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A REVIEW OF STUDIES MADE ON THE DECADE FLUCTUATIONS IN THE EARTH'S RATE OF ROTATION

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A REVIEW OF STUDIES MADE ON THE DECADE FLUCTUATIONS IN THE EARTH'S RATE OF ROTATION

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Studies of variations in the length of the day (l. o. d.) on the order of a few milliseconds over the period of a few decades are briefly reviewed. In this connection, studies of the dynamo theory of geomagnetism, the westward drift of the magnetic field, and electromagnetic core-mantle coupling preface the theory of the decade fluctuations in the l. o. d.

Key Words: core-mantle coupling, decade fluctuations, dynamo theory, earth's core, geomagnetism, rotation of the earth, westward drift.

1. Introduction

Accurate determinations of the length of the day (l. o. d.) have shown that the earth's rate of rotation is not constant. A possible secular deceleration of the earth's rotation rate is ascribed in part to tidal friction effects. Annual fluctuations in the l. o. d. (Stoyko, 1936, 1937) are due to changes in atmospheric circulation. A connection between the annual variations in the l. o. d. and solar activity has been examined by Schatzman (1966) and by Afanas'yeva (1966a and 1966b). Spencer-Jones (1955, 1961) has given a concise review of the fluctuations in the earth's rate of rotation. Munk and MacDonald (1960) have given a complete geophysical discussion of all the observed variations in the l. o. d. and in the wobbles of the earth (latitude variations). The measurement of Universal Time is based upon the rotation of the earth. Ephemeris Time is used to satisfy Newton's equations of motion for celestial bodies. Therefore, fluctuations in the l. o. d. will appear as discrepancies between U. T. and E. T. The annual perturbations discussed above can be removed from the determination of U.T. After this correction has been made, rather large-scale fluctuations of a few milliseconds over periods of a few decades persist (e.g., Munk and Revelle, 1952, or Rochester, 1960). These decade variations can be observed in the longitudes of the Sun, Moon, Mercury, and Venus. Brouwer (1952a, 1952b) has shown that these decade fluctuations are consistent with a series of minute random cumulative changes (with mean value zero) of the earth's moment of inertia about the axis of rotation. Blackman and Tukey (1958) give a statistical analysis of Brouwer's data. An analysis of the data from 1956 to 1964 by Fliegel and Hawkins (1967) has shown that it is still indeterminable whether or not the angular acceleration of the earth changes at discrete intervals or changes continuously.

Recent problems and observations of the earth's rotation are discussed by Elsasser and Munk (1958), Essen et al. (1958), Smirnov (1965), Alecsescu (1966), Dicke (1966), Stoyko (1966a, 1966b), American Ephemeris and Nautical Almanac for the Year 1968 (1966). A new alternative method of accurate determination of the l.o.d. using a technique of radio interferometry has been proposed by Gold (1967). This method's importance to geophysics is discussed by MacDonald (1967).

Stoyko (1951) suggested that there might be a correlation between variations in the earth's rate of rotation and fluctuations in the geomagnetic field. In the search for a geophysical explanation of the decade fluctuations, Munk and Revelle (1952) narrowed the field of possibilities, by a process of elimination, to motions in the fluid core of the earth. A purely dynamical theory proposed by Bondi and Lyttleton (1948) is not adequate. The complete machinery of magnetohydrodynamics is essential in untangling the complex interactions between fluid motions and magnetic fields within the earth. The theory of electromagnetic core-mantle coupling is intimately connected with theories of geomagnetism and, in particular, with the causes of the observed westward drift of the non-dipole components of the geomagnetic field. Variations in this coupling will be shown to be connected with fluctuations in the earth's rate of rotation. Consequently, in this review we shall briefly discuss the dynamo theory of geomagnetism, the geomagnetic westward drift, core-mantle coupling, and the decade fluctuations in the l.o.d.

2. Dynamo Thories of Geomagnetism

Numerous physical theories have attempted to explain the origin of the geomagnetic field. Rikitake (1966) has given a brief review of these theories. The dynamo theory as proposed by Elsasser (1939, 1946a) and developed by Elsasser (1946b, 1947, 1950, 1955, 1956a, 1956b), Bullard (1948, 1949a, 1949b), Bullard and Gellman (1954), and Parker (1955) is presently considered to be the most promising explanation of the main geomagnetic field and its variations. Reviews of theories of the earth's magnetism are given by Runcorn (1954, 1955a, 1955b), Inglis (1955, 1965), Hide (1956, 1966), Hide and Roberts (1961), Jacobs (1963), Kern and Vestine (1963), Braginskiy (1964), Lucke (1965), and DeVuyst (1966).

The basic idea of the self-exciting dynamo for the earth is the regeneration of a previously existing magnetic field. This is accomplished by means of complicated induction phenomena. The energy required to maintain a steady state dynamo is derived from the circulatory motions deep in the earth's fluidal core. A homogeneous dynamo is necessary to maintain the geomagnetic field. This means that the dynamo in the core is simply-connected rather than multiply-connected, i.e., there are no brushes or coils as would be part of a disk dynamo. Whereas a disk dynamo problem can be solved by using ordinary differential equations, the answer to the homogeneous dynamo problem lies in the solution of a set of partial differential equations. Another difficulty is contained in a theorem by Cowling (1934) which states that no symmetric motion can maintain a magnetic field symmetric about some axis. Consequently, it appears that maintenance of a magnetic field by a dynamo must be a somewhat irregular process.

A radial convective motion is postulated to exist in the core of the earth. One possible source of this thermal convection is a seat of radioactive material in the inner solid body of the core. Verhoogen (1961) believes the necessary heat comes from slow cooling and crystallization of the core. By conserving angular momentum (i.e., by including effects of the Coriolis force) in considering momentum transfer between the inner and outer regions of the fluid core, we see that a differential rotation is established whereby the outer layers of the core rotate less rapidly than the inner layers. Because of the relatively high electrical conductivity in the core, the lines of force of the magnetic field will be carried about by the convective motions (e.g., see Alfvén and Fälthammar, 1963, or Cowling, 1957). The diplole (poloidal) field lines are pulled out by the differential rotation in the azimuthal direction, and a toroidal (azimuthal) field is induced which has quadrupole symmetry about the rotation axis. This azimuthal field has opposite senses in each hemisphere. Bullard found that the toroidal field should be much larger than the poloidal field by a factor of 100. The former field (~400 gauss) is large enough to prevent magnetohydrodynamic turbulent instabilities, but does not affect convection. The next step in the dynamo process is the distortion of the toroidal field by convective motions (Allan and Bullard, 1958). The resulting distortions are carried along in the longitudinal direction by the differential rotations of the core. The field, due to these distortions, then interacts with the convective fluidal motion to reinforce the original dipole field. This cyclic process has several variations in the last step. Parker (1955) proposed a simple mechanism for the interaction of the toroidal field with the convective motions. He considered in detail the thermal convection process in a convective cell. Material is moving horizontally both at the base and at the top of the cell. The effect of the Coriolis force on this horizontally moving material would be to twist the lines of force so as to produce a vortex effect. Inside a convective cell the lines of force of the toridal field would be lifted up and twisted. Parker showed that, in this manner, loops of magnetic force are produced which reinforce the original dipole field.

An "existence" proof for geomagnetic dynamos which uses a model of two eddies in the core has been given by Herzenberg (1958). An alternative to the self-exciting dynamo theory is contained in Alfvén's (1961) "Twisted-Kink Theory." Malkus (1963) has discussed the effects of precessional torques on the core and mantle which could produce a small relative rotation. More observational material is needed to confirm his theory of geomagnetism.

3. Geomagnetic Westward Drift and Core-Mantle Coupling

Apart from the well-known secular variation of the earth's magnetic field (e.g., see Vestine, 1947, 1965, Vestine et al., 1947, 1963, Nagata and Rikitake, 1961, Nagata and Syono, 1961, Cox and Doell, 1964, Nagata, 1965, Roberts and Scott, 1965, Kahle et al., 1967), a gradual westward drift of the centers of secular variation has been observed since Edmund Halley's observation (1692). Elsasser (1949) began the search for a physical explanation of the westward drift. The data obtained by Vestine et al. (1947) were used by Bullard et al. (1950) in an extensive analysis of the geomagnetic westward drift. Each non-dipole component of the earth's magnetic field drifts at a different angular velocity. For the non-dipole field in toto, an average westward drift was found by Bullard et al. to be 0.18 degree/year. A more recent analysis by Yukutake (1962) indicates a westward drift of 0.2 degree/year. A growth and decay of the non-dipole field has also been observed and was studied extensively by Nagata (1962). The lines of force of the non-dipole magnetic field will be "frozen" in the fluid material of the earth's core and will participate in the differential rotation of the core. The observed westward drift thus indicates that the earth's mantle is rotating more rapidly than the outer layers of the core. Since the outer core and the mantle do not appear to be rotating together, there appears to be no appreciable amount of mechanical coupling present. Bullard et al. (1950) showed that viscous friction at the core-mantle boundary is inadequate to account for the westward drift. They proposed an electromagnetic coupling mechanism between the core and the mantle to explain the westward drift quantitatively. Two types of toroidal fields are produced in the core and penetrate into the mantle: (1) the toroidal field induced by the dynamo mechanism, and (2) the toroidal field induced from the main dipole field by the differential rotation at the core-mantle boundary. An accelerating couple on the mantle is produced by the interaction of the dipole field with the current producing toroidal field (1). The second toroidal field interacts with the dipole field to produce a retarding couple on the mantle. Bullard et al. (1950) approximated the geomagnetic field by a dipole and disregarded the effects of the non-dipole components. Rochester (1960) included the latter components and thereby increased the electromagnetic coupling calculated by Bullard by a factor of 1.6. The theory of electromagnetic core-mantle coupling will prove to be very important in the study of the decade fluctuations in the l.o.d.

4. Decade Fluctuations in the l.o.d.

A physical explanation of Brouwer's (1952) data of the fluctuations in the l.o.d. was first attempted by Munk and Revelle (1952). A summary of their analysis can be found in an article by Revelle and Munk (1955). Processes in the atmosphere and oceans were found to be inadequate to account for all the observed decade fluctuations in the earth's rate of rotation. The authors also eliminated turbulence of continents and other crustal or mantle movements as possible causes of the fluctuations. They discovered that variations in the electromagnetic coupling of the mantle to a turbulent core could account for the observed fluctuations if a mantle conductivity of about 10^{-9} emu is adopted. They derive a relation between the fluctuations in the l.o.d. and the variations in the westward drift of the magnetic field which agrees with the data compiled by Vestine (1952, 1953) and Brouwer for the period between 1890 and 1950. A change in the l.o.d. of 1.2 milliseconds is derived from their estimates. This is to be compared with Brouwer's rms value of 1.6 milliseconds for the decade fluctuations.

In order to arrive at a physical theory which will explain the observed decade fluctuations in a quantitative manner, a detailed theory of time-dependent core-mantle coupling must be developed. Rochester (1960) has developed a complete mathematical theory of core-mantle coupling based upon the work of Bullard et al. (1950). A qualitative discussion by Vestine (1962) includes a résumé of the coupling mechanism. Takeuchi and Elsasser (1954) studied fluid motions near the core's boundary in connection with the decade fluctuations. Elsasser and Takeuchi (1955) have proposed a simple model of the core-mantle boundary which corroborates the data gathered on westward drift and the differential rotation described in the dynamo theory. The authors also show that moderate fluctuations of the toroidal field (~0.05 gauss) near the core's boundary are sufficient to account for a variation in the l.o.d. of about 1.3 milliseconds per decade.

We must also investigate the response of the mantle to the changes in the strength of the toroidal field near the boundary of the core. The time constant of the electromagnetic coupling is inversely proportional to the conductivity of the mantle. If the time constant is found to be too large, the coupling might not be strong enough to effect the observed fluctuations in the l.o.d. Bullard et al. (1950) assumed a conductivity of 10^{-10} emu and thereby derived a large time constant (weak coupling). More recent data have increased the conductivity by a factor of 10 which increases the electromagnetic coupling by the same factor. Thus, it has become possible to attribute the decade fluctuations in the l.o.d. to fluctuations in the fluidal motions of the earth's core (e.g., Vestine, 1962). Rochester (1960) derives a time constant of 25 years assuming a conductivity of 10^{-9} emu. Roden (1963) has increased the coupling by a factor of 6 over Rochester's value. He accomplishes this by analyzing the effects of various distributions of electrical conductivity in the mantle. Roden's analysis can account for an observed change in the l.o.d. of about 1.1 milliseconds over a period of 2.5 years. This is possible if the accelerating couple decreases rapidly at the beginning of the 2.5-year period and then continues to decrease at a rate of 3 1/2% per year for the rest of the period. We would expect to observe fairly significant changes in the field at the surface of the earth due to the necessary large changes in the fluidal motion in the core. However, if these changes are localized to a certain extent, only the higher harmonics of the field will be appreciably affected. Rochester (1960) has shown the importance of these harmonics in the coupling mechanism.

Recent work on the problem of geomagnetic core-mantle coupling has been done by Rochester (1962) and by Rochester and Smylie (1965).

The latter paper shows that this coupling fails by several orders of magnitude to explain the Chandler wobble (e.g., Munk and MacDonald, 1960). Van der Waerden (1959) has proposed a mechanical explanation of the irregular rotation of the earth. Brouwer (1959) explores this possibility further. He finds that the observational evidence indicates that a theory with a frictional couple and one without may both be necessary to explain the fluctuations in the l.o.d. The decade fluctuations can most reasonably be explained at the present time, in my opinion, by the fluctuating fluidal motions within the earth's core. This reviewer's impression is that more observations of the changes in the westward drift and their correlation with the decade fluctuations of the l.o.d. are needed before the theories of electromagnetic core-mantle coupling and of magnetohydrodynamic interactions inside the earth can be expanded profitably.