# SEARCH FOR A NEW FORCE

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Horizontal motions of a well-balanced hollow copper sphere floating and almost totally submerged in a well insulated and shielded tank filled with water at 4 °C were measured in the vicinity of a large cliff. A motion was observed in a direction nearly perpendicular to, and directed away from, the face of the cliff. Conventional explanations for this effect have not been found. The observation is consistent with the existence of a weak, non-Newtonian, substance dependent, medium range force of a magnitude compatible with results deduced from gravity measurements as a function of depth in mines and with conclusions reached in a recent reanalysis of the Eötvös experiment. Further measurements with different elements and in different geometries will be required to establish definitely the existence, source, and description of such a new force.

In recent years there have been several experimental[1-5] and theoretical[6-12] suggestions of possible deviations from Newtonian gravity. In particular, studies performed over many years,[5] of the gravitational acceleration as a function of depth in mines have persistently indicated the presence of a small, non-Newtonian medium range repulsive component of the field. This component has been written[13] as a Yukawa term and the potential energy of two masses m and m' separated by a distance r is:

$$V = -G_\infty \frac{mm'}{r} \left(1+\alpha\, e^{-r/\lambda}\right) \tag{1}$$

where $G_\infty$ is the gravitational constant for $r \gg \lambda$. The best values[5] of the constants are $\alpha = -8 \cdot 10^{-3}$ and $\lambda \approx 200$ m with this last value being very uncertain.

Recently it was suggested[14] that the non-Newtonian term may be substance dependent and due to a hitherto unknown medium range baryon- baryon interaction. This assumption uncovers and explains[14] an apparently significant correlation in the old Eötvös torsion balance data[15] and also may provide a possible interpretation of recent anomalous results in the $\bar{K}^o$-$K^o$ system.[16] It was further shown[17] that, for medium range forces, local terrain inhomogeneities become the determining factor for interpreting the Eötvös results and that repeating such experiments in the vicinity of a large inhomogeneity such as a cliff would afford the highest sensitivity.

A differential accelerometer has been developed[18] which measures horizontal motions of a hollow copper sphere freely floating in water and is sensitive to small differences in acceleration between the solid and the liquid.[19] The principle of this differential accelerometer is illustrated in fig. 1a. For negligible multipole interactions, both the floating object and the liquid are subject to the same gravitational + centrifugal acceleration $\vec{g}$. If there are "hypercharge" contributions, $\vec{y}$, different for the two materials, they will produce a non-zero acceleration component parallel to the liquid surface:

$$a = \left|\vec{Y}_{Cu} - \vec{Y}_{H_2O}\right| \sin\theta \tag{2}$$

where $\theta \approx 45°$ when the device is placed close to the edge of a cliff with dimensions much larger than the range $\lambda$.

In the present experiment the horizontal acceleration, $\vec{a}$, is determined by measuring the velocity, $\vec{v}$, of the sphere moving through the liquid after steady state conditions are reached. Applying Stokes formula to a sphere of radius, r, which is neutrally buoyant in a liquid of density $\rho$

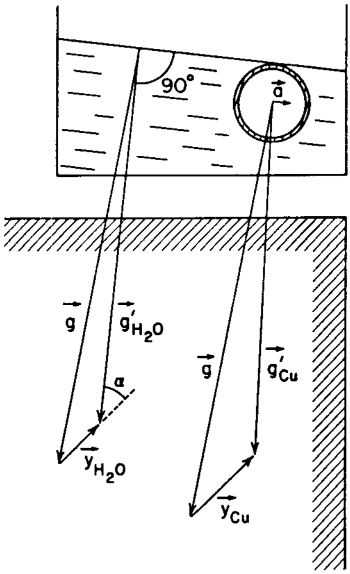
and viscosity $\eta$ one obtains the following applied horizontal acceleration field, $\vec{a}$, for a measured end velocity, $\vec{v}$:

$$\vec{a} = \frac{9}{2}\vec{v}\frac{\eta}{r^2}\left(1 + \frac{3}{8}\frac{|\vec{v}|}{\eta} r\rho\right) - \hat{n} \times [2\vec{v} \times \vec{\Omega}) \times \hat{n}] \qquad (3)$$

where the first term in parenthesis is a correction for a non-negligible value of the Reynolds number[20], and the last term is the horizontal component of the Coriolis acceleration where $\hat{n}$ is the unit local vertical vector and $\vec{\Omega}$ is the angular velocity of the earth's rotation. (Both these corrections are small for the present experiment.) Other corrections arise from the finite size of the tank and from the fact that the top of the sphere is submerged by only 2 cm below the water surface. (A small stabilizing stem breaks the surface.) The magnitude of these corrections was estimated to be 10% which was incorporated in the final error.

The experimental arrangement is shown in fig. 1b. The 4925 g, 21.11-cm diameter, evacuated copper sphere is carefully balanced by adjusting internally placed copper counter weights (total weight ~200 gr) until the center of mass coincides with the center of mass of the displaced water to within 0.002 cm. The possibility of achieving this accuracy and the close approximation to spherical symmetry are important advantages of this method which ensure insensitivity to gravitational field gradients. The water temperature was adjusted to 4.0±.2 °C; the temperature of maximum density to effectively eliminate motions due to convection currents. Water temperature differences across the tank were $<5\times10^{-3}$ °C. To reduce any chemical reactions distilled water was used and the dissolved oxygen content was reduced by exchange with nitrogen.

The positioning coils were used before the μ-metal shield was installed, to produce a known non-uniform DC magnetic field. The field gradient interacting with the different dimagnetic constants of $H_2O$ and Cu produces a known force useful for testing the motion of the sphere. In one of these tests a velocity change of 1.4±.0.1 cm/hr was measured when the field was turned on, while a value of 1.5±0.1 cm/hr was expected from eq. (3) and the calculated field, thus proving the absence of significant ferromagnetic contaminants. Magnetic field gradients of the order of 10 Gauss/meter were required to produce motions similar to the ones observed in the experiment and it was thus shown that one can neglect effects due to residual magnetic fields which were measured to be <0.1 Gauss inside the μ-metal shield.

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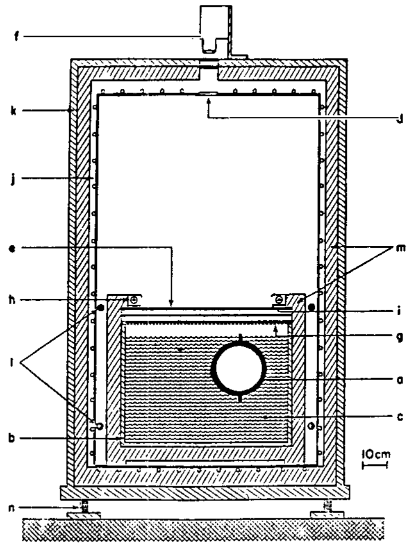


b

FIG 1a Principle of the differential accelerometer developed for this experiment. (See text.) In order to be able to see the vectors and angles the deviation of g due to the cliff has been exaggerated by ~4 orders of magnitude, the values of "hypercharge" accelerations by ~6 orders of magnitude, and the relative difference $\Delta y/y$ by ~3 orders of magnitude.

FIG 1b Schematic diagram of the differential accelerometer used in the experiments. A precisely balanced hollow copper sphere (a) floats in a copper lined tank (b) filled with distilled water (c). The sphere can be viewed through windows (d) and (e) by means of a television camera (f). The multiple pane window (e) is provided with a transparent x-y coordinate grid for position determination on top and with a fine copper mesh (g) at the bottom. The sphere is illuminated for short periods by four lamps (h) provided with infrared filters (i). Constant temperature is maintained by means of a thermostatically controlled copper shield (j) surrounded by a wooden box lined with styrofoam insulation (m). The μ-metal shield (k) reduces possible effects due to magnetic field gradients and four circular coils (l) are used for positioning the sphere through forces due to AC produced eddy currents and for DC tests (see text).

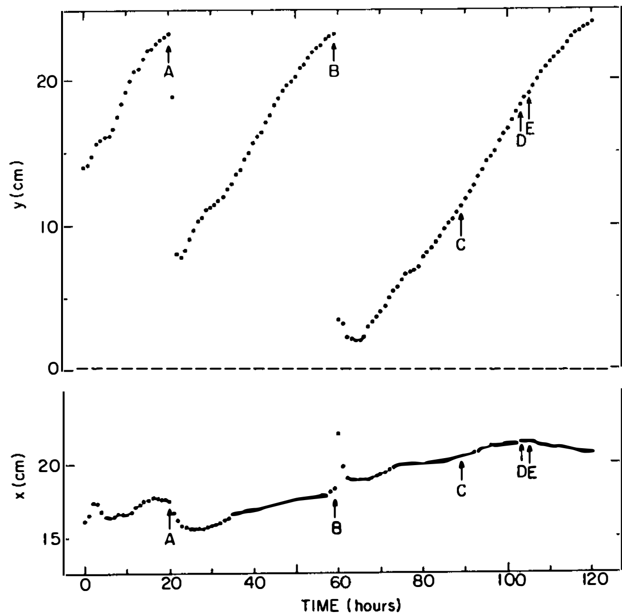


FIG 2 Position of the center of the sphere as a function of time, measured with respect to an x-y grid placed on the tank window. The y-axis points approximately east; away from the cliff. On a circle with north at 0° and E at 90° the y axis is at 88°, the x axis at 178°, and the edge of the cliff averaged over ±200 m intersects this circle at about 188°. Coordinates for which the sphere touches a tank wall are x=0, 40.1 and y=0, 24.8 cm. The position of the sphere was reset at points A and B by energizing one of the coils shown in Fig. 1b.

The instrument was located near the top edge of the Palisades cliff in New Jersey at a location denominated State Line Lookout at 73°54'23" longitude and 40°59'24" latitude at an elevation of 161 m above the Hudson River. The center of the tank was at about 5 m from the edge of the cliff and the height of the floating sphere above the cliff was 0.7 m. The instrument was protected by an aluminum shed and connected to remote readout instrumentation located in an adjacent camper.

Figure 2 shows the result of a 5-day measurement which started about eighteen hours after the instrument box was closed (this delay time is the minimum required for sufficient thermal equilibrium to be reached). Figure 3 shows the same data plotted as x-y trajectories. The dotted line indicates the orientation of the cliff averaged over ~150 m. There is a con-

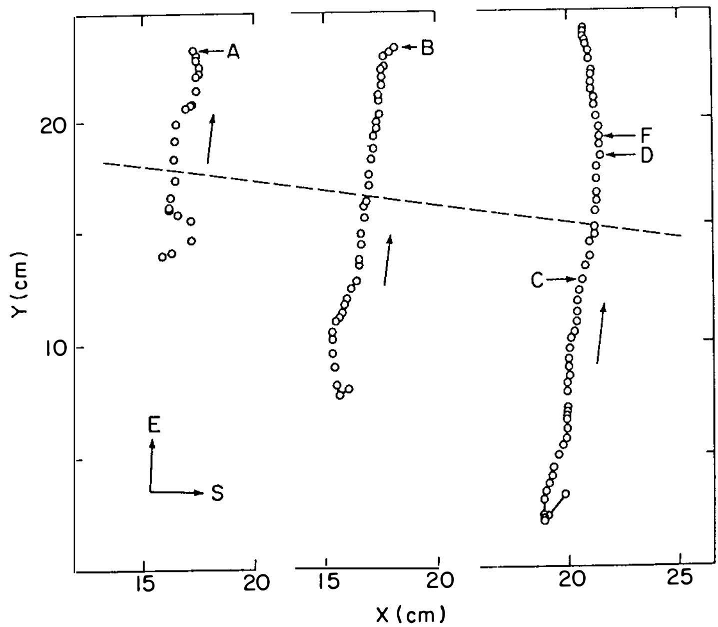


FIG 3 The same data as in Fig. 2 but shown as x-y trajectories. The dotted line represents a cliff orientation averaged over ~±150 m and the arrows are perpendicular to this orientation. When averaging instead over ±50 m, the effective cliff-normal points almost exactly east. This is in better agreement with the expected ~8.4° southward deviation of the trajectory due to the Coriolis force.

sistent 4.7±0.2 mm/hr motion in the y-direction pointing away from the cliff and a 0.6±0.2 mm/hr motion is observed in the x direction. The direction defined by these components is 5° ± 3° south of east consistent with the normal to the local orientation of the cliff which, when averaged over ±150 m points in a direction ~6° south of east. Due to the Coriolis term the trajectory is expected to point ~8.4° south of the normal to the cliff and better agreement with this expectation is obtained by adopting an average over ±50 m instead of ±150 m. The proper distance for averaging depends on the range of the force which is unknown. For periods of about 6 hours after repositioning the sphere transient motions are observed and these points were omitted when determining the slopes. It is seen that significant velocity reduction only occurs when the sphere gets within 2 or 3 cm of touching the east wall, indicating that at larger distances the

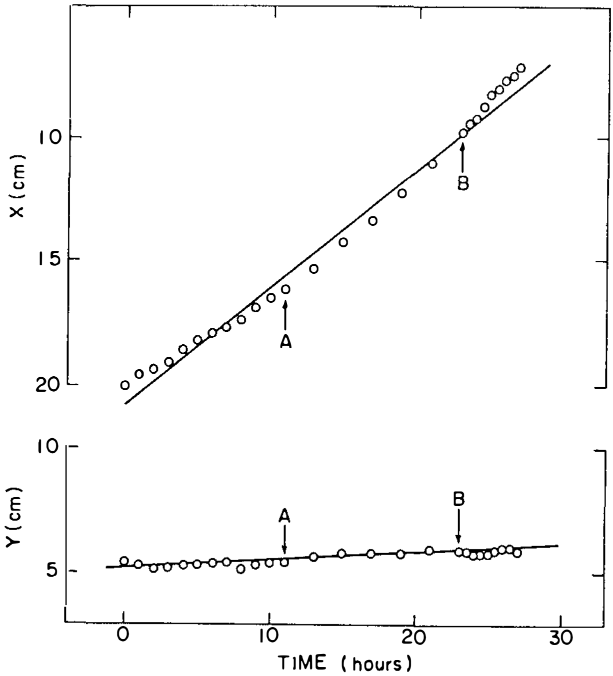


FIG 4 Position of the center of the sphere as a function of time, measured with respect to an x-y coordinate grid placed on the tank window. The device has been rotated clockwise by 90° with respect to the previous orientation. Therefore the x axis now points approximately west, into the cliff. The illumination was changed from one hour to two hours between points A and B and to 1/2 hour after point B to check for possible heating effects.

corrections due to finite tank size are small. Using eq. (3), we find that the measured velocity corresponds to an acceleration of $(8.5\pm1.3)\text{x}10^{-8}$ cm/sec$^2$ or a total force of $(4.2\pm0.6)\text{z}10^{-4}$ dyn. The quoted errors result from the linear sum of an estimated 5% error in the velocity measurement and a 10% uncertainty in the applicability of eq. (3).

During a 14 hour period marked by points C and D on figs. 2 and 3, the temperature of the external west wall of the box was elevated by an average of 6°C above the east wall temperature to test for possible sensitivity to external temperature gradients. This difference is over twice as high as the maximum difference ever observed between these two walls and over ten times higher than the average difference. No appreciable effect on the slope is observed. To estimate possible effects of leveling errors the

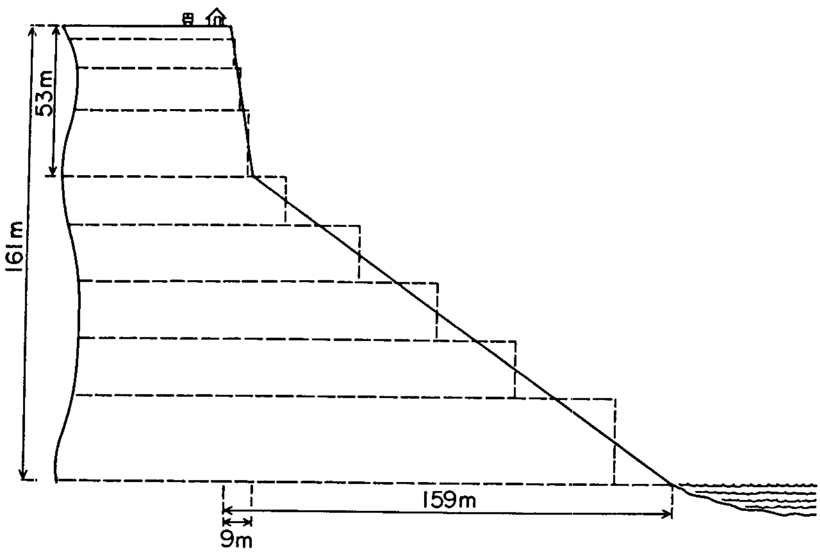


FIG 5 Cliff profile model used for the computer calculations (see text).

east side of the instrument was dropped by 4.6 mm at the point labeled E on figs. 2 and 3. This variation is over ten times larger than the maximum possible error estimated for the rest of the experiment. Again no effect can be seen on the y-motion but a small unexplained effect on the x-motion seems to have occurred.

Results obtained from a 28 hr measurement performed after rotating the entire instrument by 90° are shown in fig. 4. The velocity is 4.5±0.5 mm/hr and the angle with respect to the normal to the cliff is 7°±4°. To test for possible heating perturbations the illumination frequency was varied by a factor of four during this measurement without appreciable effects. In the absence of a cliff but under otherwise similar conditions x and y velocity components of -0.9±0.2 and -1.2±0.2 mm/hr, respectively, were observed.

Possible conventional reasons for motions were considered, including effects due to a residual dipole moment and higher multipole moments, electrostatic and magnetic forces, surface tension and its temperature dependence, convection currents, vibrations, temperature gradients, and Brownian motion. All of these effects could be largely ruled out as described else-

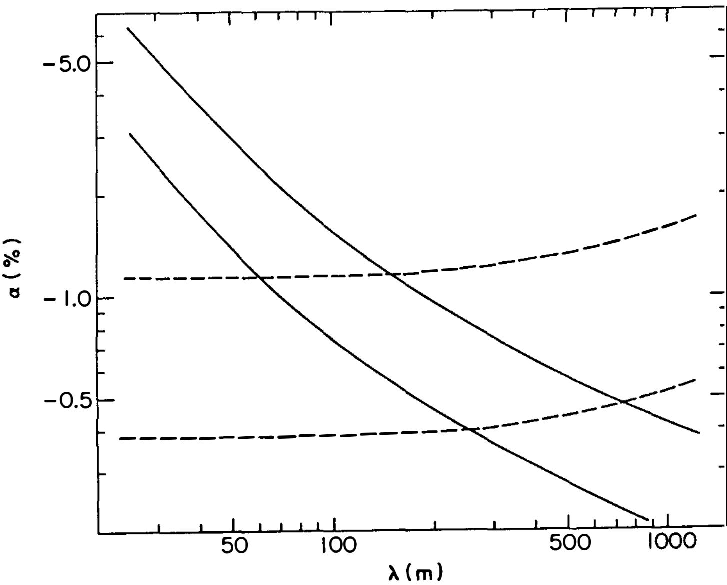


FIG 6 Shown between the solid lines is the range of possible values obtained in the present experiment for the parameters α and λ which characterize the strength and range of an hypothetical hypercharge force. For λ much smaller than the cliff height, the produce α·λ becomes 1.2±0.4 m. If it is further assumed that this is the only non-Newtonian interaction, then these results can be compared with similar limits (dotted lines) obtained from the mine gravity measurements.[5)]

where[21)] by either considering the characteristics of the observed motion or the results of the above mentioned tests and other tests conducted with unbalanced spheres, and with spheres without pins.

To evaluate the data in terms of the constants α and λ of equation (1) a simple finite-element computer program was written to integrate the non-Newtonian potential with different sets of parameters. The cliff was modeled as a prism of density 2.9 $gr/cm^3$ (diabase rock) and with an approximately correct cliff face profile shown in fig. 5. The resulting allowable α-λ combinations compatible with the measured velocity are shown in fig. 6. The previously mentioned 15% uncertainty in the value of the acceleration has been add' to an additional estimated 20% uncertainty resulting from the simp' ied modeling of the cliff.

The present results are compatible with the existence of a medium range, substance dependent force which is more repulsive (or less attractive) for Cu than for $H_2O$. The parameters allowed by this experiment are consistent with those obtained from gravity dependence measurements if one adopts the baryon number dependence used in the reanalysis[14] of the Eötvös experiment. Much work remains before the existence of such a force is conclusively demonstrated and its properties fully characterized. At present, the evaluation of possible systematic errors continues and preparations are being made to perform similar measurements at a different location and with spheres of different materials. Such measurements will hopefully resolve the apparent contradiction between the present results and the results of a recent torsion balance experiment[22] performed at the University of Washington where no effect was found for a copper-beryllium comparison.

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