sun translates into information on their radial distribution in the galaxy.

Large deviations from circular motion mean that we can observe, near the sun, starry messengers from the outer and inner galaxy. These motions must also reflect some properties of the early collapse phase of the galaxy — a theme which of course underlies the celebrated work of Eggen, Lynden-Bell, and Sandage and its later successors.

Having mentioned Oort's avoidance of theory for its own sake, it is remarkable to note that the seeds of the currently very fashionable field of Hamiltonian chaos were put down in early studies of large amplitude motions perpendicular to the galactic plane. The appendix to Oort's article by his colleague Ollongren represents one of the earliest of such studies, lesser known (and possibly less comprehensive) than the work of Henon and Heiles somewhat later which is rightly viewed as a landmark. Oort's motivation came, of course, from high velocity stars. It is again worth noting that Oort was ready to harness computer power to reach astronomical goals at a time when many others suffered from ideological inhibitions which have not entirely disappeared even today.

It is worth quoting from the remarks with which the article concludes '... requirements that should ultimately be satisfied by a model of the galaxy is that not only should there be consistency between velocity and density distributions for each of the populations but that (they should imply a) field of force fitting the rotation curve'. The spirit of doing justice both to dynamical principles and to all the observations when one builds models could scarcely be expressed more concisely or forcefully.

It would be a daunting task indeed to review stellar dynamics about a decade later in the same series of volumes. Yet advances in observation, especially of external galaxies, and in theory and computation made this necessary and the result was Freeman's article 'Stellar dynamics and the structure of galaxies' in Volume IX, edited by Sandage, Sandage and Kristian. This excellent successor to Oort's article is worth mentioning, especially valuable to students and others entering this field of astronomy. More than a decade later, the subject finally found its *magnum opus* with the publication of 'Galactic dynamics' by Binney and Tremaine (Princeton 1987). Much water has indeed flowed under the bridge since 1964, but it is remarkable how much can still be learnt from Oort's fortysix pages.

Oort and the comets

H. C. Bhatt
Indian Institute of Astrophysics, Bangalore 560 034, India

To an unaided eye the most spectacular sights in the sky are undoubtedly the 'comets'. For their sudden appearance, peculiar shapes (a compact head surrounded by a coma and extended tail pointing away from the Sun), large dimensions (sometimes spanning almost the entire sky) and swift movement across the sky, comets must have been viewed with awe and fear by our ancestors. The physical nature of comets and their origin had not been clearly understood even by the first half of the twentieth century. Not until 1950, when Oort[1] published his theory of a huge reservoir of comets surrounding the solar system, in which he showed that there must exist a spherical cloud of about 200 billion comets reaching out to about 150,000 AU from the Sun, where 1 AU (the Astronomical Unit $= 1.5 \times 10^8$ km) is the mean distance of the earth from the Sun. This cloud of comets is now popularly called the 'Oort Cloud' and is schematically shown in Figure 1.

Oort's theory is based on the observed frequency distribution of the original semimajor axes (a) of the orbits of the long-period ($\gtrsim$ 200 yr) comets determined from cometary positions before they enter the perturbing influence of the planets. The distribution is sharply peaked toward very small positive values of the inverse semimajor axes $1/a$. The peak is at $1/a \simeq 3.2 \times 10^{-5}$ AU^{-1} with a width $\triangle(1/a)$ of only $\simeq 2 \times 10^{-5}$ AU^{-1}. Thus the aphelion distances ($Q = a(1+e) \simeq 2a$, where $e \simeq 1$ is the eccentricity of the orbit) of the comets are concentrated in the range $\sim 2 \times 10^4$ to $\sim 10^5$ AU. Although the long-period comets come from great distances, they cannot be visitors from interstellar space (as had been generally believed earlier), because no hyperbolic orbits ($1/a < 0$) are known. Oort therefore argued that there must exist a cloud of comets bound to the solar system in a shell between $\sim$20,000 and $\sim$100,000 AU from the Sun. The narrow peak in the frequency distribution of $1/a$ is however surprising. In 1948 Van Woerkom[2], then a student of Oort, had shown that a single passage of a comet through the inner planetary system (where a

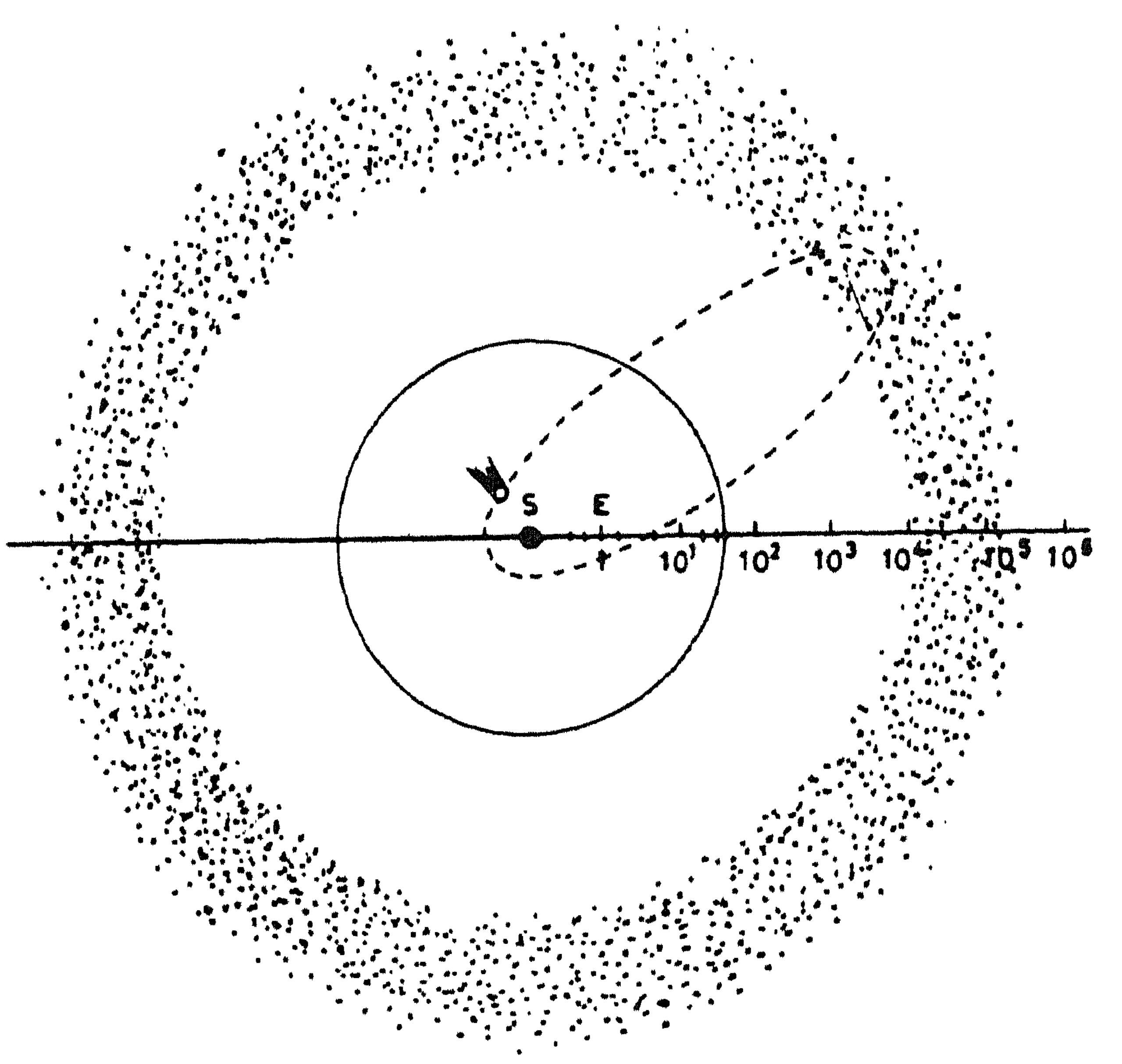

Figure 1. The Oort comet cloud is shown schematically. The radial dimensions are logarithmic in astronomical units. The planetary system is encircled and the relative positions of the Sun (S), Earth (E) and other planets are marked. A long-period comet on an elliptic orbit is also shown.

comet generally becomes observable as it develops the ephemeral coma and the tail) produces an average dispersion in $1/a$ of about $\pm 50 \times 10^{-5}$ AU^{-1} primarily due to the perturbative effects of Jupiter. Therefore, comets from the 'comet cloud' with $1/a \sim 3 \pm 2 \times 10^{-5}$ AU^{-1} will be permanently removed from the cloud population in a time of the order of the orbital period ($\sim 10^7$ yr). They will be either ejected from the solar system on hyperbolic orbits ($1/a < 0$) or put into orbits with short periods ($a \simeq 2000$ AU). Therefore the comets belonging to the observed peak in the frequency distribution of $1/a$ should all be coming into the observable zone of the inner planetary system for the first time. Oort called them 'new comets'. If the frequency of appearance of the 'new comets' has been steady over the age of the solar system ($\sim 4.5 \times 10^9$ yr), there must be a mechanism that replenishes, in the 'comet cloud', the population of comets on orbits that will bring them into the inner solar system as observable comets, on a time scale $\simeq 10^7$ yr. Oort showed that random perturbations of comet orbits in the 'comet cloud' by passing stars provide such a mechanism.

The solar system is moving through a more or less uniform background of stars in the galactic disc. These stars have a velocity dispersion of the order of ~ 30 km s^{-1}. Thus a typical star (of mass $M_* \sim$ the solar mass $M_\odot$) passes by the solar system with a relative velocity $V_* \sim 30$ km s^{-1}. For a distance of closest approach D the resultant impulse causes a change in the velocity of a comet $\triangle V$ of the order of $\simeq 2GM_*/DV_*$, where G is the gravitational constant. Likewise the Sun is also perturbed. The integrated effect of a large number of passing stars, over an interval of time, is to change the velocity of the comet relative to the Sun in a random manner. Oort showed that these perturbations are large enough to cause 'cloud comets' to diffuse into orbits that are depopulated by planetary perturbations as comets pass through the inner planetary region during their perihelion passages, on time scales of the order of $\sim 10^7$ yr; and they are not strong enough to eject the comets from the solar system even on time scales of the order of the age of the solar system, except for aphelion distances $\simeq 150{,}000$ AU. Thus, the 'comet cloud' is bound to the solar system and has an outer boundary at a distance $\sim 150{,}000$ AU from the Sun. This is in agreement with the earlier observations. By making use of the observed number of 'new comets' that appear per century with perihelion distances $q < 1.5$ AU Oort calculated the total number of comets in the 'comet cloud' to be $\sim 2 \times 10^{11}$.

Where did the 'cloud comets' come from? Oort argued that they could not have been born in the region of space which they populate at present, because at such large heliocentric distances the densities in the pre-solar nebula must have been vanishingly small and no objects as dense and as large as the comet nuclei could have grown there. They could have grown in the high density inner regions of the pre-solar nebula where the planets formed. But then they would have to be transported to the 'Oort cloud' region. Perturbations of the proto-comets in the planetary region by the giant proto-planets (Jupiter, Saturn, Uranus and Neptune) diffuse these objects gradually outward. When their aphelia reach heliocentric distances $\sim 20{,}000$ AU, stellar perturbations begin to take over. Unlike the planetary perturbations that influence only the major axes of the cometary orbits, the stellar perturbations can also cause changes in the perihelion distances q and inclinations i of the cometary orbital planes, thereby removing the orbits from the influence of the planets. Comets are thus trapped in a region extending from $\sim 2 \times 10^4$ AU to $\sim 10^5$ AU. Thus the 'Oort comet cloud' is produced. Later, the same random stellar perturbations can send in comets on orbits that bring them in the observable zone in the inner solar system. Oort had originally suggested the asteroidal belt, between the orbits of Mars and Jupiter, as the zone of formation of the proto-comets. However Kuiper[3] argued in 1951 that the composition of the comet nuclei consisting of volatile frozen gases as in the 'dirty snowball' model of Whipple[4], indicates that proto-comets could not have formed in the hot asteroidal belt. He suggested that proto-comets formed farther out in the solar system and a trans-Neptunian belt of these objects still exists. Recent work has shown that the region around the orbits of Uranus and Neptune is the most likely place where proto-comets that now populate the 'Oort cloud' initially grew up.

From the observed frequency distribution of the inverse semimajor axes of comet orbits Oort could also derive a significant result about the brightness evolution of 'new comets' and their composition. The observed distribution of $1/a$ has a sharp peak at $1/a \simeq 3.2 \times 10^{-5}\,\mathrm{AU}^{-1}$. After their perihelion passage, planetary perturbations would have produced a dispersion in $1/a$ of the order $\simeq 50 \times 10^{-5}\,\mathrm{AU}^{-1}$. But this is not observed. It can therefore be concluded that the comets that are now observed with $1/a \lesssim 3 \times 10^{-5}\,\mathrm{AU}^{-1}$ do not return at comparable brightness. Their nuclei evaporate to such an extent during their first perihelion passage that their absolute brightness decreases by several magnitudes. The comet nuclei probably have an outer layer that is composed of highly volatile frozen gases. The long-period comets must greatly differ from those with shorter periods. With Maarten Schmidt, Oort[5] investigated the differences between the long-period and short-period comets. They found that the long-period comets are characterized by much stronger continuum spectra. This is attributed to the presence of dust entrained by the gases from a very volatile icy component. Oort and Schmidt[5] also found that the absolute brightness of long-period comets increases more slowly with decreasing heliocentric distance r, than that of the short-period comets. Expressing the absolute brightness as $m_0 = A + B\sqrt{r}$, where m_0 is the magnitude reduced to 1 AU geocentric distance, A and B are constants. In this formula originally given by Levin[6] in 1943, the constant B is related to the latent heat of sublimation by: $B = 1.086L/RT$, where R is the gas constant and T is the temperature. Recent observations give $B = 2.8 \pm 0.3$ for long-period comets, while for the short-period comets $B = 8.6 \pm 0.7$. Thus the 'new comets' coming from the 'Oort cloud' appear to have much lower values for the latent heat of sublimation than the older short-period comets as Oort had suspected.

Since 1950, when Oort proposed his theory, there has been great progress in the studies and our understanding of the physical nature of comets. There have been extensive numerical simulations of the dynamical evolution of cometary orbits. The basic ideas put forward by Oort have survived these investigations and the 'Oort comet cloud' has become a permanent part of humankind's world view.

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