Pramāṇa – J. Phys., Vol. 32, No. 3, March 1989, pp. L303–L306. © Printed in India.

A satellite-borne experiment to study the fifth force

R COWSIK, N KRISHNAN, S UNNIKRISHNAN,
S N TANDON and P SARASWAT
Tata Institute of Fundamental Research, Bombay 400 005, India

MS received 16 August 1988; revised 3 March 1989

An experiment with a satellite-borne torsion balance capable of measuring the hypothetical fifth force which couples to baryon number or lepton number with a strength $\sim 10^{-11}$ of gravity and range $\sim 10^{9}$ cm is described.

Keywords. Gravitation; space experiments; fifth-force.

PACS No. 04·90

The possible existence of a long-range force which couples to an additive quantum number such as the baryon number (Lee and Yang 1955) has come recently under the careful scrutiny of the physics community (Fischbach *et al* 1986, 1988; Rujula 1986; Glashow 1986; Cowsik *et al* 1988a for a detailed review). Following the suggestion of Fischbach *et al* (1986) that the residuals in the classic experiments of Eötvös, Pekar and Fekete (1922) indicate the existence of such a force with a strength $\sim 10^{-2}$ of gravity per atomic mass unit and a range $\sim 10^{3}$–10^{5} cm. In making this suggestion they also identified this force as the possible cause for the difference between the measurements of the dependence of earth's gravity with depth in mines and that expected from surveys of density of the terrain (refer to Stacey *et al* 1987 for a review of these studies). In the two years that have elapsed since the resurgence of interest in these studies several new experiments on the existence of such a new force have been conducted (Thieberger 1987; Stubbs *et al* 1989, Adelberger *et al* 1987; Boynton *et al* 1987; Niebauer *et al* 1987; Eckhardt *et al* 1988; Fitch *et al* 1988; Moore *et al* 1988; Speake and Quinn 1988 and Cowsik *et al* 1988b). These studies indicate that considerable uncertainties exist and fresh efforts should be directed towards a search for composition dependent forces whose range could be quite different from that estimated earlier on geophysical grounds. In this paper we propose a satellite-borne experiment which makes use of a new type of torsion balance (Cowsik 1981, 1982; Cowsik *et al* 1982) to study this force with considerably higher sensitivity than before.

The balance consists of a sphere of uniform macroscopic density but has different composition in its two hemispherical parts; this is anchored with a thin torsion fibre along a common diameter, as shown schematically in figure 1. A thin coating of gold on the surface ensures uniform reflectance. There are two basic advantages this balance has over the design adopted by Eötvös and others. The first relates to the effects of spatial gradients in gravity over the object. A mass M located at $\mathbf{R}$ will, in general, generate a torque $\boldsymbol{\tau}$ on any body with a density distribution $\rho(\mathbf{r})$: with obvious notation

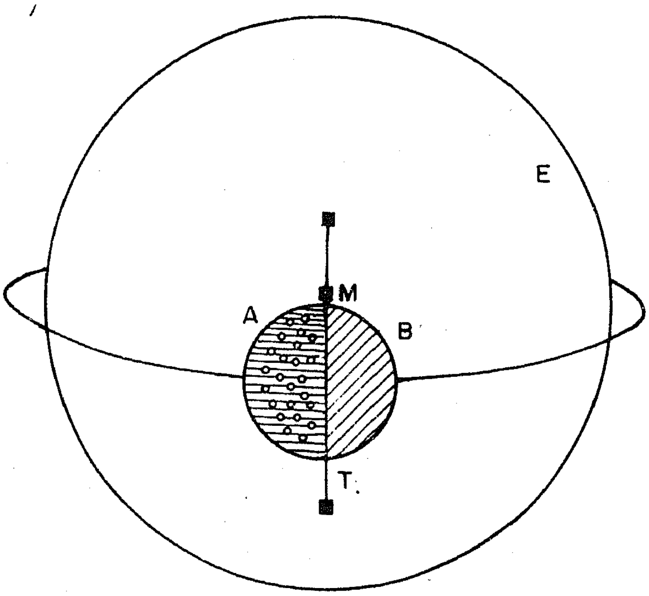

Figure 1. Schematic of torsion balance. A—Porous lead hemisphere to match the density of copper hemisphere; B, M—mirror for measurement with an optical autocollimator; T—the torsion fibre anchored at the ends and E—the earth.

we have

$$\tau_k = \sum_{ij\alpha} \int \frac{3GM}{R^5} \varepsilon_{ijk} R_\alpha r_\alpha r_j \rho(\mathbf{r})\, \mathrm{d}^3 r \equiv \frac{GM}{R^5} \varepsilon_{ijk} Q_{i\alpha} R_j R_\alpha . \tag{1}$$

Here **r** is the coordinate system fixed with the centre of mass of the body. It is interesting to note that this torque vanishes for the spherically symmetric $\rho(\mathbf{r})$ of interest here. The second advantage relates to the symmetry of the surface A of the body; for specular reflection of radiation and of gas molecules, which are important sources of noise in most experiments due to finite time varying gradients in temperature, the momentum transfer is normal to the surface element and the torque induced by it is proportional to $\mathbf{r}_s \times \mathrm{d}\mathbf{A}$ which again vanishes for a sphere. Also, even for diffusive scattering on the surface the average transfer of momentum is normal to the surface and leads to zero average torques on the sphere as in the case of specular reflection. This advantage of having the surface area of the balance rotationally symmetric about the torsion axis has not been discussed in earlier reviews; see for example the excellent review by Everitt (1977).

The advantages of setting up such a system in an artificial satellite orbiting the earth are three-fold: (i) For sufficiently long range for the fifth force its effect on the satellite-borne instrument is proportional to the acceleration due to earth's gravity $g \sim 10^3\,\mathrm{cm\,s^{-2}}$ and this is much larger than the accelerations that can be generated with laboratory masses $\sim 10^{-6}\,\mathrm{cm\,s^{-2}}$. (ii) The composition dependent torque τ_c on the balance will be sinusoidal with a period of $T_s \sim 5000\mathrm{s}$ equal to the orbital period of the satellite

$$\tau_c \approx g\alpha\Delta B \tfrac{3}{16} m r_s \sin 2\pi t/T_s . \tag{2}$$

Here α is the factor by which the new force is weaker than gravity and ΔB is the fractional difference in the number of baryons in the two halves of the sphere whose mass and radius are m and r_s respectively. By choosing the diameter and the length of the torsion fibre suitably the natural period of the balance can be made close to the orbital period so that the balance will resonate with the driving torque, (iii) in the weightless conditions on the satellite the torsion fibre can be kept sufficiently thin to achieve the requisite long period without the constraints placed by the tensile strength of the fibre which are relevant in an earth-bound laboratory.

Under conditions of resonance and for times shorter than the damping time the amplitude $a(t)$ of the torsion balance will increase linearly with time

$$a(t) \approx \frac{\tau_c}{I\omega^2}\frac{\omega t}{2} \approx \frac{g\alpha\Delta B m r_s}{\frac{2}{5} m r_s^2}\frac{3}{8}\frac{t}{2}\frac{T_s}{2\pi} \approx 0{\cdot}1\,\frac{g\alpha\Delta B T_s t}{r_s}. \tag{3}$$

Taking $r_s \sim 5\,\mathrm{cm}$, $t \sim 1$ day $\sim 10^5\,\mathrm{s}$ and $\Delta B \sim 10^{-3}$ as typical values we see that the amplitude increases at the rate of $10^7\,\alpha$ per day. Since inertial guidance systems and star-sensors are capable of measuring $\sim 10^{-8}$ rad, it may not be a formidable task to measure changes in $a(t)$ which are ~ 50 times larger say $\sim 5{\cdot}10^{-7}$ rad per day. Thus even values of α is small as $\sim 10^{-14}$ would become measurable in this set-up, in principle. However, to assess the actual performance it is important to estimate the amplitude of various noise terms. (For a careful and detailed study of noise and perturbating effects on experiments in earth-orbit, see Worden 1976). Variations of magnetic field strength and temperatures in the apparatus can be shielded adequately to cause no serious problems. The most serious sources of noise probably arise from non-uniformity of the density distribution and the non-sphericity of the ball used in the experiment; without a major effort these cannot be reduced to below $\sim 10^{-4}$. Such an imperfect sphere will have various components of quadrupole moment randomly at levels of $\sim 10^{-4}\,m r_s^2$ which could be very serious but for the fact that their coupling to gradients in earth's gravity generates torques only at even harmonics of the orbital frequency as is made obvious by the quadratic dependence of τ on R in (1). But since the duration of observation is limited the effects of the higher harmonics cannot be filtered out completely. If the observation lasts for n orbits of the satellite the best possible reduction of the higher harmonics is only by a factor of $\sim n^{-2} \sim 10^{-2}$ for $n \sim 10$, i.e. one day's observation. The amplitude of the gradient torque τ_n is inversely proportional to r_e, the radius of the earth and this $\tau_n \sim 3{\cdot}10^{-4}\ g m r_s^2/r_e$ becomes equal to that of the signal torque $g\alpha\Delta B m r_s$ for $\alpha = 3{\cdot}10^{-4}\ r_s/r_e\Delta B \sim 10^{-9}$. Since the best filtering factors are $\sim 10^{-2}$ the minimum value of α that can be measured is $\sim 10^{-11}$. Correspondingly the amplitude build up will be $\sim 10^{-4}$ rad/day and measurements of the angular position of the balance to an accuracy of about one second of arc $\sim 5{\cdot}10^{-6}$ rad would be adequate. If the space vehicle is not equipped with inertial guidance systems or star sensors of this accuracy, it would then become necessary to have on board a second torsion balance made with a sphere of uniform composition but identical to the main balance in other characteristics. Monitoring this allows one to subtract in real-time the torques induced by the non-inertial motions of the satellite.

Now if the range λ of the force is smaller than the radius of the earth then the sensitivity will progressively drop as the force weakens at the height of the satellite

$\sim 300\,\mathrm{km}$. These limits are listed below:

$$\begin{aligned} &\alpha_{\min} \sim 10^{-11}; \quad \lambda \geqslant r_e \\ &\alpha_{\min} \sim 10^{-11}\frac{r_e}{\lambda}; \quad 300\,\mathrm{km} \leqslant \lambda \leqslant r_e \qquad (4) \\ &\alpha_{\min} \sim 10^{-11}\frac{r_e}{\lambda}\exp\left(\frac{300\,\mathrm{km}}{\lambda}\right); \quad \lambda < 300\,\mathrm{km}. \end{aligned}$$

These limits of observational sensitivity make such an experiment attractive if λ is larger than $\sim 30\,\mathrm{km}$. Also, with torsion balances made of different pairs of substances as suggested by Glashow (1986), forces which couple to baryon number, lepton number or fermion number may be distinguished from one another.

Finally we note that the considerations of noise discussed here for a spherical mass are equally valid for torques in the direction of the suspension fibre for any distribution which is axially symmetric about this (Everitt 1977; Cowsik 1981, 1982; Cowsik *et al* 1982). Preliminary results from a laboratory version of such an experiment with a dual-ring of copper and lead of mass 1500 g have been obtained (Cowsik *et al* 1988b).

This research has been supported in part by the DST.

References

Adelberger E G, Stubbs C W, Rogers W F, Raab F J, Heckel B R, Gundlach J H, Swanson H E, and Watanabe R 1987 *Phys. Rev. Lett.* **59** 849

Boynton P W, Crosby D, Ekstrom P and Szumilo A 1987 *Phys. Rev. Lett.* **59** 1385

Cowsik R 1981 *Indian J. Phys.* **B55** 497

Cowsik R 1982 *Challenges in experimental gravitation & cosmology*, (A proposal submitted to Dept. Sci. Tech.)

Cowsik R, Tandon S N and Krishnan N 1982 *Sensitive test of the equivalence principle*, (A proposal submitted to Dept. Sci. Tech.)

Cowsik R, Krishnan N, Saraswat P, Tandon S N and Unnikrishnan C S 1988a, *Proc. symposium on relativistic gravitation*, COSPAR, (Finland: Espoo) (Eds) R Vessot and R Reasenberg

Cowsik R, Krishnan N, Tandon S N and Unnikrishnan C S 1988b *Phys. Rev. Lett.* **61** 2179

Eckhardt D H, Jekeli C, Lazarewicz A R, Romaides A J and Sands R W 1988 *Phys. Rev. Lett.* **60** 2567

Eötvös R V, Pekar D and Fekete E 1922 *Ann. Phys.* (*Leipzig*), **68** 11

Everitt C W F 1977 in *Proc. first Marcel Grossmann meeting on general relativity* (Ed). R Ruffini, (Amsterdam NH Publ. Co.)

Fischbach E, Sudarsky D, Szafer A, Talmadge C and Aaronson S H 1986 *Phys. Rev. Lett.* **56** 3

Fischbach E, Sudarsky D, Szafer A, Talmadge C and Aaronson S H 1988 *Ann. Phys.* (*NY*) **182** 1

Fitch V L, Isaila M V and Palmer M A 1988 *Phys. Rev. Lett.* **60** 1801

Glashow S L 1986 in *Proc. Rencontre de Moriond* (Tignes, France)

Lee T D and Yang C N 1955 *Phys. Rev.* **98** 1501

Moore G I, Stacey F D, Tuck G J, Goodwin B D, Linthorne N P, Barton M A, Reid D M and Agnew G D 1988 *Phys. Rev.* **D38** 1023

Niebauer T M, McHugh M P and Faller J E 1987 *Phys. Rev.* **59** 609

Rujula de A 1986 *Phys. Lett.* **B180** 213

Speake C C and Quinn T J 1988 *Phys. Rev. Lett.* **61** 1340

Stacey F D, Tuck G J, Moore G I, Holding S C, Goodwin B D and Zhou R 1987 *Rev. Mod. Phys.* **59** 157

Stubbs C W, Adelberger E G, Heckel B R, Rogers W F, Swanson H E, Watanabe R, Gundlach J H and Raab F J 1989 *Phys. Rev. Lett.* **62** 609

Thieberger P 1987 *Phys. Rev.* **58** 1066

Worden P 1976 Ph.D. Thesis Stanford University