The Earth and Its Mountains

R. A. Lyttleton F.R.S.

Formerly Professor of Theoretical Astronomy
University of Cambridge

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Preface

In 1978 the Milne Society honoured me by an invitation to deliver the annual Milne Lecture under the auspices of Wadham College and the Mathematical Institute of Oxford University. The title adopted for the Lecture was Gravitation, Ancient Eclipses, and Mountains.

The occasion provided an opportunity to give a coherent account of ideas on the theory of the structure of the Earth that had been under investigation by the author during the past two decades, and the present book covers more fully topics that could only be dealt with briefly in a single lecture to a general audience. In certain respects these new ideas differ widely from views that have long since come to be regarded as being established beyond reasonable doubt. The views here put forward lead in the first place to the conclusion that the Earth (and other terrestrial planets) began their individual existences in solid form throughout, and that the basic cause of their evolution is the still-continuing release of energy in their interiors by the long-life radioactive elements uranium, thorium, and potassium.

The central novel feature that this book offers for consideration concerns the age-old standard theory of tidal friction of the Earth-Moon-Sun system, which for over forty years has been generally accepted without question as correct. However, with improved values of the apparent secular accelerations of the Moon and Sun becoming available in the early 1970s, a re-working of the tidal-friction theory disclosed that an invalid dynamical assumption had tacitly been made in setting up the fundamental initial equations of the theory. This error has passed unnoticed by geophysicists for several decades despite its frequent re-publication during this period. It turns out that correction of the error has far-reaching and profound consequences for geophysics as a whole, particularly in showing that the moment-of-inertia of the Earth is steadily decreasing, and with it on average also the surface-radius. The existing seismic data show that when originally in all-solid form, the moment-of-inertia of the Earth would have been over 25% greater than at present, with the radius some 370 km greater, and the amended theory also shows that the long-standing assumption that the core consists of iron and nickel cannot be sustained. But perhaps the conclusion of most general interest that emerges from the revised theory is that contraction of the Earth sufficient to account for more than twenty major eras of mountain-building must have taken place, a scale of contraction that geologists have considered essential from time immemorial.

These conclusions importantly affect many areas of geophysics, and in order that a reader may more easily appreciate the general account of the formation and evolution of the Earth, the book commences with brief, non-technical summaries of each chapter, before the full mathematical exposition which comprises the main body of the work is given.

The book is not intended as a comprehensive textbook on geophysics, which would need an encyclopaedic volume. Nor, it should be emphasised, does it attempt to deal with the purely verbal and pictorial explanations of alleged terrestrial phenomena now in vogue, not because these already have been widely disseminated

in a vast and repetitive literature, but because in the author's view they simply do not constitute scientific theories in the proper sense at all.

My special acknowledgments of his assistance are due to Professor J.P. Fitch, now of the University of Bath, who carried out an immense number of computations of the properties of terrestrial and planetary models (not included in this book) in order to make certain that the results put forward herein were independent overall of any particular assumptions and approximations relied upon. Though based on work over many years, the book itself was written mainly in 1979 when the author was holder of a Leverhulme Fellowship, and my grateful thanks are therefore due to the Leverhulme Trustees for the benefit that their award contributed to numerous aspects of the book.

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R. A. LYTTLETON

disc rotating round the Sun, and this would subsequently develop into a set of planets. Such a nebula of suitable mass and adequate range of extension from the Sun could also readily be captured from an interstellar gas-and-dust cloud, which abound within the Galaxy. This could occur directly by accretion by the Sun, or through the combined dynamical action involving another adjacent star. Such occurrences may happen so often in the Galaxy that a great many stars may at some time have captured a nebular gas-and-dust disc in this way, and come to possess a retinue of planets. The dust component would necessarily settle into a flat disc only a few centimetres thick, with all its elements in circular orbital motion round the Sun, and the density in this disc would be high enough for planets to aggregate by gravitational forces. But due to the thinness of the disc, the material gathered into a growing planet would fall only onto a narrow circumferential band, and no general heating of the whole surface would take place. The Earth would take about 50,000 years to reach its present mass. The Moon would have been an embryo planet adjacent to the Earth in its orbit, first captured by the Earth and then becoming permanently bound to it as a result of only slight further infall of the last vestiges of the dust disc. Planets so formed would have rotation periods of a few hours resulting from the vorticity inherent in the disc-material through its orbital motion about the Sun, but subsequent tidal actions would slow the rotations. This mechanism of formation shows that the Earth and other terrestrial planets and the Moon can never have been wholly gaseous or molten but began their individual existences sufficiently cool to be solid throughout their entire volumes.

Radioactive elements of long half-lives, comparable with the age of the Earth itself, such as uranium, thorium, and potassium would gradually raise the internal temperature of the Earth and must still be continuing to do so especially in the deep interior. There

Chapter Summaries

1 - THE ORIGIN OF THE EARTH 1 - 25

The famous nebular hypothesis of Laplace regarded all the planets as being initially gaseous. The theory provided no origin for the nebula itself, and the ultimate central body to which the nebula contracted, and to be identified with the Sun, would have far too rapid rotation. Replacement of the theory by tidal or collisional encounters of the Sun with a passing star also implied initially gaseous planets, and also failed by a large factor to account for the enormous scale of the planetary orbits in comparison with the size of the Sun. However, if otherwise acceptable, these theories could be saved by supposing that the Sun originally possessed a companion-star already moving at distances from it of the required planetary order, and it would be from this body and the passing star that the necessary planetary material would be released in a close encounter. In addition as a result of the encounter, the companion-star would have its motion speeded up sufficiently to overcome its weak gravitational binding to the Sun and cause it to escape. Or again, if the companion were sufficiently massive to reach a supernova explosion stage, the Sun could capture a mere wisp of the material thereby ejected into space, and the slightest asymmetry of recoil could release the remnant star from its binding to the Sun. The captured material would expand and cool to form a pre-planetary nebular

an acceleration (negative) of its longitude inexplicable dynamically, since the observed longitude exhibits a minute term depending on the square of the time. This anomalous term produces a displacement of the position of the Moon that amounts to about half a degree, about its own diameter, in a thousand years. The rotation of the Earth has also been proved to be influenced by the same dissipative forces, and as a result its use as a true measure of dynamical time has had to be abandoned. In recent years, it has been replaced by so-called ephemeris-time depending on the motion of the Earth about the Sun, and in addition by atomic time defined by means of the cycles of a caesium-resonator.

4 - THE THEORY OF TIDAL FRICTION 67 - 84

Since both the rotation of the Earth and the angular velocity of the Moon in its orbit are undergoing accelerations, the ancient-eclipse data cannot lead to the values of these directly, but only to the combination of their effects, the so-called apparent secular accelerations of the Moon and Sun. These are related by certain strict dynamical equations to the lunar and solar couples. Hitherto, in setting up these equations, it has always been tacitly assumed that the moment-of-inertia of the Earth about its axis was an invariable constant not changing with time, but even so, had a proper solution of these dynamical equations ever been carried out, it would have led to the entirely unacceptable result that the total solar couple was acting to speed up the rotation of the Earth, and hence that the theory was in some way in error. The correct form of the equations of motion yield the lunar couple directly irrespective of whether any other complications may be involved in the problem, such as the changing moment-of-inertia, and even if the constant of gravitation were changing with time. The lunar couple turns out to be of such magnitude and form as to imply that the Moon would have been almost in contact with the Earth only about 1,000,000,000 years ago, and suggesting that other influences must have been involved over and above

those yet recognised. The solar couple can then be found from the lunar couple by dimensional scaling, according to the type of tidal friction involved, but whatever basis is adopted for this latter, the results show inescapably that the moment-of-inertia is decreasing at a rate of essential importance in the whole problem. This in turn produces an intrinsic accelerative component in the angular velocity, as if an apparent or fictitious couple were acting on the Earth in order to conserve the rotatory momentum. On the other hand, the lunar and solar couples operate to retard the terrestrial rotation. The deceleration caused by the Moon is greater in magnitude than the intrinsic acceleration owing to the decreasing moment-of-inertia, and this in turn is greater in magnitude than the deceleration produced by the Sun. Thus the term hitherto overlooked in the theory is intermediate in magnitude between the lunar and solar couples, and its inclusion absolutely essential to acceptable dynamical interpretation of the ancient-eclipse data, which themselves are not in question as to their reliability. Not only does the conclusion that the moment-of-inertia is decreasing with time follow inescapably, but the further conclusion that the Earth as a whole is undergoing contraction.

5 - THE PHASE-CHANGE HYPOTHESIS 85 - 110

The physical cause of this contraction depends on what is termed a change of phase of the solid mantle material to liquid metallic form. With steadily rising internal temperature through radioactive energy-release and at the pressures prevailing in the central regions, a phase-change of solid mantle-material to a liquid metallic phase is continuously occurring at the mantle-core boundary. The belief that the core consists of iron and nickel, which down the years has come to be widely accepted has no serious validity, and all along has been based on arguments that can now be seen to be of nugatory value. W.H.Ramsey was the first to show theoretically that at pressures of the order of a mill-

is a peculiarly high concentration of these elements in the extreme outer layers, but this concentration cannot possibly continue on downwards or the Earth would be at such a high temperature as to be molten throughout. This curious feature could have resulted from a subsequent slight addition of interstellar material of high radioactive content, but this property is not of great importance to the general evolution of the Earth. There is some evidence of a similar high concentration of these radioactive elements in the lunar surface-layers.

These particular radioactive elements enable the ages of rocks that contain them to be ascertained. Estimates of the age of the Earth so arrived at have gradually crept up during the last half-century, and the figure has presently reached about 4,500,000,000 years, but even if greater estimates emerge, certain theoretical considerations show that the age is unlikely to be as great as 6,000,000,000 years.

Seismic data inferred from the travel-times of earthquake-waves reveal the physical properties at all depths within the Earth, but not the actual chemical composition of the material. Analysis of the data indicates the presence of several successive concentric spherical layers at which reflections and refractions of waves occur. For broader questions, these layers can be merged into three main zones : first, an outer shell extending to a depth of 413 km ; then below that the solid mantle to depth 3898 km ; and next, a liquid core of radius 3473 km containing over 31 per cent of the whole mass. There is some evidence that a solid core of small mass and radius may exist at the very centre within the liquid core. The seismic data lead to the highly important conclusion that the core-material in its metallic liquid phase is much more compressible than the mantle-material in the solid phase. Also the uncompressed density of the core-material is far too low for identification with iron and nickel in any proportions, a result first established by W.H. Ramsey some thirty or more years ago.

Over long periods of time, the angular velocity of the Earth and the orbital motion of the Moon are importantly affected by the phenomenon of tidal friction. It results from the tides raised by the differential gravitational action of the Moon and Sun upon the Earth owing to the finite size and non-rigidity of the latter. These tides occur in the oceans and seas, in the atmosphere, and also in the solid body of the Earth. Because of the more rapid rotation of the Earth as compared with the orbital angular rates of the Moon and Sun about it, such tides mainly lag behind the bodies producing them, and this results in forces that dissipate the energy of rotation of the Earth. But the total rotatory momentum of the Earth-Moon system cannot be changed by internal forces, and that lost by the Earth is transferred to the lunar orbit causing the Moon to recede slowly. The amount of tidal dissipation presently occurring is extremely difficult to calculate directly, and more so for past times when conditions may have been much different from now. However, the data provided by ancient-eclipse records, which extend back about 3000 years, enable the rate of change of the rotation of the Earth, the rate of recession of the Moon, and the rate of change of the moment-of-inertia of the Earth to be calculated by means of trustworthy dynamical theory. The actual tracks on the surface of the Earth by the lunar shadow during an ancient-eclipse have been found to be far remote from the theoretical tracks calculated on the basis of purely conservative gravitational forces, and the differences reveal that the rotation of the Earth and the motion of the Moon are sensibly influenced by tidal friction. That the Moon appears to have a deceleration in its angular velocity round the Earth was first announced by Halley, and the problem was later studied by Euler, Laplace, and J.C. Adams. But it was Adams who finally established beyond any question that the Moon was undergoing

The seismic data enable the physical properties of the Earth to be inferred at all depths, and a relation between pressure and density emerges for each of the three main zones. The relation is practically linear and independent of temperature. By use of these data, computer-techniques enable evolutionary models of an Earth of increasing liquid core-mass to be calculated in detail. In both 3-zone and 2-zone models, the conditions and properties in each zone can be determined by solution of a second-order differential equation which happens to be of Emden-form. The boundary conditions to be satisfied by a physically possible model-solution are that the density must be finite at the centre, and that the pressure must vanish at the precise radial distance at which the total mass encompassed within that distance is equal to the mass of the planet. For each member of a series of adopted values of the core-mass, such calculations yield the surface-radius, the moment-of-inertia, and the total gravitational energy, together with the general march of values from the centre to the surface of the pressure, density, and other associated quantities.

As the core-mass increases from zero, the pressure at the boundary between the liquid core and the solid mantle at first increases, strengthening the conditions there for a change of phase to proceed outwards. Thus the zone of phase-change to liquid form extends rapidly at first, and it is in this way that the Ramsey-collapse manifests itself when evolution is followed by means of static models. This interface-pressure increases to a maximum with increasing core-mass but thereafter always decreases monotonically. After the sudden collapse and initial formation of a large core in liquid metallic form, all quantities continue to change only steadily and uniformly with rising temperature, and the Earth evolves steadily through thoroughly stable forms. Both the moment-of-inertia and the calculated surface-radius steadily diminish. The results for 2-

ion atmospheres and temperatures of a few thousand degrees such a phase-change would take place when either the pressure or the temperature exceeded certain critical values. Static pressures and temperatures of these orders are now coming within experimental producibility in the laboratory, and numerous phase-changes have already been shown to occur. The seismic data show the mantle-core transition to be extremely sharp, not at all to be expected for a compositional change, and this receives explanation on the phase-change theory, as also do certain curious properties of the primary and secondary wave-velocities as the innermost boundary of the mantle is approached from above.

The density-increase from solid to liquid form consequent on the phase-change is by a factor greater than 1.5, and this implies theoretically that when conditions suitable for the phase-change are reached with rising central temperature a sudden collapse of the Earth will have occurred with the formation in a matter of minutes of a liquid metallic core of initial radius 2,040 km, while the outer surface-radius undergoes an accompanying sudden decrease by 70 km. Thereafter, as the temperature at the mantle-core boundary continues to rise, the Earth evolves steadily through stable configurations, the mass and radius of the liquid core steadily increase, but the Earth as a whole undergoes contraction.

With increasing depth from the surface, the melting point temperature increases, but for the high-pressure liquid-core phase the density is greater than that of the solid-mantle phase, and as a thermodynamic consequence melting would start at the centre where the pressure is greatest in an all-solid Earth. Ramsey showed that at pressures of the order of a million atmospheres the incompressibility would be a closely linear function of the pressure, and from this could be inferred that the core-material would have uncompressed density of only 4.8 g/cm^3, rendering any identification with iron or nickel impossible.

zone models with increasing liquid-core mass surrounded by solid mantle-material follow an exactly similar course. The Earth may have remained in all-solid form for a time of the order of a billion years before the central temperature had risen sufficiently for the onset of the collapse, but the average rate of decrease of the moment-of-inertia is only weakly dependent on the adopted time of collapse. The accompanying intrinsic component of acceleration of rotation agrees closely with that determined from the ancient-eclipse data.

Among the terrestrial planets, only in the Earth and Venus are pressures high enough for the Ramsey phase-change. The associated density-jumps are both considerably greater than 1.5, and thus when the central temperature had risen to the critical value sudden collapse will have occurred. Before this temperature has been reached, ordinary melting may have taken place in a layer within a few hundred kilometres of the surface, and within it denser material would sink and lighter material rise. When later the collapse occurs of the whole Earth, with a sudden reduction of the outer radius by 70 km, the solid shell above this liquefied layer would be forced to undergo intense fracturing during the enormous reduction of surface-area. From such fissures the low-density underlying molten matter would well up to the surface under hydrostatic forces, and could thereby give rise to the less-dense continental material. Of the total gravitational energy released in the collapse, more than three-quarters goes to doing work on the material that becomes the metallic liquid core, and is about twice that actually needed solely for the phase-change. The rest of the energy goes to increasing the rotation-rate of the planet and to the necessary compression of the material remaining in solid form.

After the collapse, the Earth is thoroughly stable but evolves with further rising internal temperature, and contracts steadily everywhere, since the pressures far exceed the strength of the material, except in the

extreme outer layers. In these, stresses gradually increase as a result of diminishing support from below, and must eventually become great enough to overcome their strength. Folding and thrusting must then occur at the weakest places and result in the formation of mountains. The most violent epoch of mountain-building would of course have been the few minutes of the initial collapse itself. The subsequent decrease of radius has been about 300 km so far, and thus averages about 0.01 cm per year. This means a total decrease of surface-area by nearly 50 million square kilometres, and a total volume of solid material of more than 150 billion cubic kilometres somehow to be redistributed at the surface. If shared out for say at least twenty eras of mountain-building at intervals of order 100,000,000 years, this would involve 8 billion cubic kilometres of solid material being redistributed by folding and thrusting during each epoch, enough to provide for some 200 mountain ranges of volume comparable with the Rocky Mountains, for example.

Between the successive comparatively short periods of mountain-building, continually rising temperature at the level of the Bernal-discontinuity would cause slight expansion of the Earth and rifting of the outer layers at their tensionally weakest places would occur, but the amount of this expansion would be far outweighed by the contraction resulting from the steady increase of the liquid-core mass. If the phase-change process is the true cause of mountain-building, it would make clear why all hitherto proposed mechanisms have proved to be inadequate and unacceptable.

When radioactive energy-release eventually becomes negligible, some 10^{11} to 10^{12} years hence, the interior of the Earth will begin to cool down, and the stages of the phase-change will proceed in the opposite direction. The liquid core will decrease in mass and radius and the Earth will expand, steadily and gradually at first, but then at a certain stage the whole of the remaining liquid-core will suddenly revert to mantle-form, accompanied by an explosive expansion of the whole Earth, the outer radius increasing in a matter of minutes by several tens of kilometres.

On the hypothesis of their all having the same composition, only in Venus of the other terrestrial planets would the central pressure be high enough for the phase-change conditions to be reached and lead to production of a liquid core. Now that the solid radius of Venus is known, a satisfactory 3-zone model can be calculated with properties similar to those of Earth, which indicates slightly higher internal temperatures at corresponding depths. The liquid core at present contains 25 per cent of the total mass and has radius 3032 km, while the Bernal-discontinuity is at a depth of 515 km. The general evolution of Venus will have been similar to that of the Earth, though the initial collapse would have been delayed till higher central temperature was reached to offset the lower central pressure. When at first in all-solid form, the surface-radius would have been 6306 km. The initial liquid-core contained 4.5 per cent of the total mass, and had radius 1750 km. The sudden collapse would have reduced the outer radius by 45 km, and since then, internal contraction has led to a further decrease of 206 km to the present value. Mountain-building by folding and thrusting will therefore occur at intervals on Venus, and recent radar-measures are already finding large-scale irregularities with differences of elevation as great as 10 km.

For Mars, pressures are sufficient only for the Bernal phase-change, and thus the planet will be a 2-zone all-solid body of mantle-material surrounded by outer-shell type material. The measured radius indicates lower internal temperatures than at equal depths in the Earth, and the discontinuity occurs at a depth of about 560 km. As no metallic-liquid core will have formed, there can be no dipole magnetic field, nor any folded and thrusted mountains. Since the Bernal discontinuity requires higher pressures as the temperature rises, its level must get progressively deeper, and the planet expand to produce rifting of the surface-layers. All these predictions were subsequently verified by means of the Mariner-missions to the planet.

In the Moon, the central pressure is far too low even for the Bernal phase-change. It is thus a 1-zone body of material of the same form as the outer-shell of the Earth. Although the outer surface shows irregularities on almost every scale produced by bombardment, in the absence of any phase-change core there can be no dipole magnetic field, and no folded and thrusted mountains, nor even rifting of the surface-layers. Compression decreases the radius by less than 10 km, and the calculated value is 0.7 km less than the observed radius, a deficiency readily explicable through non-hydrostatic conditions in the near-surface layers.

The mass and radius of Mercury, generally accepted for a great many years, imply the extraordinarily high mean-density of 5.43 g/cm^3, which would require the planet to contain over 60 per cent by mass of iron. On any basis as to its internal structure, the central pressure is sufficient only for the Bernal phase-change, which means that no folded and thrusted mountains would be formed, and this was confirmed by recent fly-pasts. Despite the seemingly very different composition from the other terrestrial planets, Mercury does not supply any test relevant to the Ramsey phase-change theory, since the internal pressures are far too low. The mass which is currently accepted dates back to Newcomb (1895) but it has only recently come to light that the value that he announced may have been in error as not really being supported by his calculations. However, Mercury is so near the Sun and of such small mass anyway that such error could well not have obtruded itself in observations not specifically aimed at detecting it, such as the placing of a satellite in orbit about the planet.

9 - IS THE CONSTANT OF GRAVITATION CONSTANT ?
177 - 193

In recent years new cosmological theories have been proposed that raise the question whether the constant of gravitation .G is an absolute physical constant not changing with time, as the general-relativity theory requires it to be. If G were decreasing with time, as most of the theories suggest, the principal direct effect would be a purely kinematic increase with time