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Effects of Local Mass Anomalies in Eötvös-like Experiments

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Abstract

We consider in detail the effects of local mass anomalies in Eötvös-like experiments. It is shown that in the presence of an intermediate-range non-gravitational force, the dominant contributions to both the sign and magnitude of the Eötvös anomaly may come from nearby masses and not from the Earth as a whole. This observation has important implications in the design and interpretation of future experiments, and in the formulation of unified theories incorporating new intermediate-range forces.

The experiment of Eötvös, Pekár, and Fekete[1] (EPF) has recently been the subject of renewed interest following the observation[2] that it may contain evidence for the existence of a new intermediate-range coupling to baryon number or hypercharge. The suggestion for this coupling comes not only from the EPF data but also from earlier analyses of the $K^0 - \overline{K}^0$ system[3], as well as from geophysical determinations of the Newtonian constant as gravitation G.[4] Central to the argument that the effects in these systems may have a common origin is the claim that they can all be described quantitatively in terms of a common Yukawa potential $\Delta V(r)$,

$$\Delta V(r) = \frac{f^2}{r} e^{-r/\lambda}, \tag{1}$$

or perhaps a small number of similar potentials $\Delta V_i(r)$. Here f is the analog of the electric charge e (in Gaussian units), and from the geophysical data

$$(f^2/e^2) \cong (8 \pm 3) \times 10^{-39}. \tag{2}$$

The range of the force, λ, was quoted as (200 ± 50) m in Ref. 2, but subsequent work by Holding, *et al.*,[4] suggest that suggest that that λ could be as large as 10^4 m.

The critical question is whether $\Delta V(r)$ in Eq. (1), which arises from the geophysical data can quantitatively explain the EPF data as well. In Ref. 2, the geophysical and EPF data were compared by assuming an idealized model in which the only matter source in the EPF experiment was the Earth itself, which was taken to be a uniform sphere of radius R and the average density $\rho_\oplus = 5500\,\mathrm{kg/m^3}$. In the present paper, we refine this comparison by calculating more realistically the effects of the local matter distribution in the Eötvös experiment. Specifically, we show the following: *i*) In the presence of an intermediate-range force, local *horizontal* mass anomalies (*e.g.*, buildings or mountains) can be the dominant matter source in the Eötvös experiment, and their effects may be more important than those arising from the Earth as a whole, even though the Earth is the main source of the gravitational force. *ii*) These anomalies may determine both the magnitude and sign of the fractional acceleration difference $\Delta\kappa \equiv \kappa_1 - \kappa_2$ measured by EPF. For this reason, without a detailed knowledge of the environment, one cannot infer from the EPF data whether their results imply an attractive or a repulsive force. *iii)* Similar arguments indicate that the acceleration anomaly in Eötvös-like experiments can be deliberately enhanced by the presence of an appropriate horizontal mass distribution.

To derive our results we consider an Eötvös experiment in which two masses (of different chemical composition) are attached to the ends of a bar which is suspended by a torsion wire, as shown in Fig. 1. In its simplest form the experiment is performed by hanging the bar East-West, measuring the torque on the fibre, and then rotating the apparatus 180° and measuring the new torque. If there is a difference in the rate at which objects accelerate towards the Earth, then in principle this difference will show up as a difference in these two torques.

We first examine the effect of a hypercharge field due to a spherical Earth, which we assume to have a radially-symmetric density distribution, with $\bar{\rho}$ being the local mass density. From Eq. (1) and Fig. 2, the hypercharge force $B\vec{Y}$ due to the Earth on a point particle with hypercharge B is given by:

$$B\vec{Y} = Bm_{\mathrm{H}}\, \xi g\,(\bar{\rho}/\rho_{\oplus})\, \epsilon(R/\lambda)\, \hat{x}_3. \tag{3}$$

We have introduced the constant $\xi \equiv f^2/G_0 m_{\mathrm{H}}^2 \cong 0.01$, where G_0 is the laboratory value of G, m_{H} is the mass of ${}_1\mathrm{H}^1$, and

$$\epsilon(x) = \frac{3(1-x)}{x^3}(x\cosh x - \sinh x)e^{-x}. \tag{4}$$

For the case $R >> \lambda$, $\epsilon(R/\lambda) \to 3\lambda/2R$.

From Figs. 1 and 2 the net force $\vec{T}_{\mathrm{net}} = \vec{T}_1 - \vec{T}_2$ exerted by the fibre on the bar in Fig. 1 is

$$\vec{T}_{\mathrm{net}} = -(m_1 - m_2)a\sin\theta\,\hat{x}_2 - [(m_1\kappa_1 - m_2\kappa_2)g - (m_1 + m_2)a\cos\theta]\hat{x}_3. \tag{5}$$

where a is the centrifugal acceleration due to the rotation of the Earth, θ is the latitude at which the experiment is being performed, and where we have defined $y = Y/m_{\rm H}$, $\mu = m/m_{\rm H}$, and $\kappa = (1 - By/\mu g)$. Additionally we have defined the coordinate system such that $\hat{x}_1$ is directed West, $\hat{x}_2$ South, and $\hat{x}_3$ antiparallel to the direction of acceleration of gravity $\vec{g}$. The suspension wire (assumed to be massless) will be parallel to $\vec{T}_{\rm net}$, and hence the angle β that the suspension wire makes with respect to $\vec{g}$ is given by

$$\tan\beta = \frac{(m_1 - m_2)a\sin\theta}{(m_1\kappa_1 - m_2\kappa_2)g - (m_1 - m_2)a\cos\theta} \approx \frac{a\sin\theta}{g}. \tag{6}$$

Note that this angle β defines "true vertical" for this configuration of masses, and that in general $\vec{T}_1$ and $\vec{T}_2$ will not be parallel to $\vec{T}_{\rm net}$. We define an "apparatus" coordinate frame, in which $\hat{x}'_1$ is directed along the torsion bar pointing towards mass m_2, $\hat{x}'_2$ is the normal to the mirror attached to the torsion wire, and $\hat{x}'_3$ is the axis of rotation of the torsion balance. Then

$$\begin{aligned} \hat{x}'_1 &= \hat{x}_1, \\ \hat{x}'_2 &= \cos\beta\,\hat{x}_2 + \sin\beta\,\hat{x}_3, \\ \hat{x}'_3 &= -\sin\beta\,\hat{x}_2 - \cos\beta\,\hat{x}_3. \end{aligned} \tag{7}$$

The net torque on the fibre is given by

$$\vec{\tau}_{\rm net} = (m_1\ell_1\kappa_1 - m_2\ell_2\kappa_2)g - (m_1\ell_1 - m_2\ell_2)a\cos\theta\,\hat{x}_2 - (m_1\ell_1 - m_2\ell_2)a\sin\theta\,\hat{x}_3. \tag{8}$$

and the balance condition (*i.e.*, that there is no net torque about the $\hat{x}'_2$ axis) implies

$$m_2\ell_2 = m_1\ell_1\frac{\kappa_1 g\cos\beta - a\cos(\theta - \beta)}{\kappa_2 g\cos\beta - a\cos(\theta - \beta)} = m_1 l_1 - \mathcal{O}(\kappa_1 - \kappa_2). \tag{9}$$

From Eq. (6) we have $a\sin\theta \cong g\tan\beta \cong g\sin\beta$ (since β is small), and combining (8) and (9) we find

$$\hat{x}'_3 \cdot \vec{\tau}_{\rm net} \cong -m_1\ell_1(\kappa_1 - \kappa_2)a\sin\theta. \tag{10}$$

This gives the desired Eötvös result relating the torque about the fibre axis to the anomalous acceleration difference $\Delta\kappa = \kappa_1 - \kappa_2$, for the case where local mass anomalies have been ignored.

We next wish to consider the effects of local mass asymmetries on $\Delta\kappa$. The EPF experiments were carried out in an exterior room of a building on the ground floor facing South, with tall buildings immediately to the South.[1] For illustration, we consider only the effects due to the laboratory building in which the experiment was performed, though we cannot be certain whether this building was the dominant local mass asymmetry. The center of inertia of the building will be taken to lie directly to the North of the apparatus, with the line connecting the common centers of inertia of the test system and the building making an angle ϕ with respect to the horizontal as in Fig. 2. We then obtain an additional force component acting on the test mass due to the hypercharge field of the building, which for present purposes we will approximate by a sphere of radius R' and a mass M':

$$B\vec{Y}' = Bm_{\mathrm{H}}\,\xi g'(r)\,(1 - r/\lambda)e^{-r/\lambda}F(R'/\lambda)(\cos\phi\hat{x}_2 - \sin\phi\hat{x}_3), \tag{11}$$

where $g'(r) \cong G_0 M'/(R')^2$. Here r is the distance from the center of inertia of the building to the center of inertia of the apparatus and $F(x) = 3(x\cosh x - \sinh x)/x^3$. The gravitational force due to the building $\vec{g}'(r)$ is then

$$\vec{g}'(r) = g'(r)(-\cos\phi\hat{x}_2 + \sin\phi\hat{x}_3). \tag{12}$$

Proceeding as before we find that Eq. (10) generalizes to

$$\hat{x}_3' \cdot \vec{\tau}_{\mathrm{net}} \cong -m_1\ell_1[(\kappa_1 - \kappa_2)a\sin\theta - (\kappa_1' - \kappa_2')g'(r)\cos(\phi + \beta)], \tag{13}$$

where we have defined $\kappa' = (1 - By'/\mu g')$. Using

$$(\kappa_1 - \kappa_2) = -\frac{y}{g}\left(\frac{B_1}{\mu_1} - \frac{B_2}{\mu_2}\right), \qquad (\kappa_1' - \kappa_2') = -\frac{y'}{g'}\left(\frac{B_1}{\mu_1} - \frac{B_2}{\mu_2}\right), \tag{14}$$

Eq. (13) reduces to

$$\hat{x}_3' \cdot \vec{\tau}_{\mathrm{net}} = m_1\ell_1\left(\frac{B_1}{\mu_1} - \frac{B_2}{\mu_2}\right)\left[\frac{a\sin\theta}{g}y - y'\cos(\phi + \beta)\right]. \tag{15}$$

To explore the consequences of Eq. (15) we consider representative values of y' for typical present-day institutional buildings.[5] Consider as an example, a 4-story building with each floor having dimensions $(30-50)\,\text{m}\times(30-50)\,\text{m}\times 3\,\text{m}$, and likewise for the basement. Then for $\xi = 0.01$ and $\lambda = 200\,\text{m}$, we find

$$1.5 \lesssim \frac{y'_{\text{building}}}{(ya/g)\sin\theta} \lesssim 5. \qquad (16)$$

We observe that the contribution y' to the torque in Eq. (15) from the building is comparable to or larger than that arising from the Earth itself. Moreover, since the effect of the basement is that of a "hole" in the otherwise uniform distribution of the Earth, it acts as an *attractive* source. It follows that the net sign of the term in square brackets in Eq. (15) depends on the actual configuration and location of the local mass distribution, and cannot be fixed in the absence of more detailed information. Quantitatively, the typical buildings we have described would have a mass $M' = (2-5)\times 10^6\,\text{kg}$, but the basement would correspond to a hole with a "missing mass" of $(8-20)\times 10^6\,\text{kg}$, assuming $\bar{\rho} = 2750\,\text{kg/m}^3$. The actual EPF experiment took place over a basement whose approximate dimensions[6] were $50\,\text{m}\times 25\,\text{m}\times 4\,\text{m}$, which would thus correspond to a "missing mass" of approximately $14\times 10^6\,\text{kg}$. Thus the dominant contribution in this case would come from the basement.

For future purposes it is also convenient to display the contributions of the building and the hole in (15):

$$\hat{x}'_3 \cdot \vec{\tau}_{\text{net}} = m_1 \ell_1 \left(\frac{B_1}{\mu_1} - \frac{B_2}{\mu_2}\right)\left[\frac{a\sin\theta}{g}y - y'_{\text{building}}\cos(\phi-\beta) - y'_{\text{hole}}\cos(\phi'-\beta)\right], \qquad (17)$$

where ϕ' is the angle between the horizontal and the line connecting the centers of inertia. It follows from (17) that for the actual conditions of the EPF experiment, modeled as we have here, the sign of the EPF results would correspond to a *repulsive* force, and the magnitude of $f^2\lambda$ implied by their data would be smaller by a factor of $(6-15)$.

Eq. (17) and its consequences apply not only to the original EPF experiment but also to present and future Eötvös experiments designed to be sensitive to intermediate-range forces. To start with it follows from the preceding discussion that the proportionality factor relating $\Delta a/g$ and $\Delta(B/\mu)$ in Eq. (4) of Ref. 2 is not a fundamental physical constant, since it depends directly on $\epsilon(R/\lambda)$ or its generalization $F_{local}(\lambda)$ which describes the local matter distribution. For this reason the measured values of $\Delta a/g$ in different experiments may not agree for the same pair of materials. Hence to check the EPF results it is not sufficient to remeasure $\Delta a/g$ for a single pair, since it is only the pattern of points arising from the correlation of $\Delta a/g$ with $\Delta(B/\mu)$ that has an unambiguous physical interpretation. Another consequence of (17) is that since $F(R'/\lambda)$ in (11) is close to unity for $R' << \lambda$, one can enhance the fractional acceleration difference $(\kappa_1' - \kappa_2')$ in (14) by carrying out an experiment measuring the horizontal torque on an Eötvös balance in the vicinity of an appropriately chosen mountain or cliff for which $R' << \lambda$. In such a case $\Delta a/g'$ can be made as large as $(10^{-4} - 10^{-5})$ compared with $\Delta a/g \cong (10^{-8} - 10^{-9})$ measured by EPF. Furthermore, such an experiment lends itself naturally to determining λ, which can be accomplished by varying the distance between the apparatus and the horizontal source.

Up to this point, we have assumed that all of our measurements have been made with the bar aligned in an East-West direction, so that only North-South mass asymmetries would have an effect on the apparatus. However, in the original Eötvös experiment[1] measurements were also made with the bar aligned North-South (to correct for effects due the local gravity gradients), so that East-West asymmetries must also be considered in properly interpreting the results of Ref. 1. We have also assumed that the experiment was performed in a region where the surface of the Earth was horizontal. The effect of performing the experiment on an inclined plane is to rotate the direction of $\vec{Y}$ relative to $\vec{g}$. If we assume for illustration that the inclination of the ground level is in the North-South direction, then an angle of inclination of only 1° would produce an effective torque in the apparatus 5 times larger than that due to a spherical Earth. Other geophysical effects, such as local density variations, could produce even larger effects, as has been pointed out to us recently by Reasenberg.[7]

We next consider the effects of a non-spherical Earth by assuming that the Earth elastically deforms so that its surface lies along an equipotential of its combined gravitational field $\vec{g}(\vec{r})$ and its rotational field $\vec{a}(\vec{r})$. Under these conditions, the vector sum of $\vec{g}$ and $\vec{a}$ will be normal to the tangent of the surface at each point, and hence the vertical axis $\hat{x}_3'$ of the apparatus will be normal to the surface of the Earth. However, the Earth's hypercharge field $\vec{Y}$, which is primarily determined by the local matter distribution, will also be normal to the surface of the Earth. Hence, under these circumstances $\vec{Y}$ will be parallel to the vertical axis of the apparatus $\hat{x}_3'$, and the net torque about $\hat{x}_3'$ due to $\vec{Y}$ will be rigorously zero. From this we see that if an Eötvös experiment were performed over a deep lake, there would be no observable effect in the torsion balance. Also, since the deviation from vertical of $(\vec{a} - \vec{g})$ is only $70''$ of arc even in the vicinity of Mount Everest[8], this would contribute an effect which is typically less than 1/10 that due to the first term in (17) (in the absence of local mass asymmetries).

Finally we conclude with a discussion of the relevance of the present work to the formulation of unified theories incorporating an intermediate-range hypercharge or baryon number coupling. In the present context the critical question is whether the EPF data suggest an attractive force, which could arise naturally from scalar and/or tensor fields, or a repulsive force, whose most likely source would be a vector field. A number of authors[9] have correctly pointed out that the EPF data, when taken in conjunction with the simplified model of the matter distribution assumed in Ref. 2, do indeed imply an attractive force. If this were in fact the case, one would be confronted with the puzzle of why the sign of the force as implied by the EPF results was opposite to that suggested by the geophysical data.[4] What we have shown here is that neither the magnitude nor the sign of the effective hypercharge coupling can be extracted unambiguously from the EPF data without a more detailed knowledge of the local matter distribution. The sign of the EPF anomaly was fixed in Ref. 2 by assuming that the EPF data arose from the same repulsive source that is suggested by the analyses in Ref. 4. Future experiments will clearly be able to determine the sign of any nonzero acceleration anomaly, and hence to establish whether its source is an attractive or repulsive force.

After completing this work, we received a preprint from M. Milgrom in which similar results were obtained.

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(a) On leave from Brookhaven National Laboratory.

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Figure Captions

1. Schematic diagram of torsion balance. m_1 and m_2 represent the test masses, and ℓ_1 and ℓ_2 their separations from the axis of rotation of the torsion bar.

2. Diagram of forces acting on a mass m from a spherical Earth. $B\vec{Y}'$ and $m\vec{g}'$ represent respectively the forces due to the hypercharge and the gravitational field of a nearby local mass distribution (anomaly).

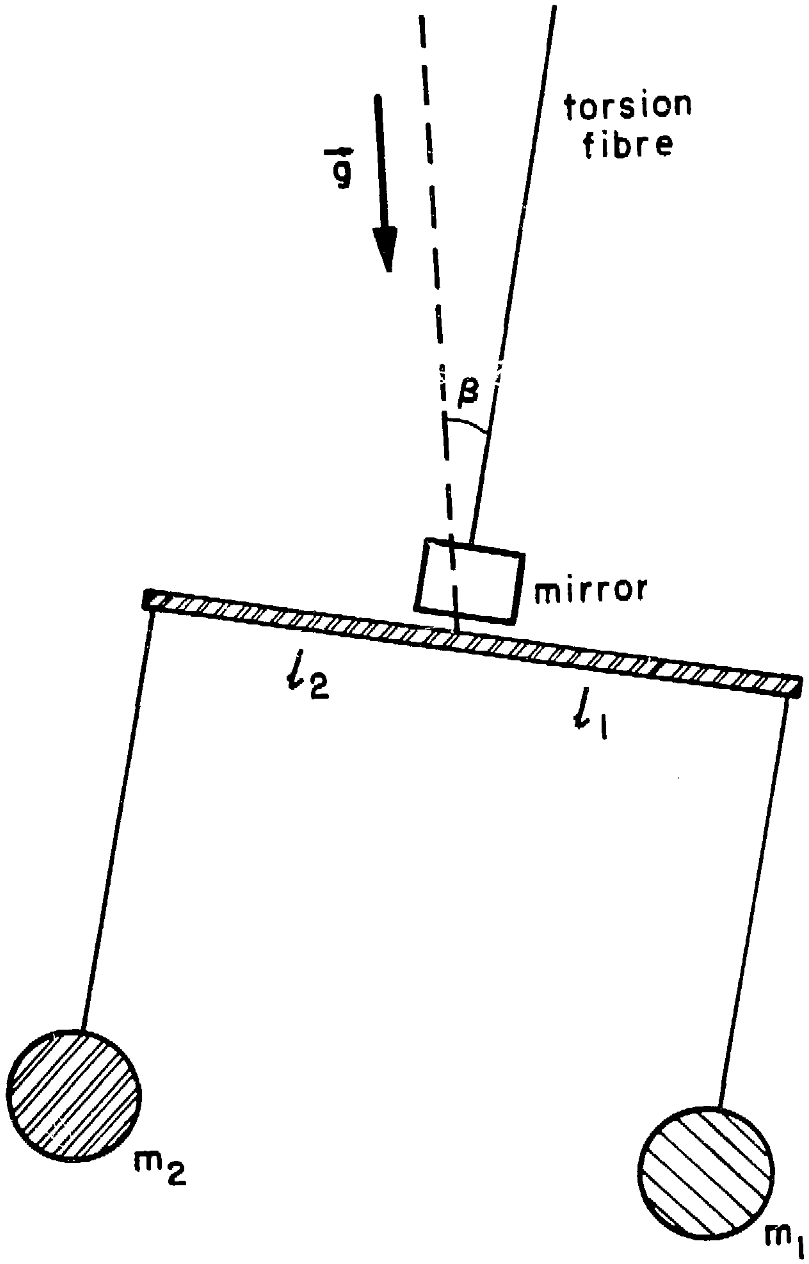

Fig 1

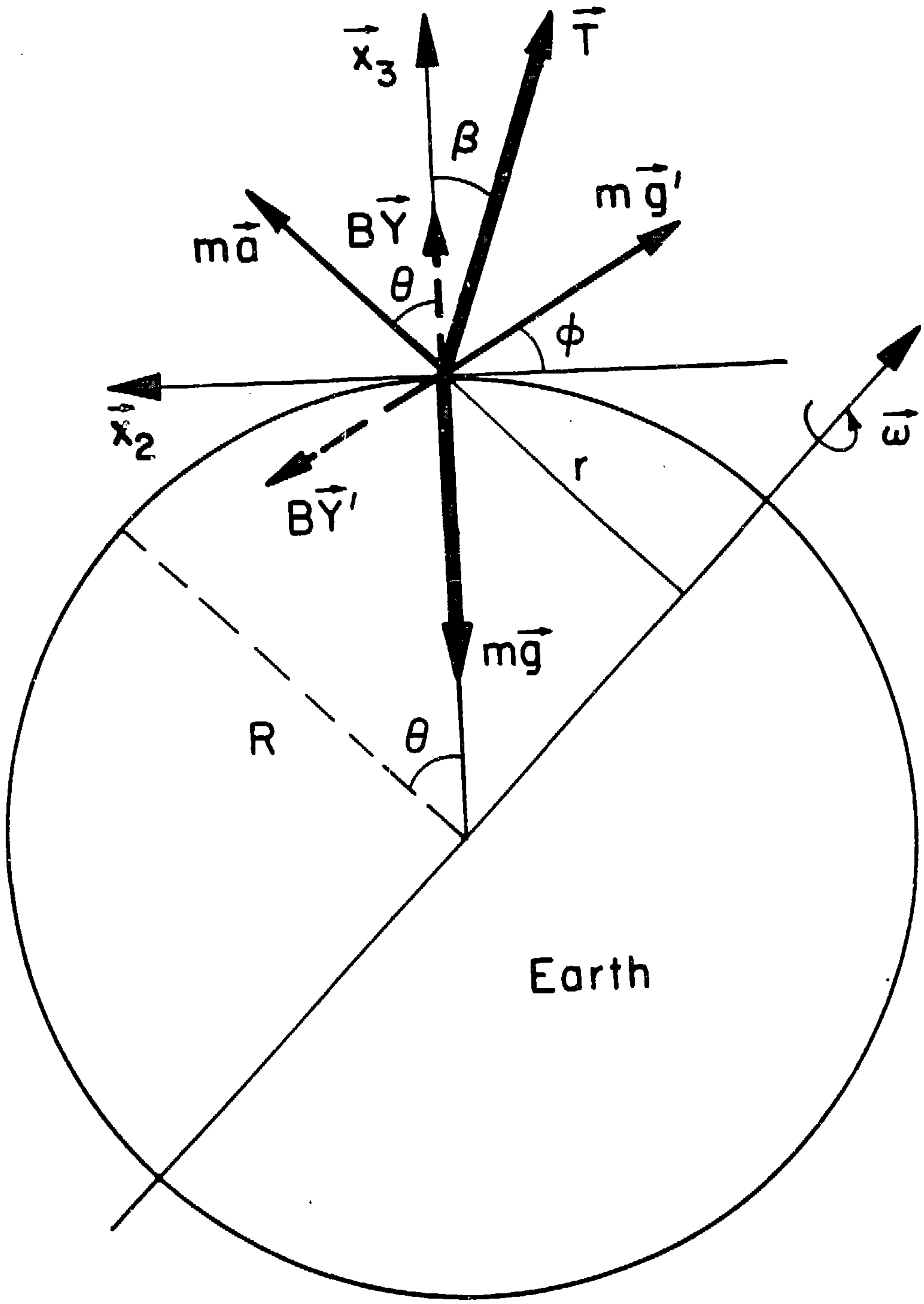

Fig. 2