

ON THE ORIGIN OF COMETS

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(Received 1948 November 27)

Summary

During the passage of the Sun through a cloud of interstellar dust the particles converge to the accretion axis where their transverse velocities are destroyed by collisions. A stream of dust forms at the axis, and for low relative speed of the Sun and cloud that part of the stream within several hundred astronomical units is captured and flows towards the Sun. Internal gravitation causes the stream to divide into separate segments that contract lengthwise. The resulting aggregations are identified with the comets. The disruptive field of the Sun sets an upper limit to the initial length of a segment and thence to the initial mass of a comet. Several thousand such comets could result from a single passage of the Sun through a cloud of moderate dimensions. Owing to the presence of the major planets, some aggregations would have enough angular momentum to avoid falling directly into the Sun, but their initial orbits would be almost line-ellipses. Subsequent perturbations by passing stars when a comet is at great distance may endow it with greater angular momentum, but for it to have sufficiently small perihelion distance to become visible, the perturbed orbit must still be nearly parabolic. Earlier ideas relating to the origin of comets are briefly discussed.

1. *Introduction.*—Whereas a large number of speculations and hypotheses have been put forward during the past two centuries with a view to explaining the origin of the planets, and many of them investigated in detail, hypotheses on the origin of comets have been few and these mainly of so vague a nature that detailed examination of them has scarcely been practicable. It appears to have been widely accepted on general grounds that the planets and comets do not demand a common explanation, their properties being so markedly antithetical in almost all respects, but whether or not there is an essential cosmogonical difference is a question that can only finally be settled when dependable theories of the origin of both planets and comets are available. As far as the hypotheses on which recent progress with the planetary problem has been based are concerned, these have thrown no light whatever on the origin of comets, and it is difficult to imagine any development of them that could do so. The present paper has for its object an attempt to fill this gap in the theory of the solar system by giving an account of what seems to be a satisfactory mechanism for the formation of comets. The process proposed is, in brief, that of accretion of interstellar dust by the Sun during its passage through a dust cloud and the development from this material of more or less compact masses, composed of dust particles, describing almost parabolic orbits. It will be convenient to give first a general qualitative description of how it is considered the process would operate.

2. *General Description of the Process.*—Suppose the Sun to approach and enter a dust cloud whose particles for simplicity are assumed to be distributed uniformly in it with a common velocity relative to the Sun both in magnitude

and direction. The line through the centre of the Sun parallel to the direction of motion of the cloud defines the so-called accretion axis, and in the postulated conditions every particle will describe a hyperbolic orbit intersecting this axis. Thus even if, when undisturbed, the cloud is of extremely low density, the gravitational action of the star will cause its particles to converge towards the axis and thereby bring about a strong probability of collisions of some of them occurring at and near the axis. At a collision of two particles a portion of their kinetic energy of relative motion will be transformed into internal energy and heat the material. If they came originally from points on directly opposite sides of the accretion axis and in a plane with it, they would at impact have the same radial component velocity along the axis but equal and opposite transverse components, and only these would give them relative velocity. If the particles were of the same mass, and inelastic, as would be practically the case for dust particles, then in a head-on collision the whole of the kinetic energy of relative motion would be transformed into heat, and the velocity of the combined mass would be simply the former common radial component along the axis. As the radial and transverse components are comparable for a range of positions on the axis, an impact of this kind, by destroying the transverse component, could reduce the velocity to an elliptic value, so that the particles would be captured and thereafter move along the axis.

Instead of just two particles coming from opposite directions, the actual process even in a small length of the axis will involve a large number converging from different directions. The radial component away from the Sun will be the same for every particle, and apart from this velocity the effect will thus be as if particles were converging from all directions at right angles to the axis. This situation will clearly be highly favourable for the occurrence of collisions. Also, once collisions begin and introduce a random element of particles near the axis, further collisions will become even more probable, and indeed will occur with complete certainty once material has begun to collect round the axis. It is not necessary at this point to specify the sizes of the particles, though for a given density of the cloud the effective area for collisions becomes greater the smaller the dust particles are. There is however a critical range of size, radius $\sim 10^{-5}$ cm., for which particles would be repelled from the Sun by radiation pressure. Particles outside this range of size, larger or smaller, suffer negligible repulsion. In the initial stages dust particles smaller than this critical size would be most effective in starting an accumulation of material round the axis, but once this had begun almost all particles subsequently arriving at and near the axis would be intercepted and absorbed into the general stream along it.

There is however a restriction on the process if matter in solid form is to collect, for the energy converted into heat at impact must not be so great as to vaporize the particles completely. Evidently the transverse component of velocity must not be higher than a certain amount and this means that only material converging to the axis at more than a certain distance from the Sun would remain chiefly in the solid state.

On the other hand the distance from the Sun at which it joins the axial stream must not be so great that the material flows away from the Sun altogether to be lost from the solar system.

These two opposing requirements place upper and lower limits on the distance at which accumulations of solid particles can form and still be captured by the

Sun. Provided the extent of the cloud is large compared with the linear dimensions involved in the mechanism of accretion, the process will have time to approach a steady state, and in such circumstances the investigation given by Bondi and Hoyle will be closely applicable.* Their work considers a semi-infinite cloud with a plane boundary across which a star enters orthogonally along a rectilinear path, and their assumption that temperature effects due to collisions near the axis may be neglected is obviously valid in the present problem when only the motion of the solid material is of interest. On this basis they show that the steady state involves a stream of material along the accretion axis flowing towards the Sun at all distances less than about $1.25 GM/V^2$ (where G = constant of gravitation, M = mass of Sun, V = relative velocity of cloud), and away from the Sun at all distances greater than this. Particles whose paths intersect the axis within this distance join the inward stream and are swept towards the Sun, and at greater distances join the outward stream and are carried away to infinity in the opposite direction.

In the idealized circumstances to which the solution accurately applies, the process clearly cannot result in aggregations in orbital motion around the Sun, since the net angular momentum of accumulations on the axis must always be zero. There are however a number of additional factors that will be present in the actual problem whose influence is to give the material of the stream angular momentum round the Sun. First, as possibly the most important, may be mentioned the feature that at large distances the attraction is directed not towards the centre of the Sun but towards the centre of gravity of the whole solar system. This point may at times be a little over two solar radii from the Sun's centre, the main displacing agency being Jupiter and to a less extent Saturn. The distances at which aggregations first form, as will be shown, are of the order of several hundred astronomical units from the Sun, so the inward flow would be directed towards the centre of gravity until the orbital distance of Saturn is approached, and the attraction would not become towards the Sun's centre until some way within Jupiter's distance. For this reason the material may come to be endowed with angular momentum about the Sun corresponding to motion at about two solar radii simply as a result of the prevailing configuration of the planetary system. The time of passage through a cloud might be many thousand years and the time of fall of material towards the Sun is shown to be as much as a few thousand years, so that suitable configurations leading to angular momentum of this order would be bound to obtain for a considerable proportion of the time.

The foregoing effect is due of course to the gravitational action of the planets, but it can produce only small angular momentum per unit mass. There is the possibility of far stronger direct disturbance by a planet if the accretion axis happens to pass near its orbit, for then sooner or later an aggregation that had not been swept into the Sun would undergo a close approach in which the influence of the planet might become comparable with that of the Sun for a time, and the body would in general thereby receive angular momentum per unit mass about the Sun comparable with that carried by the planet.

Similarly there is the possibility of deflections by passing stars, a contingency by no means negligible for the ranges of distance from the Sun likely to occur. For low relative speed of the cloud the inward stream may extend to about 1000 astronomical units from the Sun, and during 10^9 years some 50 or 60 stars

* H. Bondi and F. Hoyle, *M.N.*, **104**, 273, 1944.

will have passed within, say, ten times this distance from the Sun. Only a small perturbation at such a distance is necessary to impart considerable angular momentum about the Sun to material.

All the foregoing influences will be operative at times to prevent parts of the stream from falling directly into the Sun, and as small effects are more likely than large ones it is evident that most of the resulting orbits will be nearly parabolic.

Although its action can have no appreciable effect on the orbit of an aggregation, there is also the self-gravitation of the material of the stream to be considered. At distances sufficiently far from other matter, any accumulation of material, however small its mass, will settle into as compact a body as possible consistent with its energy and angular momentum, which in the present instance is negligibly small, since the stream is formed at the axis by collisions. Owing to chance irregularities in the stream at different points of its length, it will tend to contract lengthwise and form a number of separate pieces of finite length, but this will be hindered by the tidal action of the Sun, and the combination of the two influences sets an upper limit to the length of a segment that can form at a given distance, and hence to the initial mass of a comet. An estimate of the mass of Halley's comet has been made by H. N. Russell and there is satisfactorily close agreement of the present value with this, considering the uncertainty attached to most of the factors involved in the calculations.

3. *Conditions for Capture of Particles in Solid Form.*—According to the investigation by Bondi and Hoyle, the neutral point on the accretion axis is at approximately $1.25 GM/V^2$ from the Sun. This gives at once an upper limit to the distance at which comets could form and remain associated with the Sun, since beyond this the material streams away to infinity. A lower limit can be estimated as follows.

At the axis the radial component of velocity of a particle is V , so that its transverse component is always precisely the parabolic speed at the distance concerned, and at the neutral point this is $\sqrt{(8/5)}V$. The particle will therefore enter the stream here with relative speed $\sqrt{(13/5)}V$, and this must not be such as to cause complete vaporization. If a proportion f of the kinetic energy per unit mass, $\frac{1}{2}u^2$ say, is converted by collisions into thermal energy in the material of the particle, and if E denotes the energy per unit mass required to vaporize the material, the condition that it is not entirely vaporized is $u^2 < 2E/f$. Near the neutral point this requires $V < 1.25\sqrt{E/f}$, approximately.

The factor f for any particle may depend on the way it happens to be absorbed into the stream, especially if this consists of a loose aggregation and several collisions are involved in stopping an incoming particle. Also, as far as the general effectiveness of the mechanism for forming and maintaining a stream of material is concerned, it will be sufficient if part of the material remains unvolatilized. It is therefore difficult to assess a precise value for f , but as it does not enter to a high power in the calculation the use of a value of $\frac{1}{4}$ may not lead to serious error.

As for the value of E , according to an estimate made by Hoyle* for iron, the heat of evaporation at boiling-point is about 1000 calories per gram. The dust particles, which of course will probably not consist mainly of iron, will presumably have low initial temperature, so making some allowance for the thermal energy needed to raise the material to its boiling-point, E may be roughly estimated

* F. Hoyle, *M.N.*, 106, 410, 1946.

for dust as, say, 2000 calories per gram, or about 10^{11} ergs per gram. The upper limit to V is then about 8 km. per sec., giving a distance for the neutral point of about 17 astronomical units.

This calculation shows that if V exceeds this amount (or some comparable value, bearing in mind the uncertainties involved), then as far as material capable of being captured by the Sun is concerned, impacts will volatilize most if not all of it and therefore greatly impair the efficiency of the process for capturing material in solid form. A stream of material in the steady-state motion has been assumed to be already present, but in the initial stages, while this forms, the particles arriving at the axis will have relative speeds at least of the same order as was used in the above calculation, so the result will still apply. A limiting value of 8 km. sec.⁻¹ seems reasonably satisfactory from the point of view of velocities likely to occur. Studies of stellar evolution strongly suggest that most stars must at times undergo encounters with interstellar gas at relative speeds appreciably less than this, and it may be supposed that dust clouds have motions similar to those of interstellar gas.

If, for example, $V = 1$ km. sec.⁻¹, the range of distance R from the Sun at which material can collect in non-gaseous form and still be captured is given, in astronomical units, by

$$1100 \geq R \geq 17.$$

The upper limit for different speeds varies as V^{-2} , while the lower limit is not changed. The corresponding periods in almost parabolic motion about the Sun in orbits having these limiting distances as major axes are given approximately by

$$13,000 \text{ years} \geq \text{Period} \geq 26 \text{ years},$$

and here the upper limit varies as V^{-3} .

The investigation by Bondi and Hoyle shows that the precise position of the neutral point is not determinable from the steady-state conditions alone, but depends on how the steady state happens to build up, and this would depend on the configuration of the cloud. It is shown, however, that its distance from the Sun must always lie between $2GM/V^2$ and GM/V^2 , so that the upper limit to distance may extend to nearly 2000 astronomical units for $V = 1$ km. sec.⁻¹.

4. *The Occurrence of Collisions in the Initial Stages of the Process.*—Consider an element of volume of the space of the cloud before it has reached the Sun's neighbourhood and suppose it to be of annular shape between radii p and $p + dp$ from the axis, and of small length $2b$ parallel to the axis. It need not be supposed that the cross-section of this region is rectangular. Its area will be $2b dp$ and the volume generated by its rotation round the axis will be $4\pi b p dp$. Imagine each point of this element of volume to describe the hyperbolic path that a particle initially at the point and moving with the velocity V would describe. Under such a motion of all its points the annular region will converge towards the axis and in so doing will undergo a large contraction of radius, but its other dimensions will alter only by small factors. Thus for large values of p enormous compression of volume will occur. To calculate its amount: A point of the original volume that crosses the axis at distance R from the Sun has transverse speed $\sqrt{(2GM/R)}$ and hence its initial perpendicular distance from the axis is

$$p = \sqrt{(2GMR)/V}.$$

Thus a length dR on the axis corresponds to an initial difference in distance from the axis of amount

$$dp = \sqrt{GM/2R} dR/V.$$

In calculating the shape and volume that the original element takes up near the axis the common radial velocity component V can be ignored and the points regarded as approaching the axis at right angles. Near the neutral point (to take some definite distance) the transverse speed will be $\sqrt{(8/5)}V$ and the separation $2b$ will have changed to $2\sqrt{(8/5)}b$. Thus, as far as the question of collisions is concerned, the original volume will at its smallest be compressed effectively to a circular cylinder of radius $\sqrt{(8/5)}b$ and length dR surrounding the axis, and the least volume is effectively $8/5\pi b^2 dR$. If the original volume $4\pi b p dp$ contained the centre of one particle only, then collisions will certainly occur at the axis if this reduced volume element is less than the effective volume of the particle. Taking it as a sphere of radius r , and its centre as being anywhere in the small element of volume at the axis, the conditions that it shall not overlap any other particle near the axis are

$$dR \geq 4r \quad \text{and} \quad \sqrt{(8/5)}b \geq 2r.$$

Using the values given by adopting the equals signs, it is found that

$$4\pi b p dp = 8\pi \sqrt{10} GM r^2 / V^2.$$

Collisions will therefore occur if this volume originally contained more than one particle of the adopted size. If ρ is the density of the cloud and σ that of the material of the particles, then the average volume per particle will be $4\pi r^3 \sigma / 3\rho$, and for collisions to occur with certainty for every particle this must be less than the above value. Taking $\sigma = 3 \text{ gm. cm.}^{-3}$ and writing $V = 10^5 v \text{ cm. sec.}^{-1}$, so that v is the speed in kilometres per sec., the condition becomes

$$\rho > 10^{-17} v^2 r \text{ gm. cm.}^{-3}.$$

For example, if $r = 10^{-7} \text{ cm.}$ and $v = 1 \text{ km. sec.}^{-1}$, then collisions will occur for every particle from the outset if $\rho > 10^{-24} \text{ gm. cm.}^{-3}$.

In an actual cloud the particles would not have uniform sizes and shapes, and they might also possess small velocities within the cloud in addition to the general velocity V . If however the cloud were accompanied by gaseous interstellar material, the relative velocities of the smallest dust particles would soon be reduced to zero by interaction with the gas, and it is just these smallest particles that are the most efficient, mass for mass, in producing collisions. All that is needed when the Sun first enters the cloud is for there to be a small but finite probability of a particle undergoing a collision at the axis, for there are so many particles that some collisions must then occur that leave material moving along the axis. Once it has begun to accumulate, collisions of further incoming particles with the material at the axis will proceed with certainty. Thus to start the process it is only necessary for there to be a small but sufficient proportion of the mass of the cloud in the form of particles of small radius. Also, it is clearly not essential to suppose that the whole of the material crossing within the capture radius is necessarily absorbed into the stream and captured by the Sun. A particle whose initial velocity differed slightly from V (in direction) would have a path not passing accurately through the accretion axis, and might therefore not be absorbed into the stream even when this had an appreciable radial extent round the axis. The focusing action of the mechanism will result, to begin with, in

the capture of particles of negligible internal velocities in the cloud, but as the stream builds up, its radial extent will increase till the steady state is reached, and thus some latitude in the internal velocity will become permissible. Thus in any case a finite proportion of the material passing within the capture radius will be absorbed into the stream at the axis. The particles of small relative velocity will be sorted out, as it were, and captured, while those of larger relative velocity (in directions not parallel to V), supposing such to be present in a cloud, may escape capture. The quantity ρ will evidently refer to what may be termed the "effective density" of the cloud.

5. *Estimate of the Possible Mass of a Comet.*—According to Bondi and Hoyle the line density m on the axis in the steady state is of order $2\pi\rho G^2 M^2/V^4$, and for $\rho = 10^{-24}$ gm. cm.⁻³ this gives

$$m = 10^9 v^{-4} \text{ gm. cm.}^{-1},$$

where v is the velocity in kilometres per second. If this material were in a solid stream round the axis, its radius would be of order $10^4 v^{-2}$ cm. (for density $\sigma = 3$ gm. cm.⁻³). Thus even if, as seems likely, the stream is far from being packed solid, its radial extent would be small compared with the general order of distance otherwise involved in the process, which is many astronomical units. It is therefore valid to treat the stream as a line distribution, as Bondi and Hoyle have done in their investigation.

The discussion by these authors, however, was aimed principally at the calculation of the rate of accretion by the Sun, and for this it was permissible to ignore the self-gravitation of the stream of material at the axis. But there is the possibility that its comparatively slight internal gravitation will cause it to collect into a series of separate pieces. The tidal action of the Sun, however, tends to disrupt the stream into portions of infinitesimal length, and the expression of the condition for the former influence to prevail enables an upper limit to be found for the length of a stable segment and hence to the mass of a comet. The existence in the stream of centres of attraction about which aggregations would tend to collect would probably be brought about by chance irregularities arising from such factors as departure from uniform density in the cloud. Supposing such centres to occur, then were it not for the Sun, the stream would break up into a number of finite segments each of which would contract under its own gravitation. The presence of other segments would not assist the contraction in any one of them.

If d is the initial length of such a segment, its attraction at points near its ends will be of order $4Gm/d$. Also, if $R (\gg d)$ is its distance from the Sun, the differential disruptive field to which the segment is subject as between its centre and either end will be GMd/R^3 . The internal gravitation will therefore be the stronger influence if

$$d < 2(mR^3/M)^{\frac{1}{2}}.$$

If R is measured in astronomical units and the velocity in kilometres per second, with the above value of m this condition becomes

$$d < 8 \times 10^7 R^{\frac{3}{2}} v^{-2} \text{ cm.}$$

The mass of the segment would therefore satisfy

$$md < 8 \times 10^{16} R^{\frac{3}{2}} v^{-6} \text{ gm.}$$

For example, if $v = 1$ km. sec.⁻¹ and a segment starts to develop about halfway between the neutral point and the Sun, so that $R = 550$ astronomical units, it is

found that

$$d < 10^{12} \text{ cm.}$$

$$md < 10^{21} \text{ gm.}$$

For other values of v , remembering that R also depends on v , the mass md varies as v^{-9} , so that a slight increase in v will lower the upper limit considerably, and *vice versa*. Where ρ is concerned, md depends directly on the assumed value.

This result, which is essentially an upper limit, appears to be satisfactorily consistent with the value 10^{18} gm. for the mass of Halley's comet obtained by Russell * from entirely different considerations, and his estimate (without calculation) of 6×10^{21} gm. for the great comet of 1729.

6. The time taken for a segment of length d to contract substantially under its own field will be of the same order but less than the time of parabolic fall from distance $\frac{1}{2}d$ to a point mass md , and this is $\pi d/8\sqrt{Gm}$. From the above inequality for d , this value is itself less than $\pi R^{\frac{3}{2}}/4\sqrt{GM}$. On the other hand, the time of free fall to the Sun from distance R is $\pi R^{\frac{3}{2}}/2\sqrt{2GM}$. This is not only greater than the former value but it will also be less than the actual time to fall into the Sun, because in the steady state the stream does not flow in at the parabolic rate owing to the outward momentum of the particles being continually added to it. Hence for values of d below the limit the internal forces act sufficiently rapidly for the material to collect together before reaching the immediate neighbourhood of the Sun where the tidal field is so much greater. Moreover the time $\pi d/8\sqrt{Gm}$, for values of R comparable with GM/V^2 , is also of the same order but less than GM/V^3 the time required to build up the steady state. Thus the contraction of segments will not proceed so quickly as to cause the process to depart far from the steady-state conditions by the creation of gaps along the axis.

The total amount of matter added to the Sun during its passage through a dust cloud can also be readily estimated, for from the nature of the process it is evident that a high proportion of the material will fall directly into the Sun. If the cloud were, say, 0.1 parsec in depth, the time of passage would be $10^5 v^{-1}$ years, and since material is captured at the rate $2\pi G^2 M^2 \rho/V^3$, the total amount added would be not more than $2 \cdot 10^{-7} v^{-4} M(\odot)$, for an effective density of 10^{-24} gm. cm.⁻³. Apart from the factor v^{-4} this is less than a tenth the mass of the Earth, and it would provide enough material for $4 \cdot 10^5 v^5$ comets of mass equal to the maximum value calculated above. Thus if not more than one per cent of the captured material failed to be absorbed directly into the Sun it would yet be enough to provide material for several thousand comets.

The major axes of the orbits of comets formed in this way during the passage of the Sun through a single cloud would all be practically in the direction of the accretion axis, that is in the direction of the relative motion, and even after there had been time for considerable chance disturbances of the orbits some evidence of the original direction might probably remain. But during its lifetime the Sun must have passed through many clouds and the directions of the relative velocities of the encounters would probably be widely scattered over the celestial sphere. Thus the distribution of the axes of cometary orbits could be explained by attributing the comets as a whole to the result of several encounters with separate clouds, and of course the additional after-effects of perturbations of their orbits

* Russell, Dugan and Stewart, *Astronomy*, I. *The Solar System*, 1945, p. 446.

through causes of the kind discussed earlier. There is no objection to postulating a number of suitable encounters with dust clouds, indeed a hundred of them similar to that adopted above would result in negligible addition of material of a non-hydrogen character to the Sun, and also negligible addition of angular momentum.

Deflection of a comet by a star passing at great distance from the Sun will be effective only when the comet itself is at great distance, so that of necessity the greatest focal distance $a(1+e)$ of the resulting orbit will be several hundred astronomical units. On the other hand, for such a body to become observable requires its least focal distance $a(1-e)$ to be less than, say, ten astronomical units. That is

$$a(1+e) \gg 100 \quad \text{and} \quad a(1-e) \ll 10,$$

and hence the eccentricity of the new orbit must necessarily be near to unity. This suggests however that there must be many comets of long period whose orbits do not pass near enough to the Sun for them to be observed.

The value 10^{-24} gm. cm.⁻³ adopted for the density for the purposes of numerical illustration, while probably a satisfactory average for some clouds, can scarcely be expected to be generally applicable. The estimates of masses derived above depend directly on ρ and are therefore subject to a corresponding uncertainty.

The structure of comets appears to raise interesting questions of a dynamical nature. Possibly, when sufficiently far from the Sun, the composing particles are in an almost steady dynamical state, perhaps analogous in some respects to the conditions in globular clusters. If this is so, every particle will be in orbital motion under the action of the rest of the system as a whole and the density would probably increase towards the centre, the distribution of particles being such as to reduce the frequency of collisions to a minimum. Comets have of course long since been regarded as diffuse aggregates of dust particles with possibly a small nucleus or nuclei at the centre, for they become invisible in transit over the Sun's disk, and also at all times reflect far less light than would continuous distributions of solid matter with the same general extent.

Although such an aggregation may be capable of forming and holding together while at large distance, it might nevertheless be disrupted later if it approached sufficiently near the Sun. As is well known, instances have been recorded of comets changing shape and sometimes actually dividing into parts, which thereafter follow separate but similar orbits.

Furthermore, if an appreciable proportion of the mass of a comet is in the form of particles of very small size, the comet as a whole may experience a resistance to its motion when near the Sun. This may arise possibly from the presence of gaseous material near the Sun and from the Poynting-Robertson* effect, resulting from the absorption and re-emission of solar radiation, which may be highly effective for small particles. Some slow secular development of cometary orbits, particularly those of short period, might take place through such causes.

The directions of the axes of those orbits studied (excluding the short-period comets) are widely distributed over the celestial sphere, but according to Bobrovnikoff† they nevertheless show a decided preference for the galactic plane. He has also examined the question of the rate of loss of mass of comets and believes that the majority of them must have been added to the solar system within the last few million years.

* H. P. Robertson, *M.N.*, **97**, 423, 1937.

† N. Bobrovnikoff, *Lick Obs. Bull.*, XIV, No. 408, 37, 1929.

7. *Previous Hypotheses on the Origin of Comets.*—Following Aristotle the ancients considered comets to be some kind of exhalations from the Earth itself inflamed in the upper air, and even the great Galileo failed to improve much on this in holding them to be atmospheric emanations that reflected sunlight. In more recent times Proctor, about 1870, proposed that certain of the comets, whose orbits pass so near that of a planet to suggest an intimate connection, may have been expelled from the body of the planet when in some form similar to that of the Sun. At a later date Crommelin suggested a solar origin for the family of comets grazing the Sun's surface and appearing in the years 1843, 1880, 1882 and 1887, proposing that their formation was in some way associated with solar prominences. These ideas however are of obviously little value, quite apart from the feature that they would apply only to an extremely small proportion of the whole vast number of comets in the solar system, estimated by Russell to exceed 100,000. Nevertheless, that there are groups of comets with orbits demanding a certain amount of special explanation seems definite enough, and it has long been generally accepted that several of the short-period comets must have been diverted into their present orbits by the action of Jupiter. This has led to the idea that these comets may have been captured from an originally hyperbolic orbit (about the Sun) as a result of a three-body encounter of the comet with the Sun and planet, energy being conserved in the process. It has further been suggested, with less plausibility, that all comets may have been added in this way, even though for most comets the orbits do not at present pass near that of any planet and no truly hyperbolic orbit has ever been found.

The dynamical capture idea, however, in no way explains the origin of the comets themselves as more or less compact masses of dust particles, which simply have to be postulated as already existing in space, a postulate for which there is no observational evidence and which is not justified by theoretical considerations. H. N. Russell, in discussing the problem in his book "The Solar System and Its Origin", has put forward a modification of the capture notion, though only in general descriptive terms, which bears some degree of resemblance to certain features of the process given in this paper. Thus Russell discusses the possibility of the Sun passing through a nebula, and actually writes of a "decided temporary concentration in the axial line behind the Sun" (p. 128), and he goes on to suggest that a gaseous cloud would result, associated with the Sun but almost stationary behind it, and that this would offer a resistance to the motion of comets initially describing hyperbolic orbits round the Sun, thereby possibly converting some of them to elliptic ones. The comets again were supposed already present in the nebula as condensations and in sufficiently great profusion for the process to explain the huge number left behind in the solar system. The discussion given is brief and does not suggest any great confidence in the idea. It is not perceived that the convergence of material towards the axis may itself bring about the necessary concentrations of particles, or that their capture may simultaneously be effected.

Several years earlier E. W. Brown* had discussed the passage of a star through a nebula consisting of dust particles, but with the object of attempting to explain the form of the variable nebula N.G.C. 2261. In this study Brown discerned the importance of collisions at the axis, but he assumed that all the material would be vaporized and by its subsequent expansion give rise to a gaseous conical appendage following the star as long as it remained within the nebula.

* E. W. Brown, *Ap. J.*, 53, 169, 1921.

8. As far as the present paper is concerned, its initial hypotheses are philosophically on a sounder basis than those of earlier attempts to explain the origin of comets, for the existence of dust clouds is an accepted observational conclusion, and the effect of the passage of a star through such clouds is therefore a theoretical problem automatically arising. As has been seen, the hypotheses are capable of some quantitative investigation, though as for most cosmogonic hypotheses restricted mainly to order of magnitude considerations. Even so, the results suggest that the origin of comets can probably be satisfactorily explained along such lines. If this is correct, the theory confirms what has long been conjectured, that the comets and planets do in fact represent two solar families having essentially different origins. Moreover, in view of the large number of comets in the solar system, and the fact that most stars must from time to time pass through dust clouds, it may well be that of all celestial objects comets are possibly the most numerous in the universe.

3 *Grosvenor Court,*
Woodlark Road,
Cambridge:
1948 *November 25.*