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Recent Statistical Studies in Astronomy

The nature of the galaxies and the birth-death process among comets are revealed in statistical studies.

Thornton Page

There have been many advances in statistical astronomy since Herschel first reasoned from the concentration of stars in the Milky Way that the sun must be located in a disk-shaped system of stars now called the Milky Way galaxy. Later studies of the distances and motions of stars have proved well suited to statistical analysis, and more recently the analogous studies of galaxies have been added to this list. It was therefore appropriate that a portion of the Fourth Berkeley Symposium on Mathematical Statistics and Probability, held at the University of California from 20 June to 29 July, 1960, should be devoted to recent applications of statistics in astronomy. The problems discussed were in the fields of radio astronomy, dynamics, and cosmology, and they concerned both the most massive and the least massive of astronomical bodies: galaxies and comets.

Distances of Cosmic Radio Sources

The most recent additions to the variety of celestial objects studied by astronomers are the strong sources of radio waves from outside the earth. When radio telescopes first came into use it was found that much of the cosmic radio emission comes from our Milky Way galaxy, or from objects belonging to it, such as the Crab nebula (a cloud of turbulent gas remaining from the explosion of a star several centuries ago) or the sun itself. However, there are about 100 small regions of apparently empty sky from which strong radio signals are also coming—signals which could not at first be identified with any visible object but which are now known to be from extragalactic sources located far outside our galaxy. Two questions then arose: How far away are these extragalactic radio sources, and, if we built even more powerful radio telescopes, how many more such sources would be detected?

R. Minkowski of the Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, and California Institute of Technology has identified many of the extragalactic radio sources with distant galaxies found on photographs taken with the 200-inch telescope and other large optical instruments. Over the past five years he has obtained a sufficient number of these identifications to study the radio sources statistically.

Since the radio observations themselves offer no direct evidence of the distance of the source, Minkowski obtained optical spectra of 17 of the faint galaxies identified with the nearer radio sources; from these he measured the red shift or apparent velocity of recession, and from the Hubble law (that the red shift is proportional to distance) computed distances ranging from 30 million to 3000 million light years. Though they appear faint, these radio-emitting galaxies have an average optical brightness 25 billion times that of the sun and 3 or 4 times that of a normal galaxy, when the distance is taken into account. In the same manner, their individual outputs of radio power can be determined; these are as large as 5×10^{32} watts per cycle per second at a radio frequency of 158 megacycles per second.

Comparing the numbers of radio sources found in surveys of over half the sky with data from comparable

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surveys of ordinary galaxies, Minkowski has found that less than 1 percent of the ordinary galaxies nearby emit as much as 5×10^{16} watts per cycle per second, less than 0.005 percent emit 5×10^{18} watts, less than 0.000025 percent emit 5×10^{20} watts, and so on. However, the radio-survey counts (Fig. 1) increase so rapidly as fainter and fainter sources are counted that the proportion of radio emitters is much higher in very distant galaxies that are too faint to be photographed, even with the 200-inch telescope.

This enigma—that the density of radio sources seems to increase with distance from us on all sides—may be explained in terms of some evolutionary effect; at the great distances involved—billions of light years for the strongest sources—we are observing galaxies as they were billions of years ago, and at that time the mechanism of radio emission from galaxies may have been more prevalent.

The mechanism of radio emission is itself an enigma; Minkowski's photographs show that some of the stronger, identified (nearer) radio sources are close pairs of galaxies, apparently in collision; others appear peculiar in form, some with faint, jetlike structures. From the nature of the radio emission it is clear that the source must be ionized gas in violent motion, such as might occur in a collision between gas clouds at several hundred miles per second or in a very large release of energy from a sudden nuclear explosion. After an interval of time these mass motions would be expected to damp out, heating up the gas. The implication is that collisions between galaxies, or vast nuclear explosions in huge unstable stars, must have been more frequent in the past than they are today. (Minkowski used the Einstein–de Sitter model of the universe, which takes into account [Fig. 1, solid curve] another factor affecting the apparent density—namely, that since all the galaxies are receding from us and from each other, the general density would have been much larger billions of years ago.)

The enormous distances of extragalactic radio sources, suspected for the past few years, can now be determined quantitatively by Minkowski's analysis, confirming the belief that the radio telescope is the most powerful tool for probing the farthest reaches of space and time.

Average Mass of a Galaxy

In our galaxy there are many billions of stars, some larger than the sun, some smaller. It would be impossible to count them, but the total mass can be estimated quite simply from the motion of stars near the edge under the gravitational attraction of the whole; the total mass is thus determined at several hundred billion times the mass of the sun—more precisely, at 2×10^{11} suns. A few nearby galaxies can be "weighed" in the same manner, by measuring shifts in the spectra of their outer parts. These masses are found to vary widely, from 10^{9} to 10^{11} suns.

The average mass of a galaxy is of importance in relativistic cosmology for determining the average density of matter in space, a parameter that is expected from Einstein's theory to affect geometry through the curvature of space. One attempt to determine this average mass involved study of random motions of galaxies in clusters. The mass of the cluster acts by gravitation on the individual galaxies in much the same way that each galaxy acts on its

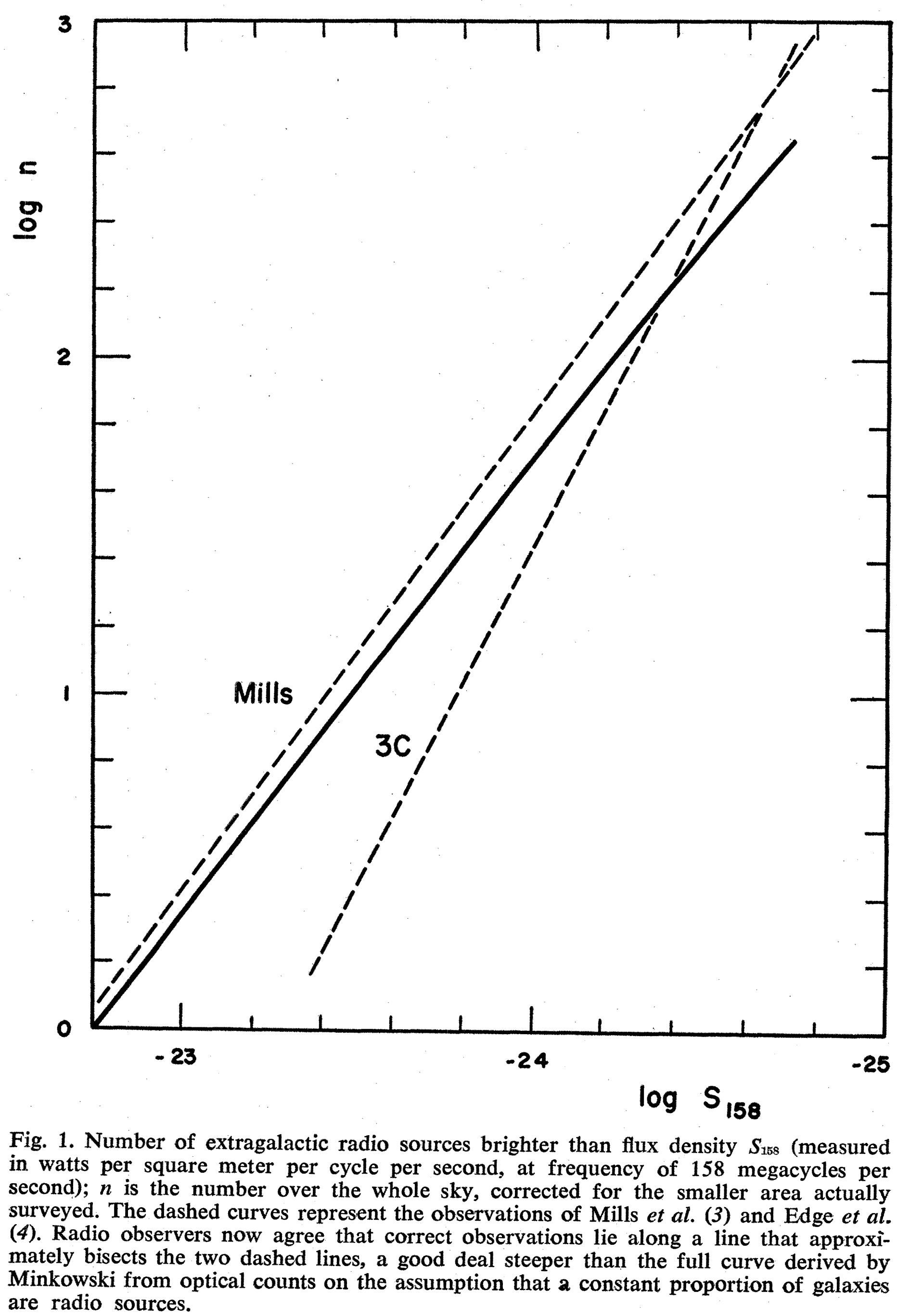

Fig. 1. Number of extragalactic radio sources brighter than flux density S_{158} (measured in watts per square meter per cycle per second, at frequency of 158 megacycles per second); *n* is the number over the whole sky, corrected for the smaller area actually surveyed. The dashed curves represent the observations of Mills *et al.* (*3*) and Edge *et al.* (*4*). Radio observers now agree that correct observations lie along a line that approximately bisects the two dashed lines, a good deal steeper than the full curve derived by Minkowski from optical counts on the assumption that a constant proportion of galaxies are radio sources.

component stars. However, this method yields an average mass of over 10^{12} suns—100 times the median mass of nearby galaxies.

In an effort to resolve the matter and to learn more about differences in mass between galaxies of different types, I measured motions in pairs of galaxies. In each pair, the galaxies appear to be moving round one another just as the earth moves round the sun, and the total mass of each system is simply related to the size of the orbit and the period. The masses and orbit sizes are such that the periods are 200 million years or more. Moreover, the orbit plane is oriented at some unknown angle, and the line between the two galaxies is oriented at yet another unknown angle; hence I could measure only the instantaneous projected separation and projected orbital motion in each pair, getting a "snapshot" of the full orbital motion.

However, for a considerable number of pairs it can be assumed that the orientation is random—that is, the average mass of galaxies in a number of pairs can be determined statistically. Because the measurements of velocity from small-scale spectra of these faint objects are subject to error, and because the distances between galaxies in a pair are not all the same, the statistical analysis is fairly complex. The theory is based on the assumption that the orbits are circular and leads to the prediction that the regression of projected orbital velocity on the reciprocal of the apparent separation is proportional to the average mass.

I applied this result to my own measures and to others made by Humason at the Mount Wilson Observatory and by Mayall at the Lick Observatory, for a total of 52 pairs of galaxies or groups of galaxies, obtaining an average mass of 3×10^{11} suns with a probable error of $\pm$ 20 percent. For 14 pairs of galaxies of the spiral type, the average mass is only 0.3×10^{11} suns ($\pm$ 70 percent), and for 18 pairs of the elliptical type, $6.5 \times 10^{11} \pm 30$ percent. It thus appears that the average mass of a galaxy in this sample depends very strongly on the type, and the fact that the spiral galaxies are only 1/20 as massive as the elliptical galaxies is inconsistent with the evolutionist conception that spirals evolve into ellipticals in the course of time.

In connection with the evolution and make-up of galaxies themselves, the ratio of mass to luminosity (M/L) is important. Using the sun as standard (M/L=1), we find that the large, hot blue stars have small mass for their luminosity, whereas cool, red stars generally have large M/L. Modifying the statistical theory to include measured brightnesses of the galaxies, I determined M/L to be 0.3 ± 70 percent for spirals, an indication that they consist almost entirely of hot blue stars, and 100 ± 30 percent for ellipticals, an indication that they consist of very cool stars (inefficient radiators) or an admixture of nonluminous material.

Since this method of mass determination includes all the matter within the orbit of each pair of galaxies (a sphere of some 150,000 light years' diameter), it is possible that the resulting masses include a portion of intergalactic matter; however, the intergalactic density would have to be 10^{-27} gm/cm^3 to affect the results for spirals appreciably, or 10^{-26} gm/cm^3 to affect the results for ellipticals. These densities are very much greater than any that have as yet been suggested.

Another possibility is that the orbits of double galaxies are not stable—that is, they may be moving in hyperbolas. It is unlikely that the pairs are simply galaxies passing one another in near-collisions—their number is over ten times greater than would be expected by chance—but it is possible that they are flying apart because of some unspecified explosion, such as the explosions postulated in explaining the extragalactic radio sources. As the Armenian astronomer Ambartzumian has shown, there is evidence that clusters of galaxies are expanding, possibly from similar causes, and that all groups of galaxies may be fragments of larger, unstable bodies. Although the mechanism that could produce such fission in bodies of more than 10^{11} times the sun's mass, as postulated by Ambartzumian, is difficult to imagine, it may be possible to distinguish statistically between circular orbits and radial motion in the observed pairs (*1*).

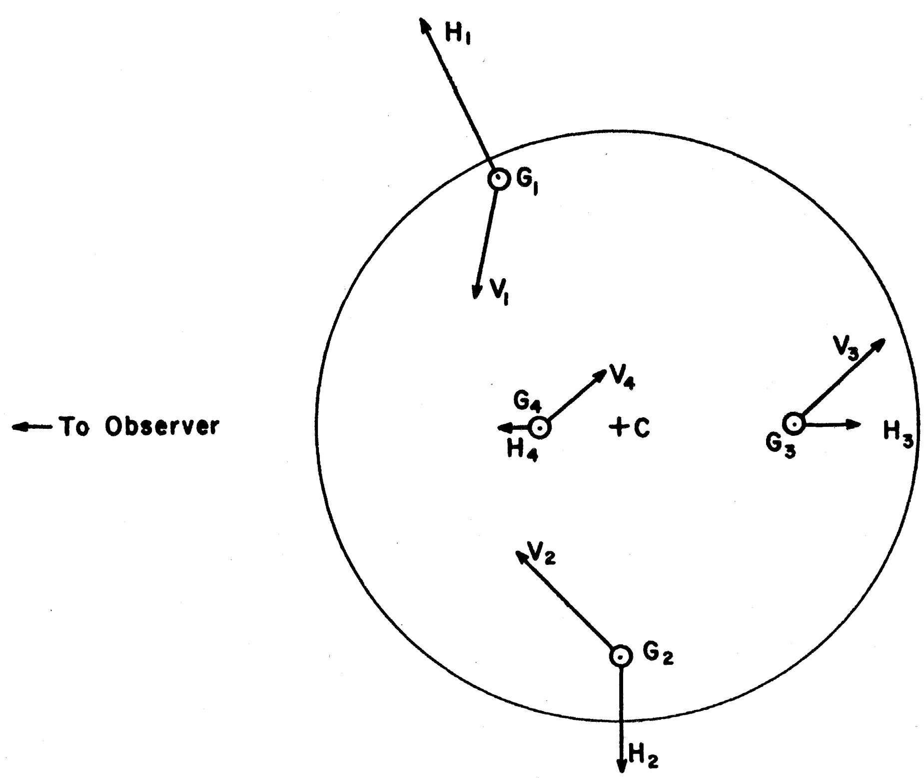

Fig. 2. Centrifugal expansion of a cluster of galaxies. The large circle represents a cluster with center at C and member galaxies G_1, G_2, and so on. The vectors **V** represent random velocity components, and the vectors **H** represent the centrifugal component proportional to the distance from C, as in Hubble's law for field galaxies. The observer, it is presumed, views the cluster from the left.

Expansion of Clusters of Galaxies

As mentioned above, the question as to whether the clusters of galaxies are stable dynamical systems or systems that are flying apart is important in a number of problems of cosmology. Thus far, the arguments in favor of expansion have been based on the fact that, with reference to some clusters or groups of galaxies at least, the observed radial velocities of presumed members of clusters show a considerable variation. If this variation is interpreted as the effect of internal motions of galaxies within the cluster, then these motions appear to be too rapid for the gravitational forces to keep the cluster together, unless the masses of galaxies (and thus, the gravitational attraction) are very much larger than is indicated by other studies, such as my study of mass, discussed above. In other words, the problem of stability of clusters has so far been studied on the basis of the relation between the masses of the presumed members of clusters and their velocities.

A paper by J. Lovasich, N. U. Mayall, and E. L. Scott of the University of California throws new light on the problem. The authors combine new observations of radial velocities and apparent magnitudes of galaxies belonging to 20 clusters with a theoretical analysis by Neyman and Scott published in 1953. In their preoccupation with the chance mechanism underlying the hypothetical expansion of the universe, Neyman and Scott posed the question of whether or not, in addition to receding from each other according to Hubble's law, the clusters of galaxies also *expand* in accordance with the same law. In addition to random velocities within a cluster, each member would then have a velocity component in the direction away from the cluster center and proportional to its distance from the center. A statistical test based on apparent brightnesses, radial velocities, and angular distances of presumed cluster members from the cluster center was deduced and applied to the then-existing data for 12 galaxies in the Coma cluster. The result was negative: there was no evidence of a centrifugal component of the velocity among cluster members.

Notably through the persistent work of N. U. Mayall, there are now available measured radial velocities and apparent brightnesses (magnitudes) for 50 galaxies of the Coma cluster. Lovasich, Mayall, and Scott used these data, together with others relating to 19 other clusters and smaller groups of galaxies. In several cases, including the Coma cluster, the test indicates that the observed relation between the apparent brightnesses, positions, and radial velocities could hardly be ascribed to purely random causes—that is, these clusters and groups are probably expanding. In other cases, particularly for clusters and groups with only a few measured velocities and magnitudes, expansion cannot be established with reasonable confidence. However, an over-all test of centrifugal expansion in *all* of the 20 clusters and groups indicates that it is more likely than not that such expansion is taking place.

In Fig. 2 the circle symbolizes a cluster of galaxies with members G_1, G_2, . . . G_i . . . . The vectors $\mathbf{H}_i$ represent the hypothetical Hubble velocity component proportional to distance from the cluster center, and the vectors $\mathbf{V}_i$ symbolize the random velocity components. If not equal to zero, the centrifugal velocity component will create a positive correlation between the radial velocities and the apparent brightnesses of the galaxies.

Underlying the Neyman-Scott test, or any other test of the expansion or

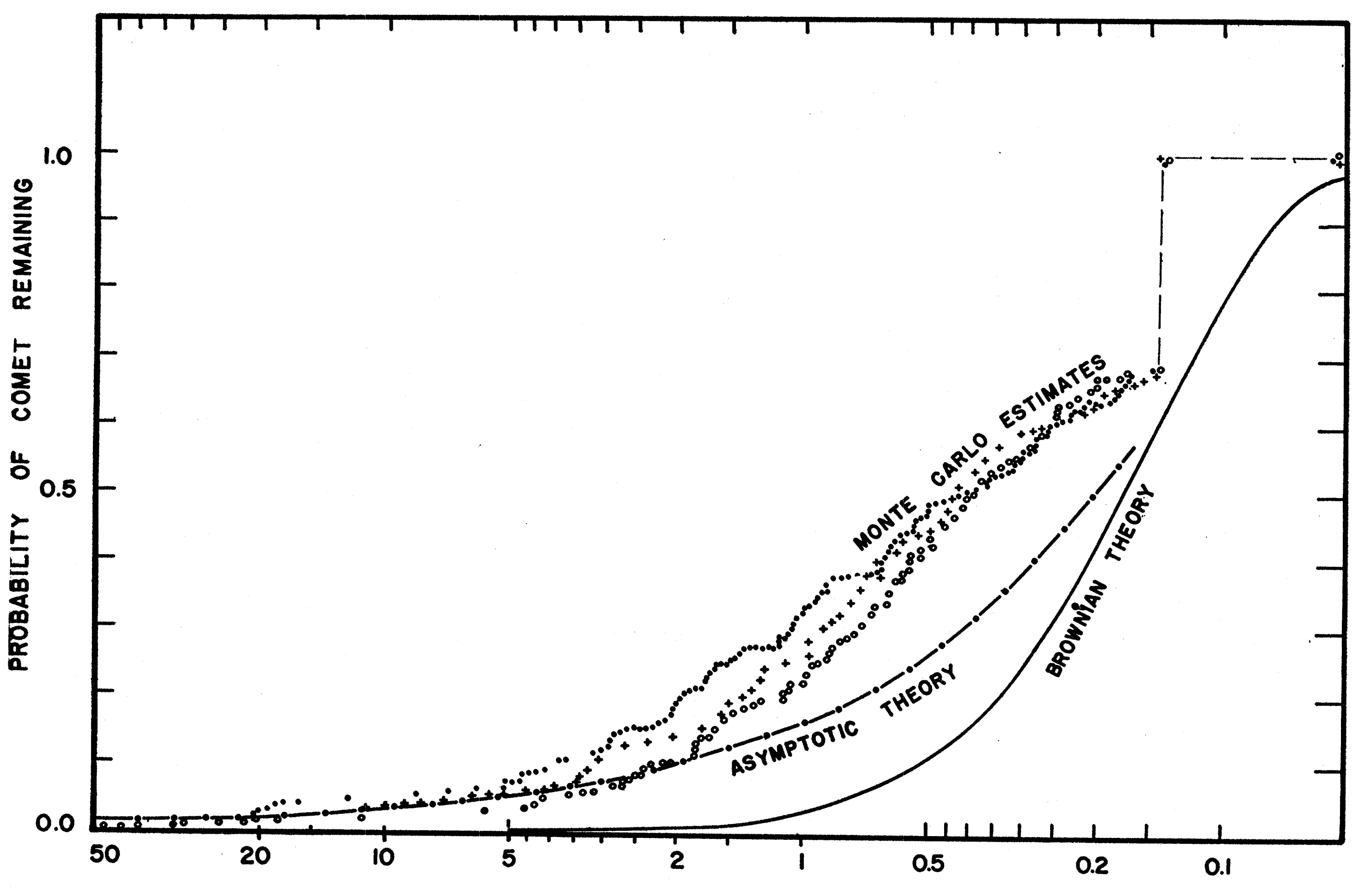

Fig. 3. Time variation of the probability of a comet's remaining in the solar system. Results of three groups of Monte Carlo trials are shown by the dots, circles, and crosses. The asymptotic theory of Hammersley fits at the left end of the curve, and his Brownian motion model fits roughly for short time intervals.

stability of clusters, there is the question, emphasized by the three authors, of whether the galaxies presumed to be cluster members really belong to the cluster concerned. Lovasich, Mayall, and Scott presented their data in plots of radial velocity versus brightness, which showed a few "outliers" for each cluster—probably foreground galaxies superimposed by chance on the photographs. However, even after the elimination of these outliers, the over-all test continues to support the hypothesis of centrifugal expansion, though at a lower confidence level.

In discussion at the symposium it was pointed out that the variation in apparent brightness of galaxies within a cluster ascribable to the variation in distance from the observer in clear space (the inverse-square law) is very small as compared to the errors of measurement and to the inherent variability of the luminosity or candle power of a galaxy. Thus, if there is a sizable correlation between magnitude and radial velocity, it may indicate not only centrifugal expansion but also some other factor causing galaxy G_3 to appear fainter than G_4 (Fig. 2). This factor may be the existence within the boundaries of the cluster of absorbing matter. The possibility of such absorbing clouds within clusters had been suggested earlier, particularly by Zwicky.

Birth and Death of Comets

Comets, the mavericks of the solar system that appear at a rate of two or three per year, were first thought to include real intruders from outer space. Some 50 years ago accurate observations and careful analysis showed that, although they come from great distances, rush around the sun at high speed, and are flung back roughly whence they came, their initial motion is no more than that expected for bodies falling from a large distance under the sun's gravitational attraction; that is, their initial orbits are parabolas or ellipses, not hyperbolas.

However, comets that happen to pass close to a planet are deflected from their parabolic motion by the added gravitational pull of the planet and may, according to chance, end up in smaller, elliptical orbits or in larger orbits, including hyperbolic orbits that carry them away from the sun, never to return. This loss, together with another, directly observed, fate of comets—break-up or evaporation close to the sun—raises the question of how there are any comets left after billions of years' exposure to such hazards.

In a series of highly mathematical papers R. A. Lyttleton of Cambridge, J. M. Hammersley and David G. Kendall of Oxford, and R. H. Kerr of Ferranti, Ltd., all from England, made great progress in answering this question by investigating the average fate of a comet in its perilous journey among the planets, and by analyzing the meager evidence concerning the formation of comets.

On the latter subject, Lyttleton had proposed several years ago that comets are formed from interstellar dust through which the sun is moving. Following the motion of individual dust particles as the sun sweeps by, he found that there would be a concentration of dust in a region beyond the sun up to a few thousand times the earth's distance from the sun. If this material coagulated and fell toward the sun it would provide an almost continuous supply of new comets in the form of swarms of dust particles which would behave just as comets do (growing a tail as the sun "bakes out" gas from the dust and blows it away by radiation pressure).

One feature that can be observed is the direction from which the new comets fall; hence, Lyttleton and Tyror plotted on a sphere the directions from which 448 long-period, long-orbit comets appeared to come during the past 50 or 60 years. Many of these comets may have already been deflected by the planets on previous trips round the sun, but the proportion of new comets should result in a slight statistical preference for the direction opposite that of the sun's motion through space.

Lyttleton's spherical plot gives only marginal evidence of such a preference but is of considerable interest in any case since it reveals, by clusters of points on the sphere, that large numbers of comets come from some directions, and, by gaps on the spherical plot, that none come from other directions. Some of these features may be explained by observational selection, others by statistical preferences in the interaction with the planets. If it were possible to include only new comets making their first trip around the sun, Lyttleton's plot would indicate accurately where the comets were formed.

An alternative theory of the origin of comets, put forth by J. H. Oort of Holland, is that they come from a spherical shell a few hundred thousand times as far from the sun as the earth is, and moving with the sun. Oort postulates that passing stars every now and then give slight impulses to the cometary material in this shell so that

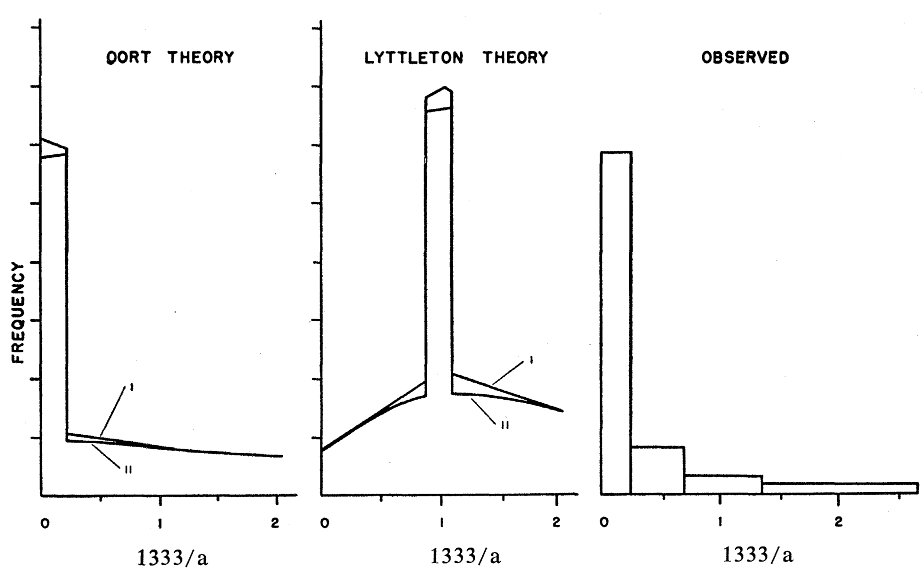

Fig. 4. Energy spectra of observable comets in population equilibrium. Orbital energy increases to the left; a is the semimajor axis of a comet's orbit, one-half the maximum distance from the sun. (Left) Theoretical spectrum for comets formed continuously at near-infinite distance from the sun. (Middle) Theoretical spectrum for comets formed continuously at 2700 astronomical units from the sun. (Right) Estimated spectrum, based on observations of 23 comets. The theoretical curves are for disintegration probability of 0.04 per passage, and the difference between curves I and II reflects different assumptions about the distribution of perturbations.

some of the small condensations fall in toward the sun (with just a little sideways motion so that they miss hitting the sun). Lyttleton's spherical plot, restricted to new comets, would reveal from which part of Oort's spherical shell comets have come, but there is no way of assessing precisely how a passing star would deflect the material. A more decisive test comes from the statistical treatment of comets' energies and their random changes due to the gravitational jerks or perturbations caused by planets the comets happen to pass. Because the space about the sun is so nearly empty, comets move with frictionless ease, and their energy (kinetic plus potential) would be determined only by the distance they fall toward the sun, were it not for planetary perturbations. Accurate observations of some 20 comets show that the difference between energy of approach and energy of recession from the sun is a small random quantity with a mean of zero (the increases balance the decreases) and a certain "spread" or mean deviation that agrees with theoretical predictions by Kerr.

Hammersley attacked the problem of how long a comet can remain within the solar system when its orbit is perturbed in this random manner on each approach to the sun. If a comet gets several large, positive-energy perturbations, its energy exceeds that required for escape and it never returns. One method of studying this problem is by many trials, the so-called "Monte Carlo" method. Hammersley also developed two approximate analytical solutions, one based on the analysis of Brownian motion that holds for a small number of passages and low starting energy and one that is expected to hold for a very large number of passages. The Monte Carlo runs, over 1.5 million on the Ferranti machine at Harwell and 1700 on the IBM 704 at the California Institute of Technology, confirm the analytical results over long time intervals, as shown in Fig. 3. Hammersley found that, depending slightly on the starting energy (that is, the distance from which new comets start falling toward the sun), the probability of a comet's remaining in the solar system decreases to 1 percent in about 200 million years. If a 4 percent chance of break-up on each passage is assumed, the decrease is a good deal more rapid, all comets being lost or disintegrating in a few million years.

The conclusion drawn by Lyttleton and Hammersley is that comets must be replaced at a fairly continuous rate. A possible alternative conclusion is that the number of comets was 1500 to 15,000 times greater when the solar system was formed, some 5 billion years ago, than it is today. (It is estimated that there are now 40 million comets.)

Adopting the former conclusion, Kendall examines the question: What energies should comets have at present if they are being formed as rapidly as they disintegrate or are lost? Using analysis similar to Hammersley's, Kendall derives the spectrum of energies which would result if new comets were all being dropped into the sun from a distance about 3000 times the earth's distance from the sun. This spectrum is modified for the effects of observational selection, account being taken of the fact that we see comets on long orbits less frequently than comets on short orbits, and the results are compared with the energies of 23 comet orbits measured accurately in the interval 1850 to 1936.

Figure 4 (middle and right) shows that confirmation is lacking; Lyttleton's theory predicts a maximum of comet energies corresponding to the 3000-unit starting distance, while the observations show a peak at energies corresponding to much larger distances. In a second trial Kendall assumed that the new comets fall from almost infinite distance, as in Oort's theory, and this theoretical spectrum of energies agrees quite well with the observations, as shown in the left and right curves of Fig. 4.

The tentative conclusion is that new comets are being formed at very great distances—10,000 to 100,000 times the earth's distance from the sun—and added to the diminishing number that we see circulating among the planets. The data cannot prove that the total number remains constant over long periods of time; in fact, it appears that *more* new comets have been added in recent times than were needed to keep the observed population constant. If Oort's theory is correct, the sun may at present be closer than usual to stars that disturb its shell of cometary material—a subject for further statistical investigation (*2*).

References and Notes

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Thurlow Christian Nelson, Marine Biologist

Thurlow Christian Nelson, marine biologist, was drowned on 12 September, 1960, off a storm-swept shore near his summer cottage at Green Creek, Cape May, N.J., while trying to secure his rowboat against hurricane Donna. He would have been 70 years of age on 22 September.

He was born in Highland Park, N.J., in 1890 and attended Rutgers elementary and preparatory schools in New Brunswick, just across the Raritan River from his home. He graduated from Rutgers University in 1913 with a B.S. degree in biology, and from the University of Wisconsin in 1917 with a doctorate in zoology and physiological chemistry. During World War I he served as a first lieutenant in the Army Sanitary Corps.

He was invited to join the Rutgers teaching staff in 1919 as assistant professor of zoology, becoming associate professor in 1922 and professor in