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ORIGIN AND DEVELOPMENT OF COMETS

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The Halley Lecture for 1951, *delivered at Oxford on May* 1

Mr. Vice-Chancellor, Ladies and Gentlemen:

On the 14th of November 1680 Godefroi Kirch in Coburg, Saxony, discovered a large comet. The comet, which remained visible until March 1681, was one of the brightest that had ever appeared, and was carefully observed by many astronomers. The long tail, to which comets owe the name that may somewhat freely be interpreted as "long-hair wearing stars" stretched over a large part of the sky, causing terror to many. Its fearful aspect was still fresh in everybody's memory when in the summer of 1682 a new comet was discovered by Jesuit priests in Orleans. The latter comet, which at the time attracted less popular attention than its predecessor, was destined to become famous as Halley's comet. "These two comets," writes the first director of the new Observatory of Leyden, Frederic Kaiser, "are the most remarkable among all that have appeared in earlier and later times, in as much as the first caused Newton to apply the principle of gravitation to the theory of comets, while the other enabled Halley, by the discovery of its period of revolution, to put the most beautiful seal on the comet theory founded by Newton."

In delivering the first Halley Lecture on comets, it is fitting that tribute be paid to that remarkable astronomer, Edmond Halley, who, starting at a time when the shape of cometary orbits was entirely enigmatic, not only revealed the true nature of these orbits and showed that the same comet could return several times, but through an enormous perseverance deduced the orbits of enough comets to indicate at that early epoch nearly all the remarkable properties of such orbits that are known today. I should like to quote a few sentences from his *Synopsis of the Astronomy of Comets**.—After having given an account of earlier investiga-

* *A Synopsis of the Astronomy of Comets*, by Edmund Halley, LL.D., Savilian Professor of Geometry at Oxford. This was annexed to the two-volume work by David Gregory entitled *The Elements of Physical and Geometrical Astronomy* (London 1715) and was a slightly extended English version of the article *Astronomiae Cometicae Synopsis* that had appeared in Latin in the Philosophical Transactions for the month of March, 1705 (Vol. 24, pp. 1882—1899).

tions, in which he mentioned especially the work of Tycho Brahe, Kepler and Hevelius, he says: "At length, came that prodigious Comet of the Year 1680, which descending (as it were from an infinite Distance) perpendicularly towards the Sun, arose from him again with as great a Velocity . . .

Not long after, that great Geometrician, the Illustrious *Newton*, writing his *Mathematical Principles of Natural Philosophy*, demonstrated not only "that what *Kepler* had found, did necessarily obtain in the Planetary System; but also, that all the Phaenomena of Comets wou'd naturally follow from the same Principles; which he abundantly illustrated by the Example of the aforesaid Comet of the Year 1680, shewing, at the same Time, a Method of delineating the Orbits of Comets Geometrically; therein solving (not without meriting the highest admiration of all Men) a Problem, whose Intricacy, render'd it scarce accessible to any but himself. This Comet he prov'd to move round the Sun in a Parabolic Orb, and to describe Areas (taken at the Center of the Sun) proportional to the Times.

Wherefore (following the Steps of so great a Man) I have attempted to bring the same Method to arithmetical Calculation; and that with all the Success I cou'd wish." He then gives a table with orbital elements of 24 comets, "the Result of a prodigious deal of Calculation. . . . in the making of which, I spar'd no Labour, that it might come forth perfect, as a Thing consecrated to Posterity, and to last as long as Astromony it self."

Halley then remarks that no hyperbolic velocities have been found and that, consequently, it is probable that the comets would really move in very excentric ellipses, and thus, he says, "make their Returns after long Periods of Time: For so their Number will be determinate, and perhaps, not so very great. Besides, the Space between the Sun and the Fix'd Stars is so immense, that there is Room enough for a Comet to revolve, tho' the Period of its Revolution be vastly long. . . . And, indeed, there are many Things which make me believe, that the Comet which *Apian* observ'd in the Year 1531, was the same with that which *Kepler* and *Longomontanus* more accurately describ'd in the Year 1607; and which I my self have seen return, and observ'd in the Year 1682." He continued to explain that also the comets of 1456 and 1305 were likely to have been returns of the same comet, and he predicted that it would return again in 1758, a prediction which was beautifully fulfilled.

In more recent times many earlier returns of Halley's comet have been identified. The most complete study was made by Cowell and Crommelin, who traced reports of the returns of the comet as far back as that of the year 240 B.C.

In tracing the history of Halley's comet many episodes of the history of the human race are called back into our memory, because the appearance of this bright comet was invariably associated with important happenings on our Earth. In the days when the heavenly bodies were considered to be intimately interwoven with human fate it was natural that the sudden arrival of a bright comet was considered as the foreboding of terrible changes. Innumerable are the references in old literature which testify of the awe and terror inspired by comets. Mostly, they were considered a bad omen, and were held responsible for floods, fires, epidemics, wars and famine.

The great comet of Halley has been blamed and praised for many important turns in history. As Flammarion says, she might have been charged with a fair part of the superstitional terrors of mankind. I will only remind you of its influence on the battle of Hastings when it appeared in April 1066, about the time when William the Conqueror invaded England. A monk of Malmesbury in those days addressed the comet in the following terms: "I see you then, origin of the tears of many mothers; I have seen you for long, but now you appear more terrible; you threaten my country with entire ruin".

In later days comets gradually lost influence. In his *Merveilles Célestes* Flammarion gives the following quotation from Maupertuis in 1742: "Ces astres, après avoir été si longtemps la terreur du monde, sont tombés tout à coup dans un tel discrédit, qu'on ne les croit plus capables de causer que des rhumes". To some extent Maupertuis' words might also be applied to the *scientific* interest in comets during the last half century. They were very much in the foreground during the nineteenth century, but in the present century they have lost much of their grip on the imagination of astronomers. Yet, the main problems presented by them had not been solved.

The laborious investigations by Newton and Halley had brought a splendid test of the new theory of gravitation as well as a clear understanding of the motions of comets. Of course, there remained many questions. In the first place: Why are their orbits so entirely different from those of planets? And secondly: what causes their strange appearance, the varying size and intricate structure of the head, and the remarkable long tails?

Let us first turn our attention to the second group of questions.

What is a comet made of? We observe a head, or coma, and, when the comet is bright, a striking tail, which sometimes stretches over a considerable part of the sky. The coma is a roundish, hazy patch of light. It is large, nearly always larger than the Earth, often much larger. The coma of Halley's comet sometimes had a radius of about 200,000 km, or 30 times the Earth's radius. The tails are much larger, with lengths up to one astronomical unit (*i.e.* a distance equal to that of the Earth to the Sun). Both tail and coma are transparent, we can see stars through them without perceptible weakening. This is because the density is extremely low, the number of gas molecules in the coma may not be more than perhaps a million per cm^3, or ten billion times less than in air. Spectrographic observations show that beside *gas*, in which C_2 and CN appear most prominently, the coma also contains *solid* particles which reflect the Sun's light. There is evidence that the majority of these particles must be smaller than 1 cm, probably even much smaller, so that we may adequately refer to them as "dust".* They are, however, certainly larger than the wavelength of light. The contribution of the dust to the total material density in the coma is at least as large as that of the gas, and may be a few factors of ten larger.

All phenomena observed indicate that the particles composing the head are no permanent residents; they are just passing through, in the process of escaping forever from the comet.

* The evidence comes from the meteor showers connected with some periodic comets (cf. page 136.)

In order to prove this we must first try to obtain an estimate of the masses of comets. These masses are so small that no effect of their attraction upon the Earth, Moon or other celestial bodies has ever been observed. Indeed, it would be idle to look for such effects. When a comet is discovered at a relatively large distance its coma is often still small. Let us take Halley's comet as an instance. When rediscovered at its latest apparition, in September 1909, it shone largely by reflected light. If we would assume that all this light were reflected from one solid body with an albedo equal to that of the Moon the diameter of that body would have to be 40 km. In reality, a large fraction of the light came from the coma, which, although small for a coma, still measured about 20,000 km. in diameter. The solid nucleus could therefore not have measured more than 20 km. at most. With a density of 5 (corresponding to the mean density of the Earth) this would make the mass of the hypothetical solid nucleus 2×10^{19} gm., or one three-hundred-millionth of that of the Earth. This must be considered as an upper limit; if the light were reflected from a swarm of smaller blocks instead of from one body the total mass would be reduced.

Now it can easily be shown that a body of such mass cannot by any means exert sufficient attraction to keep a coma of gas together. The velocity of escape from the surface of a solid nucleus of this size is but 18 metres/sec. The ordinary temperature motions of the molecules would exceed this by a factor of 30. All molecules that become detached from the solid surface will therefore escape freely into space. As regards the solid particles we may remark that it is hardly conceivable that a stable coma with diameter between 1000 and 10,000 times that of the nucleus could ever have been formed from such a nucleus, or, if formed, could be held together in the face of outside perturbations.

Halley's is one of the larger comets. Similar estimates for other comets, show still smaller upper limits for the mass. From Cunningham's earliest measurements of Encke's comet during its latest approach we find a diameter of 3 km. and a mass of 8×10^{16} gm., while Baldet's measures on comet Pons-Winnecke 1927 VII gave a diameter of only 0·4 km. As has been mentioned, these masses are maximum values. The actual values may easily be one or two factors of ten smaller. The dimensions quoted are so small that there is not the least possibility of observing these directly. What we sometimes observe as a nucleus is probably only the central concentration of the escaping particles.

It does not seem possible to avoid the conclusion that the comas of all comets are entirely transient features. All particles are escaping continuously, and at a fast rate: molecules do not stay in the coma for more than one or two days. The source of these particles must be the invisible solid nucleus; this, then, is the essential and permanent part of the comet, in which all other features originate.

Several astronomers prefer the view that, similar to the coma, the nucleus of a comet would not be a single body, but a swarm of bodies, distinguished from the coma only through its greater compactness and the larger size of its constituent blocks. I must confess that I see no good reason for supposing such a complication. On the contrary, it can be shown that any nucleus that would be sufficiently compact to withstand disruption by the tidal force exerted by the Sun cannot consist of a swarm of separate bodies, as these would collide together and in a few years time would end up as one, or two, large lumps.

Very direct evidence for the singleness of a comet's nucleus is provided by some other phenomena, such as, for instance, the periodicity with which shells of gas are developed in the heads of some comets. A very interesting indication that the main body of a comet must be one single mass is given by the systematic shortening observed in the period of Encke's comet. This acceleration, which has long puzzled astronomers, can be explained by assuming that the expulsion of gas from the nucleus is systematically asymmetrical with respect to the direction to the Sun. This explanation, suggested by Bessel as early as 1836 has recently been worked out by Dubiago, and in particular by Whipple, who suggested that the asymmetry is caused by the rotation of the solid nucleus. There is some evidence of similar accelerations or retardations in other comets though no other case lends itself so well to an accurate determination.

What is the composition of a comet's nucleus? There is little we can say with certainty about this. No comet has ever come so close to the Earth that the nucleus proper could be studied. The astronomer is at the great disadvantage that he cannot experiment with the objects of his study. He can only watch attentively and wait until Nature itself makes some experiment for him.

One such experiment was made when in February 1843 the bright comet of that year passed through the Sun's corona. From the fact that it did not evaporate to a considerable extent Minnaert has calculated that its nucleus, or nuclei must have diameters of at least 0·5 km. Possibly, the experiment would also permit some inference as to its structure; this has not yet been investigated.

Other experiments are constantly being performed when comets come from the distant, cold parts of the solar system into our vicinity, and are exposed to intense radiation from the Sun. This radiation releases considerable amounts of gases and solid particles from the surface of the nucleus. Some of the gases that happen to have emission bands or lines in the observable part of the spectrum can be identified, but there are likely to be many more invisible molecules of such common gases as H_2, O_2 or N_2. Two facts deserve special attention, namely that a very considerable amount of dust is expelled with the gas, and that the release, in particular of the dust, begins already at distances of more than 3 astronomical units, at temperatures below $-150°$ centigrade. The frequency of C_2 and CN molecules relative to the solid particles varies greatly from comet to comet and, also, for a given comet, with the distance from the Sun.*

The matter is apparently mostly emitted from the sun-lit side of the nucleus. This is especially indicated by the visual observations; on the drawings made by visual observers the emission often resembles a fountain. When Halley's comet during its 1910 return came relatively close to the Earth it afforded a fine opportunity for studying the intricacies of the way in which the expulsion of gas and particles from the nucleus takes place.

* I cannot enter upon the interesting questions concerning the origin of the various chemically unstable molecules in the coma, nor can I discuss the way in which these molecules are excited by the solar radiation. For these problems I may refer to Swings' Council Note on *Cometary Spectra* (*M.N.* **103**, 86, 1943).

During this period straight jets were almost continually seen to proceed from the nucleus, ejected apparently from one or more small regions of its surface. Sometimes small pieces of the nucleus seemed to be detached, and to become themselves centres for new jets of luminous matter. These jets appear to be a very common feature. They are not limited to the sun-lit side. Several are even found to proceed in a direction exactly opposite to the Sun (cf. Figs. 1 and 2).

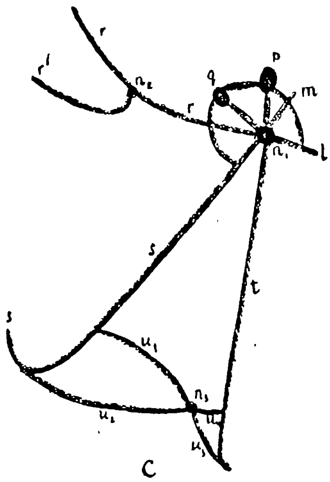

Fig. 1.
The head of Halley's comet on June 5·689, 1910.
Sketch by Bobrovnikoff after a plate taken with the 60-inch reflector of the Mt. Wilson Observatory. l, m, p, q, r, s, t are jets proceeding from the primary nucleus n_1; n_2 and n_3 are secondary centres of activity; the distance between n_1 and n_2 is about 40″. The Sun's rays are coming from below. (From *Lick Publ.* **17**, 408, 1930).

Another common feature is the formation of parabolic or semi-spherical halos on the side towards the Sun. These were particularly well defined in the great comet of 1858, called after its discoverer Donati (cf. Fig. 3). Bright rims or envelopes were seen to expand from the nucleus towards the Sun at more or less regular intervals of 5 days. Bright halos were also a striking feature in comet Morehouse, in which their behaviour was studied by Eddington from a series of plates taken in Greenwich (cf. Fig. 4). He concluded that the halos must be envelope curves due to some recurrent explosive action on the nucleus, by which particles are expelled in various directions with equal velocities. He found great difficulty in explaining the observed phenomena, and was led to conclude that unknown forces must be at work which exceed the solar attraction by a factor of more than 2000, while the initial velocities of the explosions would be between 10 and 100 km/sec.

It would be outside the scope of this lecture to give a description of all the intricate phenomena displayed by comets, but there is one sort of occurrence that seems to me of extraordinary interest, namely the so-called outbursts. These happen as follows. In a very short time, possibly of only a few minutes, a bright star-like nucleus is formed which in some cases is so bright that the whole comet appears 1000 times brighter than before. In the course of a few days the bright nucleus spreads into the coma, and the comet's brightness returns to the normal level. Expansion

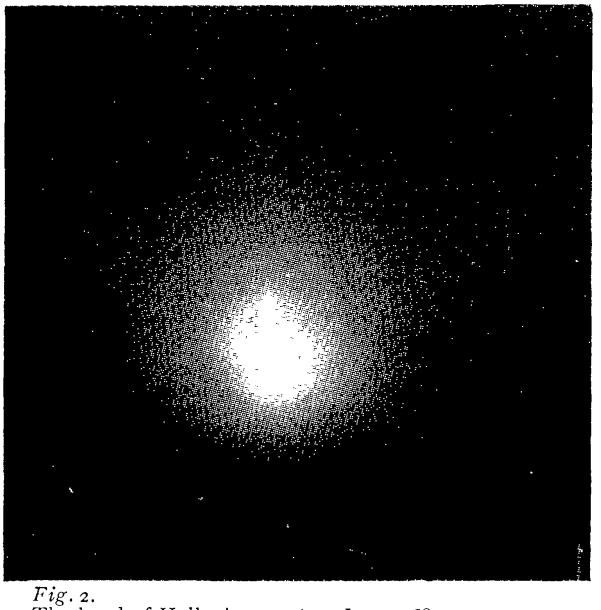

Fig. 2.
The head of Halley's comet on June 2·685, 1910.
Example of a conspicuous jet directed almost exactly away from the Sun. The jet has a length of 1′ 48″. The reproduction shows two of the four spherical halos visible on the original negative, which was taken with the Mt. Wilson 60-inch reflector. (From *Lick Publ.* **17**, 401, Fig. 44, 1930).

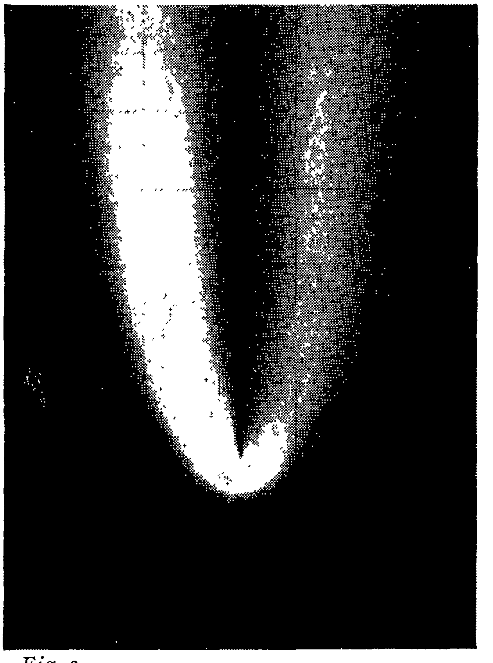

Fig. 3.
Comet Donati, Sept. 29, 1858.
Drawing by G. P. Bond, showing three parabolic halos on the side towards the Sun. (From *Harvard Annals* **3**, 214, Pl. XXXIII, 1862). The Sun's rays come from below.

Fig. 4.
Comet Morehouse (1908 III) on Sept. 29, 1908.
From negative taken with 30-inch reflector at Greenwich, showing bright rims in the head.

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FIG. 6 (opposite)

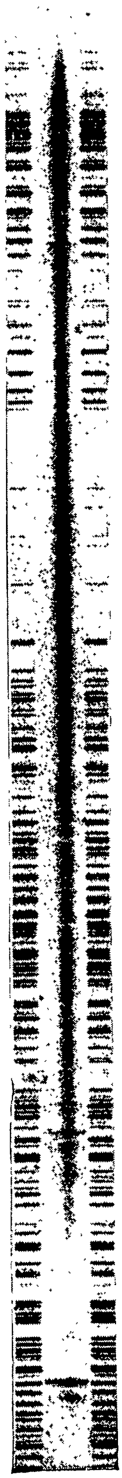
Comparison of spectra of an almost new comet (comet Whipple-Bernasconi-Kulin, 1942 IV; original value of $1/a$ 0·000261) on the left, and an old, short-period comet (comet Encke, 1947 II; period 3·28 years) on the right.

Note the almost entirely continuous spectrum of the former, indicating the prevalence of dust reflecting the Sun's light, and the weakness of the continuous light in Encke's comet, the head of which apparently consists almost wholly of gas. The most conspicuous bands in the second spectrum are the Swan bands of C_2 with edges at 4737 A. and 5156 A. The two bright lines running right across the upper part of this spectrum are the night-sky lines at λ 5577 due to [O I] and at λ 5890 (the D-doublet of sodium). The bands near λ 3883 in the spectrum of comet 1942 IV are due to CN. The comparison shown is not quite satisfactory because the distance from the Sun of Comet 1942 IV was 1·75 A.U. at the time the spectrum was taken, while that of comet Encke was 0·93 A.U. However, similar differences have been found between old and new comets at equal distances from the Sun, but no suitable material for reproduction of such a comparison was available. I am indebted to Dr. Swings for the permission to reproduce the above spectra, which were taken with the 82-inch reflector of the McDonald Observatory.

velocities seem to range from 0·05 to 5 km/sec. The spectrum shows that the increased brightness is due to dust. Some comets, such as the distant, and permanently observable, comet Schwassmann-Wachmann I, are more susceptible to such outbursts than others. It is entirely unknown to what mechanism they are due. But Nicholson has drawn attention to a most remarkable coincidence between one of the most striking outbursts of comet Schwassmann-Wachmann I in January 1946 and the appearance on the hemisphere of the Sun towards the comet of the largest sunspot ever photographed. Another, less spectacular, coincidence between an outburst of his comet and a big sunspot was found by Beyer. The latter's careful observations have further enabled him to discover fairly convincing evidence of a general connection between solar activity and brightness of comets, which, if substantiated by further observations, may prove of essential significance for our insight into the mechanism of comets. It would show that evaporation through heating is not the only process by which matter is released. The occurrence of other processes had already been suspected from the high velocities of expulsion required to explain certain observed features, and also from the fission of comets. The liberation of gas and dust certainly takes place in a rather complicated way, and we seem to be still far from understanding its mechanism.

Occasionally the experiment of a comet's passage near the Sun takes another turn. It happens now and then that about the time when it is closest to the Sun a comet breaks up, sometimes into two halves, as in the famous case of Biela's comet in 1846, sometimes into half a dozen comparable parts, as happened to comet 1882 II when it passed within less than a solar radius from the Sun's surface. There are several more cases of breakage; judging from these we can estimate that an average comet runs a risk of about 1/50 of breaking during its perihelion passage. It must be the solid nucleus that splits up. We don't know what causes

Spectrum of
Comet Whipple
1942 IV.

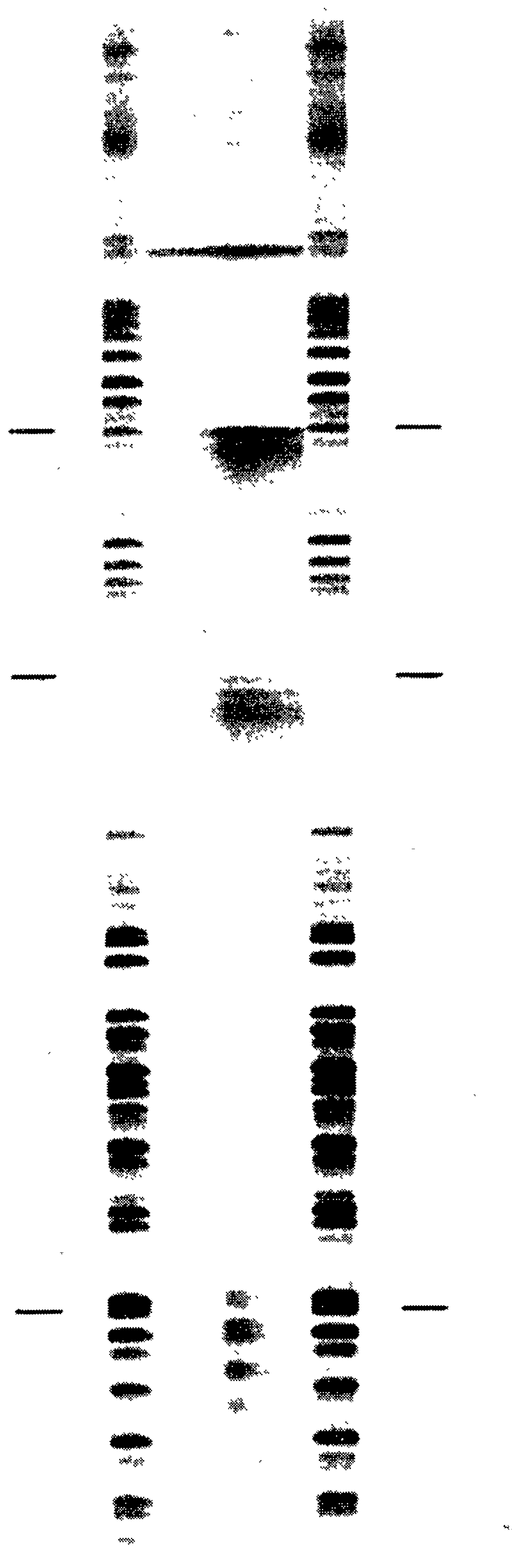


5156 A.

4737 A.

4050 A.

3883 A.



Spectrum of Comet Encke 1947 II.

Fig. 6.

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the fission; tidal forces are insufficient. Often these breaks seem to lead to complete disintegration, or, at least, to invisibility of the comet. The two parts of Biela's comet, for instance, after having remained visible for at least six years, were never seen again at subsequent passages, although they should have easily been found if they had remained anything like they were before. They apparently dissolved gradually. There is most remarkable evidence about the debris into which they dissolved. This debris expanded into a huge swarm. Now, the probability for the Earth to actually collide with a large comet is vanishingly small. But if the comet disperses itself into a big swarm the probability of meeting a part of this swarm may increase so much that a collision becomes quite likely. Such a collision with the swarm of Biela's comet took place on November 27, 1872. At that occasion we actually caught, so to say, fragments of the comet, which showed up as a magnificent meteor shower. This proved that at least part of the disintegration products were ordinary shooting stars, which, as inferred from their light and spectra, are little pebbles with diameters between 0·1 and 1 cm. Closer investigation indicated that probably all periodic comets are accompanied by meteor swarms. It seems quite possible that all shooting stars have originally come from comets. And, going one step further, it is not unlikely that the particles responsible for the so-called zodiacal light are likewise derived from comets.

Do the phenomena that I have described enable us to obtain a picture of a comet's nucleus ? We must confess, I think, that they still leave us pretty much in the dark, except that we may conclude that the nucleus consists in all likelihood of a single body, that it easily crumbles, and is apt to be split into parts under the Sun's action. The clue that is perhaps the most illuminating, is that its solid disintegration products are meteors and fireballs. In as much as there is a quite gradual transition between meteors, fireballs and meteorites (the latter are the big iron stones that actually come down on the Earth) it is tempting to believe that the latter are also parts of comets, or perhaps, that some of them *were* nuclei of small comets. We might then suppose that the nuclei of the larger comets are giant meteorites, or conglomerates of meteoritic blocks. If this were so, it would be possible to draw an interesting conclusion concerning the origin of the comets. For, according to geologists, the peculiar structure of meteorites indicates that in the past they must probably have formed part of a much larger body, like an ordinary planet. However, there is still considerable controversy among astronomers on the question of the relation between comets and meteorites, and we must postpone a conclusion.

A definite difficulty, which, to my knowledge, has not yet sufficiently been investigated, is how a nucleus of meteoric structure could crumble sufficiently to liberate the required amounts of dust and gas, even under the stresses caused by the rapidly varying temperature to which the surface of a rotating body would be exposed. We must remember, however, that we do not yet seem to understand the basic process by which dust is released on *any* nuclear model. Whipple has recently developed an interesting model for a cometary nucleus in which the difficulty of providing a sufficient supply of gas has been overcome. He supposes the nucleus to be composed of frozen gases, mixed with meteoric material. As the nucleus evaporates, the meteoric material forms an insulating outer layer, by which further evaporation is retarded. The nucleus on this "icy conglomerate" model might look somewhat like a glacier flying around in space, but a very dirty one, covered by layers of dust and stones. This boldly new picture has several attractive features. But, again, our knowledge is insufficient to decide about its truth.

I shall now leave these speculations to turn your attention for a brief moment to what is the most spectacular part of a comet, its *tail*. Part of the dust and gas expelled from the nucleus goes into the tail. The tails present a great variety of often rapidly varying structures. There is no time to enter upon these. I only want to point out that the intricate features sometimes presented by the tails must reflect the erratic manner in which material is released from the nucleus. In particular, the remarkable, long streamers may well be related to the local jets or fountains, through which the material is detached from the solid nucleus (cf. Fig. 4). After Bredichin's well-known work on the general forms of comet tails little actual progress had been made until quite recently in explaining the phenomena. From the fact that the general direction of the tails is away from the Sun it was clear that the force propelling the particules through them must ultimately be caused by the Sun. For a long time it has been thought that the tails were pushed away by the pressure of the radiation from the Sun. But the accelerations and velocities shown by recognizable clouds in the tails were often very much higher than could be due to direct radiation pressure. Other forces, presumably electro-magnetic, must play a predominant role. This is also quite evident from the enigmatic diverging systems of rays near the heads, which have so beautifully been displayed by comets Daniel (1907 IV) and Brooks (1911 V) (cf. also fig. 4).

A very interesting investigation on the magnitude of electrical and magnetic fields to be expected has been made by Biermann, who has kindly permitted me to quote from his unpublished article on the subject. It is well known that the Sun emits more or less continuously streams of particles. These streams, which leave the Sun with high velocity, are emitted especially from sunspot regions. When a particularly strong stream happens to collide with the Earth it causes striking displays of aurora borealis. In northern countries smaller displays are going on almost continuously, showing that solar particles are coming in all the time. Biermann points out that near the Earth the general density of these solar particles will be almost of the same order as the gas density in the heads of comets. He shows, further, that the pressure exerted on the CO^+ ions in the coma by the free electrons in these streams of ionized solar particles is ample to explain the straight tails and the exceedingly high accelerations observed. This investigation gives an important new insight; in particular, the sudden variations that are often observed in the tails can now be understood as a consequence of the well-known strong variability of the particle streams from the Sun. Biermann also points out that these variable streams may carry important magnetic fields with them, which are likely to have considerable influence on the tails. It should be pointed out that the effects of light-pressure should not be altogether discarded. The strongly curved tails displayed by many comets, sometimes simultaneous with the straight tails, may well be ascribed to light-pressure. The growing evidence of the effects of solar corpuscular streams on comet's tails, and of enhanced ultraviolet radiation on the brightness of comets and on cometary outbursts, is an interesting development, not only for our knowledge of the comets, but likewise for that of the Sun. Comets may ultimately be used as test objects around the Sun, by means of which more complete information regarding solar eruptions may be recorded.

It is clear that the beautiful firework display of a comet cannot continue perpetually, and that, for periodic comets at least, it could not have been kept up during the life-time of the solar system. It seems that in some way fresh comets are being continuously supplied. We are thus led to inquire after the source from which the comets come.

This brings us back to the first question formulated at the beginning of my lecture, which was, why the orbits of comets are so entirely different from those of the planets. The former are strongly elongated, often almost parabolic, while the orbits of the planets are very nearly circular; moreover, cometary orbits occur in all possible orientations, while all planets move practically in one plane, and in the same direction.

Now, while nearly circular motions were—rightly, in my opinion—looked upon as the natural way of moving, such as might be expected if the solar system had been formed from a rotating disk of gas, the highly elongated orbits of the comets were—also rightly—considered as needing a special explanation. A good many speculations have therefore been proposed to account for the queerly elongated shapes and random orientation of the orbits of comets.

Halley had determined orbits for 24 comets, and this comprised all the knowledge of those days. Today we have fairly reliable orbits for nearly 500 objects. They exhibit the same two properties that we have just mentioned, but they show also something more. Let me summarize the principal facts that are known at present. Halley's comet has a period of 75 years. We now know some forty comets that have periods shorter than this. These short-period comets have a remarkable distribution, the vast majority of the periods being concentrated between 5 and 7½ years, while the orbits of all these extend fairly closely to the orbit of the most massive planet, Jupiter. For this reason they are usually called the Jupiter family of comets. All short-period comets have direct orbits, in general with small inclinations to the plane in which the planets are moving. Their orbital characteristics are intermediate between those of planets and long-period comets.

About 80 per cent of all comets observed have periods over a century. Their orbits often extend to enormous distances. For two-thirds of the long-period comets for which sufficiently reliable orbits have been determined the orbits extend to distances of more than 2000 astronomical units, while for one-third they even extend to more than 40,000 of these units, or more than a thousand times the distance of the farthest planet. The orbital planes of these long-period comets bear no relation to the ecliptic; they appear to be oriented entirely at random.

When you consider these facts you might be inclined, at first sight, to think that the comets originally had no connection with the solar system, but came from the space between the stars. Indeed, several orbits seem to extend into the domain of the other stars, the nearest of which is at a distance of 300,000 astronomical units, However, it is easily shown that they do not come from other stars or interstellar space, but must be considered quite definitively as members of the solar system. If a comet came from interstellar space it would enter the "sphere of attraction" of the solar system with a certain velocity, and this would cause its orbit to be hyperbolic, entirely different from the elliptic or nearly parabolic orbits observed.

In order to illustrate further arguments which I shall have to discuss in connection with the origin of comets, it is desirable to introduce *one* more or less technical quantity. Instead of using the orbital period or the overall length or major axis to indicate the size of a comet's orbit it is practical to use for this purpose the reciprocal value of the semi-major axis; this is denoted by $1/a$, a being expressed in terms of the mean distance of the Earth to the Sun as unit. The quantity $1/a$ measures the energy of a unit of mass moving in the orbit considered.

The distribution of the values of $1/a$ for those comets for which very precise orbits have been calculated is shown in the diagram (Fig. 5).

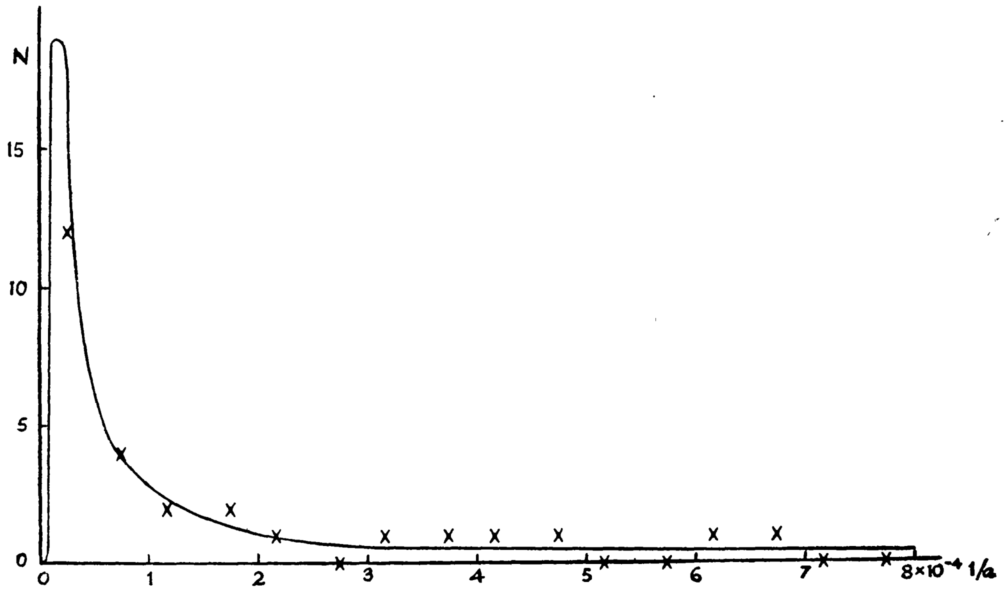

Fig. 5.
Distribution of reciprocal semi-major axes of comet orbits.
The semi-major axes are expressed in astronomical units; one division of the horizontal scale corresponds to 10^{-4} A.U.$^{-1}$, ordinates are numbers of orbits per interval of 5×10^{-5}. (From *B.A.N.* **11**, 259, 1951).

It shows only the first part of this distribution, from $1/a = 0$ to $1/a = 0{\cdot}0008$, that is, from orbits extending to infinity to orbits extending to 2,500 astronomical units. Hyperbolic orbits, such as would be described by objects coming from outside the solar system, correspond to negative values of $1/a$. No significant negative value has ever been found. The values of $1/a$ used refer to the orbits described before the comets approached the domain of the planets. It is essential to mention this, because, when the comets move through the inner parts of the planetary system, their orbits are changed radically. The largest changes are caused by Jupiter, being the most massive of the planets. For simplification I shall only consider Jupiter's perturbations. The omission of the other perturbations

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makes no difference in the reasoning or the conclusions. Furthermore, the only perturbations that for the present are of interest are those causing a change in $1/a$. These perturbations have been accurately calculated for roughly three dozen comets (mainly by Elis Strömgren and by Fayet) while van Woerkom has made a statistical calculation for all kinds of orbits. From these investigations it is found that, on the average during a passage through the region of the planets, Jupiter causes a change of $\pm$ 0·00050 in $1/a$. In individual cases the changes can take all possible, positive or negative, values.

If, in the light of this knowledge about Jupiter's perturbations, we consider the diagram again, we can at once make one interesting inference, namely, that the majority of the comets with $1/a$-values below 10×10^{-5} cannot have passed through the planetary region before. If they had, Jupiter's influence would have entirely effaced the sharp maximum shown in the diagram, whose width is at most one-thirtieth of that which would be caused by Jupiter after one passage.

We must conclude that these comets come originally from distances larger than, say, 30,000 astronomical units. The average corresponding to the sharp maximum is roughly 100,000 astronomical units. So far, this conclusion can only be drawn for the comets corresponding to the maximum in the diagram. However, further consideration indicates that it is likely that the source of *all* comets lies at this enormous distance, at the outer edge where the solar system merges, so to say, into adjacent "foreign solar systems". To avoid possible misunderstanding I wish to stress again that their coming from these practically "stellar" distances does *not* mean that they only half belonged to the solar system, or might almost as well be considered as having belonged to a neighbouring star. They were quite definitely members of the solar system because they shared very exactly the Sun's motion through space.

Let us now consider this "source" of new comets. Although the comets in these far-away regions are part of the solar system, they are nevertheless *influenced* by the surrounding stars. Just as the orbits of the comets are changed by the attraction of *Jupiter* at their passage *near* the Sun, they are changed by the attraction of *stars* in their parts *far* from the Sun. The latter action becomes of importance only at distances beyond about 30,000 astronomical units. As nearly all "new" comets come from larger distances, the stellar perturbations must therefore certainly be taken into account.

Their effect is quite different from that of Jupiter. We can best discuss them by considering the velocity distribution of the comets in an element of volume at a large distance from the Sun.

We have sufficient knowledge of the number of stars per unit of space, and of their velocities to obtain a good estimate of the average change of cometary velocities caused by passing stars. Speaking very roughly, we find that for comets at 100,000 A.U. from the Sun the change in velocity brought about by these encounters in 3×10^9 years (which is the approximate time of existence of the solar system) is just about equal to the velocity of escape from the solar system. It may be concluded that something like one half of the comets whose orbits extended to 100,000 A.U. must have escaped. At $r = 200{,}000$ A.U. practically all will have escaped, so that we shall not expect to find many comets coming from distances beyond 150,000 or 200,000 A.U. It is clear that the perturbations by other stars must have completely changed the velocity distribution of the comets at distances larger than 50,000 A.U. As the effects of stellar encounters are nearly the same in all co-ordinates, they will tend to make the velocity distribution isotropic. Now, as we have seen, the new comets come from these regions. If their coming in is not just a phenomenon of the last few million years, but has been going on during the existence of the solar system, the assembly of comets from which they come must necessarily have a velocity distribution that is practically at random, and has a large dispersion. This means two things: first, that for every comet moving in the direction of the Sun there must be a multitude of others (in fact, about 100,000 times more) whose orbits come nowhere near the small inner region of the planetary system where they could become observable; second, that their orbital inclinations cannot have any preference for the plans of the ecliptic, but must be oriented at random.

From what has been said it follows that the Sun must be surrounded by a vast spherical swarm of comets extending to a radius of about 150,000 A.U. The number of comets in this swarm can be calculated from the frequency with which new comets pass through our vicinity. We thus find that the swarm must contain about 10^{11} comets of observable size. This is a considerable number, but as the masses of comets are small the estimated total mass of the cloud is only 1/10th of that of the Earth.

Besides affording this estimate of the total number of comets that must exist in the solar system, the above considerations make it possible to understand the two features of cometary orbits that have always been so puzzling, namely the random orientation of the long-period orbits, and the fact that the comets come from such large distances. To understand that new comets can come *only* from very large distances, we note that it is only through the continual re-shuffling of their velocity distribution by stellar perturbations that new comets are constantly made to move in the direction of the Sun, so that they can reach the observable region. But this mechanism works only at distances beyond 30,000 astronomical units.

We thus see that it is through the stellar perturbations that fresh comets are coming in all the time. In fact, the comets are the only objects in which we notice the effect of perturbations of other stars on the solar system.

It is now of some interest to follow up statistically the further history of the comets. It can easily be seen that half of the new comets will be thrown out of the solar system after their first perihelion passage by the effect of Jupiter's perturbations. Of the others, a certain fraction will be gradually diffused into smaller and smaller orbits. A small number will come so close to Jupiter that after one or a few passages they are caught into the Jupiter family of short-period comets. This process of diffusion would set up a state of semi-equilibrium, in which the stream of new comets being diffused towards larger values of $1/a$ would be equal to the stream of old comets diffused outwards. If comets were permanent bodies the distribution curve of $1/a$, as was first pointed out by Van Woerkom, would become a horizontal line: the numbers of comets in a given interval of $1/a$ would be the same for all values of $1/a$. However, as we have seen in the first part of this lecture comets have a chance of about 1 in 50 to break up during a passage near the Sun and as a consequence, to disintegrate, or at least to weaken so much as to become invisible at subsequent returns. Furthermore, a comparison of the physical properties of *new* comets (that is, comets which come afresh from the outer regions of the swarm) with those of comets that have smaller orbits, and must therefore have passed several times through perihelion, shows that there are considerable differences. In new comets the amount of dust relative to the observable gas appears to be larger (cf. Fig. 6) and their brightness increases more slowly with diminishing distance to the Sun than in the case of older comets. These facts, which were first studied by M. Schmidt, indicate that new comets deteriorate markedly during their first, or first few perihelion passages, and it may be estimated that only a fraction of them can be discovered again at a following passage. These differences between new and old comets are interesting enough in themselves: it may be that new comets carry with them some of the atmosphere of the practically interstellar space where they have been hitherto.

But we now pass again to the distribution curve of $1/a$. The disruption of comets will cause an increasing loss in number during the process of inward diffusion. The frequency must therefore be expected to decrease towards larger values of $1/a$. As will be seen from the table, it actually does decrease; it can be shown that the amount of decrease is compatible with the observed frequency of disruptions. The last two columns give the numbers predicted by theory, assuming that the probability of disruption, k, is ·019 or ·003 respectively. The observed numbers are similar to those in the calculated columns, and roughly intermediate between the two. Only that in the first interval does not agree, being five or six times the number calculated. This difference should in all likelihood be ascribed to the deterioration of new comets during their first perihelion passage, to which I have referred above.

$1/a$		*Number per interval of* ·00050		
		Obs.	*computed* $k=$ ·019	$k=$ ·003
·00000	·00050	24	(4·8)	(3·4)
50	100	3	2·2	1·8
100	200	1·6	1·8	1·7
200	400	·9	1·2	1·5
400	1000	·46	·35	·84
1000	2000	·14	·04	·31
·02000	·04000	·04	·001	·06

From the fact that the frequency decreases towards large values of $1/a$ we can infer that the net "stream" of comets is passing from large orbits to small ones, as would be required by our theory, and not *vice versa*. There is a second, more compelling argument in support of this view, namely that when we pass to larger values of $1/a$ the inclination of the orbits decreases. This could never be so if the stream were going outward instead of inward.

A few words should be added about the short-period comets. The simple diffusion theory, based on the accumulating effects of small perturbations is not applicable to orbits that are much smaller than $a=25$

A.U. The connection with the short-period comets is made entirely by casual very large perturbations. This problem has already been studied by H. A. Newton in 1893. Recently Mr. Van Woerkom has again taken it up, especially with a view to investigate whether the Jupiter family can be considered as being in equilibrium with the general field of long-period comets. The problem is somewhat difficult to solve in a complete manner. All that can be said at present is that the number of captures from the long-period field is of the same order as the number of losses to the Jupiter family by large perturbations and disintegrations. It is a plausible hypothesis, therefore, that the Jupiter family is in equilibrium with the long-period comets.

It seems difficult to escape the conclusion that at least a large part, and probably all of the comets we observe have come from the big swarm extending around the solar system.

One important question has still be to answered before the above theory about cometary orbits can be considered as satisfactory. The question, namely, how the huge cloud of comets could have been formed. It does not seem possible that the comets have *originated* at these large distances. For it is difficult to conceive that the gas density in these regions has been of a much higher order than the average density in interstellar space. But with the latter density the radius to which a solid particle could have grown during the life-time of the solar system is only of the order of a thousandth of a millimetre. Certainly no bodies with radii of 1 km. could have grown in these parts.

We have already seen that it is impossible for the comets originally to have come from outside the solar system. We are thus led to conclude that they were formed in its inner part, in the general region where the planets were formed.

Several theories have been proposed for the origin of comets. According to one theory they would be formed from solar eruptions, but on general physical grounds this possibility can now be discarded. It has also been held that they are due to a kind of volcanic eruption from the major planets, in particular from Jupiter. A very original theory has recently been proposed by Lyttleton, according to which the comets may have been formed in a concentration of the interstellar medium occurring in the wake of the Sun when this moved at low speed through an interstellar cloud. Apart from difficulties due to the turbulence of the interstellar medium, a serious objection to this idea seems to be that encounters with clouds at sufficiently low relative velocity would be exceedingly rare. The hypothesis has also been put forward that, like, probably, the Minor Planets and the meteorites, the comets may have been formed by the breaking up of a larger planet. Finally, we may think of the comets as being a kind of residue left over after the big planets had been formed at the time of the birth of the solar system; the residue might have been formed either between the planets, or, as Kuiper has suggested, just beyond the orbits of Neptune and Pluto, where the density in the gaseous disk from which the planetary system was presumably formed, would have been too low for the formation of planets. At the moment I have no desire to enter upon a discussion about which of these various speculations is the most plausible. My own preference would go either to the last hypothesis or to a genesis together with the Minor Planets. However this may be, I must point out that none of these modes of formation, not even that proposed by Lyttleton, explain at all why at the present time all comets seem to come from those extremely distant confines of the solar system. But from the considerations given in this lecture we can now, I believe, fairly well understand how this would have come about. It seems plausible that, in whatever way they were formed, the small cometary bodies would not move in such nicely circular orbits as the large planets, and that, accordingly, they must have crossed at some time or other the orbit of a major planet. They must then necessarily have been diffused *outwards* in exactly the same way as the comets are *now* being diffused *inwards*. The major planets are like gardeners. They slowly rake the garden of the solar system, thereby throwing outside all small objects whose motions deviate from the normal way of moving. It is a big garden, and it takes them more than a million years to complete the raking, but they do it fairly efficiently.

While these small bodies were thus gradually diffused outwards they had a certain chance—of about 1 in 20—to come into the range where the perturbation of the stars could influence their orbits. The changes which these perturbations bring about are just the opposite of what one might have expected at first sight. They do not tend to remove the comets from the solar system, but on the contrary change their orbits in such a way that they do not return to the neighbourhood of the large planets, and are consequently liberated from further planetary perturbations. They have then become part of the large swarm of comets, where most of them can live quietly, as we have seen, for a period as long as the age of the solar system. The comet swarm is a sort of "trap": if a small body happens to fall into it on its way out of the solar system, it is kept in it semi-permanently. Because at the distance of this swarm the solar radiation is as weak as in interstellar space, and the temperature only a few degrees Kelvin, these bodies must have kept the original constitution and all the gases they contained when they escaped from the more central region in the early days of the solar system.

We can easily understand that this swarm-trap, which works through the combined effect of the perturbing action of *Jupiter and the fixed stars*, must extend over just those distances from which *at present* the comets come in to us by exactly the same combined mechanism. To sum up: the life-history of a comet may be pictured as follows: It was probably formed in the same period and in the same region where the planetary system was born, as a small fragment moving in an orbit that was less regular than that of the large planets. Relatively soon after its formation it was thrown out through perturbations and caught in the big swarm. Since that time stellar perturbations have steadily been directing some members of this swarm back to our vicinity, where under the influence of solar radiation they develop comas and tails, and become true comets. They end up by being dissolved into gas and meteorites or by being definitely thrown out of the solar system.

We seem to have gained an insight into the cause of *some* characteristics of comets that appeared so puzzling at the start. But there remain, as I hope to have made clear, enough puzzling features the understanding of which is not even in sight.