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Geomagnetic reversals?

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Abstract. The enigma of geomagnetic reversals and their apparent link with other phenomena, such as faunal extinctions, is shown to be explicable by treating these reversals as a relative rather than an absolute effect.

Instead of reversing the magnetic field, it is suggested that a reversal of the Earth itself in a particular manner is sufficient to account for the behaviour of the field in detail during a reversal, and for explaining the links with the various other phenomena. It is shown that a wide variety of data is compatible with this hypothesis, not only from modern geological and related investigations, but also from astronomy and from ancient sources.

1. Introduction

The origin of the Earth's magnetic field is problematical. Currently it is supposed that the rotating metallic core acts as a dynamo (Bullard 1972). This is not the only possibility. It has also been suggested that the Earth is charged, and a rotating charged body generates a magnetic field (Juergens 1977), but neither of these suggestions immediately accommodates the phenomenon of geomagnetic reversals. The dynamo theory has to be extended and complicated by proposing that the core acts as a double cross-linked dynamo, or, as Verosub (1975) has alternatively suggested, that there are two distinct sources, perhaps the inner and outer cores, that generate opposing fields, both of which may vary slightly to allow one or the other to dominate alternately. For the charged Earth theory it is suggested that the charge changes from negative to positive—a seemingly inplausible event at first sight, though possible in the appropriate context. None of these extensions of the theories are satisfactory, for they are *ad hoc* extensions which do not explain the more subtle behaviour of reversals, nor do they provide any additional enlightenment or understanding. And, with the exception of the charge reversal concept, they do not provide any direct explanation of the seemingly baffling coincidence of other phenomena.

Massive faunal extinctions have been strongly linked with magnetic reversals (Black 1972, Reid *et al* 1976). So too have climatic changes (Tarling 1975) and periods of extensive volcanic activity. None of the attempts to relate these phenomena are very convincing. For example, Reid *et al* invoke solar outbursts as a source of damaging radiation that could penetrate to the Earth's surface provided the magnetic field drops to zero strength. This requires the coincidence of two separate events on a number of occasions, and conflicts with the evidence that the field does not totally disappear during a reversal.

The non-zero transient state of the field is itself a problem for the current theories since, in their direct form, they all yield a zero field at some moment during the transition. The idea has been put forward that the field flips, or topples, rather than simply decaying and then recovering in the reversed sense. This idea is also proposed to account for the apparent wandering of the magnetic poles that has been found to occur, though no-one has explained how it might topple. There are suggestions from the data that the polar wander occurs along a preferred path, though this path is not necessarily constant through the various epochs.

Added to all this, there are some interesting phenomena which have not previously been linked with magnetic reversals, but which are, I believe, highly relevant. Degens and Stoffers (1976) have reported evidence of rapid changes in the stratification of lake waters in Africa which they describe as 'catastrophic overturns'. They comment on related faunal extinctions and point out that the Black Sea has suffered similar changes on the same time scale. Cifelli (1976) has reported variations of ocean climate around the North Atlantic, with apparent alternating expansions and contractions of warm surface water. He notes a 'remarkable' coincidence with a salinity crisis in the Mediterranean. Norman and Chukwu-Ike (1977) have reported large-scale crustal fractures which they tentatively suggest may be due to a change of the Earth's speed of rotation resulting from a near miss or collision with another large cosmic body. Various hypotheses have been put forward to explain ice ages, such as the Milankovitch model of cyclic precessions and changes of eccentricity of the Earth's orbit (Calder 1976) or McCrea's (1975) model of more random encounters of the Solar System with interstellar dust clouds. However, Bray (1976) points out that there is a seeming coincidence of glacial periods and extensive volcanism, and suggests that the change of stratospheric dust ensuing from the volcanism is a likely cause. Bray does not mention magnetic reversals but McElhinny *et al* (1974) have related Precambrian glaciations and magnetic polar wander to plate tectonic movements, though they note that the poles migrated quite rapidly over various parts of the globe. Fairbridge (1977) notes a more striking correlation of very rapid ice-cover advance in recent times with the Gothenburg magnetic event.

A feature of many of these recent investigations is the rapidity of change. Many workers are forced to conclude that sedimentation, glaciation, climate, water temperature, polar wander, and outbursts of volcanism occurred or changed suddenly, and often such events occurred on a worldwide scale.

The theory proposed here could account for all of the above data and observations. Ironically, perhaps, and seemingly contradictory, one of its essential features is *not* to have a magnetic reversal at all. Instead I propose a *geographic reversal.* Not only can this explain the above data but it also brings into perspective many otherwise enigmatic archaeological, astronomical, historical and other data.

2. Geographic reversals

In figure 1 is shown a top, known as a 'magic top' or 'tippe top', commonly available in toy and novelty shops and Christmas crackers. Its behaviour when spun is quite intriguing. Figure 1(*a*) shows its initial state when spun, with the handle uppermost. When released it rapidly inverts itself, as shown in figures 1(*b*) to 1(*d*). The motion is classed as a fast precession, or nutation. The inversion occurs as the result of friction between the top and the supporting surface, giving rise to a torque which causes the centre of mass to rise (Braams 1952, Hugenholz 1952). The tippe top is not unique in this behaviour. A slightly asymmetric ball will execute a similar motion, and any

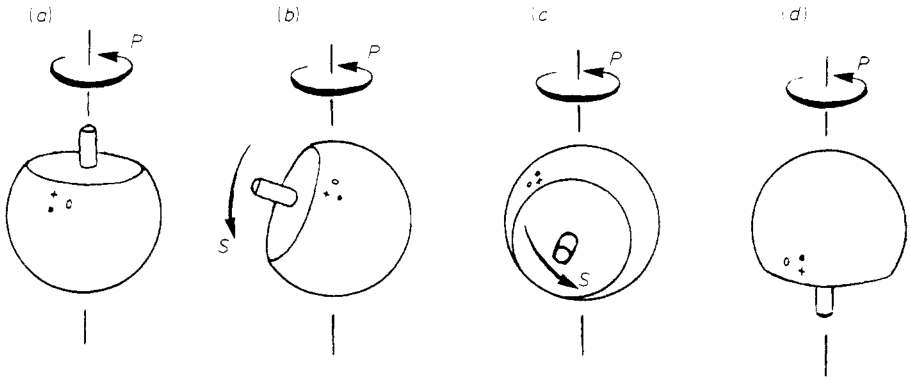

Figure 1. (*a*) Initial spin state, with rotation *P* about the vertical axis. (*b*) and (*c*) Transition states during inversion, with primary spin *P* continuing and with secondary rotation *S* about a horizontal axis fixed in the top. (*d*) Final spin state, with the top fully inverted. The direction of the *P* rotation vector remains essentially unchanged through the sequence with respect to an external observer.

spinning body may to some degree, though usually in the lesser form termed nutation. A wheel-on-axle type of top will normally execute a slow, or normal, precession where the body of the top and the spin axis drift integrally, but on slowing down, the dominant motion changes to a fast precession, or wobble.

The analysis of the motion of a tippe top is not particularly straightforward (Cohen 1977) but simple observation provides some indications of the relevant properties. The motion may be sub-divided into two components: there is a primary spin which is more or less *fixed in space*, and this is combined with a transient secondary rotation which appears to be about an equatorial axis *fixed in the body*. It is this secondary rotation which leads to the inversion. The interesting features to note are that the angular momentum vector for the primary rotation remains of constant sense throughout the inversion with respect to an external frame, but the secondary rotation yields an effective reversal of the spin with respect to a frame fixed in the body of the top. This may be seen in figure 1 and in figure 2 which illustrates the resulting behaviour of features on the surface of the top.

Observation indicates that the energy requirement for inversion is small relative to the primary spin energy. The initial provision of energy is in the form of primary spin and only a fraction of this is diverted to the secondary rotation since the body

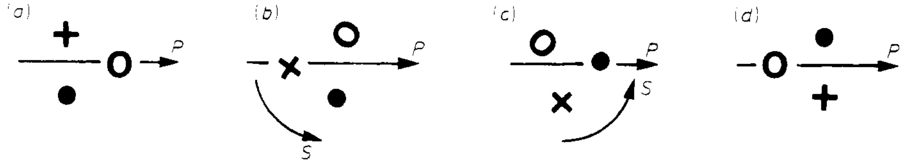

Figure 2. Equivalent components of motion of 'landmarks' on the surface of the top through a sequence of states corresponding to those of figure 1. For the Earth, these might be thought of as, say, Japan (+), Australia (●), and Central America (○), as viewed by an observer in 'geostationary' orbit over Christmas Island in the Pacific. Note that, although the *P* spin component does not change its sense with respect to the external observer, it appears as a reversed rotation with respect to the landmarks or a surface observer in passing from state (*a*) to state (*d*).

maintains primary spin throughout. For a top restrained in a gravitational field, this diverted energy is retained, in part at least, in the form of potential energy to maintain the centre of mass in its raised position, and consequently the top spins more slowly in its inverted state. For a top in free fall the energy requirement would only be transient and for a complete inversion the initial and final spin rates would be equal in a conserved system.

A patterned beach ball, with a small asymmetry produced by the inflation valve, when spun on a calm water surface, also executes fast-precessional motion and the secondary rotation or oscillation can be observed superimposed on the primary spin. In this case the diminution of primary spin rate is virtually undetectable by visual observation. Tippe-top action can be elicited from solid, rounded pebbles. A roughly oblate-spheroidal pebble can rise towards its 'equator' when spun from either 'side'. In one case full inversion was achievable when spun from both sides, though generally, as would be expected, inversion occurs from one side only. In the case of one tippe top to hand, the spherical surface has become slightly flattened above the 'equator' as the result of a defect in the moulding process. This top, when spun vigorously, often rises to that level, falls back toward the upright state, then rises again and succeeds in completing its inversion. In general these tops take longer to invert when spun vigorously than when spun gently.

It may be concluded that the susceptibility of a rotating body to fast precession—its inherent stability, or rigidity—is a function of its natural frequency, given by the expression $\omega I_1/(I_2 I_3)^{1/2}$ where I_1, I_2, I_3 are the principal moments of inertia, with $I_1 \geqslant I_2 \geqslant I_3$. For a uniform sphere $I_1 = I_2 = I_3$; for a thin disc $I_1 = 2I_2 = 2I_3$. Thus a disc is only twice as stable as a sphere for a given rotation rate ω, and the rate of rotation is the dominant factor since it can vary over a wide range. It may be noted that this inherent stability is independent of the absolute size of the body.

It has been argued that the equatorial bulge of the Earth renders it stable, but I_1 exceeds I_2, or I_3, by only about one part in three-hundred, so the increase in stability over that of a perfect sphere is trivial. A gyroscope rotates at tens to hundreds of revolutions per second; the tippe top is in the one to ten revolutions per second range, and the Earth rotates at about 0·00001 revolutions per second. The gyroscope, or wheel-on-axle top, is quite resistant to fast-precessional motion. The tippe top inverts very easily, yet it is still tens of thousands of times more inherently stable than the Earth. This rather startling fact must, of course, be offset by the fact that the magnitude of the required torque will be many orders of magnitude greater for the Earth than for the tippe top.

Gold (1955) has stated that, if the Earth were a perfect sphere, it 'would possess no stability of its axis of rotation at all; the smallest beetle walking over it would be able to change the axis of rotation relative to markings on the surface by an arbitrarily large angle'. He adds that, for the actual Earth, 'it is spinning around the principal axis of inertia of greatest moment and hence (possesses) less kinetic energy than if it spun with the same angular momentum about any other axis'. The most extreme cases are for spin about the polar axis and about an equatorial axis, with a progressive change between the two, and it is reasonable to conclude that the required energy to produce an inversion is a function of the difference in the principal moments of inertia.

The Earth, then, is potentially an excellent candidate for fast-precessional motion, but first it is necessary to be able to apply a torque and secondly a source is needed to provide the torque, which must increase and decay rapidly to achieve the fast form of precession. The equatorial bulge provides the means. This small asymmetry is sufficient to permit the application of torque, as is shown by the precession of the equinoxes—a slow precession caused by the slowly changing torques exerted by the Moon and the Sun. To produce the torque required for fast precession we would need a large cosmic body on a near-miss course. The torque, to a first approximation, obeys an inverse cube law of distance, so there would be a rapid rise and fall as the body passed by, as required. Norman and Chukwu-Ike have suggested just such a near miss to account for the stress lines in the Earth's crust, though they relate this to a change in the speed of primary rotation. Fast-precessional behaviour is the more likely outcome. They do, however, plead for their readers to offer a practical alternative to their cosmic body. In the present theory one can sympathise with their problem for we must account for many 'geomagnetic reversals'. Nevertheless such bodies are an appropriate source, and there is ample evidence for such near misses in the recent past.

It must be noted that gravitational forces need not be the only, nor even the main, source of torque. Walker and Walker (1977) have found that a disc of high dielectric constant, suspended in an intense magnetic field and subjected to a radial electric field in time quadrature with the magnetic field, experienced an unusual and substantial torque. This may be of relevance to both the charged Earth theory and to the dynamo theory since Djurić (1976) has pointed out that there must be an electric field in the stationary system surrounding a rotating axisymmetric permanent magnet made of electrically conducting material.

The rotational kinetic energy of the Earth is about $2{\cdot}1 \times 10^{29}$ joules. The principal moments of inertia differ by 1 part in 300, so it would seem that an energy pulse of about 7×10^{26} joules would be needed to turn the Earth over. In conventional ice-age theories it is supposed that ice is added in large quantities to the polar caps. The associated sea-level changes are variously estimated to be in the region of 70 to 200 metres. Simply to evaporate a depth of, say, 100 metres of sea throughout the world would require about 8×10^{25} joules. Some of the evaporation energy would be released as the moisture turned to snow, allowing the possibility of recycling some of the energy, but even if that recycling process were as much as 90% efficient it would still leave about 8×10^{24} joules effectively locked up in the ice. To transport the moisture on average an eighth of the way round the globe would also require energy in the order of 10^{24} joules. Doake (1977) has calculated that a 100 metre depth of sea transported to the poles as ice would, for a constant angular momentum, change the Earth's rotational energy by $1{\cdot}9 \times 10^{24}$ joules—a value, as might be expected, comparable with the transport requirement by itself.

Global events such as ice ages, however they occur, require high energy levels, and these levels are not grossly dissimilar from that required to turn the Earth over. Furthermore, the conventional Ice Age would lock up the energy for some time, whereas to turn the Earth over requires only a transient input. I propose, then, that such events are plausible, and in the remainder of this paper attempt to demonstrate that events of this form can account for geomagnetic reversal phenomena and many other phenomena and observations, including ice ages. The likely sources of these events will also be discussed.

3. Geomagnetic reversal phenomena

Whatever the mechanism of field generation, whether it be by some dynamo action or by virtue of a rotating charged body, an essential feature is that the Earth is rotating. Although the direction of the magnetic moment is not necessarily defined by the angular momentum vector it is certainly controlled by, and aligned with it. For a simple dynamo, once the direction of the field has been established, it remains in a fixed relationship with the rotation vector. Whilst there might be some special circumstance for which this does not hold, generally the realisation of this fact led, with the advent of the discovery of geomagnetic reversals, to various attempts to modify the simple dynamo model to one for which the magnetic moment could be reversed without reversing the direction of rotation. All current conventional models seek a method of reversing the field, such as with the aid of a double cross-linked form of dynamo. The thought of stopping the Earth and restarting it in the reversed sense on thousands of occasions during its lifetime was generally considered totally inplausible, although there are less-conventional theories for which this is postulated.

For a perfect sphere, rotating and producing a magnetic field, it does not matter whether the sphere is 'right-way-up' or 'upside-down' since, for a homogeneous sphere, these two states are indistinguishable. However, if, from a given position, we roll the sphere by fast precession to an inverse position it is likely that the motion will give rise to, say, eddy currents which would disturb the field arising from the primary spin. But this disturbance is unlikely to be large enough to invert the primary field, since it will probably be in proportion to the energy involved in the secondary rotation relative to that involved in the primary rotation.

Thus we have a means of effectively reversing the field, not by a direct action on the field itself, but indirectly through a geographic reversal. For such a reversal the primary spin continues with little disturbance and the magnetic field therefore remains more or less fixed with respect to space whilst the Earth is turned upside-down so that, for an observer on the surface, there is an effective reversal of the magnetic field with respect to his frame of reference.

During the period of secondary rotation, as the Earth is a viscous body, the motions within the core and other layers may not all follow the general inversion at the same rate. The field will almost certainly diminish in strength but it is very unlikely to reach a zero value. We have, in fact, the exact conditions to cause the field to topple as a number of investigators have suggested, although it is actually the Earth rather than the field that moves. Following the event itself there will be a period when the various layers within the Earth are resettling to their effectively reversed rotation and this is likely to be long compared with the time for the inversion.

The problem of preferred polar wander paths can be accounted for in this tippe-top action. As already mentioned, the secondary rotation appears to occur with respect to an axis fixed in the body. It may, in fact, occur in such a manner that any given point on the surface would follow a specific path during the inversion. This can be demonstrated with a tippe-top by marking a point which lies on its 'primary equator' and also on its 'secondary equator'. If the top be spun, then caught and held at the half-way stage of its inversion, this mark will appear uppermost. Whilst not perfectly consistent, probably due to slight irregularities in the two surfaces in contact and also to the difficulty of catching the top at the exact half-way stage, this behaviour is highly repeatable.

Due to vagaries in manufacture, these tops are not quite perfectly symmetric in an equatorial sense (they are normally made in two halves—top and bottom—which do not always join neatly, and it is necessary to smooth this joint to prevent extraneous influences on the motion). The Earth is also not quite perfectly symmetric equatorially. The polar and equatorial radii differ by about 21 000 metres. From geodetic data Uotila (1963) computed that the equatorial radius pair differ by 79 metres. More recent satellite data indicate a similar value. This may seem insignificant but it is based on a whole-Earth calculation, with the oceans included. During a rapid inversion event the effective asymmetry will be for the solid and viscous components, and the free liquid of the oceans must be partly discounted.

Uotila's calculations define axes through longitudes 18°W and 72°E, but bearing in mind the effect of discounting the oceans there is a more obvious geographic asymmetry, with the Pacific occupying one hemisphere and the land masses the other. The axis defined by this asymmetry is through longitude 30°E and the effective 'secondary equator' lies on longitudes 60°W, 120°E. These are precisely the longitudes quoted by Steinhauser and Vincenz for one of their two preferred polar wander paths (Nöel and Tarling 1975).

The existence of any preferred wander path may be disputed but other features will be related to this particular path. For now, it may be noted that the polar wander path is not necessarily constant through time. Clearly the Earth is not a rigid body and plate tectonic motions could easily alter the delicate equatorial balance. What one can expect is that in a given epoch there will be a trend along a particular great circle path, which does not necessarily include the present poles. It is noted further that there is no suggestion that a record is left of the polar wander during a single event. A reversal is far too rapid for that to be likely. What is likely is that a series of events occur, each varying in the degree of completeness of the reversal, and including minor tilts, so that the Earth is left rotating about different poles between the events. These intermediate poles would then be recorded in the rock magnetism and they would show an alignment about a particular secondary axis during a limited geological period.

4. Time scale

The magnetic field, or the Earth, has reversed on numerous occasions in the past at random intervals, on average about 10^5 to 10^6 years apart. Periods of predominantly 'normal' and of 'reversed' polarity have been delineated, although it is possible that these are merely artefacts of the randomness. Some investigators have suggested that reversed periods predominate but any such dominance is marginal. The reversal events themselves are acknowledged to occur in a surprisingly short interval by geological standards. Estimates vary from about 10^3 to 10^5 years. A typical time scale of, say, 10^4 years is considered to contain a precursor period of about 2–3000 years when the field decays; the reversal itself, occupying 1–3000 years, and a resettling period of 2–3000 years during which the field recovers. These figures are based largely on data from rock magnetism over the last four or five million years. Evidence of very recent reversals from various investigations indicates that even this time scale needs to be reduced considerably.

The most recent event from the rock data is usually quoted to be at about 700 000 BP, but a number of more recent events have been claimed. A brief reversal, lasting perhaps no more than 2000 years, the Mungo event, is generally recognised to have occurred at about 30 000 or 40 000 BP. Fairbridge has provided evidence for the Gothenburg event dated to about 13 500 BP; Nöel and Tarling have discussed the evidence for the Laschamp event, dating it to about 10 000 BP, and mentioning evidence covering a wide range of dates from around 7000 BP to 17 000 BP from a variety of sources as candidate data for that event. It is possible that the Gothenburg event and the Laschamp event are one and the same, and Thompson and Berglund (1976) have even suggested that the evidence for any event in this period is largely spurious. The weight of evidence suggests otherwise, however, and other data will be quoted to support this view. Nöel and Tarling also mention an anomaly dated to 860 BC. This remarkably recent date coincides with data presented by Folgheraiter on measurements of Greek and Etruscan vases which indicate an event in the 8th century BC. Mercanton, in similar tests, found a normal polarity in the 10th century BC and confirmed Folgheraiter's results and method (Ransom 1973).

These all suggest a time scale much shorter than 10^4 years, and Mercanton's results in particular indicate that we must reduce the period to 10^2 years or less. I suggest that the actual reversal takes place in a matter of days—even as little as one day.

By the nature of this present theory we would expect such a short period since fast-precessional motion is necessarily a rapidly-occurring phenomenon. The postulated cause—a large cosmic body—is likely to pass in a single transit rather than to orbit for any extended period. A period in orbit would not be impossible, but it implies a slow approach followed later by a slow recession. This would produce a significant disturbance but it is unlikely to yield a marked degree of fast precession. This startlingly short period also provides the link we seek with the various other phenomena.

Suppose that a reversal does take place in one day. One's first reaction is that nothing could survive such an event, perhaps not even the Earth itself. However, if, for simplicity, we assume that the first half of the rotation occurs with uniform acceleration and the second half with a corresponding deceleration, then a simple calculation shows that the maximum acceleration at the Earth's surface is only about 1 cm s^{-2}, i.e. 1/1000 of 'g'. This is hardly sufficient to spill one drop from a brim-full glass of water, but of course the effects on oceans and other large bodies of water, and on the air masses would be considerable. The land masses too, resting on their viscous support, would show marked stress, but the total effect need not be as devastating as one might first imagine. Indeed, a minor tilt of, say, 10–20° would have surprisingly limited immediate effects.

5. The link with other phenomena

'Sotuknang commanded the twins . . . to leave their posts at the north and south ends of the world's axis, where they were stationed to keep the Earth properly rotating. . . . the world, with no-one to control it, teetered off balance, spun round crazily, then rolled over twice. Mountains plunged into seas with a great splash, seas and lakes sloshed over the land, and as the world spun through cold and lifeless space it froze into solid ice.'

That is an oral legend of the Hopi Amer-Indians (Waters 1969). To this description we may add some detail from Plato (Jowett 1937):

'God himself guides and helps to roll the world . . . and there is a time . . . when he lets go, and the world . . . turns about and by an inherent necessity revolves in the opposite direction. . . . Hence there occurs a great destruction of animals which extends also to the life of man.'

The descriptions of the motion of the Earth given by these two quotations are quite remarkably precise and concise descriptions of the motion of a tippe top. Such a motion provides a cause of so-called geomagnetic reversals, and provides an explanation that accounts for the detailed behaviour of the field during a reversal. Such a motion produces massive tidal waves, carrying vast quantities of debris and sediment from the ocean floors and depositing them over the land. The inevitable severe storms as the atmosphere tries to adjust to the new positioning of surface features will be augmented by ash and gas ejected by the equally inevitable volcanic activity. The continental plates themselves would be set in motion, thus giving rise to the volcanism at their boundaries, and with enough impetus to collide eventually and form mountain chains. Some fauna, large or small, could be rendered extinct, others could survive; flora might have a somewhat better chance of survival. Indeed, of all the events that take place on such an occasion, the reversal of the magnetic field is probably the least significant. Only long after the event does it become important in that it has acted as a recorder of history.

It is not, as Reid *et al*, Black and others have suggested, that faunal extinctions, and even climatic changes and volcanic maxima, are the result of magnetic reversals. All of these phenomena, including the magnetic reversal itself, are caused by the inversion of the Earth. There is no need to invoke another coincidental phenomenon, such as a solar outburst or a nearby supernova discharging excessive radiation, nor do we need to envisage some obscure means by which a magnetic polarity reversal could influence the climate, or vice versa. The link between these phenomena is self-evident, as is the link with crustal fractures and catastrophic overturns of lake waters.

Norman and Chukwu-Ike do not provide sufficiently recent or precise dates for the crustal fractures to be able to link these to any particular reversal, but the data given by Degens and Stoffers for the overturning of African lake waters is quite interesting. In the period from 13 500 to 12 500 BP manganese deposits indicate a rapid series of oscillations. Their dating of the period from about 11 000 BP to the present is not precisely delineated, but for carbonate and organic carbon records they show marked fluctuations at about 2000 BC and at about 1000 BC. There is a clear correlation with the Gothenburg event at 13 500 BP and the Folgheraiter event of the 8th century BC. The change around 2000 BC does not correlate with any reported magnetic reversal, but it is interesting to note that Santorini erupted violently in the 15th century BC and Bond (1976) has pointed out that there is in fact a multiplicity of sources of the volcanic deposits in the Aegean area. Magaritz and Kaufman (1973), in a study of fossil shells in the Eastern Mediterranean, also note an abrupt change in composition at about 3000 BC.

The polar wander path, in the present model, is applicable to both the magnetic and geographic poles, since it is the Earth that moves relative to the rotation axis. Evidence of glaciation at the current equator and of fossil coral at the poles has been taken as evidence that plate tectonic motions have carried the various parts of the crust through appropriately large excursions. Studies of polar wander have associated magnetic polar wander with wander of glaciated regions, but these have been rapid movements on a geological time scale. Moving the whole Earth provides a better fit with the data than does the concept of plate drift alone, as Gold (1955), Wegener, Hapgood and others have pointed out (Sullivan 1977). Furthermore, the extent of glaciation in the recent ice ages was not uniformly increased about the pole but is best described as a displacement of the polar cap. The boundary is roughly delimited by the East Siberian and Laptev Seas at 70°N, Great Britain at 55°N and the Great Lakes of North America at 40°N. The limit is an approximate circle through these points and centred on Baffin Bay at about 75°N, 60°W. It is seemingly not a coincidence that the longitude of this centre is the same as that for the Steinhauser and Vincenz preferred wander path of the magnetic pole.

Treating ice ages as a simple displacement of the pole resolves a vexed question. On conventional theories it is generally assumed that ice is added in large quantities to the polar cap, but to do that it is necessary to transport water from temperate and equatorial regions. This requires energy, and energy almost invariably ends up in the form of heat. That heat would then prevent the necessary cooling to form the additional ice. If it be argued that the Earth for some reason enters a simple cooling phase, then water will freeze *in situ*. The polar caps will be extended but only by a thinly-layered permafrost zone which would not yield massive glaciers. Displacement of the polar cap requires neither heating nor cooling, and this is in keeping with the general evidence that the Earth was not cooled overall during ice ages. Parkin (1976), for example, notes that the Sahara remained arid during the last ice age. The Sahara lies close to the secondary axis of rotation and would therefore remain close to the primary equator. Fairbridge (1977), commenting on the Gothenburg event, mentions a sudden re-advance of the glaciers over North America. He calculates that within less than a thousand years a volume of ice was newly formed equivalent to twenty times all the world's present mountain glacier ice, or a third more than all the ice in Greenland. On the other side of the pole, in Siberia, a number of mammoths have been found, some with undigested food in their stomachs, some even with grass still in their mouths, and some still standing (Cardona 1976a). The state of preservation of the flesh indicates that they were frozen very rapidly indeed, yet their diet is that of a temperate zone. The recently discovered baby mammoth, radiocarbon dated to 44 000 BP, was found near the Kolyma river in the Yakutsk region of Russia. Both the mammoth discoveries and the re-advance of the North American ice sheet are compatible with the concept of rapid shifts of the geographic pole and polar ice cap along the 60°W, 120°E preferred magnetic polar wander path.

Cifelli's observations on the variation of ocean climate around the North Atlantic introduce a more subtle effect of geographic reversals. Figure 3 shows the world in its present state and in the orientation following a complete inversion. The primary spin remains the same with respect to space and the Coriolis forces acting on the surface also remain in the same sense, but the Earth has been turned upside down. The net effect, as shown in the figure, is to reverse the flow of ocean currents. Cifelli's data fit a pattern that shows a strong clockwise northward displacement on the western side of the (North Atlantic) ocean'. On the eastern side he seeks a retraction of tropical waters southward, but without there being a general cold wave. The reversal of the ocean currents provides precisely that. He notes that 'there have been long term cycles in the development of ocean climate and circulation, with alternating expansions and contractions of warm surface water'. He mentions 'expansions' in the late Cretaceous, the Palaeogene and Miocene, and 'contractions' in the early and middle Cainozoic and probably in the Pliocene. Numerous magnetic reversals are recorded for these epochs (Vine 1972).

Not only will ocean currents be reversed, so too will be atmospheric flows. Dury (1963), describing climatic changes in the British Isles, states that 'The birch spread far and wide as temperatures rose and the glaciers melted back, but its dominance did not last. Some 9000 years ago there was a rather sudden change in climate. The British area came under continental influences (the Boreal phase) ... The next climactic development produced the Atlantic phase which lasted from about 5500 to 2000 BC and was marked by the powerful streaming of oceanic westerly air ... the

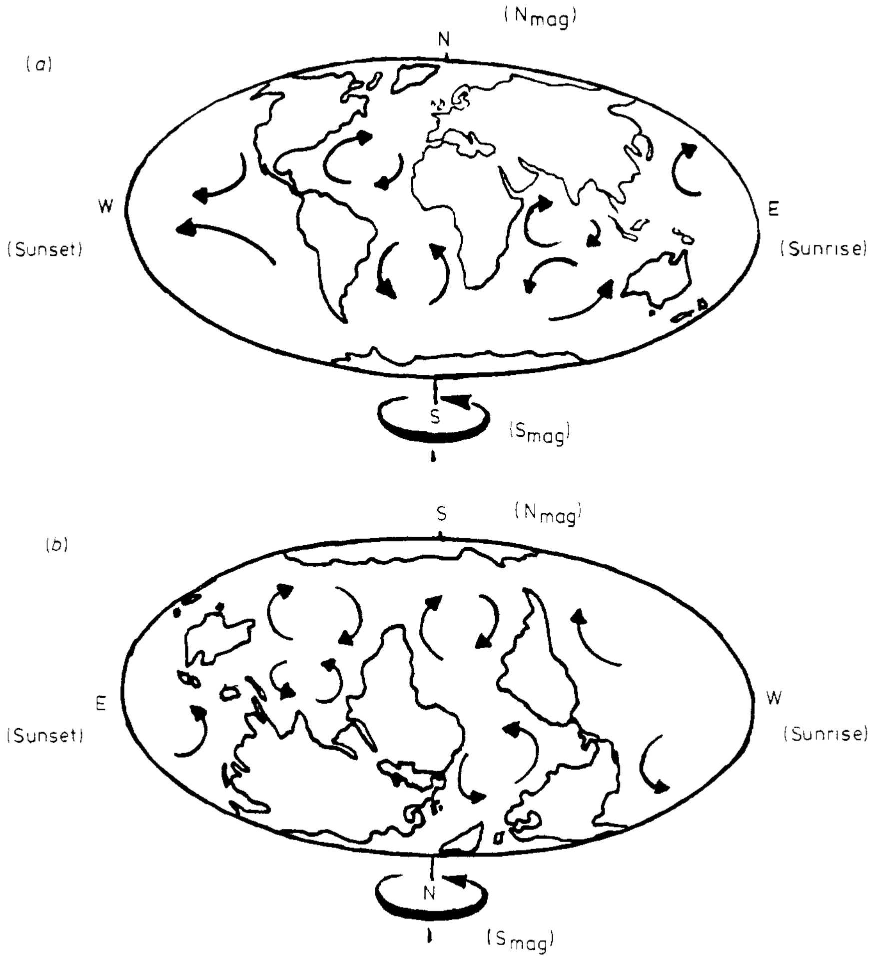

Figure 3. (*a*) The Earth as it is today; rotating anticlockwise as seen from 'above' (north magnetic), and showing the circulation of ocean currents. (*b*) The Earth following an inversion: still rotating anticlockwise as seen from 'above', so that the ocean currents also still show the same sense in their circulation—but the rotation appears to be reversed with respect to geographic north, and the ocean currents are reversed with respect to the surface features.

damp-loving alder suddenly increased in importance ... These highly oceanic conditions were modified in the sub-Boreal phase, which lasted from about 2000 to 750 BC (but) the regrowth of the northern forests was halted by a return to oceanic conditions in the sub-Atlantic phase, which set in about 750 BC.'

Lamb (1974, also published in Hodson 1974) in a review of ancient climates, considers 'the sites of the early centres of civilisation, particularly those that flourished between about 3000 and 1000 BC, and routes of travel by land and sea, some of which stand in a surprising relationship to the natural environment as it exists today.' He argues that around 2000 BC there was a dominant anticyclonic influence with a 'blocked meridional and rather stagnant circulation pattern', but around 500 BC there was a 'withdrawal southward of the anticyclonic influence ... with the belt of cyclonic activity surrounding the polar cap having spread to rather lower latitudes than before.' He adds that 'the features of this deterioration, i.e. lower temperatures and increased windiness, which was taken as defining the onset of the so-called 'Sub-Atlantic' climatic period in the older European literature, have continued more or less to the present time, though with century to century variations.' As with Cifelli's ocean current data, Dury and Lamb seek, in effect, reversals of the air flow patterns.

Dury notes that the cultural changes from Old to Middle Stone Ages 'correspond quite closely to a drastic change in the natural environment (around 9000 years ago)', and that the New Stone Age 'was brought to an end by a new series of immigrations, which happened to coincide roughly with a further change in climate (about 2000 BC)', and yet again that 'At about the time that the iron users invaded the British Isles there was a change towards more maritime conditions of climate—the change from the sub-Boreal to the sub-Atlantic' about 750 BC. Fairbridge also notes a 'curious coincidence (which) seems to match the timing of the Gothenburg Excursion. Kopper has demonstrated that in the evolution of man, each of the key subspecies introductions or cultural boundary horizons seems to correspond with an important magnetic reversal or excursion. The Gothenburg event appears to mark the end of the Neanderthals.'

Data on the alignments and astronomical significance of stone circles is rather sparse and still somewhat controversial, but Burl (1976) describing Stonehenge, notes a slight change of axis at one point 'perhaps because the midsummer rising of the Sun had changed a little over the centuries. More important, as in some other later stone circles, there seems to be a greater interest in the midwinter sunset.' This reversal in direction of interest from the sunrise to the 'sunset' appears to be linked with the other changes from Neolithic to Bronze Ages, i.e. about the time of the 2000 BC climatic change described by Dury.

Ice ages are normally assumed to involve additions of ice to the polar caps and this leads to complementary changes in sea level. For the present theory the ice age is attributable to a shifting of the poles with no significant change in the quantity of ice being necessary. However, this does not mean that there will be no related change in sea level. The sea, being liquid, can very rapidly adjust to a change in the positioning of the pole, but the land and its support, being solid or viscous, will take time to adjust. Thus for a minor or incomplete tilt of the Earth the equatorial bulge will be misaligned with the spin axis for the solid parts of the Earth, but not for the sea. This discrepancy in the rate of adjustment to the dynamic shape results in changes of sea level, both up and down, depending upon the particular situation with respect to the rotation axes. In theory the changes could be as great as the difference in the present polar and equatorial radii—21 500 metres—but in practice there is simply not enough sea to reach that extreme. Guyots occur with their flat tops as much as 1 or 2 kilometres below the present sea level (Harris 1972). John (1977) mentions a raised beach in the South Shetland Islands at 274 metres above sea level, and comments that this is 'too high for comfort and creating a host of difficulties of interpretation.' Equally difficult of interpretation by conventional means are the many ancient legends of massive floods which submerged islands and mountains completely. A South American legend claims that the flood was a result of earthquakes and volcanic eruptions. In Africa, in the Lower Congo, the flood is stated to be the result of the sun meeting the Moon and throwing mud at it. Pacific Island myths claim that the islands were fished up out of the sea for the benefit of the survivors of the flood.

Gold has indicated that the plasticity of the Earth can be assessed from the damping of the free nutation occurring at present. He estimates that the rate of movement of the axis of figure would be at least one tenth of the angular displacement from the spin axis per annum. At that rate, if the Earth were left tilted about 5° off-axis it would take only 100 years to adjust to within $\frac{1}{4}''$—the present limit, approximately. For a tilt about 45° off-axis the same rate of movement of the axis would permit recovery of the equilibrium state within 130 years. These modern calculations indicate that mountain tops would re-appear in quite a short time, just as the ancient legends claim.

This might be thought to imply also that 'ice ages' would be of equally short duration. However, that would only be true if the return to dynamic balance were by a rigid, whole-body tilting. It is possible that such whole-body tilting plays only a minor part in the recovery and that the major effect is achieved by plastic distortion of the Earth. In that case the oceans would return toward their original level at all points on the globe but the ice caps would remain in the displaced position. Such plastic deformation would completely obliterate Uotila's 79 metre equatorial asymmetry but, as the dynamic balance is for the combined masses of land and sea, the geographic asymmetry would remain as a function of the ocean basins.

Mörner (1978) notes that 'Drastic environmental changes and mammalian extinctions have been reported to coincide with low ocean levels.' In an attempt to explain this association he invokes the concept of geoidal eustasy—gravitational and rotational changes controlling the geoid configuration—and suggests that such changes would lead to eustatic regression of the water table, thereby affecting the local environment and fauna. He mentions several of these drastic changes, 'one of the best examples of (these) being the 10 000 BP change in global climate . . . now also shown to correspond to a faunal change and a sudden appearance of a microlithic culture in East Africa.' Devoy (1977) has studied marine transgressions in the Thames estuary since about 8500 BP. He charts four distinct transgressions in close temporal agreement with Dury's climatic changes, and for the first three of these he shows subsequent lesser regressions.

The African legend of the flood mentions associated astronomical events. (In passing, I note that the use of the lower case form of the word 'sun' was deliberate. It is not certain to which sun they allude since in some ancient literature and records Saturn is referred to as 'The Sun of Night'.) Another astronomical phenomenon that has been associated with magnetic reversals is that of tektites (Gaskell 1970, Black 1972). Bailey (1960), Bruce (1973) and Crew (1974) have pointed out that numerous stellar phenomena can be satisfactorily explained by treating them as electrical effects, and Bailey states that 'It has been found possible to account for the known order of magnitudes of five different astronomical phenomena and the directions relating to three of them by means of the single hypothesis that a star like the Sun . . . carries a net negative charge (of $-1{\cdot}5 \times 10^{28}$ esu).' Michelson (1974) notes that Bailey's value is of the right order to account for the anomalous perihelion drift of Mercury. Non-gravitational effects are apparent in the majority of comet orbits, some comets showing secular accelerations and others showing decelerations. Djurić has pointed out that a magnetic Earth must have an electric field associated with it, and Juergens begins with a charged Earth in order to explain the magnetic field. Juergens (1976) has also reported that artificial button-like tektites have been produced by immersing cold glass spheres in the plasma jet from an electric arc, and also that 'tektites' have been obtained by subjecting Earth materials to a beam of electrons.

It seems that electrical effects have a greater contribution than is normally recognised and in particular with respect to the present context if cosmic bodies carry charges then, in a near-miss encounter between two bodies of differing net charge, some discharge between them is to be expected. A discharge concentrated at a point on the surface would leave a crater with the debris scattered radially, and perhaps in the form of tektites. Tektite-like objects have been found on the Moon and the ray patterns from various craters behave remarkably like glass-beaded projection screens. Durrani (1969) and others have dated the Australasian tektite field to about 700 000 BP but note that a date of no more than 10 000 BP has been claimed on stratigraphic evidence. Taylor and Solomon (1962), discussing Darwin Glass, note that 'The shallow depth of occurrence and the lack of abrasion indicate that the glass is no more than a few thousand years old', though they too found greater ages by rubidium–strontium dating of 450×10^6 years 'the significance of (which) is obscure'. Cardona (1976b) mentions a claimed age for tektites of no more than 5000 BP and notes that tektites are also known as 'fire-pearls' and that ancient records state that they had fallen from the sky.

6. Historical data

The legend of the Hopi Indians and the writings of Plato have already been mentioned, and whilst it is possible that they could have derived from the same source, it is difficult to imagine how such descriptions could have originated if they were not based on some actual experience. There is, in fact, a plethora of historical and 'legendary' data to support these stories.

The ancient Egyptians called the western Sun Harakhte'. This is conventionally assumed to mean that they allotted different deities to the Sun at different times of the day. However, the original texts actually state that Harakhte *rises* in the west. According to the ancient historian Herodotus the Egyptians claimed that the Sun had reversed its direction four times within their recorded history (Sélincourt and Burn 1972). This period he states to be three hundred and forty one generations, which he calculates to be 11 340 years. These four Sun-reversals within the period from about 12 000 BC to 450 BC are in both numerical and overall temporal agreement with Dury's climatic reversals for the British Isles, and within the period covering the Gothenburg, Laschamp and Folgheraiter magnetic events.

In the 18th dynasty tomb of Senmut there is an astronomical ceiling decoration which Pogo (1930) describes as having an objectionable orientation, as it appears to be reversed, with the constellations apparently moving in the wrong direction. In the Bible there are several references to aberrant behaviour of the Sun. For example, Amos, ch 8 v 9, states that God will cause the Sun to go down at noon. Amos is dated to the 8th century BC. In Chinese records there is a reference to the Sun setting and then coming back, and in Mexican annals there is a reference to the night lasting a long time.

These last three references are particularly interesting. Taking a tippe-top reversal lasting one day, for an observer on the equator at a position on the secondary axis of rotation the Sun would, for example, rise normally in the east, then proceed across the sky as though having risen from a point progressively further north, and finally set in the south. The south is the *noon position* of the (normal) Sun for an observer north of the equator. The day length would not be changed significantly for this observer, and during his night the Sun would complete its errant track and rise in the west the following day. For another observer, again on the equator but this time at a point also on the secondary equator, the Sun would, for example, rise normally in the east, then proceed on an ever-lowering course as the observer tilted towards the pole. Then, instead of setting in the west, it would proceed to rise again on a reversed course as the observer passed over the pole, giving a long day. An observer on the opposite side of the globe would experience a correspondingly long night. The Middle East is in the region of 35°E. Mexico is about 100°W and China about 120°E—very roughly 90° either side of the Middle East, and close to the 60°W, 120°E preferred polar wander path of Steinhauser and Vincenz.

The above-mentioned records of the Sun's aberrant motions also mention associated catastrophic events, such as earthquakes and floods, but it is nevertheless assumed that Amos is referring only to a total eclipse calculated to have occurred in 763 BC (Lowther-Clarke 1952). It is an often-repeated claim that eclipses are fully regulated and traceable back through all known records with reasonable precision. This is not so. Bury (1951), for example, finds it necessary to accuse Herodotus of heightening the dramatic effect of a report by moving an eclipse from 481 BC to 480 BC, and also displacing it from Sparta to Sardis. Newton (1974, also published in Hodson 1974) in his discussion of ancient eclipse records, warns of a 'lack of veracity in many records', but admits that he has not carefully studied a tendency for the probability of error to improve with later records. He classes Herodotus' eclipse as a hoax, as he does other records, including solar data recorded by Ptolemy, but he concludes that 'an uncomfortably large number of ancient records are either untrue or are in error by amounts larger than those expected from the technical ability of the times. Further, the recorded dates are often in error by serious amounts, even in terms of the calendrical system used by the observer. In a sample of nearly 700 records of solar eclipses, the year is wrong in about one record in four. The errors range up to 550 years.' He also notes that, in the eclipse tables of Ptolemy, the minimum apparent diameter used for the Moon is so large that annular eclipses cannot occur, and suggests that 'ancient astronomers did not learn to distinguish annular eclipses from total eclipses until about the year 1000 (AD)'. Gold notes that 'the Moon shows signs of a tidal bulge appropriate to a greater proximity to the Earth'.

Lewis (1974, also published in Hodson 1974), describing the impressive abilities of the Polynesians and Micronesians to navigate by the stars, mentions a Maori legend of "the Sun travelling southward to join 'Hine-takarua', the Winter Maid and, after the June solstice, returning northward to 'Hine-raumati', the Summer Maid. The myth", he points out, 'seems logical enough to us here in the Northern Hemisphere, but for New Zealand in the 30's and 40's of south latitude, it reverses summer and winter. Makemson suggests that the story represents memories of a sojourn in the Northern Hemisphere.' Indeed so, but not, perhaps, in quite the sense that Makemson envisaged.

Not only are there many such records of aberrant events, but these records fit a pattern, and this pattern is being revealed again in present-day geological and other studies. The earliest Babylonian and Hindu astronomical records both refer to the four planets Mercury, Mars, Jupiter and Saturn, but not Venus. Those records are dated to around 3000 BC or earlier. Later records, dated to around 1650 BC, record erratic appearances and disappearances of Venus (Rose and Vaughan 1976). Thompson (1974, also published in Hodson 1974) notes that 'the Maya were certainly more interested in Venus than in any other planet' and that it is known from Mexican sources that Venus was much feared at heliacal rising after inferior conjunction.

Venus today is suprisingly hot, it has a remarkably dense astmosphere and, although the planet rotates very slowly, its upper atmosphere rotates relatively rapidly. These data, both the old and the new, are consistent with the idea that Venus is a recent addition to the Solar System. To quote Plato again: 'Your own (Greek) story of how Phäethon, child of the Sun, harnessed his father's chariot, but was unable to guide it along his father's course and so burnt up things on the Earth and was himself destroyed by a thunderbolt, is a mythical version of the truth that there is at long intervals a variation in the course of the heavenly bodies and a consequent widespread destruction by fire of things on the Earth.' (Lee 1971).

7. Fast precession

The precession of the equinoxes occupies about 25 to 30 000 years for a complete cycle, i.e. about 10^7 days. Since the precessional rate is small compared with the rotation rate ω of the Earth about its own axis, and since this axis deviates only slightly from a principal axis, the torque is given approximately by the equation (Alonso and Finn 1967)

$$\tau_e = I_1 \dot{\psi} \dot{\phi} \sin\theta \tag{1}$$

where $\dot{\psi} = \omega$ and θ, ϕ, ψ are the Eulerian angles as shown in figure 4. In this instance

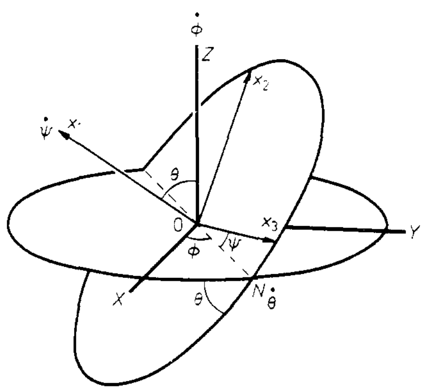

Figure 4. Fixed frame axes: OX, OY, OZ. Body frame axes: Ox_1, Ox_2, Ox_3. Line of nodes – ON; intercept of OXY and Ox_2x_3 planes. Eulerian angles: θ, between OXY and Ox_2x_3 planes; ϕ, between OX and ON; ψ, between Ox_3 and ON. Rotations: $\dot{\theta}$ about ON; $\dot{\phi}$ about OZ; $\dot{\psi}$ about Ox_1.

$\dot{\phi}$ is taken to be the precessional term, but in the case of fast precession its role is changed to that of the primary rotation, so that $\dot{\phi} = \omega$. In slow, or regular, precession θ is constant or cyclically varying between two fixed limits if nutation be present superimposed on the main precession. In fast precession, as for the tippe top, θ varies steadily from 0 through $\pi/2$ to π, and the secondary rotation is given by $\dot{\theta}$. In the initial state when $\theta = 0$ we have $\omega = \dot{\psi} + \dot{\phi}$. Hence we can write $\dot{\psi} = 0$. Additionally, for simplicity, we shall consider the case where $\psi = 0$, that is, the case where the Ox_3 axis remains aligned with the line of nodes, ON. The components of rotation with respect to the axes in the body then become

$$\Omega_1 = \dot{\phi} \cos \theta \tag{2}$$

$$\Omega_2 = \dot{\phi} \sin \theta \tag{3}$$

$$\Omega_3 = \dot{\theta}. \tag{4}$$

From (2) we have $\Omega_1 = \dot{\phi} = \omega$ when $\theta = 0$, and $\Omega_1 = -\dot{\phi} = -\omega$ when $\theta = \pi$, which is the result mentioned earlier that the primary rotation reverses with respect to the body as a consequence of the inversion.

For a general case, the components of torque are given by the equations

$$\tau_1 = I_1\dot{\Omega}_1 + (I_2 - I_3)\Omega_2\Omega_3 \tag{5}$$

$$\tau_2 = I_2\dot{\Omega}_2 + (I_3 - I_1)\Omega_3\Omega_1 \tag{6}$$

$$\tau_3 = I_3\dot{\Omega}_3 + (I_1 - I_2)\Omega_1\Omega_2. \tag{7}$$

For precession about Ox_3 only, we may neglect τ_1 and τ_2, and consider τ_3 alone, which, from (2) and (3), becomes

$$\tau_3 = I_3\dot{\Omega}_3 + \tfrac{1}{2}(I_1 - I_2)\dot{\phi}^2 \sin 2\theta$$

or

$$I_3\dot{\Omega}_3 = \tau_3 - \tfrac{1}{2}(I_1 - I_2)\dot{\phi}^2 \sin 2\theta. \tag{8}$$

Thus, in order to initiate and just maintain fast-precessional rotation, we require τ_3 to just exceed the value of the second term on the right-hand side of (8), i.e. we require

$$\tau_3 \geqslant \tfrac{1}{2}(I_1 - I_2)\dot{\phi}^2 \sin 2\theta. \tag{9}$$

It may be noted that the torque requirement becomes negative when θ exceeds $\pi/2$. In other words, the body tends to be self-stabilising and will seek to settle to a state where $\theta = 0$ or $\theta = \pi$, depending on whether the net effect of the external torque sets θ short of, or in excess of $\pi/2$. For a rigid body in the presence of drag, one of these states will be essentially achieved. For a non-rigid body the process of self-stabilisation will be augmented by configurational changes. In an ideal case, in the absence of any external drag and for a rigid body, the action reduces to a form of the usual Eulerian free-precession.

From (9) it is clear that, to induce fast precession, τ_3 must increase initially. The expression on the right-hand side of (9) reaches a maximum value for $\theta = \pi/4$, but it is not a necessary condition that τ_3 should reach its maximum value at this point. For example, τ_3 could peak earlier provided that the integrated effect was sufficient to provide enough fast-precessional momentum to carry the body through the $\pi/4$ state. Thereafter, the torque requirement decreases. Any maintenance of torque in the same sense beyond this point would accelerate the precession and could even lead to multiple rolling, but in practice it is more likely that, for the Earth, a passing cosmic body would be in transit through the Earth's equatorial plane at some stage, so the torque would reverse its sense and is, in fact, more likely to assist the self-stabilising action.

The work done by the torque can be obtained by integrating the expression in (9) over θ, to give

$$\int \tfrac{1}{2}(I_1 - I_2)\dot{\phi}^2 \sin 2\theta \, d\theta = \tfrac{1}{2}(I_1 - I_2)\dot{\phi}^2 \sin^2 \theta. \tag{10}$$

Between $\theta = 0$ and $\theta = \pi/2$ the work done is $\frac{1}{2}(I_1 - I_2)\dot{\phi}^2$, which is simply the difference in energy for rotation about the polar axis compared with rotation about an equatorial axis, as would be expected. In general we may expect a small change in $\dot{\phi}$ between these two states but this is neglected in the present simplified analysis. The energy derived here is a minimum requirement and higher values would be involved for more violent fast precessions. The total energy of the system may remain conserved as this energy requirement can be satisfied by a temporary transfer from the primary rotation.

Angular momentum will not be conserved under the action of the external torque. The direction of the angular momentum vector will depend upon $\dot{\phi}$ and $\dot{\theta}$, and since $\dot{\theta}$ increases and then decreases, for an external observer the vector will be seen to deviate away from the OZ axis and then return towards it, but without a change in sense. The Earth's magnetic field is likely to execute a similar temporary excursion, although the fluid nature of the core may render the excursion more complex and protracted. For a surface observer, the angular momentum vector and the magnetic field will appear to reverse their sense, and to do so by following a particular path governed by the direction of the secondary rotation vector.

The choice of $\psi = 0$, thereby setting the secondary rotation about Ox_3 in the above analysis, was purely for simplicity and is not a justification in itself for asserting that the fast precession would occur of necessity about this particular axis. However, in general a cosmic body will exert a torque on the Earth which may be sub-divided into two components. The major component is that about an equatorial axis, causing the polar axis to tilt in the fast-precessional mode, and this component has a maximum efficacy if the equatorial axis be the Ox_3 axis. The minor component is that about the polar axis, causing an equatorial precessional tilt. This component arises from the tri-axial nature of the Earth, and it acts in such a manner that the Ox_3 axis tends to be aligned at right-angles to the line through the centres of the two bodies, which is just the condition to cause the major component to act about Ox_3.

Such an alignment seems to be confirmed in the experiment with the marked tippe top, where the antinode defined by the mark passes consistently over the highest point of the top at its half-way stage of inversion. Furthermore, this particular antinode applies for both clockwise and anticlockwise rotation, suggesting that it does lie on the Ox_2 axis, and that the minor torque has a powerful aligning influence. For the Earth, the minor torque may not be so effective, particularly since the passing body may 'move round' the Earth at a rate not commensurate with the aligning process. It may be for this reason that a trend in the results indicative of a preferred polar wander path is only marginally, or uncertainly, distinguishable.

The above analysis, although very simplistic, does appear to be in good accord with the practical observations of instances of fast precession, and it also appears to provide an explanation which can account for the data on geomagnetic reversals. It remains, then, to establish the probability of occurrence of such events. To permit an assessment of the probability, the torque given by (9), taken at its maximum necessary value by setting $\sin 2\theta = 1$, may be compared with the torque that produces the equinoctial precession, given by (1). Bearing in mind the differing roles of $\dot{\phi}$ and $\dot{\psi}$ for the two different forms of precession, we can write

$$\frac{\tau_3}{\tau_e} = \frac{\frac{1}{2}(I_1 - I_2)\omega^2}{I_1 \omega \dot{\phi} \sin\theta}. \tag{11}$$

From the known values of the parameters, we require, then, a torque for fast precession in the order of 4×10^4 times greater than that for the equinoctial precession.

This is the maximum value the torque needs to be in order to permit a complete inversion. No consideration has been given to a possible additional torque arising from electrostatic effects in the seemingly likely event that the Earth and/or the other body are charged. Furthermore, the Earth has been treated as a rigid body in the analysis. Studies of the Chandler wobble indicate that earthquakes seem to correlate with small but distinct disturbances of the wobble, but the earth movements involved appear to be about an order of magnitude too small to account for the observed displacement. It has also been noted that the damping of this wobble indicates that the Earth could be more fluid than is normally deduced from observations of other phenomena. These factors all suggest that the derived torque requirement may be too stringent but the uncertainty in these factors, and the approximate nature of the basic calculation, do not permit any sensible modification to the above figure.

The torque exerted on the Earth by another cosmic body depends upon the mass, M, of the body; its distance, D, from the Earth, and on its declination, δ—the angular position from the Earth's equatorial plane. The relationship, to a first approximation, is of the form

$$\tau = kMD^{-3} \sin 2\delta \tag{12}$$

where k is a constant and a function of the Earth's mass and shape. The sense of the torque is such that it seeks to tilt the equatorial plane, or the equatorial bulge, into coincidence with the line through the centres of the two bodies.

The Moon and the Sun provide the main contributions to the equinoctial torque. They act from or near the ecliptic plane, so that their declination varies between 0° and about $\pm 23\frac{1}{2}°$ and the mean effective declination may be taken to be about 12°. As a result of the orbital motions, the magnitude of the net torque may be taken as a statistical addition of the two individual contributions and, from a consideration of equation (12), this magnitude is only slightly larger than that for the Moon's contribution alone. We may reasonably use the Moon, then, at its present distance from the Earth and at a declination of 12°, as a datum for the comparison of the torques. The postulated body passing near the Earth is very likely to pass through a declination angle of 45°, and from that position the torque necessary to bring about an inversion of the Earth would be obtained from, for example, a body of ten times the mass of the Moon at a (centre to centre) distance of about $3{\cdot}3 \times 10^4$ km, or for a body of Earth mass at a distance of about $6{\cdot}6 \times 10^4$ km.

8. Sources of torque

Surveys of cosmic debris incident on the Earth have been made (Hindley 1976, Hughes 1976), and as a first approximation of the likelihood of a near miss by, for example, an Earth-sized body we might extrapolate these data to Earth mass, allowing for an increased cross-sectional 'capture' area out to a radius of $6{\cdot}6 \times 10^4$ km, or about 10^2 times the Earth's cross section. From Hughes' data the simple average curve would yield an event about once in 10^{16} or 10^{17} years. The Solar System has been in existence for a period of only 10^9–10^{10} years according to present estimates, so even a single event would seem unlikely on this basis. However, the data do not form a smooth curve and this is a rather pessimistic estimate. Taking the large-mass data (comets) alone, an extrapolation yields an event about once in 10^{13} years. Hindley notes that recent data have raised the large-mass incidence rate quite markedly—by a factor of about 10^2—but even if Hughes' data did not include this revision the estimate would remain too low, as an event rate of about one in 10^5 to 10^6 years is required.

It might just be feasible to extrapolate the fireball data (which truncates at the limit of directly observed mass), which would give an event rate of about one in 10^7 years, but this extrapolation is dubious for two reasons. Firstly, it is over a very large range of about twenty orders of magnitude of the mass scale, and secondly, it is quite likely that the fireball curve may drop off just beyond the present observation limit to meet the comet data curve, much as the micrometeorite curve falls abruptly beyond masses of about 10^{-5} g to meet the fireball curve itself. Indeed, had we only the micrometeorite data to go on, an attempt to extrapolate from that alone would yield an incidence rate of around 1 to 10^2 events per year! This absurd figure—even allowing for some concentration of fine particles around the Earth—together with the large variations in these extrapolated estimates, suggest that such extrapolations may be generally invalid. The variations themselves, in fact, indicate a more plausible interpretation of the data.

It is reasonable to suppose that small debris is generated by collisional decay from larger debris and, if this be a steady process through time, a steadily varying concentration through the mass range would be expected. This implies that the debris incident on the Earth should also show a steady variation, with a smooth curve of incidence rate against mass. This is not the case. The data show several fairly distinct points of inflexion, with three uniform, parallel intervals, micrometeorites, fireballs and comets, linked by two transition zones. The micrometeorites, fireballs and comets represent three distinct stages of decay, separated by hiatuses. In other words, the data seem to indicate that the general influx arises from the presence in the Solar System of large bodies at discrete intervals of time. The comets, then, would represent a relatively early stage of decay from, or an association with, a comparatively recent body or bodies; the fireballs represent a middle stage of decay from an earlier event or events; the micrometeorites represent a final decay stage from bodies present in the remote past, and the transition zones arise from the intervening quiescent periods within the Solar System.

The data are not quite as clearly distinguished as described above, but in part this may be due to inaccuracies in the very high mass data, and in part to the possibility that there could well be some overlap of the decay from different initial bodies. There is, for instance, the possibility that 'non-periodic' comets are survivors from early events, preserved by the fact that they were displaced well-clear of the main System, whereas periodic comets may stem mainly from more recent events. Hindley notes that the periodic comets undergo rapid decay, with lifetimes of at most a few millenia.

Hartmann (1977), discussing cratering in the Solar System, states that there is 'good reason to believe ... that the largest bodies that struck each planet were 1000 km or more in diameter. An asteroid 1000 km across, striking a primordial planet could have given rise to a fundamental asymmetry in the planet, perhaps by knocking the crust off one side.' He points out the asymmetry of the Moon, Earth and Mars, and he adds: 'The impact of large asteroids may well explain the fact that . . . the planets are less uniform than one would expect them to be if (they) had built up in a purely evolutionary way by accretion . . . The largest interplanetary bodies probably carried so much energy and momentum that, depending on the direction from which they approached the planet, they could have tilted it, speeded up its spin, slowed down its spin, destroyed a satellite or perhaps even have left rings round it after breaking up under gravitational forces.'

It is worth noting that Hartmann is referring to actual impacts, and these large-body collisions, he suggests, occurred on at least three of the five inner planets known today. For the present purpose, near misses through a cross section of space 10^2 or perhaps more times greater in area than the planet itself are of interest. Hartmann does not suggest that the events are recent—rather the contrary—but he admits that there are problems of interpretation in some instances, and his assumptions may be questioned in the light of the model presented here. He notes, for example, that there is a curious kink in the crater spectrum of Mars, and comments that 'what appears to be indicated is a long period of erosion and deposition that ended fairly abruptly in recent Martian history.'

Hindley, in his discussion of debris in space, finds difficulty in explaining the maintenance of the zodiacal cloud and suggests that it could receive sudden random injections of huge quantities of dust. Neither the asteroids nor the periodic comets supply enough dust to replenish the losses. He also states that recent studies of the nature of the particles producing the scattered glow of the zodiacal light lead to a new model with larger particles. This model has a 'serious consequence' in that it requires an upward revision of the mass of the zodiacal cloud.

An injection of a large cosmic body at relatively frequent random intervals would seem, then, to be a reasonable proposition. Such injection need not be from an external source. There is no reason to dismiss the possibility that the present suite of planets comprise some of these bodies and that the Solar System, rather than having been formed at one relatively short period in the past, has come into being step by step.

9. Summary

The data drawn together in this paper are admittedly selected, but the selection process became one of limitation rather than one of discreet sifting. Where papers are quoted, as with all quotations, the words are removed from their context, but every attempt has been made to retain the intended sense of the remarks whilst extracting the relevant points. The views and data are taken from popular sources and some less well-known sources as well as from recognised authoritative sources, but all of the sources are probably of equal reliability and they appear to be by no means untypical and are representative of current research and current thinking.

The theory put forward in this paper describes a type of motion for the Earth which is not only possible but probable in the event of a meeting with another cosmic body of comparable size and in close proximity for a brief period. That such meetings can occur at relatively frequent intervals seems to be feasible based on existing data. That such events have occurred seems to be confirmed by data from many fields of study. Data from studies of geomagnetism, volcanism, ice ages, palaeontology, oceanography, archaeology, history, astronomy and even mythology could be explained by such events, not only individually but particularly in the otherwise puzzling interlinking and coincidences of phenomena across these diverse studies.

The theory has taken recent data such as that on magnetic reversals, together with the links to other phenomena such as faunal extinctions, ice ages and massive volcanism, and extended the concept of a common factor relating these. Additional data have been considered such as the catastrophic overturns observed in lake waters and temperature fluctuations in ocean waters, and various ancient data have been added, to show that a single common factor can account for many of these data both in broad outline and in detail.

It may justifiably be argued that these apparent links are each open to question. This is true, as any single piece of information contains inevitable experimental uncertainties and may be interpreted in a variety of ways, but when these pieces are put together, as they have been here, a pattern emerges which indicates unusually strongly that such coincidences are real. Additional cross-links presented here even more firmly cement the relationships. Furthermore, whilst it is admittedly unusual to introduce mythology into such studies, the likelihood of 'hoaxes', clerical errors, fanciful imagination, or pure invention—to which much of the historical and 'mythical' data is attributed—fitting a common pattern with the modern data is quite remote. The data taken at face value have a marked consistency in the light of the present model. The pattern suggested here raises many new questions, but it provides a unifying answer for many existing questions.

Once, it was thought that the Earth was the centre of the Universe. Then it was realised that a better understanding of the motions in the Solar System could be had by putting the Sun at the centre and relegating the Earth to a peripheral role. In some ways, present theories of geomagnetic reversals continue to treat the Earth as the central body. The question asked is 'How does the magnetism reverse?' It is an Earth-based observer's question. A better understanding can be expected by taking a more general viewpoint and asking the question in a slightly different way—'How does the magnetism interchange its poles with respect to the geographic poles?' This gives a degree of freedom not usually considered in most theories.

The additional degree of freedom leads to the possibility that it is the Earth that inverts rather than the field, and this possibility immediately provides the sought-after link between faunal extinctions and magnetic reversals. It further provides an explanation of the detailed behaviour of magnetic reversals in that it accounts for the displaced poles at various epochs, the probable existence of preferred polar wander paths and the fact that the field does not pass through a zero state. The link with massive volcanism is also explicable, as is the link with ice ages, and the very reason for the existence of these phenomena becomes manifest.

The motion of the Earth explains the overturn of African lake waters and Black Sea waters. It demands that these be linked to magnetic disturbances and it has been shown that the dates do seem to correlate. The same is true for other marked changes of climatic regimes. Principal ocean currents and air movements will become effectively reversed with respect to the Earth's surface, and warm ocean currents will be replaced by cold currents and vice-versa, providing an explanation of changes of faunal collections around ocean margins at intervals. An explanation of many otherwise enigmatic statements in ancient records also emerges, and data generally interpreted as imaginative myth are shown to be equally consistent with the hypothesis of a disturbance within the Solar System leading to a situation to cause the Earth to invert.

An inversion of the Earth in the particular manner described seems to be the only possible event capable of satisfying this array of data. The Earth is of a form which enables such an inversion to occur. Stray bodies in the Solar System, capable of causing the inversion, are not impossible and the pock-marked surface of all of the planets and bodies so far examined indicate that many such stray bodies have been present at some time in the past. It is usually considered that these were present only in the early stages of the formation of the System, in a settling era following the creation of the System as a whole. The evidence, from Earth-based data, is that either this settling period is still continuing, or, and seemingly more likely from the data, that such bodies arrive at random intervals through the life of the System which is in a process of continual creation.

In their paper on the overturning of lake waters, Degens and Stoffers state that they did not expect their researches to lead to a questioning of an established concept of geology, namely Hutton's principle of uniformity of process—that the present is the key to the past. I came upon the idea presented here from a little toy that fell out of a Christmas cracker. In a sense, that Christmas 'present' may prove to be the key to the past. I too did not expect such a thing to lead to a questioning of established concepts, not only in geology but in astronomy and other fields.

Perhaps it is not just a coincidence that the world we live on, like Christmas crackers, may not be destined to end with a whimper—but with a bang.

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