Physical Theory of Comets in the Light of Spectroscopic Data

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AMONG celestial bodies comets occupy a peculiar position. They are transient objects varying in apparent brightness by many magnitudes and often exhibiting remarkable changes in their aspect within a few hours. A thorough observation of one bright comet would not only task the resources of a well-equipped observatory but would also involve an international cooperation. Such observations are difficult to organize as the last apparition of Halley's Comet in 1910 has proved. Consequently, in spite of a tremendous amount of observational material, with whole volumes devoted to a single comet, we are very far from understanding even the basic phenomena of comets.

Spectrum analysis of comets dates from 1864 when Donati (1)[1] observed visually the spectrum of Comet 1864 II. Since that time the spectra of 108 comets have been observed. There is no exaggeration in saying that the study of the spectra of comets has not helped in elucidation of cometary phenomena. On the contrary, a host of new and baffling problems has been introduced. Before we knew anything about the spectra of comets, the mechanical theory of their forms bequeathed to us by Bessel[2] and developed to a great degree of perfection by Bredichin[3] and his pupils seemed to give a perfectly consistent picture of cometary phenomena. One could speak of cometary tails as consisting of hydrogen or of metallic vapors, such as gold or mercury, solely on the basis of the ratio of molecular weights of these elements and the observed repulsive forces of the sun acting in the tails. Now we know that one and the same substance, CO^+, is moving in the tails under repulsive forces ranging from zero to several thousand times the force of the Newtonian gravitation. Moreover, before CO^+ gets into the tail, some remarkable transformations occur in the matter released by the nucleus. The nature of these transformations is still very imperfectly understood.

In the present paper I shall attempt to give a brief summary of the general problems raised by the new data of spectrum analysis, to point out why certain proposed solutions in cometary physics are not acceptable, and to outline an observational procedure which may help us to arrive at a better understanding of cometary phenomena. The detailed problems of identification and structure of molecular bands in comets will be considered in other papers of this conference.

We assume that the nucleus of a comet is a loose agglomeration of comparatively small particles or meteors. There is overwhelming observational evidence in favor of this conception, not to speak of the established connection between some comets and meteoric showers. These meteors in some way generate gases which escape from the nucleus either uniformly in every direction, or within two definite directions, or in a very narrow stream. The observational indications for these three possibilities are halos, emission fans, and jets. It is not known exactly how gases are produced from meteors, nor why these gases are ejected with velocities reaching sometimes several km/sec. as if they were under high pressure, nor how some comets can, with their exceedingly small mass, retain their atmosphere without any appreciable change for weeks and months at a time.

Suffice it to say that the action of the sun on cometary matter plays an important part in these phenomena, although it is evident that the characteristics of the comet itself also must be taken into account. One of the most active comets in the generation of fans, jets, halos, etc., 1862 III (connected with the Perseid meteoric shower), had a perihelion distance of 1.0 astronomical unit, while many other comets with smaller perihelion distances were quiescent. The remarkable distortions in the tail of Comet 1908 III occurred when the comet was 1.7 astronomical units from the sun. Comet 1886 V, with a small

[1] Figures in parentheses refer to the bibliography at the end of this paper.
[2] Bessel, Astronom. Nach. **13**, 185, 345 (1835).
[3] R. Jaegermann, *Bredichin's Mechanische Untersuchungen über Cometenformen* (St. Petersburg, 1903).

perihelion distance 0.3, never had a trace of tail, whereas the great comet of 1811, with a perihelion distance of 1.0, was remarkable for the length and brightness of its tail. These examples show that there must be a considerable difference in the ability of comets to generate gases out of the constituents of their nuclei.

REPULSIVE FORCES

The observational evidence is quite conclusive that there is a repulsive force, presumably the radiation pressure of the sun, acting on particles ejected from the nucleus of a comet. We must assume that this repulsive force is central and that it varies inversely as the square of the distance from the sun. The ratio μ of the effective repulsive force to the Newtonian force of attraction of the sun is negative. The total repulsive force is then $1-\mu$ measured in terms of the gravitational units k^2. The value of $1-\mu$ is independent of the heliocentric distance.

If a particle is ejected at the time t_0, with the velocity g, in the direction G, and is subject to a repulsive force $1-\mu$, its position in cometocentric coordinates, ξ, η, is given by

$$\xi = -\tau g \cos G + \frac{\tau^2}{2}\left(\frac{1-\mu}{r^2} - \frac{2(p)^{\frac{1}{2}} g \sin G}{r^2}\right) + \cdots,$$

$$\eta = \tau g \sin G - \frac{\tau^2}{2} \cdot \frac{2(p)^{\frac{1}{2}} g \cos G}{r^2} + \cdots, \tag{1}$$

where $\tau = (1/k)(t-t_0)$, r is the heliocentric distance of the nucleus, and p is the parameter of the orbit of the nucleus. The coordinate ξ is measured along the prolonged radius vector of the nucleus, and η in the perpendicular direction with the positive direction opposite the motion of the nucleus.

It is obvious that the motion of a particle in space is determined by the six ordinary orbital elements i, Ω, π, q, e, and T and the value of $1-\mu$. The general problem of determining these seven quantities from the observed motion of a particle is insoluble, or, at least, it has not yet been solved. Some simplifying assumptions, therefore, must be made before observational data are subject to mathematical treatment. The usual assumption which is implied in formula (1) is that the axis of the tail is in the plane of the orbit of the nucleus; that is, the elements i and Ω are assumed to be known from the motion of the nucleus. This assumption has been carefully scrutinized by Bredichin and others, and it appears to be valid.

Limitations of formula (1) must be mentioned. First, with small g and, consequently, large τ, the convergence of the series may be too slow, and higher terms must be taken into account. Second, in many bright comets there are several centers of activity so that a particle does not necessarily start into the tail from the primary nucleus. Third, the nucleus itself exerts a repulsive force on the particles in its neighborhood. All this was recognized by Bessel who introduced the concept of a "sphere of action" (Wirkungsphäre) of the nucleus instead of a nucleus as a mathematical point. When these circumstances are allowed for, formula (1) becomes exceedingly complicated and difficult to handle.

The repulsive force can be determined from the curvature of the tail. This is not the apparent curvature of the tail as projected on the celestial sphere but rather the curvature in the plane of the orbit of the nucleus.

If τ is eliminated from formula (1), on the assumption for the axis of $G=0$, we obtain

$$1-\mu = (8p/9r^2 \tan^2 \phi)\xi + \cdots, \tag{2}$$

where $\tan \phi = \eta/\xi$. Angle ϕ is evidently the angle which a point on the axis of the tail makes with the prolonged radius vector as viewed from the nucleus in the plane of the nuclear orbit.

It may seem that $1-\mu$ can be determined from (2) without any difficulty. However, if the earth is near the line of the nodes of the comet's orbit, the evaluation of the angle ϕ is uncertain. Also, for large values of $1-\mu$ the axis of the tail approaches the η axis, and $1-\mu$ becomes indeterminate. Moreover, the axis of the tail is not always easily recognized, for in some comets one side of the tail is sharply defined while the other is diffuse.

Bredichin studied the curvature of the tails of 51 comets. His method was essentially approximate. He computed syndynams, that is, the curves on which particles ejected at different times and subject to the same repulsive force are situated. The equation of a syndynam is obtained from Eq. (1) by the elimination of τ:

$$\xi=\left(\frac{9r^2(1-\mu)}{8p}\right)^{\frac{1}{3}}\cdot\eta^{\frac{2}{3}}+\frac{2re\sin v}{p}\cdot\eta+\cdots, \qquad (3)$$

where r, e, v, and p are the familiar quantities pertaining to the orbit of the nucleus. He then assumed different initial conditions and found the best fit of these curves with the observed value of ξ and η as projected on the celestial sphere.

On the basis of his studies, Bredichin divided cometary tails into three groups or types:

	$1-\mu$	g
Type I	18	6.5 km/sec.
Type II	2.2–0.5	1.5 km/sec.
Type III	0.3–0	0.4 km/sec.

It is true that most bright comets, the only ones studied by Bredichin, have strongly curved tails indicating small repulsive forces, and yet the distinction between types II and III is hardly sufficiently marked to justify their separate existence. Insofar as type I is concerned, Bredichin's method of computing $1-\mu$ fails utterly. There were warnings[4] even in his own time that some comets have tails with so small a curvature that the repulsive force must be enormously greater than 18. Now there is no doubt that the repulsive force in the tail can sometimes attain a value of several thousand times the force of gravitation.

Even more fundamental difficulty is presented by some of the most spectacular comets, such as 1744, 1858 VI, and 1910 I, the tails of which could not be represented at all by syndynams. The idea of a constant repulsive force acting on particles in the tails of these comets had to be abandoned altogether, and the concept of a synchrone had to be introduced. A synchrone is the curve on which particles ejected simultaneously but subject to different repulsive forces are situated. The tail appears, then, as a fan, the components of which converge to the nucleus. The equation of a synchrone can be derived from (1) by the elimination of $1-\mu$:

$$\eta=\frac{2p\tau}{r(3r(p)^{\frac{1}{2}}+4e\sin v\cdot\tau)}\cdot\xi+g\sin G\cdot\tau -g\cos G\frac{(p)^{\frac{1}{2}}}{r^2}\cdot\tau^2+\cdots. \qquad (4)$$

In the case of Comet 1910 I, investigated by Pokrowsky,[5] the repulsive force in the synchrone varied from 0.6 to 2 times the gravitation. There was, therefore, no definite value for $1-\mu$ acting in the tail.

If we now turn to spectroscopic data concerning tails, we do not find clear-cut evidence as to their constitution. Visual observations often refer to the spectrum of the tail as being wholly continuous. Such are the results obtained by Huggins (40) for Comet 1874 III and by Riccó (131) for Comet 1882 I. Most observers agree that the Swan bands do not extend far into the tail, although from time to time these bands are described as prominent throughout the tail.

The photographic observations are very few. For Comet 1910 I, Wright (292) found the spectrum of the tail wholly continuous with the maximum of intensity near λ4700. Baldet (283) agrees with his results but reports faint traces of CO^+ bands. This comet had a tail with a large curvature and, consequently, a small repulsive force.

Comets with straight tails like 1908 III invariably showed almost exclusively CO^+ with faint bands of N_2^+ in the tail, corresponding to a much greater $1-\mu$.[6]

The crucial test of Bredichin's theory is the spectra of tails of different curvature. Such comets were 1910 II, 1912 I, and 1914 V. In the first comet the straight tail showed $1-\mu$ between 9.0 and 16.0, and the curved tail had $1-\mu$ between 0.1 and 0.2. The detailed investigation of Halley's Comet by the author (297) showed that both of these tails consisted of CO^+, although in the more strongly curved tail CO^+ was less prominent, and the agent giving the continuous spectrum of the solar type was very prominent. Analogous results were obtained by Slipher and Lampland (311) for the same comet. In Comet 1912 II the two tails of widely different curvature[7] had exactly the same spectrum, although Baldet (355) identifies it with CO^+, while the present writer (356) identifies it with C_2. Since Baldet's

[4] Bruhns, Astronom. Nach. **123**, 113 (1890) calculated for Comet 1886 I $1-\mu=11{,}478$.

[5] Pokrowsky, Publ. K. Univ. Sternw. zu Juriew **24**, Part 1.

[6] The difference in the spectra of the tails of Comet 1910 I and 1908 III is strikingly illustrated in the reproduction of Baldet's article, Conf. d'Act. Sci. et Ind., No. 16 (1930).

[7] According to Vsessviatsky [Astronom. Nach. **221**, 13 (1924)] the main tail was a syndynam with $1-\mu=40$, the secondary tail was a synchrone with a very small $1-\mu$.

spectrograms (objective prisms) were of much greater dispersion, his identification is undoubtedly more correct. In Comet 1914 V again both tails of different curvature showed identical spectra, probably of the same character as in Comet 1910 I (374).

The situation is undoubtedly even more complicated, as there is evidence that the proportion of CO^+ and dust (if we assume it to be the agent producing the continuous spectrum of the tail) in tails of comets is changing continuously throughout the tail. The present writer (266) found a progressive shift in the maximum of intensity from the violet to $\lambda 4700$ in the tail of Comet 1908 I with the recession from the nucleus. This was noted before in visual observations by several observers.[8] This result is indirectly confirmed by the fact emphasized by practically all observers that the CO^+ images of the tail are always nearly uniform in brightness from the nucleus to the end of the tail, whereas the direct image of the tail shows a rapid decrease in brightness. Consequently, there must be some other substance in the tail producing such an effect. The diffuse spectroscopic image of the tail, apparently due to reflected light, does show the necessary rapid decrease in brightness depending on the distance from the nucleus, as can be immediately seen on the reproductions of the spectrum of Halley's Comet published by V. M. Slipher (311) and by the author (297). It should be noted, however, that Vsessviatsky (346) in his investigation of Comet 1911 V did not find the displacement of the maximum intensity of the continuous spectrum from violet to red with the increasing distance from the head, and so the situation may well be different for different comets.

As has been mentioned before the repulsive forces acting in straight tails cannot be determined even approximately by the method of syndynams. Often the only thing that can be said in such cases is that the repulsive forces must be very large. Sometimes, however, condensations are seen in the tails, and their motion can be followed for several days.

Appropriate formulae have been developed for the motion of these condensations in hyperbolic orbits in reference to the sun under the repulsive force $1-\mu$. As in the case of syndynams, the problem cannot be solved in its entirety, and it must be assumed that these condensations are moving in the plane of the orbit of the nucleus. This assumption has been challenged, and attempts have been made to calculate the repulsive force acting on a condensation which is moving in the plane of an orbit different from that of the nucleus. The improvement in the situation is wholly illusory, however, as another assumption must be made in this case, namely, that at a certain moment the coordinates of the nucleus and of the condensation were identical. While there is no doubt that the matter in the condensation originally belonged to the nucleus, it has been shown that often the motion does not start at the nucleus. As an illustration, we can take the motion of a condensation in the tail of Halley's Comet (297) on April 17–20, 1910. The matter in the envelope was moving for three days under no effective repulsive force. Suddenly a condensation developed at the tip of the envelope. Of the four centers of activity of this condensation two were moving under $1-\mu=48$, one under $1-\mu=238$, and the repulsive force acting on the fourth one could not be determined but was very small. In the same comet on June 5–8 a condensation moving in the northern branch of the tail, from the curvature of which the general repulsive force of about 16 was determined, changed its orbit three times with the change of the repulsive force from 1656 to 155, to 2309, and finally to 1013. There was still another condensation in the southern branch of the tail which was moving under no effective repulsive force. All of these condensations showed very well in the monochromatic images of CO^+ on the objective-prism spectrograms although their relative brightness was significantly different. The one moving under no repulsive force was comparatively weak in CO^+.

In all cases when spectroscopic material was available, the condensations in the tails of comets showed CO^+ as their main material. In addition, in no cases could the condensations be traced immediately to the nucleus. They developed out of rather quiescent formations, like the edges of envelopes or out of jets, with a suddenness re-

[8] See, for instance, Campbell (254), Comet 1907 IV: "The spectroscopic observations of the tail seem to show that the inherent light, existing in large proportions near the head, decreases in proportion to reflected or diffused sunlight with increasing distance from the head."

sembling an explosion. In several cases in Halley's Comet, jets consisting chiefly of cyanogen and moving under small repulsive forces were the foci where the CO^+ condensations were formed and where they began moving with much greater accelerations.

It should be noted that the method of following condensations in the tail and of computing their orbits has its limitations. The condensations are usually diffuse by their nature and also because of their motion during the exposure. Their shape is variable, and, unless photographs are available from other observatories of different longitudes, it is sometimes difficult to recognize the condensations on the next day. The probable errors of ten percent in the value of the repulsive force are not unusual. Several certain facts, however, emerge from the data based on the motion of condensations: (a) the existence of very large repulsive forces, up to several thousand times the force of gravitation, (b) frequent changes in the value of $1-\mu$, (c) the sudden development of the condensations out of quiescent formations, and (d) the presence of CO^+ as their main constituent.

All of these results are confirmed by the study of another type of formation in the tails of some comets, namely bright rays or streamers. In Halley's Comet condensations in them showed $1-\mu$ from 488 to 878 (297). The application of a modified syndynam method to streamers in Comet 1908 I resulted[9] in $1-\mu=1{,}700$; S. V. Orlow[10] and Eddington[11] found for the same comet (September 17) $1-\mu=4000$. For another case (November 14), however, Orlow found $1-\mu$ only 134. In Comet 1893 IV Vorontsov-Veliaminov[12] found $1-\mu=3000$.

The repulsive force can finally be determined from the structure of the envelopes. From (1) we can obtain by the elimination of τ:

$$\xi=-\cot G\cdot\eta+\frac{1-\mu}{r^2}\cdot\frac{\eta^2}{2g^2\sin^2 G}+\cdots. \quad (5)$$

If further terms in expression (1) be taken into account, the resultant curve is an hyperbola with a slight hyperbolic excess. The head of the comet in space is then nearly a paraboloid of revolution with the axis along the prolonged radius vector of the nucleus. Of course, the observed outlines of the head may be any conic section depending on the conditions of projection.

Now it has been found in many comets, such as 1858 V, 1910 II, and, recently, 1941*c*,[13] that the outlines of the head are not a conic section but rather a catenary, thus introducing still another complication into the mechanical theory of comets. The repulsive forces cannot be generally determined from the outlines of the head without making assumptions as to the value of g. The direct determination of $1-\mu$ from the motion of matter in the envelopes of Halley's Comet gave $1-\mu$ approximately equal to unity. The spectrum of the envelopes in this comet always showed CN and C_2.

If we now turn to the values of repulsive forces obtained on the bases of physical data, we find $1-\mu=151$ calculated for the molecule CO^+ by Baade and Pauli.[14] It was shown by Wurm[15] that the correct value should be about one-half of this figure. Furthermore, there cannot be just one value owing to the fact that the oscillatory strength of the molecule may vary within certain limits. Wurm finally comes to the conclusion that $1-\mu$ should be between 65 and 121 times the gravitation acting on the molecule. He compares his result with the values of $1-\mu$ calculated from the motion of matter in the tails of comets and finds a satisfactory agreement.

Unfortunately, these conclusions cannot be accepted. Wurm considered only the values of $1-\mu$ calculated without the assumption that the condensations in the tail move in the plane of the orbit of the nucleus. These orbits gave an average $1-\mu=94$ which is considered by Wurm to be in agreement with his calculations. It has been shown, however, (297) that the values of $1-\mu$ calculated under this assumption deserve no confidence. On the other hand, the extremely small and large values of effective repulsive forces obtained for the condensations moving in the tail, from almost zero to several thousand times gravitation, do not find any explanation in Wurm's theory.

[9] Aristov, Russ. Astronom. J. **12**, 573 (1935).
[10] S. V. Orlow, Russ. Astronom. J. **7**, 81 (1930).
[11] Eddington, M. N. R. A. S. **70**, 442 (1910).
[12] Vorontsov-Veliaminov, Russ. Astronom. J. **7**, 90 (1930).
[13] Stoy, M. N. R. A. S. **101**, 337 (1941).
[14] Baade and Pauli, Naturwiss. **8**, 281 (1934).
[15] Wurm, Zeits. f. Astrophys. **10**, 285 (1935).

CHANGES IN THE SPECTRUM

The continuous background in the spectrum of the nucleus, often showing the Fraunhofer lines because of the reflection of the light of the sun, has been observed in many comets. The continuous spectrum of the coma has also been observed, although, in this case, the bright sky owing to moonlight or dawn may produce a spurious effect.

The relative strength of the continuous background to the emission bands varies in wide limits, presumably in accordance with the physical composition of the comet. Comet 1892 III displayed only a continuous spectrum in which no bands could be observed. On the other hand, Comet 1908 III had such a faint continuous spectrum that it was overlooked by many observers.

The question of the variation in the continuous spectrum of the nucleus and neighboring parts of the coma as a function of heliocentric distance has not been settled. The present writer[16] found in many comets a gradual displacement, with the increasing heliocentric distance, of the continuous spectrum of the solar type with another type of the continuous spectrum. This latter has the maximum of intensity near $\lambda 4000$. The average distance at which the change occurs is 0.8 astronomical unit. This study was based on objective-prism spectrograms of very small dispersion, and it is possible that we may have to deal here with the variation in the strength of the "$\lambda 4050$ group" of bands at $\lambda 4000$. The existence of a continuous spectrum with the maximum intensity in the violet had been found earlier, however, by Rosenberg (280) in Comet 1908 III. The present author confirmed his results on objective-prism spectrograms of much greater dispersion (334) and also on slit spectrograms (297). The same result was obtained by Vsessviatsky in his study of Comet 1911 V (346) and Encke (379). The difference in the distribution of intensity in the continuous spectrum of Comet 1911 V at $r=1.38$ and $r=0.50$ is obvious on the reproductions of the spectrograms of much larger dispersion taken by Baldet,[17] and it agrees with the results obtained by the author. Among recent comets, the microphotometer record of the spectrum of Comet 1937 V (438) shows clearly the maximum of intensity in the violet at $r=0.87$. On the other hand, a photometric measurement of slit spectrograms of Comet 1936 II at $r=1.18$ gave according to Wellmann and Richter (429) the distribution of intensity of the continuous spectrum of exactly the solar type.

That there is a considerable difference in the distribution of intensity in the continuous spectra of comets can hardly be denied. The question of the correlation with the heliocentric distance, however, is open to argument, pending further study.

The theory that the continuous spectra of comets are produced by a bombardment of different ions with electrons was discussed by W. Cohn,[18] without, however, conclusive results.

Rapid changes in the distribution of intensity in the continuous spectrum of the nucleus occurring within a few hours were recorded by the author in Comet 1910 II (296) and 1914 V (374). Both the gradual and sudden changes in the continuous spectrum find their partial confirmation in the variation of the color index of comets, although the interpretation of these changes is made somewhat uncertain by the possible variation in the intensity of the molecular bands. Thus, for Halley's Comet, Knox-Shaw[19] found a variation of the mean color index from $+1^{m}.38$ for $r=3.93$ to $+0^{m}.95$ for $r=4.54$. Tikhov[20] found for Comet 1908 III the color index varying from $-1^{m}.75$ for $r=1.37$ to $-0^{m}.15$ for $r=1.10$. Kukarkin[21] found for Comet 1930 III a variation in color index from $-0^{m}.55$ for $r=0.51$ to $-1^{m}.1$ for $r=1.72$. These and other results can be interpreted in the sense that comets show more concentration of light in the violet part of the spectrum at greater distances from the sun.

Rapid changes in the color index are also well established. According to Tikhov, Comet 1908 III changed its color index from $+1^{m}.00$ on November 15 to $-1^{m}.00$ on November 19. Reports on the variation in observed color of the nucleus are quite common.

The variation in intensity and extent of the monochromatic images of CN and C_2 on objective-

[16] N. T. Bobrovnikoff, Astrophys. J. **66**, 440 (1927).
[17] Baldet, *Conf. d'Act. Sci. et Ind.* No. 16 (1930).
[18] W. Cohn, Astrophys. J. **76**, 277 (1932).
[19] Knox-Shaw, Helwan Bull. No. 2 (1911).
[20] Tikhov, Pulk. Mitt. **3** (1909).
[21] Kukarkin, Tashkent Pub. **4**, No. 2 (1933).

prism spectrograms has been studied by the present writer in the case of Halley's Comet (296) and by Vsessviatsky in the case of Comet 1911 V (346) and Encke (379). The variation in intensity of various cometary bands depending on heliocentric distance has been studied also by Hogg[22] on the basis of all observations available up to the year 1929.

The general result of these investigations is the variability of spectral images both progressive with time and rather sudden, agreeing with numerous older reports of the variability of Swan bands observed visually (21, 30, 31, 32, 164, 165, 174, 200, 201, 212). Of especial interest are Vsessviatsky's conclusions that Encke's Comet in different apparitions (at approximately the same heliocentric distance) may exhibit very different spectra. For instance, in 1914 the "λ4050 group" of bands were almost as strong as the main CN bands; in 1924 they were much weaker, and in 1928, quite insignificant.[23] The spectrophotometric study of the intensity and structure of cometary bands is obviously an important problem but one hardly attempted as yet.

The same remark applies to the diffuse image of the tail on objective-prism spectrograms exhibited by some bright comets.

Of especial importance are the observations of the spectra of comets at the time of their changes in aspect or in brightness. Naturally, there are very few observations of this kind. Vogel (174) observed the remarkable outburst of Comet 1884 I on January 1, 1884, when the nucleus of the comet increased in brightness by 0.53 in 70 minutes and subsequently decreased by 0.33 in 29 minutes. The continuous spectrum of the nucleus greatly increased in intensity during the outburst as if a large amount of dust was thrown out by it. Similar conclusions were reached by the author in the study of Halley's Comet (297).

It stands to reason that the variations in the visual brightness of the comets must be accompanied by variations in their spectra, but the spectroscopic material is too meager to allow any safe conclusions. It is possible that the cyclic variations in the brightness of comets established by the present writer[24] are reflected in their spectra.

EJECTION OF MATERIAL

We have come now to the problem which is obviously of fundamental importance but on which there is but scanty information. The principal seat of cometary activity is the nucleus of the comet out of which material for the head and the tail is produced. What is this material ejected from the nucleus? There are numerous visual and photographic observations on the activity of the nucleus, but spectroscopic data are few and far between. One of the reasons for this state of affairs is that we have not recently had magnificent comets like 1858 VI and 1862 III displaying a bewildering sequence of phenomena and well situated for observation. There are also numerous practical difficulties in spectroscopic observations of different parts of the head. Usually the slit of the spectrograph is directed along right ascension with the nucleus kept in the middle of the slit. What portions of the coma are thus studied depends largely on chance.

That this situation may result sometimes in apparently contradictory results was shown by the writer.[25] The spectrum of the periodic comet Pons-Winnecke was observed by Moore (407) and by V. M. Slipher (409) who reported an unusual faintness of the Swan bands. The slit in both cases was directed along a jet. The objective-prism spectrograms, on the other hand (406, 408), showed strong Swan bands. Fortunately, on the Yerkes spectrograms by the writer and Pogo (406), the spectrum of the jet was visible in the cyanogen and "Raffety" bands but not in the Swan bands, a fact which explains the results obtained with the slit spectrographs.

There seems to be considerable difference in the spectra of the jets and the emission fans so far reported. In Comet 1874 III Lockyer (42) and Christie (37) observed the continuous spectrum

[22] Hogg, J. R. A. S. C. **23**, 55 (1929).

[23] Another but less certain case of the difference in the spectrum of a periodic comet at different apparitions is discussed by Balder [An. Obs. Meudon. **7**, 99 (1926)]. Comet Brorsen in 1868 showed CO^+ bands in its nucleus and head. In 1879, however, the spectrum was composed of ordinary Swan bands. This comet is remarkable for its disappearance in 1879 and its connection with Comets 1894 I and 1911 VII (Mahnkopf, Astr. Mitt. St. Gött. **20**, 1919).

[24] N. T. Bobrovnikoff, Perkins Observatory Contribution No. 16 (1942).

[25] N. T. Bobrovnikoff, Pub. Astronom. Soc. Pac. **40**, 1 (1928).

of the fan without any bands. On the other hand, Bredichin (36) found for the same comet that the spectrum of the fan was continuous with the usual Swan bands, and Vogel (48) states definitely that there was no variation in the spectrum of different parts of the head. These observations are not necessarily contradictory as they do not refer to the same time. In Comet 1881 III, again, P. Smith (95) on June 27 observed the Swan bands in a jet very distinctly, but on June 29 Young (103) found the spectrum of a jet wholly continuous. On June 30 Vogel (101) observed the Swan bands in all parts of the head and most distinctly in the emissions from the nucleus. In Comet 1907 IV Quénisset (260) found the Swan bands especially strong in the fan directed toward the sun. The present writer found the spectrum of the jet in Comet 1913 VI (365) to be identical with that of the head. In Halley's Comet (297) the jets consisted largely of cyanogen. The proportion of cyanogen to carbon differed from jet to jet, however.

It is seen from this short summary which includes all available observations that the composition of jets and fans must be different for different comets or even for the same comet at different times. One thing is reasonably certain, the absence of CO^+ in the jets and fans. Halley's Comet in which CO^+ was so prominent in the tail failed to reveal the slightest traces of CO^+ in the jets in spite of a special search for it.

The halos and "parabolic" envelopes in Halley's Comet (297) consisted also of cyanogen, but C_2 was present in them in far greater proportions than in the jets. The great comets which displayed the sodium *D* lines had sodium extended through considerable portion of the envelopes and even into the tail. Such were Comets 1882 I (122), 1882 II (136), 1910 I (290), 1910 II (297), and 1927 IX (410). It is interesting to note that a very close approach to the sun is not a necessary condition for the appearance of the *D* lines as they were observed in comet 1882 I at $r=0.87$, before perihelion and in Comet 1914 V (376) at $r=1.21$. The perihelion distance of the latter comet was 1.11. To account for the presence of the sodium vapor in these comets is difficult, for the boiling point of sodium is 877°C, whereas the temperature of a blackbody at $r=1$ is only 4°C.

One of the important results established by the direct study[26] of the motion of matter near the nucleus is the small velocities involved. They seldom exceed 1 km/sec. and are of the order of the thermal velocities of gases under moderate temperatures. That there is no great turbulence in the cometary atmospheres is clear from the radial velocity determinations from the absorption lines (302, 373, 375, 410) which agree with the velocities derived from the orbital motion of the comets. The equivalent widths of the Fraunhofer lines in Comet 1936 II (429) were exactly the same as in the solar spectrum, a fact which also speaks against any great turbulence. The large initial velocities of molecules required by the mechanical theory of comets[27] have never been observed.

GENERAL THEORY

It should be obvious from the foregoing that our present knowledge of cometary phenomena is too fragmentary for any consistent general theory. Much remains to be done in organizing the already existing voluminous material on comets and in furthering well-planned observations before we are ready for generalizations. It is probable that some parent molecules, such as CO_2 and NH_3, exist in comets, and their discovery in the infra-red region of the spectrum may bridge some gaps in our knowledge. Considerable information can also be obtained from polariscopic, visual, and photographic observations of comets.

Among numerous papers on the subject I shall mention only those by Wurm,[28] as they make use of the modern data of molecular physics. Wurm's fundamental point is the difference between short-lived molecules (C_2 and CN) and long-lived molecules (CO^+ and N_2^+). This explains the difference in the spectra of the heads and of the tails. The first kind of molecules forms elliptical envelopes, while the other kind produces parabolic envelopes. The contraction in the head of comets with the approach to the sun is necessitated by increasing density of solar radiation and consequent decrease in the length of the life of

[26] N. T. Bobrovnikoff, Pub. Astronom. Soc. Pac. **44**, 296 (1932).
[27] Such as 67 km/sec. in Comet 1908 III calculated by Cherrington, Astrophys. J. **43**, 73 (1934).
[28] Wurm, Zeits. f. Astrophys. **8**, 281 (1934) and **9**, 62 (1935); Astrophys. J. **89**, 312 (1939).

the molecules C_2 and CN. The treatment of the problem is necessarily simplified, but it is easy to see that Wurm's treatment fails to explain the most fundamental facts of observation. In Halley's Comet, for instance, both the elliptical (or circular) envelopes and the parabolic envelopes had the same composition, namely, CN and C_2, without the slightest trace of CO^+. On the other hand, the contraction of the heads of comets with the approach to the sun, although common enough, is by no means general. Thus, according to Vsessviatsky,[29] among the fourteen short period comets studied by him, only Comet Encke shows a definite decrease in diameter with the diminishing heliocentric distance. Comet Faye shows a definite increase, but the rest exhibit only irregular fluctuations in size without any correlation with the distance from the sun. Meteoric dust must play an important role in most comets as evidenced by their spectra, but it finds no place in Wurm's theory.

OBSERVATIONAL PROCEDURE

The study of the structure of molecular bands in comets requires the largest dispersion possible. Coudé spectrograms of bright comets will probably supply much information on the physical condition of comets.

Spectrograms in the infra-red region with average dispersion (say, 50A/mm) are very desirable. The increase in our knowledge of the spectra of comets will undoubtedly be as greatly advanced by the studies in the infra-red as it has been furthered by the recent studies in the ultraviolet.

Spectrophotometric investigation of the intensity of various bands and of the continuous spectrum depending on the heliocentric distance requires a long series of observations. The main difficulty in this respect is that few comets remain conveniently situated long enough for one observatory.

The spectra of different parts of the comet are of extreme interest, and an effort in this direction should be made with the next bright and active comet. The slit of the spectrograph should be placed on such formations as jets, fans, edges of envelopes, etc.

Objective-prism spectrographs may elucidate the mystery of the continuous spectrum of the tail of some comets. For this purpose, the shortest possible focal length and the largest possible dispersion are desirable in order to separate monochromatic images of the CO^+ bands.

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There is much information on the subject even in old papers based on visual observations. Going through these papers one may learn to his surprise that such a modern approach to the problem of comets as the study of polarization of the Swan bands (464) was already attempted in 1874 (46). The apparitions of such bright comets as 1882 II are too infrequent to neglect the most careful observations by Copeland and Lohse of this comet (136). No person seriously interested in the subject can afford to remain ignorant of what already has been done in this field. It is the hope of the writer, therefore, that the labor spent on the compilation of this bibliography is not all lost.

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DISCUSSION

J. Franck, *University of Chicago,* asked whether the apparent speed of propagation of luminosity in comet tails is produced by actual movement of ions, atoms, and molecules, or whether it might not be the propagation of electrical discharges. There are various possibilities to explain the occurrence of potential differences in the atmosphere of a comet tail.