

Memorial to Sir Harold Jeffreys

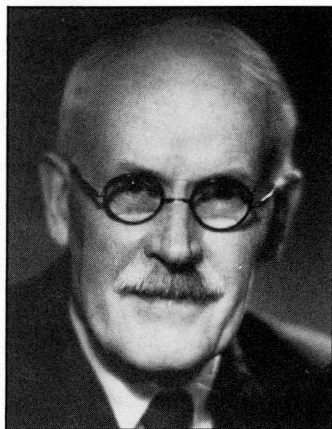
1891–1989

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Harold Jeffreys was one of this century's greatest applied mathematicians, using mathematics as a means of understanding the physical world. Principally he was a geophysicist, although statisticians may feel that his greatest contribution was to the theory of probability. However, his interest in the latter subject stemmed from his realization of the need for a clear statistical method of analysis of data—at that time, travel-time readings from seismological stations across the world. He also made contributions to astronomy, fluid dynamics, meteorology, botany, psychology, and photography.

Perhaps one can identify Jeffreys's principal interests from three major books that he wrote. His mathematical skills are displayed in *Methods of Mathematical Physics*, which he wrote with his wife Bertha Swirles Jeffreys and which was first published in 1946 and went through three editions. His *Theory of Probability*, published in 1939 and also running to three editions, espoused Bayesian statistics, which were very unfashionable at the time but which have been taken up since by others and shown to be extremely powerful for the analysis of data and, in particular, image enhancement. However, the book for which he is probably best known is *The Earth, Its Origin, History and Physical Constitution*, a broad-ranging account based on observations analyzed with care, using mathematics as a tool. Jeffreys's scientific method (now known as Inverse Theory) was a logical process, clearly stated in another of his books, *Scientific Inference*. *The Earth* was first published in 1924 and the sixth and last edition appeared in 1976, when Jeffreys was 85 years old.

Jeffreys's lifelong interest in Earth, its moon, and the planets was established at an early age. At sixteen his imagination was caught by the book on tides by Sir George Darwin (grandson of Charles Darwin), and in 1963 he wrote, "I think that nearly all of my own work has been directly or indirectly inspired by Darwin." Born in Fatfield, County Durham, the only child of schoolteachers, he was educated in Newcastle upon Tyne at Rutherford College, followed by Armstrong College (later the University of Newcastle) where he studied mathematics, physics, chemistry, and geology. In 1910, having won an entrance scholarship to St. John's College, he went to Cambridge, and in 1913 took a first class in mathematics. In 1914 he was elected a Fellow of the College for work on the structure of Earth and the moon. From 1915 to 1917 he worked partly in the Cavendish Laboratory in Cambridge and then, in 1917, left Cambridge to join the Meteorological Office in London where he worked on the effects of wind on the ocean, using data from the North Sea. Jeffreys returned to Cambridge in 1922 as a lecturer in mathematics and remained there for the rest of his life. He was appointed reader in geophysics in 1931 and later, in 1946, elected to the Plumian Professorship of Astronomy and Experimental Philosophy. An active member of the Royal Astronomical Society, he was its president from 1955 to 1957, and his papers did much to establish the reputation of the Society's *Geophysical Supplement* (now *Geophysical Journal International*). Made a Knight Bachelor in 1953, he retired in 1958.



In 1940 Jeffreys married Bertha Swirles, a lecturer in mathematics at Girton College in Cambridge, who had taken a Ph.D. in atomic physics under R. H. Fowler and D. R. Hartree.

To many, Harold Jeffreys's greatest achievement was the construction of the Jeffreys-Bullen (JB) tables of seismological traveltimes. K. E. Bullen came to Cambridge in 1931 to take the mathematical tripos but, instead, worked under Jeffreys's supervision to reduce the very large quantity of data, consisting of arrival times of seismic waves at stations around the world, which had been collected and published in the International Seismological Summary. The work was done on a hand-operated calculator and provided accurate estimates of the time and position of each recorded seismic event and of the traveltimes for the principal ray paths as a function of epicentral distance from source to receiver. All epicentral distances from 0° to 180° were covered, but the baseline was provided by an accurate study of crustal P and S wave speeds which Jeffreys had made with Dorothy Wrinch in 1923, using records from an explosion at a chemical factory near Mannheim in Germany. The tables, published in 1940, have remained standard in seismological stations for 50 years. They are, perhaps, the best estimate for traveltimes constructed on the basis of a spherically symmetric Earth. Jeffreys worked for many years on refinements to the tables and on regional variations. He was convinced that the next step should be to construct regional tables. Plans are now afoot to compute such tables.

The JB tables not only provided the seismological community with a means of identifying seismic arrivals and of determining the position and time of the earthquake source, but they may be inverted to give the wave speeds of both P and S waves from the surface to the center of Earth. Furthermore, Bullen used the distribution of wave speeds to calculate density as a function of depth, and his results are still regarded as largely accurate.

The existence of Earth's core had been inferred by Oldham in 1906 from the shadow that it imposes on seismic radiation. No phases could be detected which had traveled as shear waves through the core, and so it was considered to be fluid. In 1926 Jeffreys confirmed from a study of Earth's bodily tide and the variation of latitude, that the rigidity of the core is indeed negligible.

One of Jeffreys's main preoccupations was with the strength of Earth, not only the elastic response at seismic frequencies which he was able to determine from the traveltime tables, but also the yielding due to stresses maintained over longer periods. He calculated the equatorial radius and ellipticity of Earth and also the gravity field up to harmonics of the third degree. These results, together with a study of the surface features of Earth, enabled him to estimate the shear stress sustained within the planet in geologic time. The values he obtained compared well with measurements of tectonic stress estimated from the radiation release from earthquakes. He also measured creep and dissipation within Earth, using data from the uplift of the Scandinavian shield and the attenuation of the Chandler wobble. The fact that seismological phases are observed and also that they do not run on forever provides an additional constraint. In fact, a study of the variation of seismic amplitudes with epicentral distance gives a reasonable estimate of dissipation at those frequencies. It was these studies of the strength of Earth materials, in particular the ocean floor, which led Jeffreys to the conclusion that Wegener's model of continental drift, with the continents ploughing through the oceanic crust, was completely untenable on mechanical grounds.

In 1957, Cinna Lomnitz proposed a logarithmic law of creep to account for laboratory observations on rocks. Jeffreys took up this empirical law, generalized it, and named it the modified Lomnitz law, although it should probably be called the Jeffreys law. It is essentially power-law creep with modifications to avoid singularities at time zero and, as such, was not particularly novel. In Jeffreys's version it has three parameters; one gives the instantaneous elastic response and the other two, q and α , govern the creep behavior. While q is just a magnitude, α determines the power of t in the power law. In the limit as α tends to zero, the model reduces to

the logarithmic law. Jeffreys estimated the values of q and α from the attenuation of seismic waves and the Chandler wobble and found α to be around 0.2. The law works surprisingly well even though the data set covers a range of 10^7 in frequency. In addition, it must be realized that this is an average result relating to Earth's crust and mantle as a whole. What was clear to Jeffreys was that the Maxwell law (that is, Newtonian viscosity given by $\alpha = 1$) does not fit.

A theoretical law is only good if it can account for observations, and Jeffreys, working on the principle that the best test of a law is to apply it as far as possible away from the data on which it was originally constructed, jumped another factor of 10^7 to bring the time scale up to geologic time. Even more surprising was the fact that Jeffreys's law of creep accounts for the existence of low harmonics in the gravity field and of mountain ranges. On the assumption that the moon is largely made up of materials similar to those in the mantle and crust of Earth, he applied his law of creep there and was able to account for both the maintenance of the moon's inequality of figure and its lack of rotation. It is quite remarkable, and very useful, to find a simple law which may be applied over such a range of time scales. However, very few people, apart from Jeffreys himself, have taken advantage of this discovery. The chief difficulty is that it is incompatible with plate tectonics. Jeffreys took the view that the law of creep was soundly based on clear observations of processes of which some had time scales in line with those of plate tectonics, and therefore that the latter hypothesis is untenable. Most geophysicists have taken exactly the reverse view.

Jeffreys argued that the existence of continents and the upward concentration of radioactivity suggested that Earth had once been fluid and had convected. However, he believed that such convection had ceased relatively early in the history of the planet. He suggested that cooling and subsequent contraction had led to the formation of mountains, and he regarded the contraction theory as the only explanation of mountains that was even qualitatively satisfactory. He accepted the field evidence for horizontal displacements of the order of 50 km in major mountain chains but considered that there was no evidence for supposing they could reach thousands of kilometres. Nevertheless, he was puzzled by and could not account for the concentration of mountains in western China and bordering regions.

He dismissed paleobiological arguments for drift based on the similarity of faunas and floras as similarities brought about by occasional natural migration across oceans. Jeffreys did not try to explain the paleomagnetic data that seemed to support drift. He believed it was not possible to find satisfactory answers from these data to the interrelated problems of drift and polar wandering.

He argued that the coasts of eastern South America and eastern Africa had a mismatch of 20°, which was not greatly improved by using the 1000-fathom line. His remark, "I simply deny that there is an agreement," stimulated the quantitative estimate of the mismatch and somewhat ironically led to an important piece of evidence in favor of geologically recent drift.

He appears not to have commented on the significance of the symmetry of magnetic anomalies across oceanic ridges. This and the other evidence for the current view of drift, as expressed in plate tectonics, probably came a little too late to be assimilated into his view of the world. He was in his seventies when the theory was first discussed. At the same time, all too few people then appreciated his own arguments against drift based on the strength of Earth. Among his geological papers, Jeffreys wrote about transverse circulation of streams; the physics of how heavy particles can be lifted by fluid motions and the mechanics of scree formation. In 1929 he used the existence of the mountains on the moon as evidence to support Blackwelder's view that temperature variations were less important in denudation than were then generally supposed, remarking that not enough attention had been given to the probable effects of dew. He made some of the first mathematical analyses of peneplains, showing that an existing peneplain with a uniform soil cover and water to a particular depth on a given slope would be denuded at a

uniform rate and reproduce the general appearance of actual peneplains. He then went on to discuss the effect of corrugation parallel to and transverse to the slope.

Long after he had retired from his Cambridge chair, Jeffreys continued to make acute observations with far-reaching consequences. In 1961 he showed how Rayleigh's principle could be used to calculate group velocities of surface waves without numerical differentiation. The same approach allowed the straightforward calculation of small changes to dispersion curves as a result of small changes in structure. In 1967 and 1970 he pointed out the effect that viscoelasticity has on the free periods of Earth's oscillation and that this might be used to reconcile differences between body-wave and free-period data and to estimate damping as a function of depth.

Harold Jeffreys was a great scientist who has left a lasting memorial of achievements in the study of the structure and dynamics of this planet. More than that, his scientific work presents a model of how to do science. Finally, to those who knew him, he has left a memory of a man with great clarity of mind, of high courage and equal modesty, sociable but not very talkative, and impossible not to respect and admire.

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