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GRAVITY AND EXPANDING EARTH

Abstract. The analysis of different clues indicating a variation of the local gravity (*g*) through geological time is performed. The examined data come from Astrogeodesy (PM and TPW), Paleogeography, Tidal torques, J_2 variation, and paleogravity data from Geology. It is shown that a joint reasoning about all these data can constrain the possible variation rate of *G*, *g* and *M* (Earth's mass). The result is that, albeit in the past great theoretical and experimental efforts were made in proposing and searching for *G* time-decreasing, a major role could be played by an increase of *M*. The present analysis converges toward an upper limit of the Earth's mass variation in the order of magnitude of $\dot{M}/M = 10^{-9}$ /yr.

GRAVITÀ ED ESPANSIONE DELLA TERRA

Riassunto. Si è analizzata una serie di indizi che sembrano indicare una variazione della gravità locale (*g*) nel corso del tempo gelogico. I dati presi in considerazione provengono dalla Astrogeodesia (PM e TPW), Paleogeografia, sforzi torsionali mareali, variazione del J_2, dati geologici di paleogravità. Si dimostra che un ragionamento che consideri tutti questi dati insieme può porre dei limiti alla posibile variazione secolare di *G*, *g* ed *M* (massa della Terra). Il risultato della presente nota è che sebbene in passato siano stati fatti considerevoli sforzi teorici e sperimentali nel proporre e rilevare una diminuzione di *G* nel tempo, un ruolo più importante potrebbe essere giocato da un aumento secolare di *M*. La presente analisi converge verso un limite superiore per il tasso di variazione della massa terrestre nell'ordine di grandezza di $\dot{M}/M = 10^{-9}$ /anno

Symbols used

$J_2 = (C - A)/(M_E a^2) = 0.00108263$
$J_2 = (C - (A + B)/2)/(M_E R^2) = 0.001082627$ (Cox and Chao, 2002),
C, *A*, *B*, Earth's inertial moments polar and equatorials ($C > B \geq A$)
M_E = Earth mass
$R = (a^2 c)^{1/3}$
a = equat radius = $6.378137 \cdot 10^3$km = $6.378137 \cdot 10^8$cm
c = polar radius = $6.356752 \cdot 10^3$km = $6.356752 \cdot 10^8$cm
$f = (a - c)/a$ = flattening of the Earth
$h = \omega^2 a^3/(GM_E) \approx \omega^2 a/g_e$ = Helmert's geodynamical constant
g_e = equatorial gravity acceleration
m_m = Moon's mass
R_{Em} = Earth-Moon distance
v_m = Moon's orbital velocity

INTRODUCTION

The second zonal geopotential coefficient $J_2 = (C - A)/(M_E a^2) = 0.00108263$, also called dynamic shape factor, is linked to the flattening f of the Earth: $f = (a - c)/a = (3/2)J_2 + (h/2) = 0.00335281$, where $h = \omega^2 a^3/(GM_E) \approx \omega^2 a/g_e$ is the Helmert's geodynamical constant. The formula is only a first order approximation and of the same order should be considered all the results obtained by its use. The dynamic shape factor is not constant, and a secular variation of J_2 has been observed analysing the shift of the satellites orbits (Caputo, 1967; Kaula, 1983; Yoder, 1983).

The decrease of the J_2 has been detected since twenty years, and also episodic still unexplained irregularities are present (Cox and Chao, 2002). The observed best fit of the J_2 decrement is:

$$\Delta J_2/\Delta t = -2{,}8 \,.\, 10^{-11} \text{ /yr} ,$$

while the expected decrement caused by the purely secular decrease in centrifugal force because of the secular Earth's observed despinning is two orders of magnitude lower:

$$\Delta J_2/\Delta t = -5{,}53 \,.\, 10^{-13} \text{ /yr} .$$

The observed J_2 decrement is nearly exactly *50 times* the expected one, which is a large excess still without a definitive explanation, albeit it is grossly ascribed to a glacial rebound in the Recent. It should be noted that a deformation of the Earth that tapers the planet along the polar axis *50 times* the expected amount, should also produce a large excess of acceleration of the planetary spin, which is not observed. Indeed the observed despinning is nearly completely in agreement with the Moon-Sun tide action. Then it is easy to hypothesise that a *surplus of deceleration* – able to compensate the surplus of acceleration due to excess of changing shape, the tapering, – should be provided by other kinds of phenomena like – among possible others (capturing of space dust, meteoritic rain, ecc.) – an expansion of the globe. All these effects have to be evaluated in their effective order of magnitude, to decide which of them could be neglected.

EVALUATION OF THE EARTH' SHAPE VARIATION

To make clearer the ideas on the low order shape variation of the Earth, it is convenient to compute the value, in cm/yr, of the polar radius increase due to the J_2 decay.

If l=LOD = sidereal day = 86164. 103 s, and $\omega = 2\pi/l$ then:

$$f = (a-c)/a = (3/2)J_2 + 2\pi^2 \cdot a/l^2 g_e = (3/2)J_2 + (h/2) = 0.00335281, \qquad (2.1)$$

$$h = 4\pi^2 \cdot a^3/l^2(GM_E) \approx 4\pi^2 \cdot a/l^2 g_e = 3.\,4615 \cdot 10^{-3} \qquad (2.2)$$

$$\Delta l/\Delta\varpi t = +\,2.2 \cdot 10^{-3} \text{ s/century} \approx 0.4 \cdot 10^{-6} \text{s/yr (observed)} \qquad (2.3)$$

$$\omega = 7.292115 \cdot 10^{-5} \text{ rad/s}$$

If the Earth is expanding ($\Delta a/\Delta t > 0$), while its angular velocity changes due to any possible acting cause, then the annual Δf will be, performing the time derivative of (2.1):

$$\begin{aligned}\frac{\partial f}{\partial t} &\cong \frac{3}{2}\cdot\frac{\partial J_2}{\partial t}+\frac{1}{2}\cdot\frac{\partial h}{\partial t}=\frac{\partial}{\partial t}\left(\frac{3}{2}J_2+2\pi^2\cdot\frac{a}{l^2 g_e}\right)\\ &=\frac{3}{2}\cdot\frac{\partial J_2}{\partial t}+\frac{h}{2}\cdot\left(\frac{1}{a}\frac{\partial a}{\partial t}-\frac{2}{l}\frac{\partial l}{\partial t}-\frac{1}{g_e}\frac{\partial g_e}{\partial t}\right).\end{aligned} \tag{2.4}$$

Initially, to fix the ideas, g_e is considered constant, then (2.4) reduces to

$$\frac{\partial f}{\partial t}\cong\frac{3}{2}\cdot\frac{\partial J_2}{\partial t}+\frac{h}{2}\cdot\left(\frac{1}{a}\frac{\partial a}{\partial t}-\frac{2}{l}\frac{\partial l}{\partial t}\right). \tag{2.5}$$

from which it is possible to infer some quantitative evaluations.

Assumption is made that a small Earth's expansion is superimposed on the despinning and on the equator contraction produced as a consequence of the decrease in J_2. Assumption also is made that the special case occurs of a perfect compensation of the two competing effects on the equator length. This is equivalent to say that $\Delta a/\Delta t=0$. Then a further simplification of the equation (2.5) is obtained:

$$\frac{\partial f}{\partial t}\approx\frac{3}{2}\cdot\frac{\partial J_2}{\partial t}-\frac{h}{l}\frac{\partial l}{\partial t}\ . \tag{2.6}$$

And, putting in (2.6) the observed value of the J_2 time derivative

$$\frac{\partial f}{\partial t}\cong\frac{\Delta \mathrm{f}}{\Delta \mathrm{t}}\cong\ -4.2\cdot 10^{-11}/\mathrm{yr}-1{,}6098885.10^{-14}/\mathrm{yr}$$

The two terms in (2.6) are not in the same order of magnitude and then the value of $\Delta J_2/\Delta t = -2.8 \cdot 10^{-11}$/yr is not due only to the slowing down of the spin but it should be considered in excess because of other processes. A possible cause, the most probable, is the decay of the excess of the Earth's equatorial bulge – with respect to the perfect hydrostatic equilibrium – whose value is nearly 100m on the equatorial radius (Alessandrini and Papi, 1987; Alessandrini, 1989).

Recalling (2.1),

$$\frac{\partial f}{\partial t}=\frac{\partial}{\partial t}\left(\frac{a-c}{a}\right)=\frac{\partial}{\partial t}\left(1-\frac{c}{a}\right)=\frac{\partial c}{a\,\partial t}\quad ,$$

from which it is possible to compute the annual increase of the polar radius:

$$\frac{\partial c}{\partial t}=-\ a\frac{\partial f}{\partial t}\quad=-\ 6{,}378\cdot 10^{8}\mathrm{cm}\cdot\mathbf{(}-4{,}2\cdot 10^{-11}/\mathrm{yr})=0.26\ \mathrm{mm/yr}\ .$$

This variation of the polar radius is greater than the expected one due to the secular decreasing of the centrifugal force. This expected variation should be at least one order of magnitude lower. Assuming, optimistically, a possible increase of gravity

$$\frac{1}{g_e}\frac{\partial g_e}{\partial t} \cong 10^{-9} / \text{yr} \quad ,$$

it is possible to compute the contribution of the last term of (2.4) which is linked to gravity variations:

$$-\frac{h}{2g_e}\frac{\partial g_e}{\partial t} = -0.173 \cdot 10^{-11}/\text{yr}$$

This value is one order of magnitude less then the observed J_2 variation, and it would be still ten times lower if a value were assumed $dg_e/g_e dt \approx 10^{-10}$/yr, as most astronomical data seem to indicate, if compensative effects are absent. Only a variation in the order $dg_e/g_e dt \approx 10^{-8}$/yr would produce effects that could be comparable to the other terms, but this last order of magnitude would be in the range of the annual drift of the best modern superconductor gravimeters.

Finally, fixing in (2.4) the gravity variation at zero, and fixing optimistically ($\Delta a/\Delta t$) = 0.3 cm/yr, the modern contribution of the radius variation to the flatness variation is

$$\frac{h}{2a}\frac{\partial a}{\partial t} = 0.08156 \cdot 10^{-11}/\text{yr}.$$

Then, using the observed value of J_2 secular variation, all the four terms contributing to the flattening variation sum up as follow:

$$\frac{\partial f}{\partial t} = \frac{3}{2}\cdot\frac{\partial J_2}{\partial t} + \frac{h}{2}\cdot\left(\frac{1}{a}\frac{\partial a}{\partial t} - \frac{2}{l}\frac{\partial l}{\partial t} - \frac{1}{g_e}\frac{\partial g_e}{\partial t}\right) = F_j + F_r + F_l + F_g =$$
$$= (-4.2 + 0.08156 - 0.0016 - 0.173)\cdot 10^{-11}/\text{yr} \cong -4.3\cdot 10^{-11}/\text{yr},$$

while using the expected value, $-5.12 \cdot 10^{-13}$ (Varga, 2002), for a decreasing J_2 due only to tidal friction:

$$\frac{\partial f}{\partial t} = F_j + F_r + F_l + F_g = (-7.68 + 8.15 - 0.16 - 17.3)\cdot 10^{-13}/\text{yr} \cong -0.17\cdot 10^{-11}/\text{yr}.$$

Then this first order analysis – while cannot assure a high precision in the numerical computations – puts in evidence that albeit the F_g term is of preponderant importance in the group of the terms contributing to the flattening time derivative, this term – as also the others are – is practically unobservable because of the presence of the very high J_2 variation due to causes unrelated to the variable Earth's rotation. The gravitational term magnitude is also largely conjectural but also a dg/gdt in the 10^{-10} order of magnitude can give a substantial contribution to the sum. It is also important to notice that the gravitational term contains, in reality, the combination of G, the Newtonian gravitational constant, and M_E, the Earth's mass. The discrimination between both these two variable quantities and their effects is the subject of the next sections.

CLUES OF GRAVITY VARIATION FROM TIDAL TORSIONAL MOMENTS

Recently the problem of a possible variation of the gravity constant G has been enclosed among the problems geodesy must deal with and try to solve in the course of this millennium (Varga, 2002). A main clue of a gravity variation comes from astronomical considerations. Indeed, if the time derivative of the Earth's angular momentum – namely the total torsional torque – is considered:

$$\frac{\partial}{\partial t}\ (C\omega) = L\ , \tag{3.1}$$

It is possible to express L as time variation of the Earth-Moon angular momentum, which, in simplified pure circular orbits geometry, can be written:

$$L = \frac{1}{3}\cdot\frac{M_E m_m}{M_E + m_m}\cdot R^2{}_{Em}\cdot\frac{\partial v_m}{\partial t}. \tag{3.2}$$

Then only the Moon velocity time derivative $\partial v_m / \partial t$ must be known, for the comparison of the two terms of (3.1) to be possible, and this derivative can be deduced from the third law of Kepler

$$v^2{}_m R^3{}_{Em} = G(M_E + m_m),$$

by making its time derivative:

$$2v_m R^3{}_{Em}\frac{\partial v_m}{\partial t} + 3v^2{}_m R^2{}_{Em}\frac{\partial R_{Em}}{\partial t} = \frac{\partial G}{\partial t}(M_E + m_m) + G\frac{\partial(M_E + m_m)}{\partial t}. \tag{3.3}$$

To simplify the discussion, it can be assumed that G, M_E and m_m vary linearly and then that both $\partial G/\partial t$ and $\partial(M_E+m_m)/\partial t$ are constants.

$$\begin{aligned}\frac{\partial v_m}{\partial t} &= -\frac{3}{2}\cdot\frac{v_m}{R_{Em}}\frac{\partial R_{Em}}{\partial t} + \frac{\partial G}{\partial t}\frac{(M_E + m_m)}{2v_m R^3_{Em}} + \frac{G}{2v_m R^3_{Em}}\frac{\partial(M_E + m_m)}{\partial t} = \\ &= -\frac{3}{2}\cdot\frac{v_m}{R_{Em}}\frac{\partial R_{Em}}{\partial t} + Const_1 + Const_2.\end{aligned} \tag{3.4}$$

Putting $\frac{\partial v_m}{\partial t}$ in L we get:

$$\begin{aligned}\frac{\partial}{\partial t}(C\omega) = L = -\frac{1}{2}\cdot\frac{M_E m_m}{M_E + m_m}\cdot v_m R_{Em}\cdot\frac{\partial R_{Em}}{\partial t} + \frac{\partial G}{\partial t}\left(\frac{M_E m_m}{6v_m R_{Em}}\right) + \\ + \frac{\partial(M_E + m_m)}{\partial t}\left(\frac{M_E m_m}{M_E + m_m}\cdot\frac{G}{6v_m R_{Em}}\right).\end{aligned} \tag{3.5}$$

To perform a more complete discussion, I have not neglected the terms in which time derivatives of masses appear, as is normally done in literature (Burša, 1990; Varga, 2002). From astronomical data and from different tidal torque estimates we assume:

$$\begin{aligned}&\frac{\partial}{\partial t}=(C\omega)\approx -4.1\cdot 10^{16}\,Nm;\\&L_{atm}\approx 5\cdot 10^{15}\,Nm; L_{solid}\approx -5\cdot 10^{15}\,Nm; L_{liquid}\approx -5\cdot 10^{16}\,Nm;\end{aligned}\tag{3.6}$$

in which the atmospheric tide torque L_{atm} produces acceleration instead of a deceleration as the solid and liquid tides does. The liquid tide torque is one order of magnitude greater then the L_{atm} and L_{solid} which sums cancel one another out.

All these tide-terms must be enclosed in the mechanical term

$$-\frac{1}{2}\cdot\frac{M_E m_m}{M_E+m_m}\cdot v_m R_{Em}\cdot\frac{\partial R_{Em}}{\partial t}$$

of the equation (3.5), and then:

$$\begin{aligned}&\frac{\partial}{\partial t}(C\omega)=L\approx -4.1\cdot 10^{16}\,Nm=\\&=L_{atm}+L_{solid}+L_{liquid}+const\approx -5\cdot 10^{16}\,Nm+const.\end{aligned}\tag{3.7}$$

Where the two terms containing $\partial G/\partial t$ and $\partial(M_E+m_m)/\partial t$ are enclosed in *const*. To assure that the equal sign is satisfied in (3.7), *const* must be greater than zero (nearly equal to $0.9\cdot 10^{16}$Nm):

$$const=\frac{\partial G}{\partial t}\left(\frac{M_E m_m}{6v_m R_{Em}}\right)+\frac{\partial(M_E+m_m)}{\partial t}\left(\frac{M_E m_m}{M_E+m_m}\cdot\frac{G}{6v_m R_{Em}}\right)>0.\tag{3.8}$$

Consequently only three cases could be present:

$$\begin{aligned}&1)\ \frac{\partial G}{\partial t}\geq 0;\quad \frac{\partial(M_E+m_m)}{\partial t}\geq 0;\\&2)\ \frac{\partial G}{\partial t}\leq 0;\quad \frac{\partial(M_E+m_m)}{\partial t}> 0;\quad (|a|\leq|b|);\\&3)\ \frac{\partial G}{\partial t}> 0;\quad \frac{\partial(M_E+m_m)}{\partial t}\leq 0;\end{aligned}\tag{3.9}$$

Where *a* and *b* are the first and second addendum in (3.8). As can be seen in (3.9), the situation is more complex then previously stated by Varga (2002), who concludes – because of the *a priori* neglecting of the mass time derivatives – only $\partial G/\partial t$ >0 is possible, which in turn means a strong difficulty for the expanding Earth because an increasing *G* favours an elastic contraction of the planets. On the contrary, other possibilities also exist.

Case 1) in (3.9) can be judged to have low probability in nature, because the effect of a contemporaneous increase of *G* and *M* could be too strong on astronomical kinematics.

Case 2) in (3.9) is in agreement with accredited cosmological views and with some clues coming from geology (Mann and Kanagy, 1990; Neiman, 1990; Hurrell, 2001) which will be analysed in the following.

I made the explicit philosophical choice to exclude case 3) in (3.9) because I judge unrealistic a mass decreasing if the Universe is still in a state of indefinite forming.

INCREASE OF EARTH'S MASS COMPATIBLE WITH THE J_2 TIME RATE

The direction of the polar motion is 79°W. This fact has been variously interpreted, invoking different geological processes but only the hypothesis of the glacial rebound (Peltier, 1976; Peltier and Jiang 1996; Sabatini et al., 1982) have found more general consensus because the northern Canadian Shield and Siberia, were once covered by ice caps, on which real extents an ongoing debate is active today (Clark et al., 2001).

The complete derivative of J_2 should also take into account *a*, *G* and M_E variations. It is possible to put the time derivative of the dynamic shape factor in terms of relative variations of the implied factors:

$$J_2 = \frac{kh}{3} \qquad \text{(Varga, 2002)}$$

$$\frac{\mathrm{d}J_2}{\mathrm{d}t} = \frac{k}{3}4\pi^2\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{a^3}{l^2GM_E}\right) =$$

$$= \frac{4}{3}k\pi^2\left[-2\left(\frac{a^3}{l^3GM_E}\right)\frac{\mathrm{d}l}{\mathrm{d}t} + 3\left(\frac{a^2}{l^2GM_E}\right)\frac{\mathrm{d}a}{\mathrm{d}t} - \left(\frac{a^3}{l^2G^2M_E}\right)\frac{\mathrm{d}G}{\mathrm{d}t} - \left(\frac{a^3}{l^2GM^2{}_E}\right)\frac{\mathrm{d}M_\mathrm{E}}{\mathrm{d}t}\right] = \quad (4.1)$$

$$= \frac{k}{3}h\left(-\frac{2}{l}\frac{\mathrm{d}l}{\mathrm{d}t} + \frac{3}{a}\frac{\mathrm{d}a}{\mathrm{d}t} - \frac{1}{G}\frac{\mathrm{d}G}{\mathrm{d}t} - \frac{1}{M_E}\frac{\mathrm{d}M_\mathrm{E}}{\mathrm{d}t}\right),$$

and to evaluate the possible weight of each addendum in the determination of the J_2 time variation. Then, assuming the special case of d*a*/d*t*=0, the importance of the two last addenda d*G*/d*t* and d*M*/d*t* in (4.1) become clear. We know the annual variation of LOD to be $0.4 \cdot 10^{-6}$s/yr, and also that this value is responsible only for 1/50 of the expected J_2 decrement ($-5.53 \cdot 10^{-13}$ vs. $-2.8 \cdot 10^{-11}$ /yr). Then nearly all the observed $\mathrm{d}J_2/\mathrm{d}t$ value could came – in absence of spurious deformational processes – from the terms:

$$\frac{\mathrm{d}J_2}{\mathrm{d}t} = \frac{k}{3}h\left(-\frac{1}{G}\frac{\mathrm{d}G}{\mathrm{d}t} - \frac{1}{M_E}\frac{\mathrm{d}M_\mathrm{E}}{\mathrm{d}t}\right) = \qquad (4.2)$$

$$= 1.0826 \cdot 10^{-3}\left(10^{-10} + 3.0 \cdot 10^{-9}\right) \neq 2.8 \cdot 10^{-11}\,/\,\mathrm{yr(observed)},$$

where I have put in the formula (4.2) a previous result based on PM and TPW considerations (Scalera, 2002) that bounds the variation of mass in the magnitude order of 10^{-9} of the Earth's mass (M_E= 5.9736 · 10^{27}g). This value is not adequate to ensure the equality sign in the equation. Then a mass variation of 10^{-9} is not sufficient to produce the observed J_2 time variation and it needs again to appeal to a possible slow decay of the excess of equatorial bulge. In any case the 10^{-9} value for mass variation is highly compatible – because it is well contained in – with the observed J_2 time rate.

An increase of the Earth's radius, say near 0.3 cm/yr, provides the contribution

$$\frac{k}{3}h\left(\frac{3}{a}\frac{\mathrm{d}a}{\mathrm{d}t}\right) = 1.0826 \cdot 10^{-3}\left(0.470 \cdot 10^{-8} \times 0.3 / yr\right) = 0.153 \cdot 10^{-11} /\mathrm{yr}\ , \qquad (4.3)$$

still too small to be of importance.

TIME RATE OF *g* AND *M* FROM GEOLOGY

Mann and Kanagy (1990) found that in the geological past – up to Palaeozoic – the angles of repose of incoherent materials exceed modern angles. The reasoning is based on field data of fossil heaps and on simple mechanical considerations (Davidson, 1994).

From physics we know that in a heap of loose material the stress along a plane, at an angle α with respect to the horizon, can be written:

$$s = c + \frac{M}{A} g \tan\alpha \qquad (5.1)$$

with c = cohesion factor = 0 for uncemented heaps; then for loose materials:

$$s = \frac{M}{A} g \tan\alpha \qquad (5.2)$$

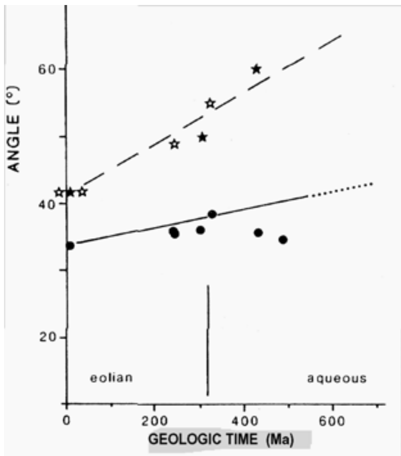

Fig.1 - The Mann and Kanagy (1990) field data for the angles of repose of uncemented materials.

The distribution of the data in Mann and Kanagy (1990) is neatly linear and if some effect provides an anomalous rising of the maximum angle in the deep past, we have to expect the same effect in more recent times and consequently a marked scattering of the data. It is not so, and this result should be considered a reliable one. Then, if the maximum shear stress does not change in the geological past:

$$\begin{aligned} &g_0 \tan\alpha_0 = g_{430} \tan\alpha_0, \\ &g_0 \tan 40° = g_{430} \tan 61°, \\ &g_{430} \cong 0.47 g_0, \end{aligned} \qquad (5.3)$$

and from (5.3) we can find the annual variation of the equatorial gravity acceleration:

$$\mathrm{d}g/g\mathrm{d}t \approx -0.5/430 \cdot 10^6 \mathrm{yr} = -1.16 \cdot 10^{-9}\ /\mathrm{yr}$$

and if we suspect some strata-compactation phenomenon that make the heaps flatter as soon as the geologic time passes, we should expect more enhanced slope of the heaps flanks. Hypothesizing a maximum angle of 70° at 430 Ma, we could obtain:

$$\mathrm{d}g/g\mathrm{d}t \approx (1-0.3)/430 \cdot 10^6 \mathrm{yr} = -1.63 \cdot 10^{-9}\ /\mathrm{yr}$$

This value, $\mathrm{d}g/g\mathrm{d}t \approx -10^{-9}$ yr, is one order of magnitude less than the value of mass variation which came from the d*J*/d*t* contributions consideration, but it is a combination of the sum of G and M_E time derivatives. Then assuming an average time variation of r equal to 1.5 cm/yr (Scalera, 2001, 2002) on a time window from Triassic to the Recent:

$$\frac{\partial g}{g \partial t} = -\frac{1}{g}\left(-\frac{GM_E}{r^3}\frac{\mathrm{d}r}{\mathrm{d}t} + M_E \frac{\mathrm{d}G}{r^2 \mathrm{d}t} + G\frac{\mathrm{d}M_E}{r^2 \mathrm{d}t} \right) \approx -10^{-9} \qquad (5.4)$$

$$\frac{1}{M_E}\frac{\mathrm{d}M_E}{\mathrm{d}t} \approx \frac{gr^2}{GM_E}10^{-9} + \frac{1}{r}\frac{\mathrm{d}r}{\mathrm{d}t} - \frac{1}{G}\frac{\mathrm{d}G}{\mathrm{d}t} \cong 10^{-9} + 2.5 \cdot 10^{-9} - \frac{1}{G}\frac{\mathrm{d}G}{\mathrm{d}t}. \qquad (5.5)$$

Then, if it is assumed that a time rate of G is negligible with respect to the time rate of M_E, the preceding formula again means that

$$\dot{M}_E / M_E \cong 10^{-9}$$

DISCUSSION AND CONCLUSIONS

The general conclusion of this note is that several different considerations lead to a preferred magnitude order for M_E variations of 10^{-9}/yr. The main clue to becoming aware that something anomalous is happening is the lack of increase of planetary spin in response to the excess J_2 time derivative. A braking process of an unknown nature – different from tides – should be hypothesized. As a matter of fact, the observed J_2 time derivative is fifty times greater then the expected one.

It should be considered that while the asymmetrical mass variation – in the order of magnitude of $M_E \cdot 10^{-11}$ /yr– is founded on the basis of the PM and TPW data (Scalera, 2002), the annual amount of symmetrical mass increase proposed in Scalera (2002) is not founded on astrogeodetic data, but is founded on paleogeographic reconstructions, which are not direct observations but are in turn founded on several assumptions. Then the real order of magnitude of the symmetrical part is less carefully bounded. However all the preceding considerations converge on an order of magnitude that could also be considered multiplied for a factor less than 1.0.

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