50.00	$P_1(1\frac{1}{2})$	50.4	$P_1(2)$
				49.8	$P_2(2)$
2–1	3153.7	52.95	$P_1(2\frac{1}{2})$	52.9	$P_1(3)$
		52.44	$P_2(4\frac{1}{2})$		
1	3156.8	56.22	$P_1(3\frac{1}{2})$	55.7	$P_1(4)$
0	3159	60.05	$P_1(4\frac{1}{2})$	58.4	$P_1(5)$

primarily due to the different values of r, combined with the smaller differences in radial velocity.

The (1, 1) band of the $^2\Sigma^+ \rightarrow {}^2\Pi_{inv}$ *system of OH.*—Because the lines around λ 3150 are so strong in the spectrum of Comet Bester at $r = 1.04$ and since the intensity distribution among them differs so much from that within the (0, 0) transition of *OH*, it might be assumed that they are blended with the (0, 0) band of the Fortrat system of *CH* ($c^2\Sigma^+ \rightarrow x^2\Pi$). Table 3 gives identifications of the lines observed near λ 3150. There are good reasons for thinking that the contribution by *CH* is minor: First, the $c^2\Sigma^+ \rightarrow x^2\Pi$ ultraviolet system should be weak compared with the violet $A^2\Delta \rightarrow x^2\Pi$ system, near λ 4313, as exhibited in the solar and interstellar absorption bands of *CH*. At $r = 1.04$ this violet system (λ 4313) has already become rather weak. Second, the fluorescence excitation of the ultraviolet system of *CH* requires solar radiation around λ 3150, where the amount of energy available is much smaller than at λ 4313. Finally, if the contribution of *CH* were important, the Q branch (which should be stronger than the P and R branches) would be stronger than is observed.

On the other hand, if we assume the λ 3150 emission to be due to pure *OH*, we find that the R_2 branch, to the violet of Q_2, is absent or extremely weak. This cannot be explained by atmospheric or instrumental absorption. The R_1 branch is also weak. Moreover, in view of the weakness of (1, 1) relative to (0, 0) of *CN* and the absence of (1, 1) of the violet system of *CH*, the intensity of the λ 3150 emission appears to be too high for identification with the (1, 1) transition of *OH*, which is a heteronuclear molecule and should therefore have a low vibrational temperature. The (1, 1) band of *OH* would be excited mainly by absorption of solar radiation in the (1, 0) band of *OH*, near λ 2811,[25] since most *OH* molecules must be in their lowest vibrational level, $v'' = 0$. The fact that the (0, 0) and (1, 1) bands of *OH* are excited by different regions of solar radiation may suffice to explain the very different rotational intensity distributions within the two

TABLE 4

NH BANDS IN COMET 1947k NEAR λ 3350

1947k		1940c*		1947n†		LABORATORY λ	NOTATION
Int.	λ	Int.	λ	Int.	λ		
		2	50.8	1	49.6	50.85 49.55 49.29	$R_2(1)$ $R_1(2)$ $R_3(1)$
10n........	From 3351.4 to 3358.6	4	54.1	2	53.7	53.64 53.96 54.2	$R_1(1)$ $R_2(0)$ $Q_3(1)$
		8	57.9	10	58.1	57.83 57.6 57.82 58.42	$R_1(0)$ $Q_2(1)$ $Q_2(2)$ $Q_2(3)$
1.........	3361.5	2	61.5	....	....	61.73 61.01 62.7	$Q_1(1)$ $Q_1(2)$ $P_3(2)$
2s........	3365.2	2	64.7	1	65.0	64.94	$P_2(2)$
5.........	3369.4	3	69.1	1	69.3	69.12 69.3	$P_1(2)$ $P_2(3)$
1?........	3372	1	72.0	....	....	72.07	$P_1(3)$

* Swings, Elvey, and Babcock, *Ap. J.*, **94**, 320, 1941.
† Swings and Page, *Ap. J.*, **108**, 526, 1948.

bands. A theoretical calculation of the two synthetic profiles seems to be the only means for deciding on the amount of blending by *CH*. Although, as shown in Figure 4, the λ 3150 emission is confined to the nucleus and the (0, 0) band of *OH* is also much stronger in the central part of the head, *CH* is also a "nuclear" emission; so the identification of the λ 3150 emission cannot be based on extension into the head.

The (0, 0) band of the $^3\Pi \rightarrow {}^3\Sigma$ *transition of NH.*—This very intense emission is not so well resolved in our present material as it was for Comet 1940c. The measured wave lengths and their identifications are given in Table 4, together with the measurements

[25] This region of the solar spectrum has now been observed from V2 rockets. For a table of solar wave lengths see Durand, Oberly, and Tousey, *Ap. J.*, **109**, 1, 1949. Also H. E. Clearman, chap. iv, Sec. B, p. 125, of *The Atmospheres of the Earth and Planets*, ed. G. P. Kuiper (Chicago: University of Chicago Press, 1949). The (1, 0) band of *OH* in comets should be mainly between λ 2819 and λ 2852. The fluorescence would be affected by the resonance line of *Mg* I at λ 2852, by the longward wing of the enormously strong resonance doublet of *Mg* II, and by several other absorption lines, mainly of *Fe* I, *Fe* II, and *Co* I.

for Comets 1940c and 1947n. It is apparent that the main contributors are the P_1, Q_1, and R_1 branches corresponding to the sublevel of highest statistical weight, $^3\Pi_2$; but even in these branches only low values of K'' are observed. The R branches especially are limited to $K'' \leq 1$, plus a possible contribution of R_1 (2). This indicates that the K' levels above 2 have no appreciable population. In the P_2, Q_2, and R_2 branches corresponding to $^3\Pi_1$, R_2 is observed only for $K = 1$; P_2 (2), Q_2 (1, 2), and possibly Q_2 (3) are also present. In the P_3-Q_3-R_3 group corresponding to $^3\Pi_0$, R_3 is absent or very weak, Q_3 appears doubtfully in a blend, and P_3 is probably absent.

It is difficult to ascertain whether the NH (1, 1) transition is weakly present or not. By comparison with NH (0, 0) and neglecting a possible effect of solar absorption lines in the fluorescence excitation, the (1, 1) transition of NH should be detected by R_1 (0) at λ 3368; R_1 (1) at λ 3364, and P_1 (2) at λ 3376. The R_1 (0) and R_1 (1) would not be easily detected, as they would appear in the shortward wings of two strong NH (0, 0) lines; there is no evidence for P_1 (2).

Since most NH molecules must lie in their lowest vibrational level, $v'' = 0$, the excitation of the (1, 1) band would require absorption in the (1, 0) transition. Since this transition is very weak compared with NH (0, 0), while in OH the (1, 0) band, although weaker than (0, 0), has an appreciable intensity, we can understand why (1, 1) of NH does not appear, while (1, 1) of OH is present.

Relative intensities of the OH and NH bands.—Bands of OH, and especially of NH, are strong in Comet Bester. The intensity of NH may be related to the high intensity of the emissions at λ 6299, λ 6363, and others in the visual region usually attributed to NH_2. In the case of Comet 1941d (Van Gent), in which NH is very weak compared with OH and CN, the NH_2 emissions in the visual region are also very weak. It seems reasonably safe to assume that NH and NH_2 result from the photo-dissociation of the same parent-molecule, ammonia.[26] Whether NH results from direct photo-dissociation of NH_3 or from that of NH_2 is at present not known.

The parent-molecule of OH has usually been considered to be H_2O, although the very low vapor pressure of H_2O at low temperatures would be expected to limit the OH band to small heliocentric distances, as emphasized by Wurm.[9] Such a fact is not confirmed by the observations. In Comet Bester, the OH band is strong at $r = 1.04$. It has been observed at still larger heliocentric distances, for example, in Comets 1940c ($r \leq 1.05$), 1941d ($1.25 \leq r \leq 1.53$), 1942a ($1.6 \leq r \leq 1.8$), and 1947i ($r \simeq 1.1$). At $r = 1.5$ one would expect virtually all H_2O to be in the form of ice.[24]

The relative intensities of the OH and NH bands vary in an extreme and unpredictable way from comet to comet. Table 5 summarizes the data available to us on this effect. In the intensity ratios listed we have corrected roughly for observing conditions and instruments used.

It is to be noted that the observed ratios of OH/NH do not seem to depend on the time or distance of perihelion passage or on whether the comet is young (newly found) or old. It varies considerably with heliocentric distance. From $r = 1.53$ to $r = 1.25$ in Comet 1941d the ratio OH/NH decreases considerably; this continues from $r = 1.20$ to $r = 0.63$ in Comet 1940c. In other words, from $r = 1.53$ to $r = 0.63$ the increase in intensity is much more pronounced for NH than for OH.

The region around the (1, 0) band of CN at λ 3590, and the identification of OH^+.—This region contains the (0, 0) band of OH^+, the presence of which has been suspected.[27] Its confirmation is difficult because of (*a*) the presence of numerous laboratory bands of

[26] While one should not necessarily identify the cometary solids with the meteorites, it seems rather strange that no NH_3 has been found among the occluded gases of meteorites (Merrill, *Proc. Amer. Phil. Soc.*, **65**, 119, 1926). Nor has NH_3 been found in terrestrial rocks (Nikogosjan, *Mem. 3d Conf. Mineralogy*, p. 55, 1940; in Russian, cited by B. A. Vorontsov-Velyaminov, *A.J. Soviet Union*, **22**, 317, 1945).

[27] P. Swings, *Pub. Lick Obs.*, Ser. II, No. 3; *Ap. J.*, **95**, 270, 1942; J. Hunaerts, *Bull. Astr. Obs. R. Belgium*, **3**, 320, 1945; and R. Herman, *C.R.*, **227**, 962, 1948.

this region, due to CN, OH^+, CO^+, N_2^+, O_2, NO, N_2, and C_2, all of which can be present in comets, and (*b*) the extreme complexity of the exciting solar spectrum in this region, which should lead to peculiar rotational intensity distributions.

The (1, 0) band of the violet system of *CN* is fairly strong in Comet Bester. The (2, 1) transition at λ 3586 probably does not play any significant role, since the (2, 2) band at λ 3862, which arises from the same upper vibrational level $v' = 2$ and which is slightly stronger than (2, 1) in the laboratory, is not observed. In Comet 1940c the (2, 2) band of *CN* was found to play only a minor role when the (0, 0) band was overexposed and the comet close to the sun.[28]

The main transitions in the $^3\Pi_i \rightarrow {}^3\Sigma^-$ system of OH^+ are (0, 0) with *R* head at λ 3565 and (0, 1) at λ 3983. Other laboratory bands such as the (1, 1) transition at λ 3695 and (1, 0) at λ 3332, arising from $v' = 1$, are unlikely to reach any intensity in comets. Hunaerts' suggestion[27] that the (0, 1) band of OH^+ may contribute appreciably to the

TABLE 5

VARIATIONS IN THE RATIO *OH/NH*

Comet	Observational Conditions	*OH/NH*	Remarks
Encke.	After $q=0.34$ at $r=0.95$	$\frac{1}{2}$	Old comet
1940c.	Before $q=0.38$ at $r=1.03$	$\frac{1}{2}$	New comet
1941c.	After $q=0.79$ at $r\approx 1$	$(\frac{1}{10})$	New comet
1941d.	Before $q=0.89$ at $r=1.53$–1.25	(2)	New comet
1942a.	After $q=1.06$ at $r=1.6$–1.8	$\frac{1}{2}$	New comet
1947k.	After $q=0.75$ at $r=1.04$	$\frac{1}{2}$	New comet
1947n.	After $q=0.11$ at $r=1.02$	$(\frac{1}{10})$	New comet

emission near λ 4000 is not confirmed by observation. First, all the cometary lines near λ 4000 are very short and behave like the characteristic nuclear λ 4050 group with respect to variation with *r*. Second, (0, 0) of OH^+ is at best very weak; (0, 1) should be still weaker and hence could not play a significant role in the λ 4050 group. A similar conclusion results from the laboratory work of R. Herman.[27]

Although the presence of OH^+ is not excluded, as shown by the measures and suggested identifications in Table 6, it is not confirmed. For these identifications great help was obtained from the synthetic, low-temperature, rotational profiles of the OH^+ bands, computed by Hunaerts.[27] Line λ 3563 seems to require the presence of OH^+; λ 3569 appears too strong to be due to the *R* branch of *CN* (1, 0) alone; there may be a contribution of OH^+ in λ 3594; and the emission observed at λ 3616 may be partly due to OH^+ (the P_1, P_2, and P_3 branches around $K' = 6$). A convincing identification will require spectrograms of higher resolution in this region.

V. THE REGION λλ 3800–5000 IN THE SPECTRUM OF THE HEAD

The $\Delta v = 0$ and -1 sequences of the violet system of *CN* are of the usual complex type; however, since the structures of the *CN* bands on our spectrograms of 1947k are not so well resolved as in prevously observed comets, they will not be described here. The (1, 1) band is present, as expected from the observation of the (1, 0) transition.

Nothing unusual appears in the $A^2\Delta \rightarrow x^2\Pi$ system of *CH*, which is the main characteristic of this molecule. On our strongly exposed spectrogram for $r = 1.06$, the $\beta^2\Sigma^- \rightarrow x^2\Pi$ system of *CH* (on the longward side of *CN* [0, 0] λ 3883) also appears. The structures of these two bands of *CH* do not differ markedly from those in Comet 1940c, which have been described in detail.[29]

Twenty "nuclear" lines observed between λ 3960 and λ 4108, the strongest at

[28] P. Swings, *Lick Obs. Bull.*, **19**, 131, 1941.

[29] Swings, Elvey, and Babcock, *Ap. J.*, **94**, 320, 1941.

λ 4051.1, belong to the "λ 4050 group." No striking intensity change occurs within the group from $r = 0.81$ to $r = 1.55$, as shown by Table 7, which gives intensities measured from tracings without standardization, as described in Section II above.

C. Fehrenbach[30] has suggested that λ 4013 and λ 4067 are stronger in Comet 1948g than in laboratory spectra and that another emission overlaps that usually attributed to CH_2. Our results on Comet 1947k, and those by Jose and Swings[12] on Comet 1948l, do

TABLE 6

REGION λλ 3550–3620, COMET 1947k COMPARED WITH COMET 1940c

1940c (r=0.63)			1947k							
Int.	λ	Identification*	r 0.86	r 0.88	r 0.96	r 0.97	r 1.04	Description†	Adopted Mean λ	Ident.
1–0....	3565	OH^+ R_3(1, 2, 3, 4)	....	....	....	....	63.3(2)	....	3563.3	OH^+ (0,0)
2......	3572.2	CN(1,0) R(14)‡ OH^+ 5 lines	....	....	71.0	68.0	74.4(2n)	1, >250″	3569.5	CN(1,0) OH^+(0,0)
1–2....	3577.3	CN(1,0) R(5)‡ (OH^+ 6 lines)	78.9	76.2	81.	79.8	....	2, >250″	3580.4	CN(1,0) CO^+(5,0) N_2^+(1,0)
2–3n...	3584.3	CN(1,0) P(2)–P(14) (OH^+ 4 lines)	....	....	....	....	83.7(1s)	....	......	....
1–0....	3589.4	CO^+(5,0) .... OH^+ 4 lines	....	....	....	....	....	....	....	....
1–2....	3597.4	CO^+(5,0) .... OH^+ 3 lines	98	....	95.4	93.4	97.7(4n)	1, >250″	3594.4	CO^+(5,0) OH^+(0,0)
....	3617.				17.	15.7	14.9(2n)	2n, 15″§	3616.3	?OH^+ (0,0)?

* According to P. Swings, *Ap. J.*, **95**, 270, 1942; with additions from J. Hunaerts, *Bull. Astr. Obs. R. Belgium*, **3**, 320, 1945. All the OH^+ lines correspond to values of $k' \leq 3$.

† For spectra at $r = 0.96$ and 0.97; the first figure is the intensity; the second is the extension of the line from the nucleus in seconds of arc.

‡ Blend of lines around this transition. § This line is long but is strongly enhanced in nucleus.

TABLE 7

INTENSITIES OF LINES OF THE λ 4050 GROUP AT VARIOUS HELIOCENTRIC DISTANCES, COMET 1947k

λ	r 0.81	r 0.86	r 1.30	r 1.55
3992............	....	4.0	6.0	9.8
4033............	8.5	....	....	6.0
4043............	8.5	8.7	10.6	13.0
4051............	....	....	....	15.0
4068............	8.8	6.1	7.8	10.0

30 *C.R.*, **227**, 519, 1948.

not substantiate Fehrenbach's suggestion. Table 7 shows that there may be a variation by a factor of $\frac{1}{2}$ in the ratio λ 4033/λ 4043 between $r = 0.81$ and $r = 1.55$. It is possible that this change might be explained by the change in dr/dt from +17 to +25 km/sec if we knew the analysis of the bands. Experimental work on the λ 4050 emission is highly desirable.

The bands of CH^+ are not easily detected on the small scale of our spectrograms, since most of them are overlapped by the tail emissions of CO^+. In the (0, 0) transition of CH^+ two of the characteristic lines, λ 4230 and λ 4254, are too near CO^+ bands, but λ 4238 does not appear with certainty. In the (1, 0) band, two lines are definitely observed at λ 3962 and λ 3972, and the line λ 3954 is blended in a CO^+ emission. We conclude that CH^+ is actually observed, the evidence being mainly the (1, 0) transition.[31]

Recent papers have emphasized the structure appearing within the Swan bands of C_2.[32] Such structure has been described in detail for 1947n[33] and 1948l.[34] Discrete emissions appear between the heads within the $\Delta v = +1$ sequence, and also within the other Swan sequences. It is not clear whether the fairly sharp features observed, especially within the $\Delta v = +1$ sequence, are due to some emission by an as yet unidentified molecule or to an effect of the solar absorption lines on the fluorescence excitation. It would

TABLE 8

DOUBLET APPEARING BETWEEN THE (3, 2) AND (2, 1) HEADS OF C_2

Comet 1940c	Comet 1947n	Comet 1948l
λ 4703.5 λ 4707.1	λ 4704.0 λ 4708.8	λ 4705.0 λ 4708.4

be possible to separate these two by drawing synthetic profiles of the Swan bands, taking into account the profile of the solar spectrum.

Certain of these emissions are observed in several comets, e.g., the doublet between the (3, 2) and (2, 1) heads of C_2, as shown in Table 8. Others are not found in all comets. Our material on 1947k does not reveal such a structure, probably because of the low dispersion and strong exposures intended to bring out the tail spectrum.

Theoretical profiles of the C_2 bands have now been determined by J. Hunaerts.[35] They reveal, for example, a secondary maximum near λ 4706 between the (3, 2) and (2, 1) heads, the wave length of the maximum depending on the radial velocity. This wave length agrees with the emission observed in Comet 1911c (λ 4706) and in Comet Halley (λ 4705.9). The doublet observed in Comets 1940c, 1947n, and 1948l must be at least partly due to these C_2 bands.

VI. THE VISUAL AND INFRARED REGION OF THE SPECTRUM OF THE HEAD

Recent work on the infrared spectrum of the bright Comet 1947n[19] revealed the presence of two strong nuclear emissions at λ 7906 and λ 8106, the first of which is also observed in Comet 1947k. A probable identification is with the red system $^2\Pi \rightarrow {}^2\Sigma$ of CN, λ 7906 and λ 8106 being, respectively, the (2, 0) and (3, 1) transitions. In contrast with

[31] A search for SiO_2, such as was conducted by A. McKellar (*Ap. J.*, **99**, 162, 1944), did not reveal any convincing coincidence in Comet Bester.

[32] N. T. Bobrovnikoff, *Ap. J.*, **99**, 173, 1944; A. McKellar, *Ap. J.*, **99**, 162, 1944; Swings and Page, *op. cit.*, p. 526; Jose and Swings, *Ap. J.*, **111**, 41, 1950.

[33] Swings and Page, *op. cit.*

[34] Jose and Swings, *op. cit.*

[35] *Ann. Obs. R. Belgium*, Vol. **5**, Fasc. 1, 1949.

the violet system $^2\Sigma \rightarrow {}^2\Sigma$ of CN, the infrared bands are confined to the nucleus; thus they are probably not excited by a fluorescence mechanism, as the violet system is. It is desirable to look for other emissions of the red system in the visual region, the most promising being (4, 0), (5, 1), and possibly (6, 1). Before reliable identifications may be made, synthetic low-temperature profiles are required for these CN bands, and in this case, since the excitation is not by fluorescence, no effect of solar absorption lines would have to be considered. The rotational temperature in the comets is low, as revealed by the small width of the infrared emissions. Since the bands of the red system have three heads roughly equally spaced with $\Delta\lambda \simeq 20$ A, each vibrational transition may actually give rise to several "lines."

Pending calculation of synthetic profiles, the identifications listed in Table 9 are merely suggestions. While λ 6332 is certainly due mainly to NH_2, the emission at λ 6200.6, and possibly those at λ 5730.1 and 5747.5, may well be due to CN.

TABLE 9

SUGGESTED IDENTIFICATIONS OF BANDS IN THE RED SYSTEM OF *CN*

Measured Wave Length (Comet Bester) $r=0.81$	Measured Wave Length (Comet Bester) $r=0.86$	Description*	Coincidence with Red *CN* Band	Previous Identification
5730.1	32	2d, 15″	(6, 1)	....
5747.5	....	3d, 10″	(6, 1)	....
6200.6	....	½, 20″	(4, 0)	....
6332.2	33	2, 5″	(5, 1)	NH_2
6345	....	1, 5″	(5, 1)	NH_2

* Intensity and extension from the nucleus.

Table 10 lists the lines observed in Comet 1947k in the region longward of the (1, 0) band of C_2, omitting the Swan bands. A discussion of this and similar, previously published tables does not appear fruitful until a laboratory analysis of the NH_2 emission bands is completed. Coincidences with bands of various types of molecules may be found, some of them rather striking, e.g., FeO, noted by Rosen and Swings[36] independently in 1943, and, less striking, NiO, CaO, and CrO.[37] Many bands of FeO, such as λλ 4448, 4544, 4604, 5789.8, 5807.4, 5903.0, 6097.3, 6109.9, 6218.9, etc., are close to cometary wave lengths.

Two spectrograms on hypersensitized I-N emulsion (B 163 and B 165 in Table 1) cover the region to λ 8800, with a dispersion of 330 A/mm and slit-width 33 A. They were taken in the same manner as for Comet 1947n,[19] in which strong infrared emissions were found by us for the first time. The most important of these, λ 7906, appears also in Comet 1947k, the mean measured wave length being λ 7907. In 1947n a weaker band had been found at λ 8106; in 1947k a weaker emission, which is difficult to measure, has been estimated at λ 8084 and many other possible maxima appear, as shown in Figure 3. This figure shows, for comparison with the "intensity-curves" of films B 163 and B 165 of Comet 1947k, similar curves reduced from spectra of a CN discharge tube and of the night sky.[20] The spectrum of the CN discharge was taken with the same spectrograph, using the same emulsion, but with slit-width 7 A instead of 33 A, as used for the comet. The night-sky spectrum was obtained by Dr. A. B. Meinel with a similar grating spec-

[36] Private communications, unpublished.

[37] McKellar (*op. cit.*) has mentioned striking coincidences between cometary and SiO_2 emissions in the violet region.

trograph on the same type of emulsion (Eastman I-N) in an exposure of 8 hours. His slit-width corresponds to ½ A. We are indebted to Dr. Meinel for making available to us a tracing of this spectrogram before publication.

It is to be noted that λ 7916 appears rather strongly in the night-sky exposure of 8 hours. With the wider slit used for B 163 and B 165, this band might be expected to show in the 2-hour exposures where the spectrum of 1947k had raised the intensity above the threshold of the I-N emulsion. However, the lack of the even stronger λ 8346 indicates that the night-sky λ 7916 cannot contribute in a major way to λ 7910 observed in the comet.

In Comet 1947k, just as in 1947n, λ 7906 is confined to the nucleus, in contrast with the second-order (0, 0) band of *CN* (λ 3883), which extends farther into the head. The

TABLE 10

EMISSIONS IN THE VISUAL REGION

(The Swan Bands of C_2 Are Omitted)

Wave Length in 1947k				Descrip-tion*	Adopted λ	Wave Length in 1947n	Suggested Identification
r							
0.81	0.86	0.88	1.30				
4780.9	...	...	...	1, 15″	4781	91	NH_2?
4811	...	...	...	1, 15″	4811	...	...
4839.1	...	...	...	2, 15″	4839	...	NH_2+C_2
...	4930.0	...	...	3, 15″	4930	24.3	NH_2
5700.0	02	...	...	2n, 15″	5701	02.2	NH_2
5730.1	32	...	...	2n, 15″	5731	32.5	*CN*
5747.5	...	...	...	3n, 10″	5748	...	*CN*
5767.4	...	...	...	½s, 10″	5767	...	...
5778.5	...	...	...	1s, 10″	5779	...	NH_2
5975.0	77.8	78	...	2n, 15″	5977	74.9	NH_2
...	5997.1	97	...	2n, 15″	5997	98.0	NH_2(+*CN*?)
6018.5	...	...	...	1, 10″	6019	17.2	NH_2(+*CN*?)
6094.1	96.8	...	...	2n, 10″	6096	94.8	NH_2
...	6109.8	...	...	1, 5″	6110	06.6	NH_2
6152†	...	...	...	1nn, 10″	6152	57.1	NH_2?
6200.6	...	...	...	½, 20″	6201	...	*CN*
6289	...	...	...	½, 30″	6289	...	NH_2
6299.3	00.0	98.2	98	2, 30″	6299	97.3	NH_2
6332.2	33	...	...	2, 15″	6333	29.5	NH_2(+*CN*?)
6345	...	...	...	1, 5″	6345	45.2	NH_2(+*CN*?)
6363.5	64	...	...	2, 5″	6364	60.6	NH_2(+*CN*?)
6430	...	...	...	1, 5″	6430	...	NH_2
6452	...	...	...	1, 5″	6452	...	NH_2
6549.1	...	...	45	1, 5″	6547	38.6	NH_2
...	...	...	6553	½s, 10″	6553	57.0	NH_2?
6564	...	...	64	½s, 5″	6564	71.9	NH_2
...	6579	...	81	2n, 5″	6580	80.3	NH_2?
...	6590.6	...	93	1, 5″	6592	96.5	NH_2?
...	...	...	6599	1, 10″	6599	...	NH_2
6620.5	19	15.1	17	2n, 10″	6618	15.6	NH_2
6641.8	40.2	...	...	1n, 10″	6641	36.9	NH_2?(+*CN*?)
6726	...	...	...	...	6726	22.1	NH_2?
...	6748.8	...	...	2, 5″	6749	48.7	NH_2
6790	...	...	...	...	6790	...	NH_2?

* Intensity and extension.

† From λ 6141.8 to λ 6162.3.

structure of λ 7906 is not so well defined in 1947k as in 1947n, and the maximum in the shortward wing does not appear so clearly.

The identification of three emissions—(2, 0), (3, 1), and (4, 2)— of the red system of *CN* remains probable, although not certain. The broad maximum appearing in Figure 3 from λ 6928 to λ 7037 may contain the (3, 0) band of *CN;* another shallow maximum around λ 7150 (extending from λ 7044 to λ 7186) may contain the (4, 1) transition of *CN*.

We have no resolution of the theoretical difficulties involved in this identification of *CN*.[19] Even if, as we suggested in our investigation of Comet 1947n, the red system is actually excited in a process of dissociation of a parent-molecule *CNX*, rather than by fluorescence, the problem of explaining the intensity of the emission would be difficult. A *CN* radical is able to emit by fluorescence several hundred quanta (at least) in the course of its life, while a *CNX* molecule would emit only once, at the moment of its photo-dissociation. For every *CN* radical formed, there would thus be emitted, at the most, one quantum in the red system by dissociation and at least several hundred quanta in the violet and red systems by fluorescence.

VII. THE SPECTRUM OF THE TAIL

Several excellent slit spectrograms of the tail have been obtained, extending into the ultraviolet to λ 3370; two of these are reproduced in Figure 2, and parts of two others in Figure 5. The main characteristics of the tail spectrum are, as is well known, the CO^+ "comet-tail system" ($A^2\Pi \rightarrow {}^2\Sigma$), and the N_2^+ "first negative system" (${}^2\Sigma \rightarrow {}^2\Sigma$), the lower electronic levels of these systems being the ground states of CO^+ and N_2^+. In addition to these bands, there are a number of emissions observed in Comet Bester which have not been observed or identified previously; most of these are rather weak, although two at λ 3509 and λ 3674 reach a considerable intensity. The CO^+ bands were very strong at heliocentric distance 0.8–1.0 but had virtually disappeared at $r = 1.1$. Table 11 gives the measured wave lengths and the identifications; for comparison we add the wave lengths measured by Baldet[3] in Comet Morehouse (1908c) and by Wright[7] in Comet Brooks (1911c).

Emissions due to CO^+.—All the bands of the (v', 0) series,[38] from $v' = 6$ to $v' = 1$ are observed; in the (v', 1) series, bands are found for $v' = 6$, 4, and 1. The absence of the other members of the (v', 1) series in Table 11 is due to blends or to the proximity of intense emissions. The C.T. bands are degraded to the red in the laboratory, which explains the fact that CO^+ wave lengths measured in the tail of Comet Bester have an average longward displacement of 3.7 A relative to the laboratory wave lengths of the *R* heads.

The C.T. system of CO^+ has the well-known typical aspect of doublets formed by the $Q_1 + R_1$ and $Q_2 + R_2$ heads, which are separated by 15–30 A. In the laboratory the Q_1 and Q_2 heads appear 2 or 3 A longward of R_1 and R_2, but they were not separated from R_1 and R_2 on our present spectrograms, these having a resolution of about 7 A. This instrumental width prevents our determining accurately the rotational temperature of the CO^+ molecules, which is estimated to be of the order of 300° K. This is low, as it is for all heteronuclear molecules of the head (*OH*, *NH*, *CH*, *CN*), in contrast with the high rotational temperature of the homonuclear molecule C_2. Hence, even if the instrumental resolution were sufficient to separate the *Q* and *R* heads of CO^+, it is by no means certain that these two heads would appear separately in the comet spectra. This prediction, based on the low rotational temperature, has been mentioned by K. Wurm.[9] The shift of our observed lines about 3.7 A to the red of the laboratory wave lengths of the *R* heads possibly results from the blending with *Q* and *P* branches and from the low temperature. It is consistent with a rotational temperature of the order of 300° K.

[38] The vibrational numbering of CO^+ is that of K. N. Rao, *Ap. J.*, **111**, 306, 1950. The v''s are three units lower than those used by previous investigators.

TABLE 11

SPECTRUM* OF THE TAIL OF COMET BESTER

Comet Bester		Morehouse		Brooks		Identification			
Int.	λ	Int.	λ	Int.	λ	Mol.	Electronic Transition†	Vibrational Transition	Laboratory λ (Head)‡ and Intensity
						CO_2^+	M	1,0	70.6 (5)
2	3378.0								78.0 (5)
						NO	β	0,9	76.4 (10)§
		1	85	......	......	O_2	S.R.	0,14	70.1 (5)§
						CO_2^+	M	2,1	89.5 (3)§
1	3388.2								94.7 (3)
						NO	β	0,9	86.4 (10)§
1–0	3416	1	20	......	......	CO^+	C.T.	6,0	13.3 (4)
1–0	3431	1	36	......	......	CO^+	C.T.	6,0	27.9 (4)
1	3478	......	......	......	......	......	......	......	......
						CO_2^+	M	0,0	03.7 (4)
4	3509.1	2	19	......	......				11.6 (4)
						CO^+	B.J.	2,0	11.7 (7)§
1–0	3525	2	30	......	......	O_2	S.R.	0,15	16.6 (5)§
						CO_2^+	M	2,2	34.4 (4)
2	3545.4	1n	30.86	......	......				46.0 (4)
						N_2^+	I Neg.	3,2	48.9 (3)
						CN	V	1,0	90.4 (8)
4	3580.4	2	86	......	......	CO^+	C.T.	5,0	84.2 (6)
						N_2^+	I Neg.	1,0	82.1 (4)
						CO^+	C.T.	5,0	00.8 (6)
2	3594	......	......	......	......				
						OH^+	$^3\Pi\rightarrow{}^3\Sigma$	0,0	‖
2n	3616.3	2	11	......	......	OH^+?	$^3\Pi\rightarrow{}^3\Sigma$	0,0	‖
						CO_2^+	M	0,1	63.2 (4)
4	3674.0	......	......	......	......				69.3 (3)
									74.1 (5)
						O_2	S.R.	0,16	73.2 (5)§
						CO^+	C.T.	6,1	88.1 (4)
2	3695	2	87	......	......	CO_2^+	M	1,2	80.5 (3)
									92.9 (4)
						CO^+	C.T.	6,1	05.3 (4)
1	3709	2	01	......	......	CO^+	B.J.	1,0	07.4 (9)
						CO^+	B.J.	1,0	11.9 (9)
						CO^+	B.J.	1,0	24.9 (8)
1	3726	......	......	......	......				
						CO^+	B.J.	1,0	29.7 (3)
1	3741	......	......	......	......	O_2	S.R.	1,17	42.2 (5)§
3	3781.3	6	83	......	......	CO^+	C.T.	4,0	77.8 (8)
2	3802.5	5	03	......	......	CO^+	C.T.	4,0	95.8 (8)
						CO_2^+	M	0,2	39.8 (5)
1–0	3839	......	......	......	......				53.1 (5)
						O_2	S.R.	0,17	41.1 (6)§

* Not including bands due to NH, CN, or C_2.

† Abbreviations:

C.T. = Comet-tail system ($A^2\Pi \longrightarrow {}^2\Sigma$).
B.J. = Baldet-Johnson system ($B^2\Sigma \longrightarrow A^2\Pi$).
V = Violet system (${}^2\Sigma \longrightarrow {}^2\Sigma$).
S.R. = Schumann-Runge system ($B^3\Sigma \longrightarrow x^3\Sigma$).
β = Beta system (${}^2\Pi \longrightarrow {}^2\Pi$).
I Neg. = First negative system (${}^2\Sigma \longrightarrow {}^2\Sigma$).
M = ${}^2\Pi \longrightarrow {}^2\Pi$ system of CO_2^+ analyzed by Mrozowski, *Rev. Mod. Phys.*, **14**, 216, 1942.

‡ For O_2 and CO_2^+, the wave lengths correspond to the origins.

§ Identification uncertain or incomplete; see text.

‖ Blend of lines; see section on OH^+.

TABLE 11—*Continued*

Comet Bester		Morehouse		Brooks		Identification			
Int.	λ	Int.	λ	Int.	λ	Mol.	Electronic Transition†	Vibrational Transition	Laboratory λ (Head)‡ and Intensity
4	3913.7	7	15	......	......	N_2^+	I Neg.	0,0	14.3 (6)
2	3951.3	1	49	......	......	CO^+ CO^+	B.J. B.J.	0,0 0,0	53.6 (10) 57.0 (7)
1	3983	2	91	......	......	CO^+ CO^+ O_2	B.J. B.J. S.R.	0,0 0,0 2,19	73.5 (9) 77.7 (4) 87.3 (4)§
7	4001.5	9	03	1	02	CO^+	C.T.	3,0	98.4 (9)
6	4024	9	23	1	22	CO^+	C.T.	3,0	18.7 (9)
0–1	4096	......	......	......	......	O_2	S.R.	1,19	95.9 (6)§
2n	4124	2	14	......	......	CO^+	C.T.	4,1	17.3 (2)
1	4140	3	41	......	......	CO^+	C.T.	4,1	38.9 (2)
1	4171	......	......	......	......	O_2	S.R.	2,20	73.2 (6)§
1	4231	3	36	0 0	30 38.5	CO^+ CO^+ N_2^+	B.J. B.J. I Neg.	0,1 0,1 1,2	31.6 (8) 36.2 (3) 36.6 (7)
5	4250.9	2	50	0–1	54.5	CO^+	C.T.	2,0	50.7 (10)
4	4273.8	10	79	1	78	CO^+ N_2^+	C.T. I Neg.	2,0 0,1	73.1 (10) 78.1 (8)
2	4543.8	9	49	0–1	47	CO^+	C.T.	1,0	39.4 (8)
1	4568.5	9	76	0–1	72	CO^+	C.T.	1,0	65.8 (8)
0–1	5048	3	21	......	......	CO^+	C.T.	1,1	39.7 (5)

It appears clearly from Figure 5 that the strongest C.T. band of CO^+ is the (3, 0) transition. The other intensities in the (v', 0) series, as estimated by eye from two spectrograms, are given in Table 12 in comparison with estimates for two other comets.

Although instrumental effects may account for some of the differences in these intensity estimates, we feel that the differences between various comets and laboratory estimates are real. Such differences would be entirely plausible, the populations on the v' levels depending on the excitation mechanism. Between comets of greatly different dr/dt there may be real differences in the populations of v' levels.

TABLE 12

INTENSITIES IN THE (v', 0) BANDS OF CO^+, "COMET-TAIL SYSTEM"

λ	Transition*	Laboratory†	Comet Bester (1947k) Plates B 190+B 192	Comet Morehouse (1908c)	Comet Brooks (1911c)
4251–4273	(2, 0)	10	5+4	10	4
3998–4019	(3, 0)	9	7+6	9	4
3778–3796	(4, 0)	8	3+2	5	1
3584–3601	(5, 0)	7	...+2	....	....

* Vibrational numbering follows that of K. N. Rao, *Ap. J.*, **111**, 306, 1950.

† According to Baldet, *C.R.*, **180**, 271 and 820, 1925.

The CO^+ molecule possesses another electronic transition in the spectral region covered by our tail spectrograms. This system, called the "Baldet-Johnson system," connects the upper level $B^2\Sigma$ of the first negative system of CO^+ with the upper level $A^2\Pi$ of the C.T. system. This $B^2\Sigma \rightarrow A^2\Pi$ transition has double double-headed bands, which are degraded to shorter wave lengths.[38] Wurm[9] has suggested that this system should be found in comet tails.

The (0, 0), (0, 1), (1, 0), and (2, 0) transitions of the Baldet-Johnson system are identified with wave lengths in comet-tail spectra listed in Table 11. The cometary wave lengths are shifted by approximately 2.5 A toward shorter wave lengths. The cometary line λ 3509.1 appears too strong to be due exclusively to (2, 0) of the B.J. system of CO^+. Two bands at λ 4230 and λ 3951 practically coincide with CH^+ lines, but the absence of other CH^+ lines at large distances from the nucleus favors the identification of these bands in the tail with the B.J. system of CO^+.

The levels $v' = 0, 1, 2$ of the B.J. system are reached from the ground state $^2\Sigma(v'' = 0)$ by means of the $(v', 0)$ bands of the first negative system $B^2\Sigma \rightarrow {}^3\Sigma$ at λ 2189.8 for $v' = 0$; λ 2112.4 for $v' = 1$; and λ 2042.3 for $v' = 2$.

The solar radiation in this region is much weaker than in the violet region and is rich in strong absorption lines. This and the lower f-values usually assumed for the B.J. relative to the C.T. system account for the observed weakness of the B.J. system compared with the C.T. transition.

Emissions due to N_2^+.—Although most of the N_2^+ transitions are blended, the (0, 0) band at λ 3914 is very strong and wider than the CO^+ bands. The rotational temperature of N_2^+ is therefore probably higher than that of CO^+. If, as is likely, the N_2^+ bands of comets are excited by the fluorescence mechanism, the profiles of the cometary bands should be of the same type as those observed in the twilight sky. In both comets and twilight the solar absorption lines should distort the profiles in a similar way, but, since the rotational temperature of cometary N_2^+ probably differs from that of atmospheric N_2^+, the widths of the bands in comets and twilight spectra are expected to differ.

Emissions due to CO_2^+.—As shown in Figure 4, two emissions appear at λ 3378 and λ 3388 on the longward side of the NH band; these emissions are not strongly enhanced in the nucleus and appear definitely like tail lines. Figure 5 shows two strong tail emissions at λ 3509 and λ 3674 which cannot be attributed to CO^+ or N_2^+. The three measured wave lengths, λλ 3378, 3509, and 3674, agree closely with those of the origins of the (1, 0), (0, 0), and (0, 1) transitions in the $^2\Pi_u \rightarrow {}^2\Pi_g$ spectrum of CO_2^+. This molecule has not previously been identified in comet tails; hence its spectrum will be discussed here in some detail.

The bands of the $^2\Pi_u \rightarrow {}^2\Pi_g$ transition of CO_2^+ have recently been analyzed by S. Mrozowski;[39] they appear in the spectral range λλ 3000–5000 covered by our spectrograms. $^2\Pi_g$ is the ground electronic state of the CO_2^+ molecule, this being a favorable factor for possible emission of the CO_2^+ bands by fluorescence excitation due to solar radiation. The CO_2^+ bands have a fairly simple structure. The CO_2^+ molecule is linear in both $^2\Pi$ states. All the strong bands observed in the laboratory may be attributed to symmetrical vibrations, ν_1, the CO_2^+ molecules remaining in their lowest states of ν_2 (bending) and ν_3 (antisymmetrical) vibrations. In the laboratory a typical band consists of two narrow subbands $^2\Pi_{3/2} \rightarrow {}^2\Pi_{3/2}$ and $^2\Pi_{1/2} \rightarrow {}^2\Pi_{1/2}$, which are degraded toward longer wave lengths. In the $^2\Pi_{3/2} \rightarrow {}^2\Pi_{3/2}$ subband the origin coincides practically with an accumulation of lines due to the Q branch; the head of the R branch is displaced 0.4–0.7 A shortward of the origin; the P branch extends toward the red. The structure is similar in the $^2\Pi_{1/2} \rightarrow {}^2\Pi_{1/2}$ subband, except that the Q branch is not observed. The $^2\Pi_{3/2}$, $v'' = 1$, level is split by perturbations into two sublevels, 1^a and 1^b, so that the (0, 1) transition has ac-

[39] *Phys. Rev.*, **60**, 730, 1941; **62**, 270, 1942; **72**, 682 and 691, 1947; *Rev. Mod. Phys.*, **14**, 216, 1942. For the numerous previous attempts at classifying the CO_2^+ or CO_2 bands see references in Mrozowski's first paper. The strong double band λλ 2883–2896 of CO_2^+ is a $^2\Sigma_u^+ \rightarrow {}^2\Pi_g$ transition which has been analyzed by F. Bueso-Sanllehí, *Phys. Rev.*, **60**, 556, 1941.

tually three components: (0, 1^a) and (0, 1^b) of $^2\Pi_{3/2} \rightarrow {}^2\Pi_{3/2}$, and (0, 1) of $^2\Pi_{1/2} \rightarrow {}^2\Pi_{1/2}$.

For the identification of CO_2^+ in comet-tail spectra, it appears safe to adopt the mean laboratory wave lengths of the origins as the wave lengths of the subbands. Moreover, we would not expect the two (or three) subbands corresponding to each vibrational transition to be resolved on our spectrograms. Confining ourselves to the CO_2^+ bands corresponding to the symmetrical vibrations $v_1 \leq 2$, we find the coincidences with otherwise unidentified tail emissions shown in Table 13.

The identification of CO_2^+ appears convincing, although the (0, 2) transition seems too weak compared with the laboratory intensity. The absence of (2, 0) in the comet tails may be due either to instrumental reasons or to a low population of the CO_2^+ molecules on the excited level $v_1' = 2$.

It appears reasonably certain that we may now add to the two characteristic molecules of the comet-tail spectra, CO^+ and N_2^+, a third one, the ionized triatomic molecule CO_2^+.

TABLE 13

CO_2^+ BANDS IN THE SPECTRUM OF THE TAIL OF COMET BESTER

Designation	$^2\Pi_{3/2}\rightarrow{}^2\Pi_{3/2}$ Subband		$^2\Pi_{1/2}\rightarrow{}^2\Pi_{1/2}$ Subband		Comet Tail		Notes
	λ (Origin)	*I* (Lab.)	λ (Origin)	*I* (Lab.)	λ	*I*	
0, 0	3503.7	4	3511.6	4	3509.1	4	1
0, 1^a	3663.2	4 }	3675.1	5	3674.0	4	
0, 1^b	3669.3	3 }					
1, 0	3370.6	5	3378.0	5	3378.0	2	
0, 2	3839.8	5	3853.1	5	3839	1–0	
1, 2	3680.5	3	3692.9	4	3695	2	2
2, 0	3247.7	5	3254.8	5	....	....	
2, 1	3389.5(1^b)	3	3394.7	3	3388.2	1	3
2, 2	3534.4	4	3546.0	4	3545.4	2	4

NOTES TO TABLE 13

1. Slightly blended with a B.J. band of CO^+.
2. Blended with a C.T. band of CO^+.
3. Uncertain identification.
4. Blended with the (3, 2) band of N_2^+.

This ion extends into the tail to shorter distances from the head than CO^+ or N_2^+. It is well known that CO_2 dissociates into $CO + O$ by absorption of radiation near λ 1700.[40] Yet it is likely that CO_2^+ results from the photo-ionization of CO_2 rather than from the photo-dissociation of a more complex compound CO_2X. The present identification of CO_2^+ would thus indicate that by absorption of ultraviolet radiation an appreciable portion of CO_2 becomes ionized.

The CO_2^+ emissions also appear strongly in Comet Cunningham, 1940c.[8] In the spectrograms of Comet Morehouse[3] λ 3674 could probably not have been separated from the CO^+ band.

Molecules other than CO_2^+ produce striking coincidences with certain tail emissions not due to CO^+ or N_2^+. Although these molecules do not give rise to convincing identifications, they will be discussed here because of their bearing upon the CO_2^+ identification.

NO molecule.—The wave lengths measured at λ 3378 and λ 3388 agree well with those of the *R* heads (λ 3376.4 and λ 3386.4) of the two subbands in the (0, 9) transition of the β system ($^2\Pi \rightarrow {}^2\Pi$) of *NO*. The other (0, v'') transitions of *NO* would be blended, except (0, 8) at λλ 3207–3198, the absence of which is, to some extent, an argument against this

[40] K. F. Bonhoeffer and P. Harteck, *Grundlagen der Photochemie* (Dresden and Leipzig, 1933), p. 133.

identification. The *R* heads correspond to low rotational quantum numbers; hence their laboratory wave lengths should be close to those of the intensity maxima in a low-temperature source, such as a heteronuclear gas in a comet.[41] The laboratory ratio of intensities of these two *R* heads of *NO* has been determined by Cavallonni[42] as 112/96, whereas, in Comet Bester, λ 3378 is at least twice as strong as λ 3388 (see Fig. 4). However, such a difference could be due to the different excitation mechanisms and does not necessarily exclude in itself the identification of *NO*.

The (0, 8) transition of the γ system ($^2\Sigma \rightarrow {}^2\Pi$) of *NO* has its P_1 head at λ 3375.5. The intensity maximum would lie to the violet of λ 3375, probably too far to be identified with the observed wave length at λ 3378.

Identification of λ 3378 and λ 3388 with the (0, 9) transition seems doubtful because it is hard to understand how *NO* molecules could live for hours or days in the field of solar radiation without becoming photo-dissociated or photo-ionized. We do not know the dissociation or ionization continua of *NO*. However, most *NO* molecules would certainly be on their lowest vibrational level and probably in the lowest rotational states, which would slow down the dissociation.

Many other laboratory bands are known in this spectral region, and their wave lengths were examined for possible identification. The head of the second positive system of N_2 is at λ 3371; its intensity maximum should lie on the shortward side of λ 3371, too far to be identified with the observed λ 3378. The (0, 1) and (0, 2) transitions of this system are blended or close to strong emissions and cannot provide confirmation. The second positive system of N_2 requires too high excitation. The Vegard-Kaplan bands of N_2 give coincidences but are excluded by a discussion of the other transitions, as is also the case for CH_2O, *CHO*, HNO_2, *SiF*, S_2, *CaF*, *SO*, *BO*, N_2^+, and O_2^+.

O_2 molecule.—A number of coincidences between unidentified tail emissions and bands of the Schumann-Runge ($B^3\Sigma \rightarrow x^3\Sigma$) system of O_2 have been entered in Table 11. This system consists of bands degraded to longer wave lengths; the origins coincide practically with the heads. The main part of the system lies in the vacuum ultraviolet; only bands corresponding to large values of v'' are found in the region above λ 3000. In Table 11 there is no systematic difference between the cometary and the laboratory wave lengths for O_2. The coincidences are good;[43] yet the identification of the O_2 bands remains doubtful for the following reasons:

1. The relative position of the potential energy-curves of O_2 is such that the excitation of O_2 from the ground state $X^3\Sigma$ to the excited level $B^3\Sigma$ will frequently lead to dissociation. It is therefore unlikely that O_2 could live for a long time in the field of solar radiation before becoming photo-dissociated or photo-ionized, as is the case in the upper atmosphere of the earth.

2. The rotational temperature of O_2—a homonuclear molecule—would be expected to be higher than that of CO^+; yet these comet-tail bands (especially λ 3674) are as sharp as those of CO^+.

3. Although we cannot calculate the radiation pressure exerted on O_2 by solar radiation around λ 2200, it seems unlikely that O_2 molecules would be found at very large distances from the nucleus.

4. The line λ 3674, which nearly coincides with the (0, 16) transition of $B^3\Sigma \rightarrow x^3\Sigma$, is definitely too strong compared with lines near the (0, 15) and (0, 17) transitions. We would expect these three transitions to have the same intensity ratios in comets as they have in the laboratory, since they all arise from the same excited level $v' = 0$. It is true

[41] The analogous problem of the identification of *NO* in the spectrum of polar aurorae has been treated by M. Nicolet, *Phys. Soc. Gassiot Comm. Rep., London*, p. 111, 1948.

[42] *Zs. f. Phys.*, **76**, 527, 1932.

[43] No other system of O_2 gives promising coincidences; this applies to the forbidden (Herzberg) system as well as to the permitted transitions.

that recent investigations[44] have indicated that certain bands of the Schumann-Runge system may be enhanced under certain conditions of excitation. However, such enhancement cannot affect transitions arising from the same v' under the conditions of low density in the comet tail. The O_2 band certainly does not contribute appreciably to the intense tail emission at λ 3674.

Other molecules.—Among the ionized molecules, O_2^+ would seem to have the best chance of existing in comet tails. The first negative system of O_2^+, $^4\Sigma \rightarrow {}^4\Pi$, corresponds to excited states; but this need not prevent its appearing, since the Baldet-Johnson system of CO^+ is present. The strongest transitions of this negative system of O_2^+ are in the visual region, where observations of tail spectra are still scanty. The second negative system, $^2\Pi \rightarrow {}^2\Pi$, has as its lower level the lowest known state of O_2^+. Its bands are double-headed and degraded to the red. The series $(0, v')$, from $v' = 5$ to $v' = 10$, lies in the observed region, as do the transitions (1, 6) and (1, 7). However, reference to wave lengths of all these bands does not reveal any convincing coincidence with tail emissions.

Among neutral molecules we might expect N_2 and CO, since N_2^+ and CO^+ are the main characteristics of comet tails and presumably result directly from the photo-ionization of N_2 and CO. Moreover, it appears probable that N_2 may have a fairly long life in the solar-radiation field.

The different systems of N_2 have therefore been examined successively by comparison with the spectra of the night sky and aurorae. The forbidden Lyman-Birge-Hopfield system, connecting $a^1\Pi_g$ with the ground state $x^1\Sigma_g^+$ reveals a few coincidences for $19 \leq v' \leq 22$, $v'' = 0$ and 1. These coincidences are not promising, since a forbidden transition is unlikely to appear with an appreciable intensity in comets (at least in the case of fluorescence). The other forbidden system, the Vegard-Kaplan transition $A^3\Sigma \rightarrow x^1\Sigma$, and the first and second positive systems also show no promising coincidences with present cometary observations.

CO has no strong band system connected with the ground state,[45] but, in view of the identification of the Baldet-Johnson system of CO^+ in comets, transitions between excited states of CO should also be investigated. None of the various CO systems (Angstrom, Herzberg, Third Positive, etc.) reveals a striking coincidence, except the (0, 0) band of the Herzberg system, $C^1\Sigma \rightarrow A^1\Pi$, at λ 3680.9. This band is degraded to the violet, so that an intensity maximum may fall near the strong unidentified line at λ 3674 (see above). None of the other $(0, v'')$ transitions is able to confirm this coincidence because of blends or the proximity of strong emissions. The excitation required (about 10.5 volts) seems too high to warrant a high intensity of λ 3680.9.

Coincidences of tail emissions with the following bands reported by Fox and Herzberg[46] are also found: λλ 3384.4, 3434.0, 3506.6, 3599.2, 3618.0, 3670.8, and 3688.7. The three bands λλ 3618.0, 3670.8, and 3688.7 are now definitely attributed to the $^1\Pi \rightarrow {}^1\Pi$ system of C_2.[47] The three tail emissions which are found near these wave lengths extend into the tail in a way which is quite different from the Swan bands of C_2. The coincidences appear purely accidental.

Many other molecules, such as BH, BO, SO, CaO, etc., showing wave-length coincidences can be rejected.

VIII. SUMMARY OF CONCLUSIONS

In this paper it has been necessary to discuss the observational data in a number of small parts, from each of which conclusions have been drawn, some tentative, some

[44] M. W. Feast, *Nature*, **162**, 214, 1948; *Proc. Phys. Soc., A*, **62**, 114, 1949; G. A. Hombeck, *J. Chem. Phys.*, **16**, 845 and 1005, 1948; H. G. Wolfhard and A. G. Gaydon, *Nature*, **164**, 23, 1949.

[45] The forbidden Cameron system, which is an intercombination to the ground state, is not found; the bands in the observed region are $(0, v'')$ with $9 \leq v'' \leq 13$.

[46] *Phys. Rev.*, **52**, 638, 1937.

[47] Herzberg and Sutton, *Canadian J. Res., A*, **18**, 74, 1940, and J. G. Phillips, unpublished.

definite, some negative, and some positive. At the risk of misrepresenting the tentative nature of some of these, we list them here briefly for the benefit of the reader.

In Section IV, concerned with the far ultraviolet spectrum, the following observations are noted:

a) The (0, 0) band of OH $^2\Sigma^+ \rightarrow {}^2\Pi_{\text{inv}}$ shows the rotational level $J' = 3$ underpopulated, probably due to absorption lines in the exciting (solar) spectrum.

b) The (0, 0) band of CH $c^2\Sigma \rightarrow x^2\Pi$ is probably present, though weak, and blended with OH (1, 1).

c) The (0, 0) band of NH $^3\Pi \rightarrow {}^3\Sigma$ shows low population in rotational levels with $K' > 2$, and the (1, 1) band is probably absent.

d) The OH bands are strong in several comets at heliocentric distances greater than 1 A.U., where H_2O, the presumed parent-molecule, would be entirely in the form of ice, with almost zero vapor pressure.

e) The intensity ratio OH/NH decreases in several comets as heliocentric distance decreases.

f) The (0, 0) band of OH^+ $^3\Pi_i \rightarrow {}^3\Sigma^-$ at λ 3563 is possibly present in Comet Bester.

In Section V, concerned with the blue region of the spectrum, the following are noted:

a) Twenty lines of the "λ 4050 group" are all limited to the nucleus, and all show the same intensity variations in Comet Bester; they probably all arise from the same molecule or ion.

b) The (1, 0) lines of CH^+ at λ 3962 and λ 3972 are present.

In Section VI, concerned with the visual and infrared regions of the spectrum, the following are noted:

a) The presence of λ 7906 is confirmed in Comet Bester, and, although the explanation of its intensity is difficult, it is identified for the present with the (2, 0) band of CN $^2\Pi \rightarrow {}^2\Sigma$.

b) Partly confirming the above identification, the (6, 1), (4, 0), and (5, 1) bands of CN $^2\Pi \rightarrow {}^2\Sigma$ are tentatively identified in the red region.

c) The (4, 2), (4, 1), (3, 1), and (3, 0) bands of CN $^2\Pi \rightarrow {}^2\Sigma$ are possibly present in the infrared.

In Section VII, concerned with the tail spectrum of Comet Bester, the following are noted:

a) The CO^+ bands disappeared at heliocentric distance about 1 A.U.

b) Nine bands of the $A^2\Pi \rightarrow {}^2\Sigma$ system of CO^+ are observed, with widths and maxima consistent with a rotational temperature of 300° K. The (3, 0) band is the strongest, and the relative intensities observed differ markedly from laboratory intensities.

c) Four bands of CO^+ $B^2\Sigma \rightarrow A^2\Pi$ are present, though weak.

d) The (0, 0) band of N_2^+ $^2\Sigma \rightarrow {}^2\Sigma$ is strong, and its width indicates a rotational temperature higher than that for CO^+.

e) The three strong ultraviolet tail emissions λλ 3378, 3509, and 3674 are due to CO_2^+. This ionized molecule, which is identified for the first time in comet tails, extends into the tail to shorter distances from the head than CO^+ or N_2^+.

f) Other weak tail emissions are possibly due to the $B^3\Sigma \rightarrow x^3\Sigma$ system of O_2, but this identification is doubtful.