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Objections Overruled - A Reappraisal Of Earth Inversion Dynamics

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‘THE TIPPE-TOP: AN ONGOING DEBATE

‘Peter Warlow's hypothesis ('Geomagnetic Reversals?', *J. Phys. A* **11**:10 [1978], pp. 2107-2130; reprinted in *SIS Review* III:4 [1979], pp. 100-112) that Earth could have inverted under the influence of gravitational torques due to the close passage of a cosmic body continues to interest our readers. This is in spite of the criticisms of Dr Victor Slabinski ('A Dynamical Objection to the Inversion of the Earth on its Spin Axis', *J. Phys. A* **14**:9 [1981], pp. 2503-2507; reprinted in *SIS Review* V:2 [1981], pp. 54-56), whose major argument has been that inversion requires a torque about Earth's axis of figure and that such a torque is almost impossible to produce gravitationally.

‘Despite the learned arguments of Dr Slabinski, it is an undeniable fact that Uranus, with a mass 14.6 times that of Earth, has suffered a very severe tilt at some time in its history. This was one of the telling points made by Peter Warlow in 'Return to the Tippe-Top, part 1' (*C&C Review* IX [1987], pp. 2-13). Peter Warlow's 1987 article contained an extended preview of his sequel paper ....

‘................. [The following article] by David Salkeld ... finds many errors in the case made by Dr Slabinski against Warlow's hypothesis, and in particular he claims that Dr Slabinski's analysis proving that a torque is needed about Earth's axis of figure is fallacious. ....

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Objections Overruled - A Reappraisal Of Earth Inversion Dynamics

by

DAVID SALKELD

1. Introduction

Peter Warlow's novel hypothesis of Earth inversion as an explanation for geomagnetic reversals and other phenomena [1] is severely criticised by Dr Victor Slabinski on dynamical grounds in a paper [2] hereafter referred to as 'the Critique'. Those convinced by Dr Slabinski's arguments know that the Earth cannot invert: they must then necessarily uphold data that argues against inversion, and decry every piece of evidence which suggests the contrary. The dangers of such a position are self-evident.

1.2 The Critique finds three errors in Warlow's dynamical analysis; they are here called the First, Second, and Third Objections. It also presents a calculation of the gravitational torque needed to invert a rigid Earth without altering its spin (body reversal, invariant primary spin - BRIPS); and the torque-impulse required by any inversion scheme. This essay scrutinises the three objections and the two calculations, revealing where and by how much they err. For clarity I shall identify sub-divisions of this essay as 'Parts' and of the Critique as 'Sections'.

1.3 It is strongly emphasised at the outset that this essay is concerned specifically with the accuracy, or otherwise, of Dr Slabinski's dynamical objections to Earth inversion under gravitational torques: the title says as much. It should not be interpreted as an attempt to validate Warlow's hypothesis; indeed, in the course of reviewing the Critique several mistakes in Warlow's original hypothesis are revealed. The Critique deals solely with effects of gravitational torques on the Earth's axis of figure; so possible contributions from other (e.g. electromagnetic) forces and torques, and interactive effects on the orbits of the two participating cosmic bodies, are ignored here. Moreover, for consistency with references [1] and [2] Earth is treated as a rigid body and a full 180° inversion is principally treated however, a partial turn of Earth's axis of figure is also briefly examined, being - in the writer's opinion - the more likely outcome of a close encounter between Earth and a cosmic body.

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2. The First Objection

The Critique finds that the torque required about the body-fixed x_3 axis is:

$$t_3 \sim I_3(4\pi/n^2) \text{ rad/day}^2 \quad \ldots\ldots\ldots\ldots\ldots\ (11)$$

and says that this is '200 times larger than Warlow's lower limit when the inversion takes place in one day (n = 1)'. More accurately, it is 190.35 times larger for n = 1, but let us not argue. The first objection is valid as far as it goes - but does it go far enough?

2.2 Firstly, it fails to point out that t_3 is equal to Warlow's lower limit when inversion takes place in $n = \sqrt{190.35}) = 13.8$ days, a period not excluded by Warlow's statement: 'I suggest that the actual reversal takes place in a matter of days, even as little as one day.' Thus although the objection validly rules out very short inversion periods, it acknowledges timescales of two weeks or more as dynamically viable.

2.3 Secondly, equation (8) proposed by Warlow and accepted by Slabinski can be re-arranged to read:

$$t_3 = I_3\, \Omega_3 + 1/2(I_1 - I_2)(d\phi/dt)^2 \sin 2\theta \quad \ldots\ldots\ldots\ldots\ldots\ (A)$$

The last term is simply the additional torque needed to turn a rigid body spinning about its axis of maximum moment of inertia through an angle q so that it is spinning about an axis of lower moment of inertia. For a rigid sphere, where $I_1 = I_2 = I_3$, this last term becomes zero, and equation (8) reduces to:

$t_3 = I_3\ \Omega_3$

which is simply Newton's second law for rotational motion. Whence the rotation produced by the torque must, in accordance with Newton's law:

2.3.1 Be about the axis of the torque, and

2.3.2 Be spin, not precessional motion (for in forced precession the angular velocity, not angular acceleration, is proportional to the torque).

2.4 None of these points is mentioned by the Critique. Their omission is serious, for, as will be shown, they are critical to Dr Slabinski's case.

3. The Second Objection

The Second Objection is in two parts. Section 2 - 'Basic Theory' presents an analysis to show that a BRIPS involves angular accelerations about three body-fixed axes, not just the inversion axis. Implying that these angular accelerations require components of torque about each of the three axes, the 3rd and 4th paragraphs of Section 3 - 'Oversights in Warlow's Theory' argue that the three required components of torque are of the same order of magnitude; that neglect of torques other than that about the inversion axis is Warlow's most important error because it is very difficult to produce a gravitational torque about Earth's x_1 axis [axis of figure]; that the error arises because Warlow assumes that the precession (i.e. *secondary rotation*) axis has the same direction as the applied torque; and that the familiar textbook example of gyroscopic precession supports this argument. I review Sections 2 and 3 of the Critique separately.

Basic Theory

3.2 Section 2 adopts Warlow's two sets of Cartesian axes: the space-fixed OX, OY, OZ; and the body-fixed x_1, x_2, x_3. x_1, is initially coincident with OZ, x_3 is the axis about which the body inverts, and x_2 is an axis perpendicular to x_1 and x_3. It also adopts Warlow's assumption that Earth spins about OZ at a constant angular rate $d\phi/dt$. It continues: 'The OZ axis lies in the x_1x_2 plane and makes an angle θ with the x, axis ....' This is an odd viewpoint. As OZ is inertially fixed and the axis of the unvarying primary spin common-sense suggests it as the baseline, with which x_1 makes an angle θ and x_2 an angle $(1/2\pi - \theta)$. Referencing the moving axes x_1 and x_2 to OZ does not conflict with the Section 2 statement: 'During the inversion, θ changes from 0 to π radians due to an additional, simultaneous rotation of the Earth about the x_3 axis at the angular rate $d\theta/dt$'.

3.3 But Section 2 goes on to state: 'the resulting angular *rates* [my italics] about body-fixed axes are:

$\Omega_1 = d\phi/dt\ \cos\ \theta$ .... (2)
$\Omega_2 = d\phi/dt\ \sin\ \theta$ .... (3)
$\Omega_3 = d\theta/dt$ .... (4)'

This statement is self-contradictory, for a rigid body can have only one resultant angular rate at any one time: the angular rate '*R*' resulting from a constant rate $d\phi/dt$ about OZ and a variable rate $d\theta/dt$ about x_3 is one of magnitude $\sqrt{(d\phi/dt)^2 + (d\theta/dt)^2}$, about an axis inclined at an angle $\alpha =$

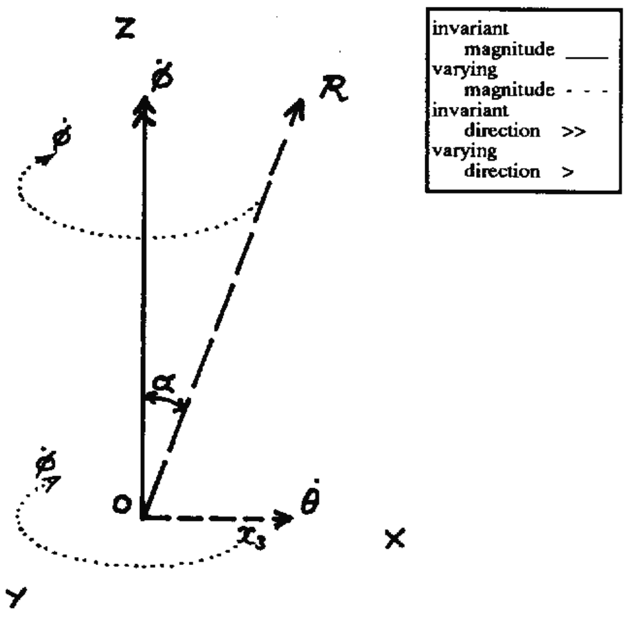

Figure 1: Spin Vector Diagram for Beach Ball BRIPS

The secondary spin vector, magnitude $d\theta/dt$, lies along x_3, which rotates with the body at rate ϕ. The resultant spin R also rotates at rate $d\phi/dt$ about OZ.

$\tan^{-1}(d\theta/dt)/(d\phi/dt)$ to OZ: it is illustrated in the spin vector diagram of Figure 1. Moreover, to talk of rates 'about body-fixed axes' is hazardous; strictly, a rigid body cannot move, in rotation or translation, relative to axes fixed in the body. In the special case of a sustained torque about a body-fixed axis (e.g. about x_3 when a tippe-top or beach ball inverts) it is convenient to refer the inversion motion to the x_3 axis: but in general, motions should be specified relative to external axes (OX, OY, OZ) as in Figure 1.

3.4 Secondly, the Critique presents equations (2), (3), and (4) as being angular rates. An angular rate $d\theta/dt$ about x_3 has already been specified: equation (4) merely re-labels it. However, equations (2) and (3) represent not angular rates but components of the angular rate $d\phi/dt$ resolved about x_1 and x_2 (as may be seen by squaring and adding Ω_1 and Ω_2 yielding $[d\phi/dt)^2$). Time derivatives of equations (2) and (3) do not give, as the Critique claims, angular accelerations. Reliable texts on rotational dynamics [3] stress that *components* of angular rate are not real angular motions, and that they can be regarded as non-holonomic quantities (i.e. time-dependent processes such as differentiation and integration with respect to time do not yield angular accelerations or positions and should not be undertaken). When the Critique goes on to say that 'time-derivatives of equations (2) and (3) give the angular accelerations ...' it is in conflict with basic principles of rotational dynamics. Its equations (5), (6) and (7) are devoid of physical meaning, except as regards the evaluation of Ω_3.

3.5 In the last sentence of Section 2 the Critique says, most reasonably: 'We may assume $I_2 = I_3$ for simplicity in Euler's dynamical equations'. As the axis about which the inverting torque first appears (x_3) is arbitrary, and as x_2, the equatorial axis perpendicular to x_3, is therefore likewise arbitrary, $I_2 = I_3$ is equivalent to assuming dynamical uniformity in the equatorial plane: it is then impossible to induce any gravitational torque about the x_1 (other than by a body of infinite mass or a finite mass body at zero distance), so Ω_1 must always be zero. Thus if the first of the three equations (7) is valid, $d\theta/dt$ must always be zero. This leads to an incredible result:- a body with an enormous but uniform equatorial bulge could not be tilted gravitationally through so much as one second of arc by a neutron star one inch away! It is hardly surprising that, three paragraphs later, the Critique quietly drops the assumption of uniformity; or even its most ardent supporters might have begun to harbour suspicions.

Oversights

3.6 Before continuing to review the Second Objection I shall examine Warlow's other example of the proposed type of inversion motion - an inflated beach ball spinning on smooth water. Primary spin is imparted via an inflation valve stem, which defines x_1 and at the start is uppermost, lying along OZ. Any deflection of this stem about an equatorial axis (x_3) results in a couple about x_3 due to the downward pull of gravity on the stem, and the upward thrust of the water's buoyancy through O, the ball's centre. The resultant torque, acting solely about x_3, is the only torque acting on the spinning ball except for the viscous drag of the water (which plays no part in the inversion itself, but opposes the spin and eventually brings the ball to rest*). The primary spin remains wholly unchanged in direction; and almost unchanged in magnitude if the viscous drag is low (as it is for a large, smooth, hard-inflated ball): but when the stem enters the water it disturbs and retards the spin. Addition of a small mass to the stem increases the torque, produces proportionally more angular acceleration about the equatorial axis, and results in a faster inversion.

3.7 From this example I draw two simple, common-sense conclusions:

3.7.1 To invert an unconstrained spinning ball it is necessary only to apply a torque about the (equatorial) inversion axis

3.7.2 Where there is no coupling between the axes of spin and figure, subsequent rotation of the body about an axis perpendicular to the spin axis has no effect on the existing spin.

3.8 Beach ball inversion demonstrates that the Second Objection's claim - that torques are needed about the x_1 and x_2 axes as well as the x_3 axis to achieve inversion - is wrong. The claim was based on two assumptions: firstly, that there are angular accelerations about the x_1 and x_2 axes - and we have shown that this finding by the Critique's Basic Theory is false. A second implicit assumption is that torques are needed about each of these axes; and the fallacious equations (7) are used to 'prove' that t_1 and t_2 are of the same order as t_3. In fact, the torque required about x, is zero. As shown by 2.3.1, the secondary rotation is about the same axis as the torque which produces it. A torque about x_1 would change the primary spin rate $d\phi/dt$, contrary to the Critique's assumption that $d\phi/dt$ is constant. Thus the First Objection (which is valid as far as it goes) contradicts the Second. Warlow was not wrong to neglect t_1: it is the Critique which errs. Moreover, though this is the Critique's most important error (leading to a gross miscalculation) it is not the largest error, as we shall see.

3.9 'The familiar textbook example of gyroscopic precession' *does not* support the Second Objection. Gyroscopic precession requires no torque about the x_1 (polar) axis; torque about one equatorial axis produces a rotation about another equatorial axis. But as the secondary rotation in a tippe-top type inversion is spin, not precession (see 2.3.2), the example is irrelevant. Thus the Second Objection is wrong on every count.

3.10 What actually occurs during a BRIPS is that the x_1x_2 plane rotates through π radians about the x_3 axis, bringing each axis in this plane into momentary coincidence with OZ - and hence with the primary spin $d\phi/dt$. At any one moment the whole of the primary spin is about whichever body-fixed axis happens to co-incide with OZ: before the inversion starts and after it has completed the coincident axis is x_1. But the primary spin is unaffected by the passage of this infinity of axes through OZ (see 3.6.2): it continues about OZ at the constant rate $d\phi/dt$]. Seen from this viewpoint, the wisdom of relating the inversion to an inertially-fixed axis (OZ) becomes evident.

4. The Third Objection

Regarding Warlow's appeal to 'precessional momentum' to carry the inversion through, the final paragraph of Section 3 says: 'There is no such thing as "precessional momentum"'. This is literally correct; but Warlow's error was one of semantics, not dynamics. He called the inversion 'fast precession', when in fact it is simply a spin motion (see 2.3.2) and as such it is characterised by angular momentum about the inversion axis.

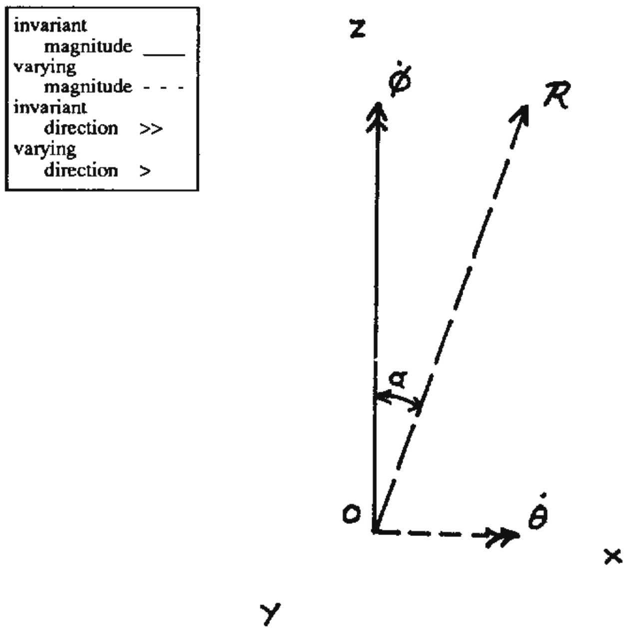

Figure 2: Spin Vector Diagram for Earth inversion.

The secondary spin vector, magnitude $d\theta/dt$, lies along OX. The resultant R lies in the XZ plane; its direction varies as $d\theta/dt$ varies in magnitude.

* For most beach balls the valve stem can be pushed inside the ball after inflation, leaving an almost smooth surface. Then, when spun with the stem downwards or stem upwards at the same initial angular rate the subsequent decay rate of the primary spin is the same. This shows that the viscous drag plays no part in beach ball inversion; [whereas friction is the source of inversion torque for tippe-tops.]

4.2 In failing to point out that the error is in Warlow's nomenclature the Critique is guilty of a minor oversight; but to the extent that the Third Objection suggests that there is no momentum about the inversion axis it is dynamically incorrect. In an article titled 'A *dynamical* objection to the inversion of the Earth on its spin axis', an error of dynamics is much more serious than use of incorrect terminology. Warlow applied the wrong term; Slabinski applies false dynamics.

5. Gravitational Torques

Section 4 presents a 'rigorous calculation' of the maximum gravitational torque which would be exerted about Earth's x_1 axis by a cosmic body in a close encounter. Regrettably, this torque - equal to $\delta V/\delta\lambda$ - is totally irrelevant to Earth inversion (see 3.6.1). For inversion about the x_3 axis the only relevant torque is t_3: fortunately Section 4 provides the means to estimate t_3 with equal rigour - we require to determine $\delta V/\delta b$ from equation (14). This yields:

$t_3 = (\delta V/\delta b)$

$\sim Gm_E m_c/r\ (a_E/r)^2\ [3J_2.\sin b \cos b\ +\ 6J_{2\cdot2}.\cos 2(\lambda - \lambda_{2\cdot2})]$ .. (B)

t_3 is largest when $b = 45°$ and λ is such that $\cos 2(\lambda - \lambda_{2\cdot2}) = 1$. Setting this equal to the magnitude of t_3 given by equation (11), gives:

$4\pi I_3/(86400n)^2 \sim 3a_E G m_E m_c/2r^3\ [J_2 + J_{2\cdot2}]$ .... (C)

Whence, using the Critique's values for these parameters, and putting m_c equal to m_E, we find that for inversion in one day a cosmic body at grazing distance ($2a_E$) would require a mass equal to $1.79m_E$. Thus the Critique exaggerates the mass required for a 1-day inversion by 417/1.79 = 233 times.

5.2 However, Part 2 has shown that the *minimum* torque leads to an inversion period of around 14 days. From equation (C) with $n = 14$, a cosmic body of mass equal to m_E would need to pass at a distance of $9.57a_E$ (6.1×10^4 km) to achieve the required torque about the equatorial plane. This separation is about 7.5% less than the 6.6×10^4 km suggested by Warlow's very simplistic analysis [4]. Thus the method and the data of Section 4 of the Critique, when properly applied, help to vindicate the dynamics of Warlow's hypothesis.

5.3 Equation (C) can be used to relate n to D (the centre-to-centre distance as a multiple of Earth's radius a_E) at which requisite values of t_3 would be generated by various cosmic body masses: figure 3 plots the results. Before the inversion starts Earth is spinning about its axis of principal moment (of inertia); as the BRIPS develops, axes of lower moment move through co-incidence with the spin axis, requiring an increase in the kinetic energy of rotation equal to the last term in equation (A). This term has a maximum value of $1/2(I_1 - I_2)(d\phi/dt)^2$, which sets the minimum torque

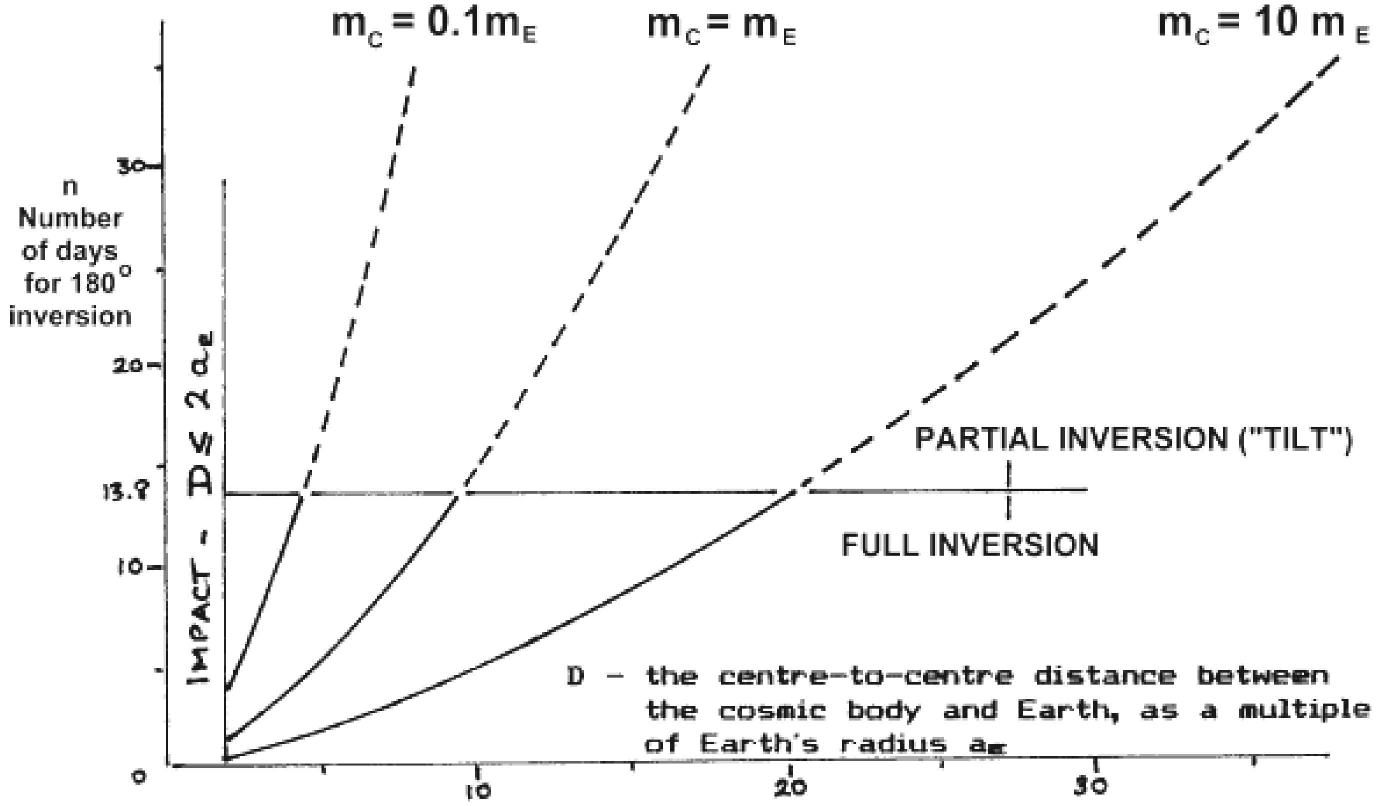

Figure 3: Relation between Inversion Period (*n*) and Separation (D) for Three Ratios of Cosmic Body Mass (m_c) to Earth Mass (m_e)

for a 180° inversion, and hence the maximum inversion period. In figure 3 periods exceeding 13.8 days (shown by broken lines) relate to torques less than the minimum for full inversion, and hence to inversions of less than 180°. The significance of partial inversions ('tilts') will be discussed in Part 7.

5.4 Figure 3 indicates that a full inversion under purely gravitational torque is theoretically possible in a period not exceeding 14 days. Warlow suggests an inversion timescale of 'a matter of days', which conventionally means 'not more than about half the next larger unit of time'. As Warlow refers throughout [1] only to days and years, we can interpret him to imply a maximum inversion timescale of about half a year - 180 days, say. Thus all periods of up to 13.8 days are well within his implied timescale; longer periods too are not in conflict with this interpretation, although anything of 14 days or more cannot relate to a full inversion.

5.5 Any inversion period greater than 1/2 day highlights questions about the inversion axis. For a tippe top or beach ball, the torque is generated about a body-fixed axis; but this does not hold for the gravitational torque exerted by a cosmic body. Regarding the body as moving in a space-fixed plane (YZ), the torque is produced about an equatorial axis perpendicular to this plane (OX). Thus the torque acts about a space-fixed, not a body-fixed axis; it can be thought of as rotating the closest part of the bulge about this space-fixed axis, with gravitation indifferent as to which point on the bulge is closest to the cosmic body at any moment. The magnitudes of torques are identical to those previously described - equations (8) and (C) continue to apply; the BRIPS produced (call it BRIPS 'B') is not a tippe-top motion (BRIPS 'A') and is even more difficult to envisage.

5.6 To picture BRIPS 'B' re-read 3.10 describing a succession of body axes moving freely through coincidence with a space-fixed primary spin; better still, spin a beach ball on water and watch the procession of body axes sliding smoothly through the vertical. The 'primary' and 'secondary' spins are equally good spin motions, the primary merely having started first and being faster. Thus it is no more difficult for body axes to pass through coincidence with a space-fixed secondary spin than with the primary spin. But when the bulge has moved 90° from its initial position, the x_1 axis - which defines the N and S poles - lies in the XY plane and at an arbitrary angle to the secondary spin axis OX. If at that moment the N pole lies in the hemisphere moving about OX towards -Z, the body inverts; but if not, the N pole moves towards +Z and returns to its original position! This ambiguity in outcome was experienced by Reade in practice [5]. A spin vector diagram for this system is given at figure 2.

6. Torque-Impulse

In Section 5, the Critique volunteers a calculation of the torque-impulse required 'for any inversion scheme'. At equation (18) it integrates the torque between limits of +w and -w, and finds that a BRIPS involves the same torque-impulse (2*I*w) as is required for a spin reversal.

6.2 Now it is fundamental to Newtonian mechanics that for an unconstrained system the torque-impulse applied equals the change in angular momentum it produces. A key characteristic of a BRIPS is that the initial and final spin rates are the same, in magnitude *and direction.* It follows that the initial and final angular momenta must be identical, i.e., zero change. Thus the torque-impulse must also be zero - unless Newton's laws are violated.

6.3 As calculations of torque-impulse necessarily imply changes in angular momentum (and angular momentum is a real physical phenomenon, as anyone who has ever tried to stop a flywheel with his hand will know), it is essential that a system of axes be used which allows angular rates to be meaningfully measured. Body-fixed axes do not satisfy this condition, for no physical meaning can be attached to 'the angular rate of a body with respect to axes which rotate with the body'. External (inertial) axes must be used; and it is relative to such axes that spin is invariant during a BRIPS.

6.4 Dr Slabinski has admitted in private correspondence that the torque-impulse for a BRIPS is zero with respect to inertial axes, while claiming that his calculation is correct for the body-fixed axes that he has used. He has been asked to explain his understanding of spin and angular momentum relative to a set of axes fixed in and rotating with the body; to date, however, no reply has been received.

6.5 With proper integration limits (+w at the start and finish), equation (18) gives the correct result - zero. The calculation is of course purely theoretical, implying an ideal system in which 100% of any kinetic energy of rotation added in the first 90° of inversion is recovered without loss in the second. Practical systems involve lossy processes (e.g. friction, plastic deformation) and not all the added energy will be recoverable; but this only means that for a practical system any solutions will be at best approximate; for an idealised system an innaccurate answer is blameworthy. The 233 times by which, the Critique implies, Warlow underestimated the required torque (see 5.1) is rather less than the factor (2*I*w/0) by which it exaggerates the answer to its own calculations of torque-impulse.

7. Partial Inversions ('Tilts')

7.1 On purely geometrical grounds, the probabilities that the path of a substantial cosmic body will satisfy 'full inversion' conditions indicated in figure 3 are much lower than those for partial inversion. Warlow's equation (8) - our equation (A) re-arranged - shows that the torque available for inversion is t_3 - $1/2(I_1 - I_2)(d\phi/dt)^2\sin 2\theta$. Figure 4 plots this function on the assumption that the first term just exceeds the maximum value of the second, i.e., the function is always positive. Clearly if t_3 does not reach this critical value, so that the function goes negative, Earth's axis of figure could not move through more than 45°, and the resultant tilt would always be some smaller angle.

7.2 For purposes of illustration only, suppose the gravitational torque induced by a cosmic fly-by had tilted the axis of figure half-way between 0° and 45° (= 22.5°) relative to inertial axes when the torque ceased to act; how would Earth behave subsequently? Apart from the directional tilt there would be two further residues. Firstly, assuming that the axis of figure has a small angular velocity about the tilt axis at the moment the torque stops acting, the resultant spin axis will lie at a small angle to its original (OZ) direction. Secondly, the axes of spin and figure will be misaligned by about 22.5°, so the body will be spinning around an axis which is not an axis of principal moment; hence it will exhibit free (Eulerian) precession, in which the axis of spin and figure perform a counterpoint coning motion about the angular momentum vector *M*. Assuming no residual torques,

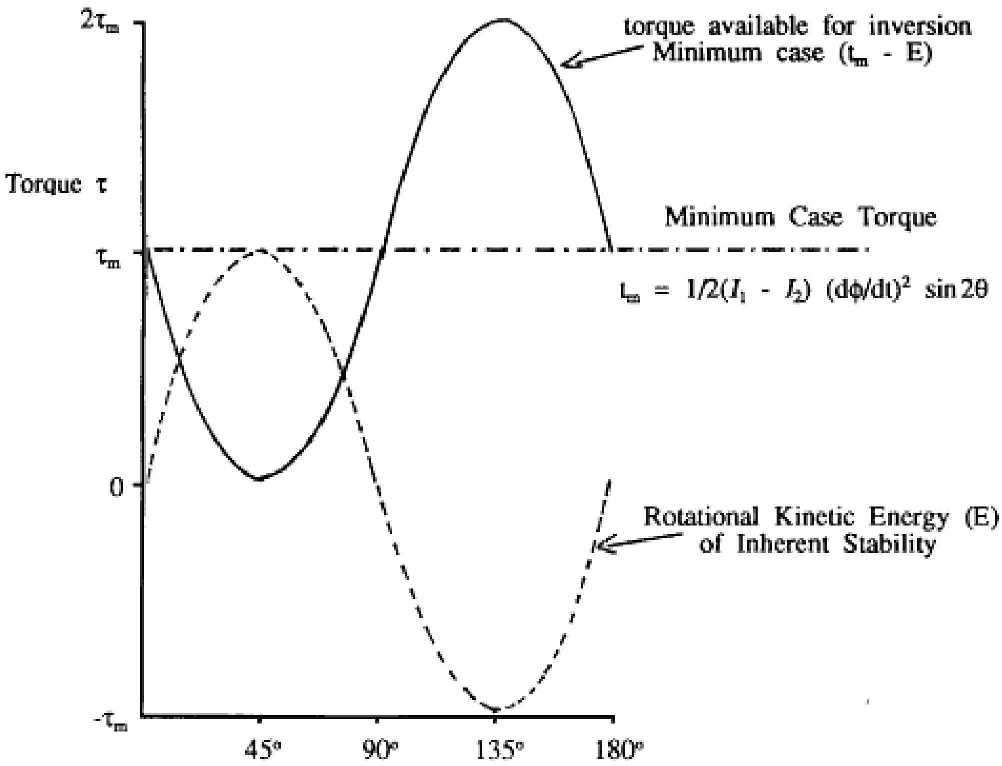

Figure 4: Effects of Stability of a Rigid Earth on the Torque Available for Inversion

M will be invariant; and the coning motion would persist indefinitely.

7.3 However, all the preceding discussion has been for a rigid model Earth as postulated in 1.3. The real Earth, as Warlow repeatedly emphasises [6], is plastic; and he alludes to a paper by Gold showing that if Earth's axes of spin and figure become misaligned, and in the absence of other effects:

> ... the axis of symmetry would approach the axis of rotation by ten per cent of their regular separation in each period of fourteen months [7].

From this it can be deduced that a misalignment of 22.5° would reduce to 1/4", its present value, in a period of about 140 years. The mechanism by which the axis of symmetry would approach the spin axis would be a progressive re-adjustment of Earth's shape, not a rotation of Earth's material to its original orientation in inertial axes. Thus in a period of less than 150 years, short by comparison with the 26,000 year period of the terrestrial precession, Earth would have achieved a rotation as smooth as that of the present; but the part of the lithosphere formerly at the poles would now lie about 22.5° from its original position, at a latitude of nearly 67.5°.

7.4 It is interesting that the residual shift in the spin axis direction should be so small, as Earth's spin axis is inclined at 67° to the plane of the ecliptic. If the 23° rotation which this seems to imply was caused by a single BRIPS, the rate of secondary rotation must have been high, which would point towards a very large and/or sustained torque, but one which obviously did not shatter the Earth. Prolonged subjection to a stream of 'cosmic' water is one - though not the only - possibility; but that is a separate issue and is not pursued further here.

8. Conclusion

I have reviewed Dr Slabinski's dynamical objections to an inversion of the Earth on its spin axis, and found that not one of them supports his conclusion that such an inversion, under the gravitational influence of a passing planetary body, is impossible. Of the three separate objections he raises, the first was found to be invalid for inversion periods and torques lying within the ambit suggested by Warlow, the third to be semantically correct but dynamically wrong, and the second to be wrong in every respect. A rigorous calculation of the gravitational torque showed a wide range of admissible values for the mass and passing distance of a cosmic body which could invert Earth in a matter of days. Dr Slabinski's calculation of torque impulse was found to be in the grossest possible error.

I conclude that there is no need to appeal to electromagnetic forces to invert the Earth (while not excluding the possibility that they would play some - perhaps even a major - part in any close cosmic encounter). Gravitational torques about the x_2 and x_3 axes suffice for the inversion. Dr Slabinski's requirement for a torque component along the x_1 axis is wrong. Those who support his non-rigorous analysis could do worse than to take a refresher course in rotational dynamics.

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