Cometary Spectra

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1. THE FIRST OBSERVATION OF A COMETARY SPECTRUM

One hundred years ago, on 1864 August 5 the first reported spectroscopic observation of a comet was made visually in Florence by Donati, (**1**) a keen discoverer and observer of comets who, on 1858 June 2, had discovered the famous comet of 1858 as it still was a tiny, faint and nebulous blob at 2·5 a.u. from the Earth. Donati's comet of 1858 became a very spectacular object, which in October 1858 exhibited a 60° long tail. It is thus not surprising that Donati, who had built a small visual spectroscope and adapted it to his refractor for stellar and nebular observations, wanted to see the spectrum of Tempel's comet (1864 II or 1864 a) which was discovered on 1864 July 4*. Since the object was fairly faint Donati had to use a wide slit. He reported his finding as follows: "The dark parts are larger than the luminous part, and one might say that these spectra are composed of three bright rays"; he found that the latter resembled the spectra produced by metals. In fact he had seen the bright Swan bands of carbon. Donati's successors confirmed his discovery that the brightness of the comets was really due to the radiation of these bodies.

2. VISUAL OBSERVATIONS OF COMETARY SPECTRA (1864–1881)

The pioneering two decades which followed Donati's discovery were characterized by the outstanding personality of one of the most brilliant astronomical spectroscopists of the nineteenth century, the English astronomer, Sir William Huggins. It is only natural that Huggins' attention had been drawn to the spectra of comets. In 1864, also one hundred years ago, Huggins had found that the planetary nebulae showed queer emission lines, the nebular lines†. He was wondering whether these two classes of nebulous objects, the planetary nebulae and the comets, could have spectroscopic similarities. Actually Huggins had observed and carefully measured the spectrum of carbon in 1864, again 100 years ago. He could not have failed to compare his laboratory observations with those of Donati. We shall see, in a moment, how excellent a comparison he actually made in 1868.

Comet Tempel 1866 I (or 1865 f) gave Huggins and Secchi their first chance to observe the spectrum of a comet. This object, which was the second to be observed spectroscopically, revealed to Huggins a continuous spectrum in addition to the three bright bands found by Donati. Huggins made this observation on 1866 January 9. (**2**)

Huggins became the most diligent investigator of cometary spectra of the sixties and seventies. During the six year period 1865–1871 he published papers on the spectra of six comets, an excellent average of one per year. Yet none of these comets was really outstandingly bright. On 1868 June 23, in the course of his spectroscopic study of Winnecke's comet 1868 II or b, (**3**) Huggins identified for the first time the three bands

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* Incidentally, Donati also discovered a comet (1864 I or 1864 b) on 1864 September 9.

† These lines were found by Huggins for the first time in the bright planetary in Draco, NGC 6543. When I embarked on a spectroscopic programme on planetary nebulae and their nuclei in 1940, I selected NGC 6543 as first object on my observing list not only for its special scientific interest, but also in memory of Huggins (P. Swings *Ap. J.*, **92**, 289, 1940).

discovered by Donati which he was able to assign to the Swan spectrum. His observational procedure was really a model of care. He placed side by side, in his eyepiece, the spectra of the comet and of a spark in olefiant gas producing the Swan bands. In this way he was able to observe the coincidences of the strongest (green) band to an accuracy equal to the separation of the D-doublet of sodium, which was about the limiting resolving power of his two 60° prism spectroscope. He added: "The apparent identity of the spectrum of the comet with that of carbon, rests not only on the coincidence of position in the spectrum of the bands but also upon the very remarkable resemblance of the corresponding bands in their general characters, and in their relative brightness. This is very noticeable in the middle band, where the gradation of brightness is not uniform". Huggins confirmed the coincidence two days later with a five prism spectroscope.

Huggins' discovery was remarkable and unexpected; it was discussed extensively in the decades that follow, especially by H. Kayser in 1894. (4) Actually Huggins was lucky in his comparison; only in the case of the C_2 bands is the profile of the cometary emission very similar to that of the laboratory bands! It would not have worked in the case of CH.*

Huggins' study of cometary spectra was conducted simultaneously with his work on the spectra of stars (in which he identified lines of various elements in 1868) and of planets. In his George Darwin lecture of 1933 V. M. Slipher stressed the great contribution made by Huggins in planetary spectroscopy. Incidentally Huggins had soon realized that the cometary emissions are completely different from those in nebulae. "The spectra of the gaseous nebulae consist of true lines, which become narrow as the slit is made narrower." On the contrary he could not resolve the cometary "bands" into "lines" when making the slit narrow. He also stressed the considerable differences of colour in the different parts of certain comets, and he related them to the spectra.

3. PHOTOGRAPHIC OBSERVATIONS: THE PIONEERING PERIOD (1881–1902)

The years 1881–1882 were characterized by the apparition of four bright comets which had a small perihelion distance: Cruls-Tebbutt (1881 III or b), Schaeberle (1881 IV or c), Wells (1882 I or a) and Cruls (1882 II or b) which were extensively observed. Approximately 80 papers were

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* Not all the observers proceeded as carefully as Huggins. Respighi, in his study of 1881 III and IV, went as far as doubting the existence of an emission spectrum. He claimed that the so called bright bands were simply due to the solar continuum as modified by great thicknesses of absorbing cometary layers.

published on the spectra of these four comets; this was a wonderful period for cometary spectroscopists.

Photographic plates were becoming available. Comet 1881 III was the first to be successfully photographed by the French astronomer Janssen. As for its spectrum it was photographed by Huggins (5) at Upper Tulse Hill on 1881 June 24, with an exposure of one hour. This first spectrogram revealed the violet and near ultraviolet region which, of course, could not have been seen. Next day Huggins obtained a second spectrogram, but it was weaker, although the exposure was 1½ hour. A few days later Henry Draper in New York obtained three spectrograms of the same comet with exposures of 180, 196 and 228 minutes. Huggins' spectrogram of June 24 revealed several emissions: the very strong band of cyanogen (CN), a group of emissions near $\lambda 4050$ (C_3), some emission near λ 4310 (CH) and between G and h (near 4220, probably 0, 1 of CN). Of the two observed bright "lines", $\lambda 3883$ and 3870 (the P and R branches of CN), $\lambda 3883$ was much stronger; a faint luminosity could be traced from it to a little beyond the 2nd line $\lambda 3870$*. On the reproduction of Huggins' spectrogram one sees the "4050 group" (C_3) which Huggins—too modestly—considers simply "suggested in the photograph". In addition this plate showed a continuum on which a few Fraunhofer lines appeared clearly. One may truly say that this spectrogram is of great historical value.

1881 III was also the first comet which revealed the D-emission of Na, but this doublet was then observed in the other three bright comets 1881 IV, 1882 I and 1882 II. It was even possible to determine the radial velocities of the comets on the basis of the measured wavelengths of the D-lines. In the very bright comet 1882 II, Lohse and Copeland observed visually emissions which they tentatively assigned to iron.

The second comet to be examined spectrographically was 1882 II. The visual observations became progressively replaced by photography, although important data were still obtained for many years by visual inspection, for example those of periodic Comet Brooks 2 by Campbell at the Lick Observatory. (6)

At the end of this second period the spectra of the heads of comets had revealed the presence of the emissions of carbon (C_2) and of cyanogen (CN), and of emissions near 4050 (C_3), 4310 (CH), and 4220 (CN), in addition to a solar spectrum showing its strongest Fraunhofer lines. Nothing definite was known about the spectrum of the tails, although the bright comets of 1881 and 1882 had shown spectacular tails; only the

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* These "cyanogen lines" had been observed in the laboratory by Liveing and Dewar at 3882·7 and 3870·5A; also the emission between G and h.

presence of a solar continuum and possibly of the D-doublet had been reported.

4. OBSERVATIONS WITH OBJECTIVE PRISMS (1902–1939)*

At the beginning of this century special dispersing instruments were equipped in order to study more systematically the spectra of comets, including their tails. These were especially developed and extensively applied in France by de la Baume Pluvinel and Baldet (Paris), and later by J. Dufay (Lyons), in the U.S. by Bobrovnikoff and in Russia by the Pulkovo group. Objective prism spectrograms were also obtained in Germany, the United Kingdom, Sweden, Belgium. Of course slit spectrograms continued to be obtained, but rather in a haphazard way, and much less frequently than objective prism spectrograms.

The objective prism, which was extensively applied to stellar spectroscopy, had been tentatively and rather unsuccessfully used for comets as early as 1881 by H. Draper†. In 1902 A. de la Baume Pluvinel constructed the equipment which is best adapted to comets, i.e. having a high angular dispersion and a short focal length. He obtained his first spectrogram (1902 III) with a one-hour exposure; he then observed 1903 IV with the same technique; so did E. C. Pickering for 1904 I.

Baldet began his systematic observations with the objective prism in 1907. His first instrument was extremely modest: 8 cm aperture, 30 cm focal length, 20° prism. The first comet investigated was 1907 IV (Daniel) which had a tail extending over 23°. The latter revealed a continuous spectrum, plus three diffuse maxima (CO^+). Actually the spectrum of 1907 IV was obtained at various observatories, and revealed discrete tail emissions for the first time. The first ultraviolet tail emissions (to λ 3580) were observed by Evershed at Kodaikanal.

The most remarkable objective prism spectra of tails were obtained for Comet Morehouse (1908 III), an extraordinary object which, although it remained telescopic during almost the whole observing period (maximum brightness 5·5), proved highly "actinic", and displayed a spectacular tail. The spectra of C_2 and CN were concentrated in the coma. The tail revealed striking emissions, mainly in the form of doublets, which were studied by many observers, especially by Baldet; there was no overlying continuum in the tail. These doublets of Comet Morehouse were first reproduced in the laboratory by A. Fowler in 1909, and later assigned to CO^+. The only other emission observed in the early tail spectrograms was that of N_2^+.

Comet Halley gave also an opportunity for obtaining slit- and objective prism-spectrograms. Many comets appearing during the period 1902–1939 were studied with the objective prism, with increasing spectral resolution, also extending the spectral range toward the visual region.

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* For a complete bibliography of this period see references in (7).

† Draper placed his prism in the converging beam, instead of in front of the lens.

5. ULTRAVIOLET AND INFRARED SPECTRA; SLIT SPECTROGRAMS OF LOW DISPERSION (1939–1957)*

The increasing interest in molecular astrophysics, the close relations between comets, late type stars and interstellar matter, the probability that comets would sooner or later become of great cosmogonical interest; these were a few of the essential factors which led to the formation around 1940 of a few astronomical groups devoting a great deal of attention to comets. One should also add the relations of cometary investigations to the studies of meteors, the phenomena of combustion and flames, low temperature physics, and fluorescence processes. It was becoming clear that comets have interesting relations to solar activity. At that time a few telescopes had been equipped with fast spectrographs, covering the near ultraviolet and near infrared as well as the ordinary spectral region. A programme of systematic spectrographic investigations of comets was inaugurated at the McDonald Observatory; it was pursued over a dozen years. Another programme was started at the Dominion Astrophysical Observatory in Victoria, under the direction of the late Andrew McKellar. An important effort was carried on at the Haute Provence Observatory as soon as conditions permitted. There were other investigators at Cordoba, Perkins, Michigan, Mt Wilson, Lowell, and elsewhere.

The first progress took place in the ultraviolet region. The McDonald ultraviolet spectrograms of Comet Cunningham (1941 I) revealed OH- and NH-bands whose detailed rotational structure corresponded to a low temperature. These resolved emissions were certainly identical with the diffuse† bands observed by Lockyer in Comet Brooks (1911 V) and by van Biesbroeck and Henyey in Comet Encke (1937 VI); but no identification was possible as long as the fine structure was not resolved. Indeed R. C. Johnson in 1927 had suggested that the bands observed by Lockyer belong to the second positive system of N_2: he was entirely wrong.

The moments of inertia of OH and NH do not differ much from that of

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* For a bibliography of this period see ref. (8).

† This diffuse character was of course purely of instrumental origin.

CH*, but are much smaller than that of CN. Therefore at equal temperatures OH, NH and CH show easily resolved lines, as compared to the many closely spaced lines of CN.

The slit spectrograms obtained around 1940 revealed features within the CN band near $\lambda 3870$ which seemed to have escaped previous detection. Old spectrograms of Comets Daniel (1907 IV), Brooks (1911 V), and others had already shown that the profiles of the (0, 0) band of CN in comets differ markedly from the laboratory profiles, even at low temperature. The spectrograms of higher resolution obtained at McDonald and Victoria revealed a progressively more detailed rotational structure which appeared more and more anomalous†. We shall see that these efforts culminated recently in a practically full resolution of the (0, 0) band.

The structure of the "4050 group" became better resolved; it turned out that this system is also present in absorption in the coolest carbon stars. After many fruitless attempts it was finally assigned convincingly to the C_3-molecule. The astronomical information was of help in reproducing the band in the laboratory and in finding its assignment.

Emissions at $\lambda\lambda 4231$, 4238, and 4254 observed in several comets were assigned to CH^+ (one of the interstellar molecules!). Strong lines of a second triatomic molecule, NH_2, were found in the visual region; the strongest emission is at $\lambda 6300$. This triatomic radical behaves like C_3. As an example: in 1943 I (or 1942 g), at a heliocentric distance $r = 1{\cdot}40$ a.u. there is no trace of CH, and the NH and C_2 bands are weak, but $\lambda 6300$ and $\lambda 4051$ are both quite strong. We shall discuss later on the case of the isotopic bands of $C^{12}C^{13}$.

In several cases extensive programmes could be planned a long time in advance. This was the case, for example, of Comet Bester (1948 I or 1947 k) for which spectrograms covering the region $\lambda 3070$–$\lambda 8760$ over a wide range of r (from 0·8 to 1·55 a.u.) could be obtained, including tail spectra. In this way variations of relative intensities with the heliocentric distance could be investigated: it turned out that the ratios CN/C_2, C_3/CH, C_3/CN, C_3/C_2 and OH/NH increased regularly with increasing r.

In the course of this work it was becoming clear that there was a real need for observations in the near infrared region, even with a modest dispersion (say 300 A/mm). This could be done only at the time of the apparition of a bright comet when sufficiently sensitive infrared emulsions could be used in the most luminous spectrographs. A combination of these three favourable circumstances took place in 1947. The great southern comet 1947 XII was observed at McDonald on hypersensitized N-emulsion with a grating spectrograph having an f/0·65 camera of the solid Schmidt type. The first spectrogram (1947 Dec. 15·05,) revealed two strong emissions near $\lambda 7906$ and $\lambda 8106$. These were observed on successive evenings; they were confirmed in later comets, especially 1948 I and 1957 V. Their assignment gave rise to difficulties. There were wavelength coincidences with vibration-rotation bands of polyatomic molecules, such as NH_3, HCN and C_2H_2. But Herzberg raised a general objection against any assignment to a vibration-rotation transition: if such a band of low probability were found in emission there should be much stronger ultraviolet absorption bands and the latter would lead to photodissociation. There were also coincidences with bands due to diatomic molecules (C_2, CN, . . .). Among these it was finally demonstrated that the observed emissions are due to the (2, 0) and (3, 1) transitions of the red system of CN.

During this period great progress was also made in our knowledge of the spectra of the tails. The only slit spectrograms obtained before 1940 had been those of Comets Morehouse (1908 III or 1908 c) and Brooks (1911 V or 1911 c); they covered the region $\lambda 3850$–$\lambda 4800$ and had very low resolution. In the near ultraviolet only objective prism spectrograms had been obtained, and their low resolution did not permit any convincing assignment, except a few strong CO^+ emissions.

A slit spectrogram of the tail of 1941 I was obtained at McDonald, but it was quite weak. The best material was secured on Comet Bester (1948 I) for which an elaborate observing campaign had been prepared. The spectrograph employed to obtain the infrared spectrograms of 1947 XII was also used for a dozen tail spectra of 1948 I, the slit being oriented along the tail, and extending approximately 4·5 minutes of arc from the nucleus; the dispersion was 330 A/mm.

These tail spectra showed the expected bands of the comet tail system of CO^+, but there were definite differences of relative intensities in comparison with the laboratory spectrum of CO^+. N_2^+ was also present as expected. In addition the Baldet-Johnson system of CO^+ was weakly present. The most important new observation was the presence of fairly strong bands of CO_2^+ in the near ultraviolet. A new abundant ion, CO_2^+, had thus been added to the two well known CO^+ and N_2^+.

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* The presence of CH lines of low rotational quantum number had been suspected for many years (Bobrovnikoff, 1931); it had been fully accepted since Nicolet (1933) demonstrated the excellent agreement between the cometary wavelengths and the first R, Q and P lines of the $A\,^2\Delta \rightarrow X\,^2\Pi$ spectrum of CH. Dufay (1938) had also identified the $B\,^2\Sigma \rightarrow X\,^2\Pi$ band near $\lambda 3900$.

† Certain anomalies had already been observed by J. Dufay on objective prism spectrograms. Dufay had also found that there is a continuous increase in the rotational quantum number corresponding to the intensity maximum, with decreasing heliocentric distance.

CO_2^+ extends into the tail to shorter distances from the head than CO^+ or N_2^+.

All our essential data on cometary spectra until 1956 have been compiled in an *Atlas of Representative Cometary Spectra*, which covers the region λ3000–λ6800. I refer to this Atlas for the descriptive details not given in the preceding remarks. The Atlas describes also the behaviour of the emissions of the head at different heliocentric distances; the usual development of the spectrum; the behaviour of the emissions of the tail; the relative intensities of the CN, C_2, CH and C_3 bands in the spectra of different comets[*]; the relations between the spectroscopic and integrated observations; and finally a comparison between the spectra of comets and the spectra of N-stars, aurorae, twilight glow, nightglow and combustion phenomena. There is not much I could add to these descriptions.

Before we describe the fifth period characterized by the use of high spectral and spatial resolution we should give the essential points regarding the main excitation mechanism. On several occasions in the earlier part of this lecture I have stressed the fact that the intensity distributions within the cometary bands of CN differ from those found in laboratory sources even at low temperatures. Until 1941 numerous fruitless attempts had been made to interpret these peculiar distributions. The CN band near λ3880 provides a striking illustration. Instead of showing smooth rotational intensity distributions within the P-branch (forming the head on the longward side) and the shortward degraded R-branch, cometary spectra reveal complex CN profiles. Even with moderately low dispersions the P-branch presents at least two maxima, one near P(3) and one near the head, with a deep minimum around P(5); similarly the R branch has a maximum near R(1) and a deep minimum around R(3). Different comets differ in the profile of CN bands. At times it was thought that the comet head contained two or more kinds of CN radicals, resulting from the photo-dissociation of different parent molecules and having different rotational temperatures. It was also suggested that the selectivity was similar to that observed by Herzberg in the laboratory in exciting the CN bands in active nitrogen. With higher resolution the structure appears even more complex. If the rotational structure is resolved, the individual CN lines follow each other with most irregular intensities. Similar, although less striking, results are observed for CH, OH, and CH^+, as well as for the other bands of the violet system of CN.

The general interpretation of these complex profiles was given in 1942. It has usually been assumed in recent years that the main molecular bands, and also the Na lines, are emitted in a fluorescence process excited by solar radiation. This suggestion was actually put forward by K. Schwarzschild and Kron in 1911, and developed theoretically by Zanstra in 1928 and by Wurm in 1934. The main result of Zanstra and Wurm is that the observed luminosities of comets having strong emission spectra are of the order of those calculated on the basis of a fluorescence excitation. All the cometary phenomena indicate also that collisional effects must be unimportant in cometary atmospheres.

An observational test of the fluorescence hypothesis was provided by Öhman's measurements of polarization which do indicate that fluorescence is operative in comets[*].

Let us assume that the excitation of the CN cometary molecules is due exclusively to the absorption of solar radiation. The population in an excited rotational level K′, from which the two emission lines P(K′+1) and R(K′−1) arise, can then be expressed as follows[†]:

$$N'_{\mathrm{K}} \propto N''_{\mathrm{K}'+1} \cdot p_{\mathrm{P}}^{\mathrm{abs.}} \cdot I_{\mathrm{P}} + N''_{\mathrm{K}'-1} \cdot p_{\mathrm{R}}^{\mathrm{abs.}} \cdot I_{\mathrm{R}} \tag{1}$$

where $N''_{\mathrm{K}'-1}$ and $N''_{\mathrm{K}'+1}$ are the populations in the rotational levels $\mathrm{K}'' = \mathrm{K}' - 1$ and $\mathrm{K}'' = \mathrm{K}' + 1$ of the ground electronic and vibrational state; $p_{\mathrm{P}}^{\mathrm{abs.}}$ and $p_{\mathrm{R}}^{\mathrm{abs.}}$ the transition probabilities of the absorption lines P(K′+1) and R(K′−1); and I_{P} and I_{R} the intensities of solar radiation for the wavelengths of P(K′+1) and R(K′−1), corrected for the radial velocity of the Sun with respect to the comet (ordinarily this correction is of the order of ± 0·25 A).

Whatever the distribution $N''_{\mathrm{K}''}$ may be, $N'_{\mathrm{K}'}$ will depend on the profile of the solar radiation. If one plots the wavelengths of P and R lines on the Utrecht *Photometric Atlas of the Solar Spectrum*, it appears strikingly that the deep minima in the solar spectrum in the region of P(6) and P(7) and between R(2) and R(7), due to strong Fraunhofer lines, are undoubtedly the cause of the very low intensity of the cometary P and R lines corresponding to $3 < \mathrm{K}' < 8$. Whatever the radial velocity of the comet relative to the Sun may be, P(6) and P(7) will always fall in a deep minimum of the solar spectrum, caused mainly by λ3878·02 (Fe I, solar int. 8) and λ3878·57 (Fe I, solar int. 7). By examining carefully the solar absorption lines it is possible to explain qualitatively in a convincing manner the observed structures in cometary bands. The radial velocity may have an important effect in bringing a specific cometary absorption line inside or outside a strong Fraunhofer line. It was known that comets

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[*] Marked spectral differences between individual objects are observed. However we have no convincing clue as to possible genetic families of comets as yet; such information would be of interest for cosmogony.

[*] The first observation of polarization in a comet was made by Arago in 1835 (Halley's Comet). Others were made by Wright on 1881 III and 1881 IV.

[†] This assumes that the molecules in the ground electronic level are all in the lowest vibrational state. In general there should be a summation over the different v″-levels, account being taken of the different absorption probabilities.

observed at the same heliocentric distance sometimes showed different CN-profiles; these differences are explained by radial velocity effects. Similar considerations may be applied to the other molecules: OH, NH, CH, C_2, etc.

The first more or less quantitative tests of this hypothesis were made by McKellar for the CN and CH bands of Comets 1939 III (Jurlof), 1941 I (Cunningham), and 1943 I (Whipple). McKellar adopted a Boltzmann type of distribution for the rotational levels of CN in the ground state. The "rotational CN temperatures" were chosen to give the best agreement in wavelength between the observed main maximum of the P branch of the (0, 0) band of CN and the corresponding maximum of the computed intensity curve. In applying formula (1) the intensities were taken from the Utrecht *Photometric Atlas of the Solar Spectrum* with due correction for radial velocity shift. The computed relative intensities of the emission lines were then plotted as rectangles of a height proportional to the calculated intensity and a width equal to the projected spectrographic slit width. A few transformations of the calculated diagrams were applied in order to make them as nearly comparable as possible with actual profiles. Every observed apparent maximum has its corresponding counterpart in the calculated profiles. Had the effect of the contour of the solar spectrum been neglected, the calculated profiles would have been smooth with no subordinate maxima.

These results provided the most direct observational proof of the fluorescence mechanism of cometary emission.

The radial velocity of the comet relative to the Sun affects considerably the rotational profiles. This effect has been found for CN, OH, NH, and CH. It may even influence appreciably the total intensity of a cometary band. The heliocentric distance r also affects the profiles: there is an increase in "rotational temperature" of the CN molecules as r decreases. This effect had been found previously, but became more clearly defined. The "rotational temperatures" found for CN are of the order of 300 or 400° K, depending on r.

When the rotational structure of CN had been totally or partially resolved, the observed intensities of the individual CN lines agreed fairly well with the theoretically expected values.

Qualitatively the resonance mechanism explains readily the profiles of the CN, CH, OH, NH, and CH^+ bands. Quantitative discussions beside those of McKellar have been performed by J. Hunaerts, J. Dufay, Fehrenbach and Courtès and others. At first a Boltzmann distribution among the rotational levels of the ground electronic state was assumed. Actually such an assumption is not justified, since the conditions for thermodynamic equilibrium are not fulfilled (no collision!). A first logical extension consists in obtaining from the observed intensity profile of a given molecular band the distribution of molecules among the rotational levels of the excited electronic state involved in its production; from this, assuming the resonance mechanism, one may derive the relative populations on the rotational levels of the ground electronic state. Such work was done by McKellar for the CH molecule, using the λ4315 band as observed in the spectrum of Comet 1941 I at $r = 0{\cdot}54$ a.u. McKellar found that nearly all the CH molecules exist in the two lowest rotational levels, $K'' = 1$ and $K'' = 2$, of the normal $^2\Pi$ state. Poloskov has also contributed to this problem.

In the absence of collisional effects, the primary mechanism which is involved in populating the vibrational and rotational levels of the ground electronic state is the absorption of solar radiation. This point was stressed by Wurm and may easily be illustrated in the case of the (0, 0) violet band of CN which has no Q-branch. In absorption, the R(K) line is stronger than P(K); this tends to overpopulate the level $K' = K+1$ relative to $K' = K-1$ in the excited electronic state. In the emission from $K' = K+1$, the P(K+2) line is stronger than R(K): this tends to populate the higher K'' levels. If the solar radiation did not have absorption lines, we should expect a smooth distribution among the rotational levels. Whether this distribution would be of the low- or of the high-temperature type depends on the depopulating process. Downward transitions between rotational levels belong to the pure rotational far infra-red spectrum. If this spectrum is theoretically permitted—which is the case for heteronuclear diatomic molecules—the downward transitions will be able to depopulate the K'' levels. The deciding factors are evidently the relative values of the time between successive absorption processes and the lifetime of the rotational states. We may thus understand why the bands of CH, OH, NH, CN, and CH^+ have, on the whole, low temperature rotational distributions. Of course, beside the heliocentric distance, the individual characteristics of the molecules are also of utmost importance in determining the actual distributions. These characteristics are mainly the dipole moments and the band structure (e.g., the presence of a strong Q branch, as in CH, reduces the tendency of molecules to reach higher K values).

The situation is quite different for a homonuclear molecule such as $C^{12}C^{12}$, for which the pure rotational spectrum is forbidden. Molecules may then accumulate on higher rotational levels and simulate a high-temperature rotational distribution. Considerations of a similar character apply to the vibrational levels.

It is easily seen that, as a result of the influence of the solar absorption lines, a more or less irregular distribution amongst the rotational states

K″ may be brought about. This explains McKellar's result in the case of the CH molecules.

These considerations illustrate the artificial character of the concepts of vibrational and rotational "temperatures" of cometary bands. The "temperatures" obtained from different molecules may differ considerably. At the same heliocentric distance the rotational temperature which best fits a CN profile may be 435 °K, while the CH profile would require 200 °K.

Until 1957 the structures of the Swan bands had not been resolved. The observed profiles of the integrated bands had been studied by various authors; the rotational and vibrational temperatures thus obtained for the lower electronic level agreed fairly well and were of the order of 3000–4000 °K. But the observed profiles were not fully explained.

These considerations show that identification should proceed with great caution, since the intensities in comets may differ so much from those in the laboratory. Wavelength coincidences are only a first indication. The final test of an identification should be based on the subdivision of the exciting radiation into a number of monochromatic excitations. The excited pattern is the superposition of resonance doublets (or singlets or triplets according to the type of electronic transition), each consisting of a P- and an R-line, and each having a specific intensity. We should thus not expect the pattern to resemble closely the intensity distribution in a laboratory spectrum, even in a low temperature source. "Synthetic profiles" are of the greatest help. If fluorescence is completely or partially absent for a band, it would be observable in the profile of the band and in its polarization.

In recent years all these considerations have been considerably clarified, as will be shown shortly.

6. THE USE OF HIGH SPECTRAL AND GEOMETRICAL RESOLUTION (1957 ONWARDS)

From the beginning of the fourth period of observations (Section 5 above) it was realized by all workers in the field that there was a great need for the highest resolution possible, and that coudé-spectrograms of bright comets would certainly supply much information on the physical conditions in these objects. Commission 15 of the International Astronomical Union had stressed this necessity in all its reports of the last fifteen years. Since 1957 several bright comets have been observed with high spectral and geometrical resolution at the coudé foci of the Palomar, Mt Wilson and Haute Provence Observatories (See Plates 1 to 4, OHP spectrograms); a few interesting spectrograms have also been obtained at the Radcliffe Observatory. The first high resolution spectra were

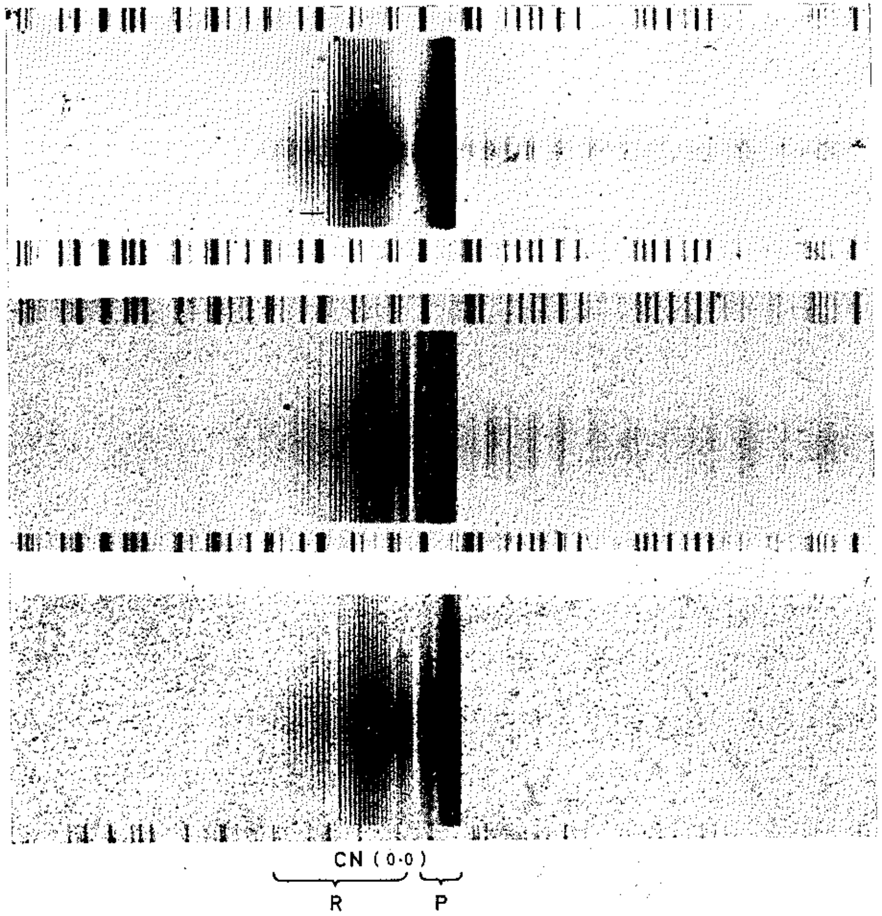

PLATE 2.—(0–0) band of CN in Comets Ikeya, 1963 a ($r=0{\cdot}66$ and 0·73 a.u.) and Seki-Lines, 1962 III ($r=0{\cdot}55$); bands of CH and C_3 in Comet Ikeya.

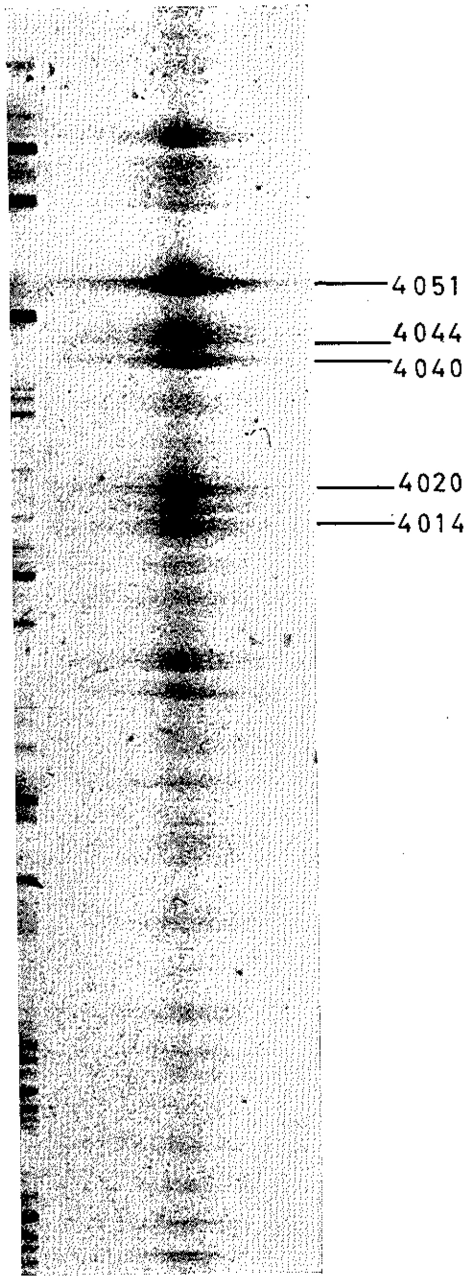

PLATE 3.—Emission of C_3 in Comet Burnham, 1960 II ($r=0{\cdot}94$ a.u.).

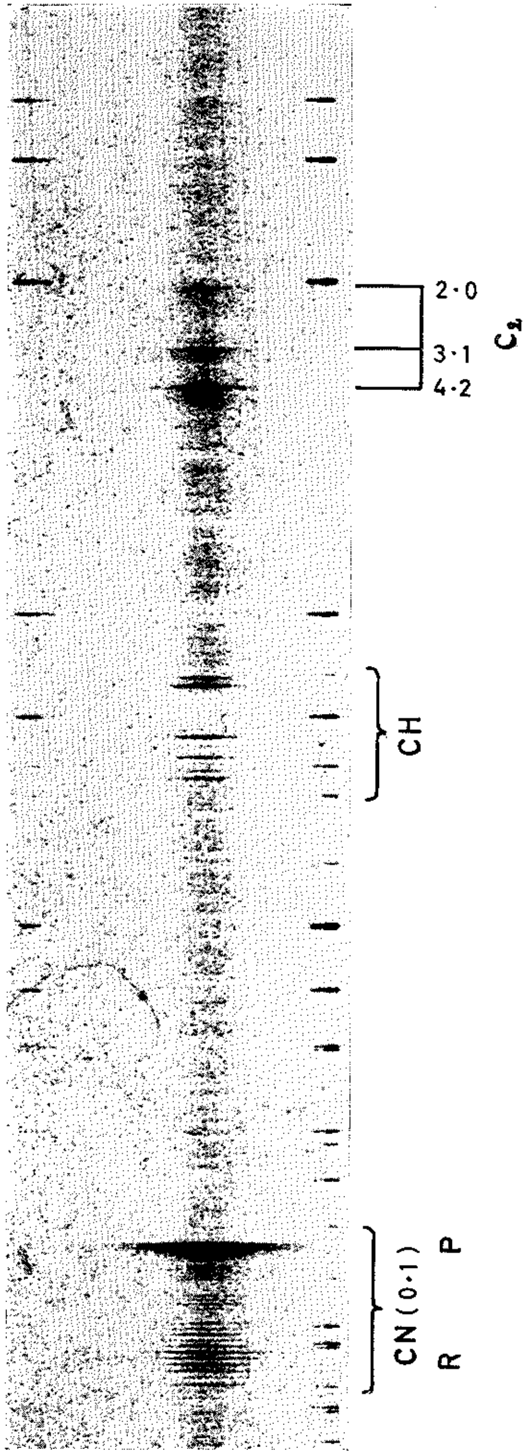

PLATE 4.—(0–1) band of CN, $^2\Delta \rightarrow {^2\Pi}$ emission of CH and $\Delta v=+2$ system of C_2 in Comet Seki-Lines, 1962 III ($r=0{\cdot}55$ a.u.).

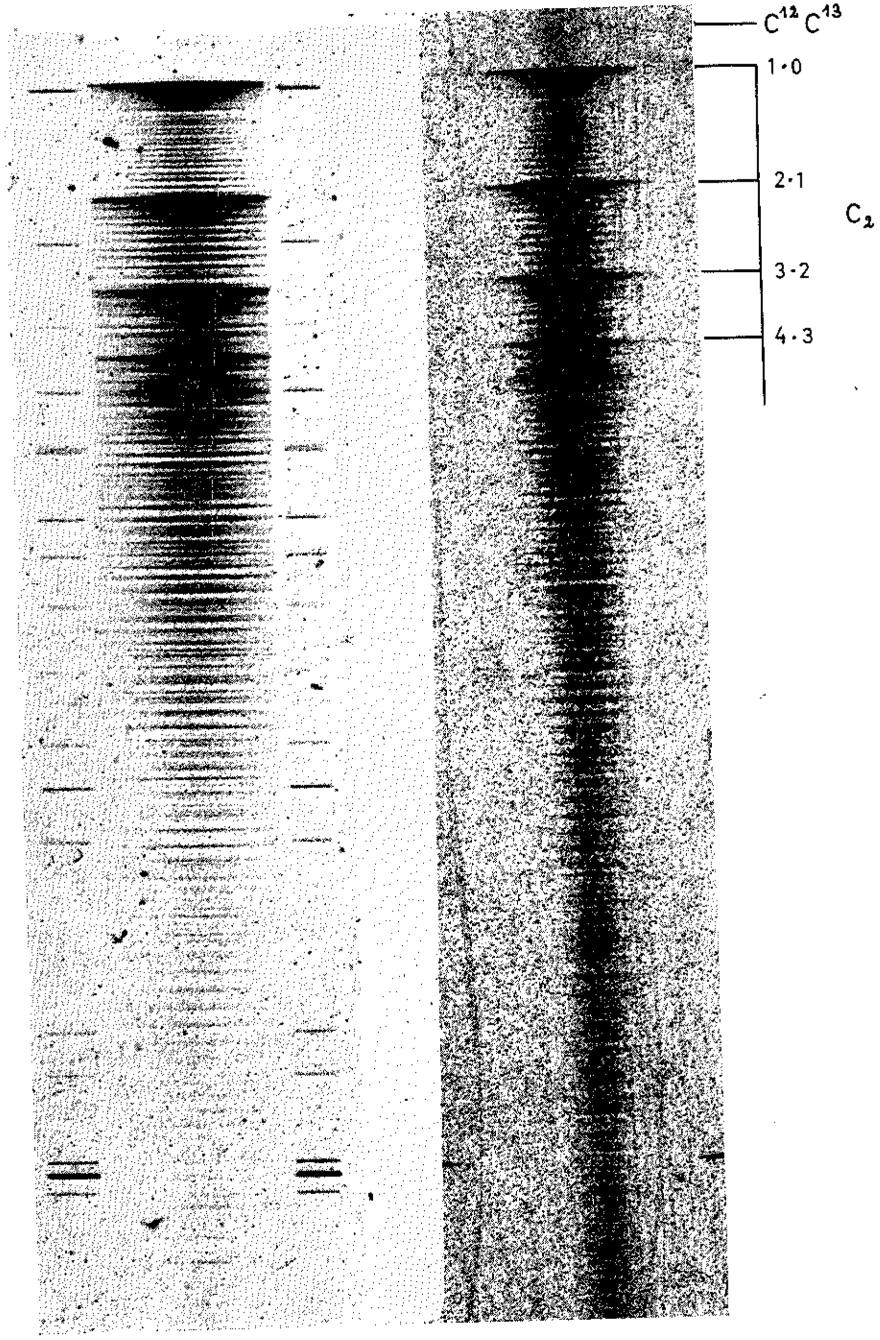

PLATE 5.—$\Delta v = +1$ sequence of C_2 in Comet Ikeya, 1963 a ($r = 0{\cdot}73$ a.u.) and Seki-Lines, 1962 III ($r = 0{\cdot}55$).

obtained for comet Mrkos (1957 V) by Greenstein (**9**) at the coudé focus of the 200-inch Palomar reflector. Coudé spectrograms were obtained with dispersions of 18 Å/mm in the blue and 26 Å/mm in the red.

The focal length of 152 metres gave an original scale of 1″·3/mm on the slit; 1 mm on the plate (dispersion 18 Å/mm) corresponded to 26″ (or 20000 km at the comet). The high spatial resolution and the high dispersion provided for the first time information on velocities near the nucleus. In the following years high dispersion spectrograms were also obtained at Palomar for comets Seki-Lines (1962 III) (**10**), Humason (1962 VIII) (**11**) and Ikeya (1963a), and at Mt Wilson for comet Wilson-Hubbard (1961 V). (**12**)

Since 1960 the coudé spectrographs of the 193-cm reflector at the Haute Provence Observatory have been used for various comets, especially comets Burnham (1960 II) (**13**), Encke (1961 I) (**14**), Candy (1961 II) (**15**), Wilson-Hubbard (1961 V) (**16**), Humason (1962 VIII) (**17**), Seki-Lines (1962 III) (**18**), Honda (1962 IV) (**19**), and Ikeya (1963a) (**20**). The coudé focal length at the Haute Provence Observatory is 59 metres giving an original scale of about 3″/mm on the slit.*

Spectra of comets Humason (1962 VIII) and Seki-Lines (1962 III) have been obtained with fairly high dispersions (86 Å/mm for 1962 VIII and 31 Å/mm for 1962 III) at the Radcliffe Observatory. (**21**)

For the first time the coudé spectrograms obtained at Palomar revealed physical and dynamical phenomena regarding the molecules and the solid particles in the central part of the head within a few thousand kilometres of the nucleus while the radius of the comet was of the order of 200 000 km and the length of the tail about 10^7 km. We shall describe later on the "Greenstein Effect": there are marked changes in the intensity ratios of certain lines of CN or CH, from one location in the head to another, due to differences in radial velocities relative to the Sun. The "dust" and the sodium atoms of comet Mrkos (1957 V) were ejected from the nucleus more strongly on the sunward side. The dust disappears gradually in the first 3 000–8 000 km sunward from the nucleus,† but has a sharp boundary

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* To secure maximum advantage of these long focal lengths accurate guiding is, of course, imperative if information on the differential motions and the distributions is desired.

† This is related to another recent observation by Dossin (**22**) at the coudé focus of the 193-cm instrument at the Haute Provence Observatory. Dossin observed that stars were appreciably dimmed (order of 1·5 mag.) when observed through comet Burnham (1960 II) very close to the nucleus at a distance of the order of 600 km (or 4 sec of arc). This effect is due to scattering by the cometary "dust". Observations had never been made with such long focal lengths before 1957. In Dossin's observations the observing field was of the order of 9′; the head had a diameter of about 30′ and the

on the tailward side at a distance of about 3 000 km from the nucleus. Actually, the Na I lines reach their intensity maximum at a distance of 2 000 km sunward from the nucleus; they then taper off to nearly zero at 12 000 km sunward. On the tailward side they show a relatively low brightness gradient beginning at about 4 000 km; they are observed (on a Mt Wilson spectrogram) out to 50 000 km in the tail. We shall see later how this distribution has been interpreted by Wurm.

The discovery of [O I] in 1957 V is also partly due to the spatial resolution and the accurate guiding (**23**). [O I] resembles NaI in distribution; it extends far into the tail, to about 50 000 km. Similar observations of differences in intensity distribution of various molecules in the central parts of cometary heads have been made at the coudé focus of the Haute Provence Observatory. As an example CH^+ appears only on one side of the nucleus on the Haute Provence Observatory spectrograms of 1960 II.

The high resolution, used on many occasions since 1957, presents many advantages in cometary spectroscopy: (1) it reveals or improves the rotational structures of the bands; (2) it reduces the number of blends and the effect of the continuum relative to the discrete emissions; (3) it reveals weak emissions which otherwise would be drowned in the continuum or in stronger emissions; and (4) it increases the precision of the measured wavelengths and velocities. These improvements are added to those which accrue from the simultaneous increase in spatial resolution; for example, a better wavelength and the simultaneous information on the length of the line (i.e. of the extension of the corresponding molecule or atom into the head) may give rise to new identifications.

The Palomar spectrograms of Comet Mrkos (1957 V) have been the subject of numerous investigations (**24**); yet this comet, which had a very strong continuum, was not favourable for the detection or measurement of weak emissions, especially those concentrated in the central parts of the head, such as NH_2, C_3 or CH. We shall see that other comets had a weak continuum, hence were much more favourable for pure spectroscopic investigations. Yet, since the Palomar spectrograms were the first ever obtained with high resolution, and since their optical quality and their guiding were superb, several workers endeavoured to gain the maximum of information out of this material. For the first time the R-branches of the (0–0) and (0–1) bands of CN were fully resolved, and some structure was obtained in the P-branches. The C_2 and NH_2 bands were resolved to a considerable extent. Better descriptions of many emission bands were possible. The new possibilities for the study of the excitation mechanism will be discussed later on. A trace of the (1–0) band of the isotopic molecule $C^{12}C^{13}$ was found at λ4744·35; similar observations had been made previously, and better evidence has been gained in more recent comets. Valuable information on the C_3 group was obtained, although later data obtained at the Haute Provence Observatory with comets having a very weak continuum were more reliable and detailed.

The second comet to be studied with high resolution is comet Burnham (1960 II) which was observed at the Haute Provence Observatory from $r = 0{\cdot}77$ to $1{\cdot}09$ a.u.; the whole region λ3000–λ8900 was covered with dispersions ranging from 19·5 A/mm to 78 A/mm. The continuum was weak and narrow, hence this comet was better adapted to the detection of weak lines than comet Mrkos. 1960 II belongs to the fairly infrequent group of comets in which OH is definitely stronger than NH; moreover NH extends into the head to shorter distances than OH, which seems to extend even farther than C_2. This is quite anomalous at $r \sim 1$. Indeed, we know of only one other comet in which OH and NH behaved similarly, namely, 1943 I, but the corresponding heliocentric distance was greater (1·55). In 1941 VIII, OH was stronger than NH in the central part, but was shorter; r varied from 1·52 to 1·28. The relative behaviour of NH and OH will certainly be of great importance for the classification of comets. Most probably it is related to differences in chemical composition and origin of the comets. It is essential to cover the region λ3070–λ3375 whenever possible, always keeping in mind the possible effects of atmospheric and instrumental absorption. The Haute Provence Observatory spectrograms of 1960 II reveal a more detailed rotational structure of the (0–0) band of OH than any previous cometary spectrogram. This profile of OH differs considerably from that in 1941 I and 1948 I, on account of differences in the radial velocity of the exciting solar radiation. Actually, a difference of 3 or 4 km/sec in radial velocity modifies the profile considerably.*

The C_3 band is very strong (λ4051 stronger than the head of 1–0 of C_2). The strongest emission near λ4050 is double: two maxima are measured at λ4051·12 and λ4051·57. The first component is due to the R-branch, the second to the Q-branch. The P-branch gives rise to an

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displacement of the star relative to the comet was about 20′/hr. Comet Burnham came close to the Earth ($\Delta = 0{\cdot}2$ A.U.). Similar observations of conjunctions of stars with Halley's Comet were made in 1835 by Struve and by Bessel; they revealed neither a perceptible diminution of the brightness of stars nor a deflection due to refraction. Observation of stars in the field of Comet Pons-Winnecke by van Biesbroeck in 1927 gave no indication of shifting of the stars seen through the head. Dossin's work should be pursued with more accurate photometry.

* A few paragraphs of this section and from Sections 8 and 9 have been taken from my article "Astronautical Investigations of Comets" in Volume 7 of *Advances in Space Science and Technology*, published by Academic Press Inc., New York and edited by F. I. Ordway, III.

inflexion in the red wing of λ4051·57. In a general way the cometary profile may be explained by assuming a low temperature of the C_3-radicals. The cometary emission near λ4073 exhibits the same double character as λ4050 (R-maximum at λ4072·6; Q-maximum at λ4073·5; secondary P-maximum near λ4074·4). There is no cometary emission between λ4056·5 and λ4062, while the laboratory spectrum reveals strong lines Q(45) to Q(65) in this region. This also indicates a low cometary temperature, which in fact gives rise to a Q-maximum intensity between Q(7) and Q(11). Several laboratory emission bands of C_3 (λλ4093·8; 4029·1; 4008·7–4007·6; 3944·9; 3939·4) are absent in the comet. The $B^2\Sigma^-$—$X^2\Pi$ system of CH is well resolved. Indeed, the Haute Provence Observatory spectroscopic material on 1960 II deserves a more thorough investigation, especially of the Swan bands, the C_3 group and the unidentified emissions; it is hoped that such an investigation will be carried out soon.

I shall not dwell on all the interesting spectroscopic details which have been revealed by the high resolution spectrograms of the recently observed comets. These have been summarized in my article in Rosseland's Memorial Volume. I shall only mention the cases of comets Humason (1962 VIII), Seki-Lines (1962 III) and Ikeya (1963a).

Comet Humason (1962 VIII) was a most unusual object. Despite its great heliocentric distance ($r \sim 2{\cdot}6$) it revealed an extremely strong emission of CO^+ and N_2^+; weak emission of the continuum; CO_2^+, CN, and C_3; and a trace of CH^+. Simultaneously, there was a tremendous activity in the tail. It should be noticed that CO^+, N_2^+, and CO_2^+ result from the ionization of the chemically stable molecules CO, N_2, and CO_2, while CN is due to the photodissociation of a parent molecule. The ionization of CO, N_2 and CO_2 may actually have resulted from anomalous collisional effects. As for the photodissociation, it proceeds much more slowly at $r = 2{\cdot}6$ than near the Sun (proportionally to r^{-2}). Most Haute Provence Observatory, Palomar, and Radcliffe spectrograms were of relatively low resolution. However, a Palomar plate had a dispersion of 18 Å/mm which, for the first time, revealed the rotational structures of the (3, 0) and (2, 0) bands of CO^+; in this way the excitation mechanism could be discussed as we shall see later.*

Comet Seki-Lines (1962 III) was observed at Haute Provence and Palomar Observatories ($r = 0{\cdot}55$ to $1{\cdot}01$), also at Radcliffe ($r = 0{\cdot}51$ to $0{\cdot}41$). For the first time the P-branch of the (0–0) and of CN was resolved to a considerable extent on a Haute Provence Observatory spectrogram of 10 Å/mm dispersion.

The most recently described high resolution cometary spectra are those of comet Ikeya (1963 a) obtained at the Haute Provence Observatory; the dispersions were 20 and 40 A/mm. The continuum was practically nonexistent, so that the discrete emissions could be studied in excellent conditions. Each of the $\Delta v = 1$ and 0 sequences of C_2 shows about 100 resolved components. The $C^{12}C^{13}$ (λ4744) band is present; and the abundance of C^{13} is much lower (order of 100) than that of C^{12}. The CN profiles differ considerably on spectrograms taken on 1963 March 4 ($r = 0{\cdot}726$; $dr/dt = -18{\cdot}6$ km/sec) and 1963 March 13 ($r = 0{\cdot}654$; $dr/dt = -9{\cdot}7$). The $B^2\Sigma$—$X^2\Pi$ transition of CH appears more clearly than ever before; the (0–0) band of CH^+ has also been measured. The most important result concerns C_3, which is more clearly resolved than on any previous spectrogram. OH is absent and NH very weak; the abundances of both radicals are abnormally low. An emission at λ4838·30 (also observed in 1957 V) is possibly due to HCO.

One of the most unexpected results is the important role played in cometary spectra by the forbidden lines of [O I]. The red doublet of [O I] was identified for the first time in comet Mrkos (1957 V). Assignment of a cometary emission to [O I] is not a simple matter for the following reasons. The strongest NH_2 emission (Q-branch of $0,8,0 \rightarrow 0,0,0$) has practically the same wavelength as the strongest component of the [O I] doublet, λ6300·23, while the weakest [O I] line λ6363·790 lies close to an NH_2 emission, λ6360·43. As for the green [O I] line λ5577 it falls in the (1,2) band of C_2. The [O I] lines of the twilight or nightglow may appear on long exposures; these sky lines should have the same intensity over the whole length of the slit, but photographic effects due to the cometary continuum may create an impression of intensity gradient along the lines.

Wavelength measurements in several comets (especially Mrkos and Seki-Lines) showed that the cometary emissions at λ6300 and λ6364 could not be assigned to the sky glow, but they could not exclude the possibility of an assignment of λ6300 to a blend of Q-lines of NH_2. This, however, was excluded since the λ6300 emission extended much farther into the head and tail than all other NH_2 emissions. In the case of comet Mrkos a weak emission measured at λ6363·87 cannot belong to NH_2 and is most probably due to λ6363·79 [O I]. As for the green [O I] line, it is probably present as a discrete weak line in comet Mrkos. On low dispersion spectrograms the assignments of emissions to cometary [O I] may be based only on their extension into the head and on their intensity gradient along their lengths. Such assignments must proceed very cautiously, on account of possible photographic effects on the twilight or nightglow

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* A low resolution spectrogram of comet Humason obtained by Dossin in 1964 as this object was at a heliocentric distance of ~5 a.u. revealed strong CO^+ emission. This spectrogram was obtained at McDonald Observatory.

lines. A critical examination of all the cometary slit- and slitless-spectrograms at our disposal revealed the striking fact that the [O I] lines which appeared on these spectrograms and were previously assigned to the twilight or nightglow are in several cases of cometary origin. (25) No convincing correlation between solar phenomena (bright solar flares, relative sunspot number), terrestrial phenomena (geomagnetic indices, aurorae) and the occurrence or intensity variations of the oxygen forbidden lines has been found. (26)

A detailed re-examination of all the cometary spectrograms showing [O I] emissions should be made, as more refined photometric measurements may lead to convincing conclusions as to the behaviour of the [O I] emissions in comets. Such an investigation is now being carried out in Liège. While waiting for its completion we shall postpone further theoretical discussions on the excitation mechanisms of [O I] and their consequences.

The great intensity of the Na I-emission in several recent comets (Mrkos, Wilson-Hubbard) has raised the hope that other resonance atomic lines may eventually be found in comets of very small perihelion distance. Indeed, the absence of λ4227 Ca I may appear strange at first sight. However, the relative abundances of cometary atoms, which may depend on the dissociation of parent molecules and other physical or chemical phenomena, should not be considered as identical to those in other cosmic objects. At any rate, the long-doubted reality of the observation of Fe I-lines by Copeland and Lohse in the famous comet 1882 II—which was visible near noon at only one degree from the Sun ($q = 0{\cdot}008$)—is becoming more and more accepted.

On account of the recent progress in the micrometric and microphotometric measurements of the C_3-emissions in comets (*) there is increasing hope that the famous λ4050 group will soon receive detailed assignments, especially since progress in the spectral resolution of the cometary spectra is paralleled by gratifying progress in the laboratory analysis of the C_3-systems. (27) Actually, it is quite probable that the strongest cometary C_3-emission λ4051 may be obtained with still higher resolution in future bright comets. A dispersion of 4 A/mm which appears possible in a bright comet would help greatly in discussing the excitation mechanism of C_3.

The low-resolution cometary spectrograms obtained until 1957 had provided convincing evidence that the bands of CN (blue and red systems), CH, OH, and NH were actually excited by a pure fluorescence mechanism. The better recent material has made it possible to study this mechanism in greater detail for CN, CH, OH, and NH, to discover an important second-order effect (the Greenstein effect), and to secure evidence in favour of the fluorescence mechanism for C_2, NH_2, and CO^+. The case of C_3 remains dependent on the laboratory analysis. It is also certain that a better interpretation of the cometary profiles will require solar microphotometric tracings of higher resolution and accuracy than presently available.

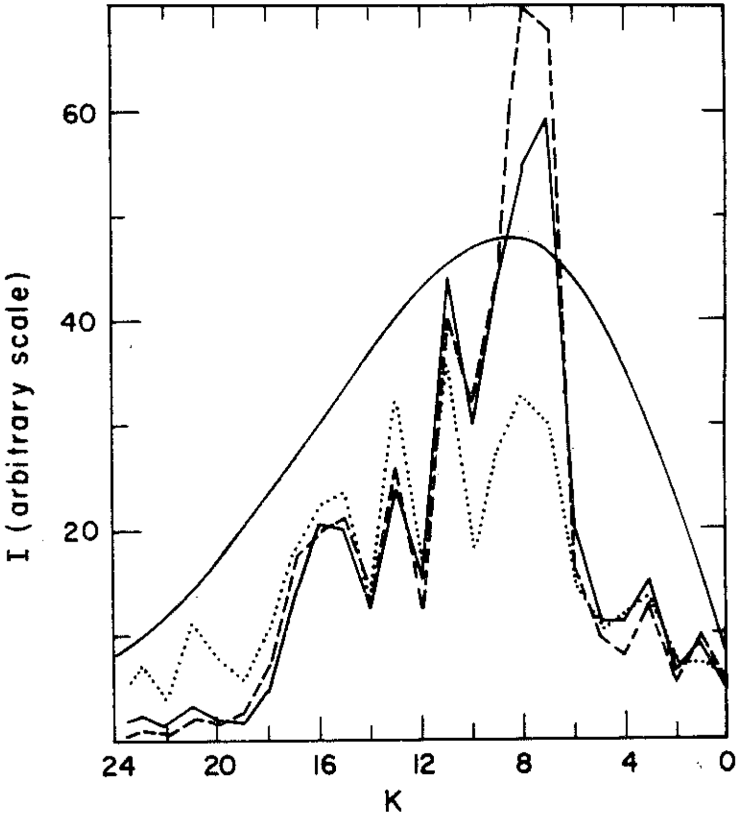

FIG. 1. Intensity distribution in the R-branch of the CN violet (0, 0) band in the spectrum of Comet Mrkos (1957). Solid curve: observed distribution. Dotted curve: theoretical curve based on x_K-distribution neglecting Fraunhofer lines. Dashed curve: theoretical curve corresponding to steady-state distribution taking Fraunhofer lines into consideration. The smooth curve represents the thermal equilibrium intensity distribution (T = 500°K).

As for the excitation of [O I], it still remains rather puzzling and requires further observational work.

The remarkable profiles of the CN-bands on the spectrograms of comets Mrkos, Burnham, Seki-Lines, and Ikeya have been studied, some in considerable detail. The most elaborate and complete discussion is that of Arpigny. (28) The first point which must be cleared up is the distribu-

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* The cometary emission of C_3 extends at least to λ3700 on the violet side (C. Arpigny unpublished).

tion of the CN radicals on the rotational levels of the ground electronic state $^2\Sigma$. It was mentioned long ago that this distribution itself depends on the Fraunhofer lines and cannot be represented by a simple Boltzmann formula, as there are practically no collisions*. Indeed, it was stressed already in 1943 that the whole problem of the fluorescence excitation should be handled with a set of equations expressing the stationary state, just as Rosseland treated the case of gaseous nebulae in 1926. This point of view could not be applied in the case of comets until electronic computers became available. In fact, Carrington's treatment (**29**) is essentially the same.

The mathematical procedure consists in writing a series of equations expressing that the number of transitions leaving a (v′, K′) level equals the number of transitions reaching this level, and similarly for (v″, K″). Difficulties arise immediately. Since we know so little of the dipolar electric moments we cannot determine the probabilities of the pure rotational transitions. Hunaerts has made estimates of these probabilities on the assumption that the last observed line of a cometary band corresponds to a rotational quantum number such that the lifetime related to a pure rotational transition from this level equals the lifetime with regard to an absorption process. Actually, however, as was shown by Arpigny, the lifetime corresponding to the absorption should take the Fraunhofer lines into account. Certain lines are weak, not because the corresponding lifetime relative to the pure rotational transition is small, but rather because little radiation is available on account of the presence of a Fraunhofer line! Arpigny has shown that the calculated profiles of CN(0–0) agree almost perfectly with the observed ones (Figure 1) if account is taken of the Fraunhofer lines when one computes the distribution of the radicals on the rotational levels of the ground electronic and vibrational state, as well as when one considers the absorption processes themselves. Minor differences remain, partly due to the fact that the rotational populations on the ground electronic state are also affected—although in a secondary way—by the other electronic transition $A^2\Pi$—$X^2\Sigma$ (red system). In this system the Fraunhofer lines play only a minor role. Moreover Arpigny used the Utrecht *Photometric Atlas of the Solar Spectrum*. A higher resolution and a greater accuracy are now needed for this problem. The required tracings may be obtained either at the Liège Solar Spectrograph of the Jungfraujoch Scientific Station, at the University of Michigan, at Kitt Peak Observatory, or at Sacramento Peak Observatory.

It is clear from Arpigny's study that no Boltzmann distribution coincides with the rotational population distribution resulting from steady state equations. However, if one tries nevertheless to find a fictitious rotational temperature such that the corresponding Boltzmann distribution resembles the actual rotational distribution one may adopt a rotational temperature $T = 300/r$ degrees Kelvin.

In the preceding considerations the same radial velocity shift of the exciting solar radiation was assumed for the whole comet. Differences in rotational profile may occur at locations in the comet which differ in radial velocities. Such an effect—now called the Greenstein effect—was found for the first time in the CN-band (0–0) of the spectrograms of comet Mrkos. The lines affected by the Greenstein effect are those which are most sensitive to slight shifts in radial velocity, i.e., those which fall on or near a steep portion of a strong Fraunhofer line. As an example, the intensity ratio R(10)/R(9) may change completely across the head; the required velocity reversal amounts to about 4 km/sec within 4 000 km. The Greenstein effect has now been observed in the central parts of several comets, for various lines of CN-R(12)/R(11); R(11)/R(10); R(10)/(R9); R(3)/R(2); P(5)/P(4); etc., and of CH. It cannot be fully interpreted by a simple rotation of the nucleus; a more complex velocity distribution is required. New, high resolution observations, using a long slit placed in a sequence of position angles, would provide important information on the distribution of the velocities inside the head; accurate guiding and better tracings of the solar spectrum would be required.

In the case of CN, the effect of the Fraunhofer lines on the profiles—the so-called Swings effect—is extremely sensitive to the radial velocity; moreover, the total width of the R-branch depends on r (more or less according to $T = 300/r$). As a result, the CN(0–0) band appears quite differently in different comets and varies considerably when a comet gets closer to or away from the Sun; indeed, CN-profiles at pre- and postperihelion phases are completely different. Near perihelion the total CN-emissions may even become fainter on account of the absorption by the undisplaced CN-Fraunhofer lines.

Similar but less sophisticated work has been conducted on the profiles of the OH-, NH-, and CH-bands. In all cases, the fluorescence effect could actually be proved even on spectrograms of medium resolution. The recent high resolution spectrograms will be studied with the help of new tracings of the solar spectrum. There are considerable differences of profile, especially of OH and NH, in the different comets. As in the case of CN, they are accounted for by differences either in radial velocity (the major influence) or in heliocentric distance or "temperature".

The case of C_2 and NH_2 required a high resolution. It has been shown previously that the effects could not be as spectacular as in the case of CN. C_2 was studied mainly (**30**) on the Palomar spectrograms of comets Mrkos

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* It is easily seen that the absorption processes are much more frequent than the collisions with solar particles.

and Seki-Lines*. Intensity anomalies which were found in various sequences of Swan bands ($\Delta v = 0, +1$ and -1) may be assigned unambiguously to Fraunhofer lines. This case is especially interesting as the lower electronic level of the Swan bands, $^3\Pi_u$, is not the ground electronic state of C_2 ($^1\Sigma_g^+$). Reasons must be found for the abundance of C_2 molecules on the excited $^3\Pi_u$ level. One may imagine that C_2 molecules are formed in the $^3\Pi_u$ state by photodissociation of a parent C_2X molecule; C_2 would be able to live for a long time on this $^3\Pi_u$ state since the transition to the ground $^1\Sigma_g^+$ state is extremely forbidden. Possibly also C_2 may be sublimated directly in the triplet state from the icy matrix.

Two triatomic radicals are observed in cometary heads: C_3 and NH_2. Our laboratory knowledge of the C_3 spectrum has not yet made it possible to discuss the excitation mechanism, but this situation will soon be corrected†. As for NH_2 the evidence in favour of fluorescence is convincing, although not spectacular (**31**). A few well-marked intensity anomalies in the NH_2-emissions may be explained by the effect of Fraunhofer lines. The differences between the NH_2-lines in comets Mrkos and Seki-Lines are due to the differences in radial velocity.

For a long time there had been a suspicion that the CO^+ bands of comet tails were also excited by fluorescence. In particular the intensity ratio of the (3, 0) and (2, 0) bands was much greater in comet Bester (1948 I) than in the laboratory. (**32**) However, no spectrogram exhibiting the rotational structure had been obtained until 1962. The Palomar spectrograms of comet Humason (1962 VIII), have been studied by Arpigny (**28**) from the point of view of the excitation mechanism of CO^+. The relative intensities of the vibrational transitions were studied with the help of the spectrograms of low dispersion (180 A/mm), while the high dispersion plate (18 A/mm) was used for a discussion of the rotational intensity distributions in the two strongest bands (3, 0) and (2, 0). Arpigny computed the populations on the v''-levels by assuming stationary conditions; the vibrational transition probabilities were used, and mean Fraunhofer weakening coefficients were determined for each transition (v', v''). The agreement between the computed and observed relative intensities of the main vibrational transitions is quite satisfactory. It is now understood why the shortward component of the (5, 0) doublet is weaker than the longward, while the two components of (3, 0), (2, 0), and (1, 0) have approximately the same intensity and the shortward components of (4, 0) and (3, 0) are stronger. It is also possible to explain why the intensity ratio (3, 0)/(2, 0) is greater in comets than in the laboratory. Next, the rotational intensity distributions of the (3, 0) and (2, 0) bands were discussed; the observed intensity anomalies could be assigned to the effect of Fraunhofer lines. It may thus be concluded that the main tail bands due to CO^+ are excited by a fluorescence mechanism just as are the head bands. Rotational quantum numbers of CO^+ up to approximately 10 are observed in comet Humason at $r = 2{\cdot}6$. This is about the same as for CN at the same heliocentric distance.

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* Work on the rotational intensity distributions in the Swan bands of several recent comets is at present under way at the Astrophysical Institute in Liège. Some of these comets had a very weak (or no) continuum, hence they are better adapted than 1957 V to the study of the profiles of the Swan bands.

† The differences in C_3 profiles which have been observed in different comets seem to be due essentially to differences in vibrational and rotational "temperatures".

The mechanism of excitation of the [O I] lines is still unknown. Excitations by fluorescence, electron-collision or proton-collision do not appear sufficient. If [O I] is due to the photodissociation of oxygen compounds (**33**) it is possible to determine the minimum amount of sublimated matter which may interpret the observations. This is of the order of 10^{30} molecules/sec or approximately 3×10^8 tons/month. Assuming for the nucleus a superficial density 0·1 and a radius 10 km, this corresponds to a layer of 2·5-metre thickness per month at $r \sim 1$. These estimates are extremely uncertain, indicating simply that a rather fast decrease in the diameter of the nucleus is not excluded.

In practically all the spectroscopic investigations of comets the emphasis has been placed on the discrete emissions. The study of the reflected or scattered solar continuum has usually been neglected, although it may eventually provide important information on cometary and interplanetary physics and on cosmogony.

Several recent cometary heads have been examined with respect to the intensity of their continua, (**34**) taking into account the effect of the linear dispersion on the relative intensities of the discrete emissions and of the continua; 1957 III (Arend-Roland) and 1957 V (Mrkos) had a very intense continuum, while 1961 I (Encke) had none and 1960 I (Burnham) had only a weak continuum which was confined in a very small central region. In 1961 II (Candy) the continuum was definitely stronger (relative to the discrete emissions) than in 1961 I and 1960 II, but was weaker than in 1957 III and 1957 V. Comet 1959 VIII (Giacobini-Zinner) had an extremely strong continuum, comet 1961 V (Wilson-Hubbard) had a fairly intense continuum, and comets 1961 VIII (Seki) and 1962 III (Seki-Lines) had average continua.

A critical discussion of the possible sources of the cometary continua leads to the safe conclusion that the continuum of cometary heads results from the scattering of the solar radiation by small solid particles. (**35**) However, on the basis of the rather scanty observations and of the available computed data on Mie scattering, it is still impossible to draw conclusions on the nature and radii of the scattering particles. A great deal of observational effort is still required. Specifically we need more and better monochromatic observations of polarization and brightness in spectral regions which are devoid of discrete emission. Additional numerical data on the Mie scattering are also necessary; in particular, narrow ranges of radius of the scattering particles should be considered.

7. ADDITIONAL COMMENTS ON THE EMISSIONS OF COMETARY HEADS AND TAILS

The spectrum of a typical cometary head consists of a bright continuum on which are superimposed bright molecular bands, and sometimes the Na-doublet and [O I] lines; but there are considerable differences in the relative intensities of the continuum and of the different emissions. There are even strange exceptions such as cometary heads which present a continuum only or almost only. Spectroscopic comparisons based on slit spectrograms may actually offer dangers since the portion of the comet covered by the slit may differ (often depending on chance!), and different features of the head may have different spectra! As a matter of fact one may also take advantage of the distributions of various emissions in the head. For example in a study of the red system of CN it is advantageous to place the slit at some distance from the nucleus and to trail the image on the slit: this reduces the continuum (normally "shorter") and all other emissions relative to CN (which is "long").

A search for the isotopic bands of the Swan system has been made by various observers. The isotopic band of $C^{12}C^{13}$ which should be most easily detected in cometary spectra is the (1, 0) transition at λ4744; no accidental solar intensity maximum could explain satisfactorily an emission at this wavelength. It is present on the low resolution spectrograms of several comets observed long ago, as well as on high resolution spectrograms of recent comets. On the other hand it seems to be absent from certain spectra, even when the $C^{12}C^{12}$ bands are strongly overexposed, such as on several McDonald spectrograms of comet 1941 I. No comet has ever been observed which shows a high relative abundance ratio C^{13}/C^{12} as is the case in late carbon stars.

The future discussions on the forbidden [O I] lines will certainly add much to our knowledge of the comets, as these lines are not excited by fluorescence; they may indeed belong to a group of emissions excited by some other mechanism. While additional observational data on [O I] are highly desirable a search for other atomic and molecular emissions, especially in the infrared and vacuum ultraviolet (by rockets or satellites) is also greatly needed. We shall return to this point a little later.

When comparing the intensities of the discrete emissions in the head and tail of a comet the geometrical positions should be taken into account. If a tail is almost parallel to the line of sight the intensity ratio of the CO^+ (tail) and CN (head) bands will seem greater than if the angle Sun-comet-Earth is large. Nevertheless there is no doubt that there are comets, such as Morehouse (1908 III) and Humason (1962 VIII)[*] which are especially rich in CO^+ tail emission, and poor in CN head emission.

There still remain a number of unidentified emissions both in the head and in the tail. In the visual region there appear striking wavelength coincidences of head emissions with bands of FeO (others less striking with NiO, CaO and CrO). McKellar has called attention to certain coincidences with SiO_2 in the violet. In the tail there are coincidences with bands of O_2 (Schumann-Runge), NO (β-system), O_2^+, C_2, N_2, and CO. The apparent coincidences of unidentified tail emissions with O_2-bands (based on spectrograms of low resolution!) seemed at first rather striking. However they are probably meaningless; O_2 is too easily dissociated, the bands should be wide (homonuclear molecule!), there are anomalous intensity ratios among bands of the same v′, and one does not see why O_2 should extend far into the tail. Actually the observed wavelength coincidences have probably no physical meaning; the pending questions will presumably be solved soon with the help of the spectrographic material of high resolution which is being gathered. The recent observation of red emissions in the tail of comet Ikeya (1963a) has not been explained as yet. **(36)**

A few laboratories are endeavouring to analyze band spectra which are important for the interpretation of cometary phenomena. Among the most important recent investigations one should especially mention the analysis of the band systems of NH_2, C_2, CN (red) and C_3, which have contributed appreciably to cometary physics. Very useful Franck-Condon factors have also been computed or measured. **(37)**

Densities of C_2 and CO^+ molecules in Comets Halley (1910 II) and Brooks (1911 V) have been estimated on the basis of the old spectroscopic and photometric observations. The average density of C_2 in 1910 II is $d(C_2) = 10^2$ molecules/cm^3; near the nucleus $d(C_2)$ may be as high as $10^{7.5}$; it is reduced to $10^{3.5}$ and $10^{1.5}$ at nucleocentric distances of 10^4 km and 10^5 km respectively. In the tail of Halley's comet the density $d(CO^+)$ is of the order of 300/cm^3 at a distance of 2×10^8 km.

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[*] Comet Humason still revealed CO^+ bands at a heliocentric distance of 5 a.u. while comet Schwassmann-Wachmann I never shows such bands, even at the time of its outbursts (F. Dossin, unpublished).

Table 1

R (km)	d (C_2) (per cm^3)
1 700	470
4 300	160
8 500	65
17 000	21
34 000	5
68 000	1

More accurate work has been done recently by various observers. As an example we give (in Table 1) estimates for $d(C_2)$ at increasing nucleocentric distances R in the head of Comet Burnham (1960 II) at $r \sim 1$ a.u. (**38**) There are comets of much greater and much lower C_2 density. Some approximate estimate has also been attempted for the densities of the dust particles in the heads and tails of a few recent bright comets. A few solid particles (of diameter of the order of $0{\cdot}5\mu$) per cubic metre suffice to explain the continua of the heads of bright comets such as 1957 III and 1957 V which had a strong continuum. (**34**)

8. PLANS FOR THE FUTURE

As will be shown later, experiments with rockets, space probes and satellites should provide information of the greatest importance. But even from the ground or from balloons there remains a lot of work to be done. It is gratifying to notice that research teams in various traditional observatories have organized systematic programmes of cometary observations and investigations, and built powerful instruments which are wholly or primarily devoted to observational work on comets. The largest telescopes of several major observatories are employed on cometary problems more frequently than in the past.

Accurate photometric and polarization measurements in well defined spectral regions (including the scattered solar continuum) are still badly needed; they should be made at specific locations in the head and tail. High resolution photographs, taken in fairly rapid succession and covering given spectral regions, will still reveal important information on the tails. We still need a variety of spectrograms, especially with high resolution. We know too little of C_3, NH_2, OH^+, and [O I] in the head and practically nothing of the whole visual and near-infrared regions of the tail. Only one (underexposed) tail spectrum has ever been obtained with a resolution that permits a discussion of the excitation mechanism on the basis of the rotational profiles of the CO^+ bands. We even need better objective prism-pictures, especially in the [O I] wavelengths. In the spectral region λ7000 to λ9000 of cometary heads, only the (2–0) and (3–1) emissions of the red system of CN have been observed with certainty. We know little about the colour, spectrum, and polarization of distant comets. Our observational knowledge of the dimensions, colours, temperatures, and magnetic properties of the nuclei is still practically nonexistent. Accurate photometric observations should be made of the dimming of stars observed "behind" a comet at small angular distances from the nuclei; the observations by Dossin are only of a pioneering nature.

There still remain promising domains which have not been exploited at all. For example, we have very little information on the infrared and radio spectra, even in the spectral ranges accessible from the ground. No really convincing observation of discrete or continuous radio-emission from a comet is available as yet. As far as we know no observation of the occultation of a radio source by a cometary atmosphere has ever been attempted, despite the valuable information which would thus be gained on the electron densities in comets. One should be on the lookout for the possibility of such occultations whenever a sufficiently precise ephemeris is available.

The infrared region will probably bring high rewards. Essentially the near infrared region is characterized by the vibration-rotation transitions of the molecules. We may hope to find the fundamental (1, 0) transitions of the molecules observed in the usual region (for example the band of CO^+ at $4{\cdot}6\mu$); of other diatomic molecules (such as CO); of certain probable parent molecules (such as NH_3, CO_2, H_2O, etc.); and of intermediate radicals (such as CH_2 or CH_3). However, we do not know what excitation mechanisms prevail. If the vibration-rotation bands are excited by fluorescence only, they will be extremely weak, since the integrated solar energy for $\lambda > 2{\cdot}5\mu$ represents only 2 per cent of the total solar energy, and since the transition probabilities of the vibration-rotation bands are low compared to those of the usual electronic emissions. But other excitation mechanisms may exist. For example, after the emission of the (0, 1) band of the $^2\Sigma$—$^2\Sigma$ electronic system of CN, the CN radicals will be left on the $v'' = 1$ level of the ground electronic state, from which they will emit the fundamental (1, 0) vibration band if they are not de-excited by another electronic absorption. The vibration bands may be excited by other mechanisms that release small amounts of energy.

Part of these infrared observations could be made from balloons and aircraft. The principal remaining trouble in the case of observations from a balloon or a high-flying aircraft results from the ozone absorptions near 4·8, 9·6 and 14μ. The absorptions by CO_2 and H_2O would be considerably reduced at 28 km altitude. The expected infrared emissions of cometary heads or tails have recently been tabulated. (**39**).

Much laboratory work also remains highly desirable. The discovery of new systems such as C_2^+, the experimental and theoretical determinations of f-values for all observed molecular systems, and the determination of cross sections for dissociation or ionization of the observed and probable parent molecules, are examples of what has to be accomplished. In preparing for future observations in the far ultraviolet, a great deal of additional laboratory spectroscopic work in the Schumann region is required. Progress in infrared instrumentation is also needed.

9. RELATIONS BETWEEN COMETARY AND SOLAR PHENOMENA AS DEDUCED FROM SPECTROSCOPIC OBSERVATIONS

The CN radical (0, 0 band near λ3870) determines the largest diameter of the head in the near ultraviolet region, while the C_2 molecules (Swan bands) give the somewhat smaller extension in the green region. A measurement of the diameter of the head near λ4050 or λ4313 or λ5977 furnishes a small value (emissions of C_3, CH and NH_2 respectively), at least one order of magnitude smaller than near λ3870. As for the tails two types must be clearly separated: the dust type and the gaseous type. The dust tails are strongly curved, diffuse and fairly homogeneous; they have little or no structure. The gas tails have fairly straight rays, whose widths are small, of the order of 2 000 km. The two types of tail appear distinct if the Earth is sufficiently far from the orbital plane of the comet. The spectrum of the gas tails is essentially characterized by ions CO^+, N_2^+, and CO_2^+ (plasma tails). It happens—as in the case of Comet Mrkos 1957 V—that the sodium emission extends into the tail, as far as one half the length of the CO^+ extension. However the structure of the sodium tail (neutral atoms) differs from that of the plasma tail: the Na-rays are straighter than the undulating CO^+-filaments. The forbidden lines of [O I] seem to behave like Na but this question is still in a most unsatisfactory state.

One should distinguish carefully between the effect of the solar electromagnetic and corpuscular radiation on: (i) the neutral gases (head and tail), (ii) the ionized gases (plasma tail), and (iii) the dust particles (head and tail). Promising possibilities appear for the utilization of comets as probes of the solar field. It should however be made clear that comets have their individuality and that they may react in different ways to solar activity. One may find a very active comet of large perihelion distance q, while other comets with small q are quiescent. We shall consider only phenomena which are closely related to the spectra, and shall say very little about the geometrical and photometric behaviours of heads and tails.

The monochromatic CN and C_2-heads are approximately spherical. This shape shows that the CN and C_2-radicals stream away in the same manner in all directions, and that the repulsive forces acting on them are rather weak. Actually the acceleration of these neutral particles by light pressure is small, as a consequence of the low f-values of their resonance system.

The radii of the CN or C_2 heads may exceed 300 000 km. Indeed such figures are found by simple visual examination of the plates of Comets Halley, Brooks or Whipple-Fedtke (1943 I). By photometric registration values found for the radius may reach 10^6 kilometres or even more. The velocities of the gases may be obtained from expanding halos; they are of the order of the thermal velocities of gases at a moderate temperature (1 km/sec) (see section on outbursts). To reach a distance of 10^6 km the CN- and C_2-radicals must have lifetimes of the order of two weeks before ionization or dissociation by corpuscular or electromagnetic solar radiation takes place. In particular such a long lifetime appears to exclude densities of protons in the solar wind which exceed $n_p = 10\ \text{cm}^{-3}$.

It is often assumed that there is no difficulty in explaining the dust tails, which would be accounted for by solar radiation pressure (the old Bessel-Bredichin theory). Indeed the radiation pressure of sunlight repulsing the small dust grains is of the order of the gravitational attraction of the Sun (while in the straight plasma tail the repulsive forces are two orders of magnitude greater). However the phenomena may be more complex on account of the charge which may form on the dust grains when they are exposed to the solar electromagnetic and corpuscular radiation. As long as there is evaporation on the sunward side of the dust particles there may also be a recoil effect; but the well separated dust tails generally do not reveal any trace of gaseous emission. The dust grains in the tails differ from those in the head, since the latter have an approximately spherical distribution.

When the heads of great comets displayed strong sodium D-lines the latter often extended into the tail. An excellent recent example was exhibited by Comet Mrkos (1957 V) in which the Na-lines appeared strongly in the head, and in bright straight streaks of the tail, to a distance of 5° from the nucleus. (**39a**) These streaks differed completely from the wavy CO^+ streamers. The behaviour of Na is explained by the high f-value of the D-doublet, a hundred times greater than $f(\mathrm{CN})$ or $f(C_2)$; also by the relatively long lifetime of the Na-atoms before ionization*. As a result of the high repulsive force due to light pressure the sodium coma should have a parabolic shape, which is actually observed. The intensity of the fluorescent D-doublet and the acceleration of the Na-atoms depend

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* The probability of ionization of Na by solar radiation is $10^{-4.3}/r^2$ sec^{-1} at heliocentric distance r. For $r = 1$ a.u., the average lifetime is thus $10^{4.3}$ seconds or 6 hours.

strongly on the radial velocity which shifts the exciting wavelengths outside the cores of the Fraunhofer lines[*].

The plasma tails (CO^+, N_2^+, CO_2^+, plus unobservable ions[†]) are the most important as far as relations to solar activity are concerned. The behaviour of the plasma tail structure has been studied on series of cometary photographs taken in the course of one night; among the best photographs are those of Comet Morehouse (1908 III) taken at Greenwich. **(40)** Yet there is a great need for additional observations, especially in the immediate vicinity of the nucleus; high photographic resolution and short exposures are required. It appears definitely that the ions have their source on the sunward side, near the nucleus; that the tail emission on the sunward side is confined to the vicinity of the nucleus; that the tail structures do not reach nucleocentric distances greater than 10^5 km at right angles to the radius vector near the nucleus.

Two main problems are involved in the composition and structure of the plasma tails:

(i) the production of the ions near the nucleus;
(ii) the kinematics and dynamics of these ions.

It is often assumed that the ionization results from the bombardment by "solar wind" protons, but K. Wurm has expressed the opposite view. **(41)** He concludes from his studies of cometary photographs that the process of ionization is an intrinsic property—thus far unexplained—of the cometary atmosphere. According to Wurm the production of CO^+, N_2^+, and CO_2^+ does not depend directly on the electromagnetic or corpuscular radiation from the Sun; the ions are not produced by chemical reactions either[‡]. The ionization happens within a limited region (less than 10 000 km) in front of the nucleus[§]; the ions are expelled in a narrow, sunward directed cone, and are then expelled away from the Sun and the nucleus. Various authors, **(42)** especially Alfvén, Marochnik and Axford have propounded the view that the ionization is due to the effect of a shock wave, possibly combined with processes of the kind described by Hoyle and Harwit. The calculations of such shock effects are not easy; the problem will not be considered in any detail here.

Although the mechanism of ionization is still in dispute, there appears little doubt that the kinematics and dynamics of the tail ions result to a

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[*] Of course the lifetime is not affected by the radial velocity.

[†] The latter are the ions whose resonance transitions fall in the ultraviolet region $\lambda < 3000$.

[‡] Nevertheless chemical reactions on or near the surface of the solid material are not excluded.

[§] CO, N_2 and CO_2 are probably the parent molecules of the tail ions. Their resonance systems lie in the unobserved ultraviolet, so that we have at present no idea regarding the distribution of CO, N_2 and CO_2 within the head.

large extent from the solar corpuscular radiation[*], although certain processes in the vicinity of the nucleus and certain individual characteristics of the comet may also be responsible for orientations and changes of the rays. The orientation of the tail axis with respect to the radius vector is generally assumed to be due to a coupling, probably magnetic, of the tail ions and of the solar wind, although the exact mechanism of coupling is not yet fully understood. The comets are more and more used as probes for the solar wind.

More than 50 years ago astronomers who observed the filamentary structure of the plasma tails already suspected the presence of a magnetic field. **(43)** The recent observations on the narrowness of the streamers (order of 2 000 km) and their helical undulations indicate clearly that magnetic fields do play a major role in the dynamics of the ion-tails. In particular the fields inhibit diffusion perpendicular to the lines of force. The magnitude of the interplanetary magnetic field has been determined with the help of space probes; it is of the order of 10^{-5} gauss. The problem has been studied by Alfvén and especially by Harwit and Hoyle.

Three types of solar corpuscular radiation must be considered:

(i) the solar wind (or breeze), a stationary component, density of the order of 3 ion-pairs/cm^3, velocity of the order of 500 km/sec;
(ii) the corpuscular radiation connected with the M-regions, which may last several solar rotations;
(iii) the flares giving rise to severe magnetic storms.

The solar corpuscular radiation is never completely absent, as is evidenced by the Earth's magnetic field and the aurorae, and therefore comet tails always show some activity. The fact that plasma tails are observed at high ecliptic latitudes shows that solar corpuscular radiation is emitted in all directions, although probably not with equal intensity.

Comets may suffer outbursts as considerable as $\Delta m = 8$ magnitudes in a few hours. Sometimes a succession of outbursts may mask the general luminosity behaviour of a comet, giving rise to a flat luminosity maximum after perihelion (as in 1943 I) or to a minimum at perihelion (1937 V). The first observation of the behaviour of the spectrum at the time of an outburst was made by Vogel 80 years ago (on 1884 January 1); he noticed the simultaneous enhancement of the continuum and of the discrete emissions of 1884 I. Several spectroscopic observations of outbursts have been made in the last 50 years, but few descriptions are clear and convincing. Halley's comet liberated dust at an outburst on 1910 May 24. In 1939 V, it seems that the intensity ratios $CN/C_2/C_3$ were modified. Three outbursts of periodic Schwassmann-Wachmann were observed spectro-

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[*] The selective radiation pressure cannot be responsible for the formation of the plasma tails, on account of the small value of $f(CO^+)$.

scopically at the Lick Observatory (1941, 1946 and 1959) and at Bergedorf (1959); there was no trace of discrete emission*; the velocity of expansion found at outbursts in 1959 and 1961 were 187 and 100 m/sec respectively. The most detailed investigation of an outburst is that of Comet Alcock (1963 b; $\Delta m = 3$ mag.). (**44**) A spherical gas shell composed of CN and C_2 expanded at a velocity of approximately 1 km/sec, while a dust jet issuing from the nucleus and showing a strong continuum was moving at a velocity of 50 to 100 m/sec. The dust particles of the burst lost their volatile gases very quickly. The velocity of the gas was probably determined by the temperature of the ejected material, while the velocity of the separated matter was due to the ejection process which took place in a well defined direction.

There seems to be little doubt that the Sun may sometimes play an important role in such outbursts, but the individual properties of the comets are also primordial. Certain phenomena are caused by unequal superficial heating and are similar to the ejection of rocks or gases in mines. The possible correlation between solar activity and cometary brightness is not yet as certain or as clear as that between solar activity and the plasma tails.

10. REMARKS ON THE COMETARY NUCLEI

A comet is a small body of the solar system, with constantly (or at least occasionally) replenished atmosphere. Certain comets (such as Neujmin I) presented, for a long time, a pure stellar aspect without trace of atmosphere. The really distinguishing feature of a comet is the ability to release dust or gas when it is heated by solar radiation. The minimum observational requirement is a more or less diffuse appearance on at least some occasions. The released material is lost to the comet; the lifetimes of periodic comets must thus be limited. Of course we observe only the comets that penetrate to within a few a.u. from the Sun, a small sample of the whole number of comets of the solar system.

There must be a source for the gases and dust particles which make the comets visible. We shall call this source the nucleus. Different authors assign a different meaning to the word "nucleus"; the photometrists call "nucleus" the central condensation of more or less stellar appearance. In what follows we shall assume that the nucleus is a small solid (or assembly of solids) whose dimension is of the order of a few kilometres. Only in rare cases and by using the highest magnification is it possible to distinguish a sharp nucleus from the gas or dust in its vicinity.

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* The heliocentric distance of Comet Schwassmann-Wachmann is always very great. However Comet Humason 1962 VIII revealed strong CO^+-emissions at a similar distance.

Seventy-five years ago G. A. Hirn suggested that icy solids are present in comets. About 15 years ago this view was independently re-examined by Vsessvyatsky and by Levin. In 1950 F. L. Whipple demonstrated a number of consequences of an icy-conglomerate model for the nucleus. Although Whipple's original hypothesis presented shortcomings it has been considered by many astronomers. In addition to the saturated volatile material (frozen H_2O, CH_4, NH_3, etc.) and the inert, non-volatile solids (silicates, oxides, carbon grains) initially considered, unsaturated reactive material (H_2O_2, C_2H_2, etc.), trapped free radicals (H, OH, NH, CH, CH_2, NH_2, etc.) and solid hydrates have been envisaged. It is probable that considerable differences exist among the structure and composition of cometary nuclei, resulting in varied spectroscopic and photometric phenomena. If the usually adopted large proportion of volatile material is really present the superficial temperature of the nucleus should always be low, probably less than 200° K at $r = 1$ a.u.*. Assuming an average density of 1, the central pressure in a spherical nucleus of 10 km radius is $1{\cdot}4 \times 10^5$ dynes/cm^2, the escape velocity 8 m/sec and the surface gravity $0{\cdot}2$ cm/sec^2. The investigations on snow densities under various conditions of packing and on the transitions to glacier ices may be adapted to Whipple's model. It is known that the density of newly fallen snow at low T and in windless conditions may be as low as 0·01. Actually cometary ices may be less easily compacted than falling snow. The presence of solid hydrates may solve the problem of the enormous vapour differences between pure CH_4 and H_2O ices. Actually the original suggestion by Delsemme and Swings (**45**) has been developed and corrected recently by S. L. Miller (**46**) who expects mixed hydrates of CH_4, CO_2 and ethane in the nuclei of comets. As for the chemical state of NH_3 it will depend critically upon the circumstances of the formation of the nuclei.

The spectrum of periodic Comet Encke is characterized by the great intensity of the C_3-emission† and by the absence of a continuum. It stands in great contrast with another periodic comet, Giacobini-Zinner, which presents an extremely strong continuum. This contrast is paralleled in the Taurid and Draconid meteoroids issued from Encke's and Giacobini-Zinner's comets respectively. (**47**) The Taurid meteoroids are

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* A superficial temperature $T = T_0/\sqrt{r}$ (T_0 = temperature of Earth's surface) is often adopted on the assumption that the outer parts of the solid material are in radiative equilibrium with the solar radiation. Such a formula does not seem applicable to an icy conglomerate model.

† The high intensity of C_3 has not been interpreted unambiguously thus far. C_3 may be due to photodissociation of an organic molecule such as diacetylene $HC \equiv C - C \equiv CH$. Or it may result from a polymerization process, or of the bombardment of the nucleus by solar protons. It has also been suggested that C_3 may have been trapped in the nucleus.

relatively rigid, while the Draconids are feather like, extremely fragile and probably of very low mean density (0·10 g/cm^{-3}?). Encke's comet must have been a very large comet which has contributed huge streams of meteors. We would be presently observing meteoroids issued from the central part of an "old" comet. On the other hand the periodic comet Giacobini-Zinner appears to be small and probably "new". The interior of the nucleus of a bright large comet does not resemble the outer fluffy structure of comets. The denser ices of the interior become exposed after a number of returns to perihelion in the course of which the uncompacted material has been lost. The high intensity of the C_3 bands in Encke's comet may possibly mean that carbon was one of the first materials to condense in a cloud of gas and might thus be more abundant in the central parts of the large comets. Indeed the chemical composition inside the nucleus may be a function of depth.

A discussion of the observed brightnesses of various periodic comets at their successive passages indicates secular decrease leading to a limited, rather short life of these objects. (48) The rate of change is not the same in all periodic comets, but the available spectroscopic observations are still too scanty to correlate the decreases in brightness and the spectral characteristics*. One may reasonably hope that good additional observational material would bring important information on the families of comets and their evolution. These observations should be concerned with (1) the spectra (with proper photometric calibrations), (2) accurate photometry (in specific spectral ranges), and (3) good photographs (in order to distinguish the dust and gaseous tails). Future spectra should cover the region of the OH and NH bands. Special attention should be paid to the relative intensities of the continuum, the C_3-band and the other violet emissions (CN, CH, C_2). The uniqueness of the spectrum of Encke's comet has a parallel in the unique character of its secular changes in brightness. The very different secular behaviour of Halley's comet is paralleled by its different spectrum—its continuum is rather strong (compared to Encke's) and its C_3 emission is weaker.

A comet may split into several fragments. The splitting of Comet Wirtanen (1957 VI) has been studied and described in detail. The great southern comet 1947 XII also divided into two parts, and spectra were obtained for the two components. (49) As far as could be ascertained by visual examination of the spectrograms, not only were the relative intensities of the different bands (NH, CN, C_3, CH, C_2 and NH_2), the same in both components, but also the rotational distributions within the individual bands were identical.

* Campbell's statement of 1897 remains as true as ever: "I desire especially to call attention to the importance of observing the spectra of periodic comets, at every opportunity".

Cometary nuclei may have formed during the development of the solar system. Laboratory work has been carried out recently on the mechanism of formation and aggregation of solid particles in space. Irregular filamentary structures are formed and lead to a porous, low density matrix. (50) A low temperature of formation may have been due to the shielding of solar radiation by condensed grains. (51) Chemical effects may also have taken place under the effects of energetic radioactive decay products and energetic solar corpuscles. (52)

II. PLANNED SPACE EXPERIMENTS

We have already mentioned the desirability of cometary infrared spectrometry from high altitude balloons or aircraft. As in various other chapters of astrophysics, a major breakthrough in the field of cometary physics requires space observations. It is probable that only a comet probe will reveal the true natures of the nucleus, of the solid particles and parent molecules of the head and tail, and of the main physical mechanisms involved, including the magnetic and magnetohydrodynamic effects. Information on the far-ultraviolet spectrum should also be gathered. Moreover, artificial gaseous and solid comets should be launched and observed with telescopic, photometric, spectrographic, and polarizing devices.

Some "colorimetric" far-ultraviolet information will certainly be obtained from the survey programmes that will be carried in future orbiting astronomical observatories, especially the Celescope or the "Liège-Edinburgh Experiment" (of the European Space Research Organization). We should not exclude the possibility of obtaining a photograph or a photoelectric record of the far ultraviolet spectrum of a comet by using an adequately equipped sounding rocket and a very luminous spectrograph. Eventually, we hope to secure spectrometric data with a spectral resolution similar to that in the usual region (in wave number units per millimetre); such detailed information will have to wait until powerful orbiting telescopes and slit spectrometers become available.

What should we expect? Of course, the unexpected will be the more exciting. Nevertheless, it may be interesting to venture a few predictions. Since the amount of solar radiation of wavelength shorter than $\lambda 3000$ represents only 1 per cent of the total amount of solar electromagnetic energy, we may expect that the ultraviolet cometary spectrum will be weak, compared with the usual spectral range.

It appears impossible to foresee the intensity and spectral distribution of the scattered ultraviolet solar spectrum. As for the ultraviolet cometary emissions themselves, it is reasonable to assume that they are excited by the same fluorescence mechanism as the cometary bands of the ordinary region. The ultraviolet region offers the possibility of discovering such cometary molecules and atoms as H_2, N_2, O_2, NH^+, CN^+, N, O and C, whose resonance transitions are shortward of λ3000 Å.

Let us, as an example, take the case of N_2. We know that the N_2 molecules of the telluric atmosphere absorb the Lyman-γ emission of the Sun. If we assume that the comets contain a sufficient number of N_2 molecules in the proper rotational level, these will also absorb solar Ly-γ and give rise to a discrete triplet-resonance series, consisting of the P(6), Q(5) and R(4) transitions in the $(2\text{-}v'')$ $(v''=0, 1, 2, \ldots)$ bands of the $b^1\Pi_u - X^1\Sigma_g^+$ system. However the intensity decrease with increasing v'' in this series will be slow, so that the available energy will be distributed among many triplets which will presumably all be very weak. Actually, will there be cometary molecules with the proper rotational quantum number in the ground electronic state? And if there are, is this rotational level not going to be partly depopulated by the absorption process, and hence become available only to a lesser extent for subsequent absorptions? Only observations will tell us.

Important differences arise in the exciting emissions. In the region $3000 > \lambda > 1700$ Å, the exciting solar radiation is mainly the continuum; of course, the profiles of the corresponding excited bands will be distorted by the solar absorption and emission lines. This distortion is more pronounced than in the usual spectral range, because of the greater number of absorption lines, and also because of the presence of discrete emissions, such as the Si II lines. But for λ shorter than 1500 Å the exciting solar radiation is mainly in the form of discrete lines, plus the Lyman, He I and He II continua. If cometary emissions are excited by radiations $\lambda < 1500$ Å, they will thus not be real bands, but discrete resonance series, at least if secondary effects are not involved. There is a narrow spectral region in which the solar continuum and the discrete solar emissions may play an equal role. It is clear also that excitation by discrete emissions will be very sensitive to the radial velocity of the Sun relative to the comet. In particular, the ultraviolet pre- and post-perihelion spectra of a comet may be entirely different.

The possible resonance series of H_2, N_2, N_2^+, CN^+, and NH^+ may be predicted. (**39**) For many other expected molecules our knowledge of the far ultraviolet spectra is still incomplete or even entirely lacking. The case of the polyatomic parent molecules is especially complicated. In most cases, for example H_2O, the far ultraviolet absorption spectrum is still insufficiently known despite numerous investigations.

Artificial gaseous comets may be created by high altitude releases of gases that are expected to be stable parent molecules in comets, such as

NH_3, H_2O, CO_2, CO, possibly CH_4 (methane), C_2H_2 (acetylene), C_2N_2 (dicyanogen), HCN (hydrogen cyanide), $(NH_2)_2$ (hydrazine), C_3H_4 (methyl acetylene), H_2O_2 (hydrogen peroxide). Their photodissociation in the field of solar radiation should give rise to the cometary radicals CN, C_2, C_3, CH, NH_2, NH, OH. The NH_3 may produce NH_2 and NH; $(CN)_2$ may give rise to CN; C_3H_4 to C_3, C_2 and CH; H_2O and H_2O_2 to OH; $(NH_2)_2$ to NH_2 and NH, etc. The CO_2 and CO are of interest only insofar as they lead to the corresponding ions, but the production of CO^+ and CO_2^+ by photoionization would be too slow.

As in the cases of the Moon, Venus, and Mars, the major breakthrough in our knowledge of the comets will result from comet probes. I shall consider here only the observations that may be carried in a fly-by experiment. Obviously, a direct sampling of the nucleus itself will eventually be required. Whipple writes: "An enormous, if not definitive, insight concerning the nucleus and the evolutionary problems of comets could be gained by a space probe made to land on a cometary nucleus. Cores of the nucleus should be stratified like geological sedimentary strata and should give the oldest and least disturbed material record of ancient processes". Whipple has also expressed interest in pacing the motion of a probe with the motion of a comet. However, the first comet probes should be designed for cometary observations at large relative velocities. All the main information on the cometary nucleus, head, and tail will be gathered within an hour or at the most a few hours. A system of storing the information and then transmitting it to the Earth will be needed. The comet-Earth distance may be shorter than the Venus-Earth distance.

Obviously, the experiment should also be equipped to furnish information on space environment en route to and away from the comet. Valuable data could be obtained outside the plane of the ecliptic, especially by using a plasma detector (for measuring the solar wind), dust detectors, a magnetometer and cosmic ray instruments. Indeed, the probe could be equipped more or less like an IMP (Interplanetary Monitoring Platform) or like Mariner 2 or a Mariner Mars spacecraft. Such instruments in any event would be needed in the neighbourhood of the comet.

Many questions regarding the cometary nuclei remain unanswered.

Is a cometary nucleus made of one block of ice, or of a few blocks, or of a multitude of relatively small solids? What is the structure of the surface: fairly clean ices, a mixture of ices and "dirt", or mainly meteoritic dirt? What are the size, shape, and magnetic properties of the nucleus? What are the temperatures on the illuminated and dark side? Are there radiation belts around certain cometary nuclei? Do the nuclei rotate?

The spectrum observed from the ground reveals only the molecules or ions that emit their resonance electronic transitions or their quasi-resonance transitions (as in the case of C_2) in the region 3000 Å$<\lambda<$ about 1μ; actually, very little is known beyond λ7000 Å, except that the strongest bands of the red CN-system are present in the coma. We cannot observe the gaseous components whose resonance systems are below λ3000 Å; in particular, we have no observational evidence on the parent molecules. Possibly we shall gain information on the far ultraviolet spectra, with the help of astronomical orbiting telescopes or of rockets. However, the source of excitation—the Sun—is weak in the ultraviolet. Moreover, the fluorescence excitation is strongly limited by the fact that the far-ultraviolet solar spectrum is essentially made up of discrete emissions. Perfect wavelength coincidences between a discrete solar emission line and a discrete absorption line of a cometary molecule do not take place frequently, and they are very sensitive to the radial velocities of the comet relative to the Sun and of the different regions of the coma and tail relative to one another. More direct methods of physico-chemical analysis should thus be used in addition to spectroscopy.

The total density may be determined fairly reliably, with, for example, a Golay detector which would measure the dynamic pressure of molecular impact. Probably mass spectrometry will have developed in a few years to the point where the partial abundances of the neutral molecules may be determined. The relative abundances of the ionized molecules may be measured by mass spectrometry. Miniaturized mass spectrometers, such as have been constructed for various space experiments (e.g. the OGO or Orbiting Geophysical Observatory), may be able to differentiate between the major molecular ions and, possibly, even certain isotopes. The total abundances of the ions and the electron densities may also be measured. We have practically no information on the continuous radio emission of comets. The measurement of plasma frequency would be interesting.

From the ground the only way to obtain information on the small scattering solid particles giving rise to the continuum of comets is by measurement of the spectral distribution of the intensity and polarization of the continuum at different phase angles. However, there are three unknowns: (1) the natures (probably different kinds and mixtures), (2) size distributions, and (3) shapes of the particles. All three unknowns affect considerably the scattering properties. They are different in the head and tail, and may even differ in different comets, just as do the relative molecular abundances and the relative abundances of gas and dust.

As much information as possible should be gathered by equipping the probe with instruments similar to those employed for the measurements of the particulate contents of space on satellites or sounding rockets.

12. FINAL REMARKS

Investigations on comets will eventually provide a wealth of information which will help in understanding the origin and evolution of the solar system. The orbits of comets extend from the inner corona to the outskirts of the solar system. Spectroscopic and photometric data on comets have already been gathered to five astronomical units. Comets have a high potential value as probes of the solar field, and especially of the solar wind.

Whipple concluded a recent paper by the following statement: "In the writer's opinion, no well-developed or even intuitively satisfactory theory for the origin of comets yet exists". I am rather tempted to share Whipple's view, but I am convinced that a fully satisfactory theory will become available in the not too distant future, as a result of all the observational and theoretical endeavours in the field of comets. By the time Halley's comet returns to our neighbourhood, about 20 years from now, probes will probably have been sent on fly-by missions to comets. Perhaps one such probe will be reserved for Halley's comet itself.

For several years, in the forties, I had luncheon five days a week with a few Mt Wilson colleagues; Drs Adams, Merrill, Joy, and Sanford. At that time I used to divide my efforts between comets and molecular astrophysics on the one hand, and bright line stars on the other. Dr Merrill regularly teased me by saying that it was a pity to waste on comets a precious time that I should have devoted to the bright line stars. Maybe Dr Merrill was right! But at any rate, I have had lots of fun studying cometary physics.

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