VII. GRAVITATION RESEARCH

Prof. R. Weiss
E. P. Jacobs
R. A. Sramek

RESEARCH OBJECTIVES AND PROJECT STATUS

Research in this group is concerned with investigating the nature of the gravitational interaction, in particular, with performing experiments that might distinguish between different theories of gravitation and cosmology. These aims are admittedly grandiose, especially in view of the inadequacy of present techniques which preclude performing many of the experiments that one can think of. The subject is, however, of such fundamental importance that even marginal experiments appear to be justified.

Our present intention is to perform an experiment to determine the constancy of G, the Newtonian gravitational constant. Interest in this has been motivated by a conjecture of Dirac[1] that G may have a secular variation of $\sim 10^{-10}$ year because of the expansion of the universe. Jordan[2] and Dicke[3] have formulated scalar theories of gravitation within the framework of general relativity which have been tailored to fit Dirac's conjecture. Dicke's theory not only predicts a secular change in G but also an annual periodic variation of $\sim 3 \times 10^{-10}$ because of the Earth's eccentric motion around the sun.

Table VII-1. Limits on G variations.

Gravitational Force versus Inertial Reaction	$\frac{\Delta G}{G}$/year
Moon period versus earth rotation period coupled with theory of tidal torques for 200 years of observations and a check point against ancient eclipse data[4]	10^{-9}
Pendulum and Absolute Measurements of g made at Potsdam over 50 years[5]	10^{-7}
Gravitational Force versus Electric Force	
Spring gravimeters	10^{-7}
Cavendish experiment[6]	10^{-3}

Table VII-1 lists the limits that can be put on G variations from present knowledge. A distinction is made between limits set by measurements of a gravitational force against an inertial reaction and the gravitational force against another force field, as, for example, electromagnetic forces. It is conceivable that G variations would not be observed in the first class of observations. The table is not exhaustive, studies of G variations as they might affect stellar evolution and the chronology of the Earth's history made by Dicke[7] and Jordan[8] do not offer smaller limits than those given in Table VII-1.

Proposed Experiment

The experiment that we propose is to measure variations in g, the Earth's gravitational attraction at the surface, with a stable gravimeter of a new design. Although the proposed method has the advantage that it measures a gravitational force against an electric force, it introduces the serious problem of the Earth's stability which will be discussed presently. All previous gravimeters employ Hooke's law forces in solids or gas pressure to balance the gravitational force on a mass. Measurements of g made with gas gravimeters fall in the first class, and are extremely temperature-sensitive. Spring gravimeters are troubled by temperature dependence of the Young's modulus of the spring material (the best give a temperature dependence $\frac{\Delta g}{g} \sim 10^{-6}/°C$), and in a much more sinister manner by random material creeps of the springs ($\Delta g/g \sim 10^{-8}$ month). In the proposed gravimeter (shown in Fig. VII-1) the spring is replaced by a measurable electric force and is fundamentally an inverted Kelvin absolute electrometer. Plate 1 is the

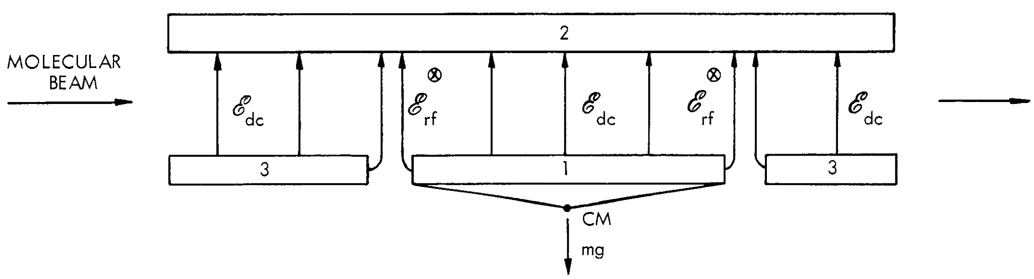

Fig. VII-1. Proposed gravimeter.

gravitating mass, which is supported vertically by the electric field $\mathscr{E}_{DC}$ and maintained horizontally by the fringing field between the guard plate 3 and the gravitating plate. The position of plate 1 is established interferometrically; the interferometer is incorporated in a null-seeking servomechanism which controls $\mathscr{E}_{DC}$ to maintain plate 1 co-planar with the guard plates. The servo maintains the relation

$$mg = F_e = \frac{1}{8\pi} \left\langle \mathscr{E}^2_{DC} \right\rangle_p A,$$

where $\left\langle \mathscr{E}^2_{DC} \right\rangle_p$ is the average of the square of the electric field over the surface, A, of plate 1. In order to measure $\left\langle \mathscr{E}_{DC}^{-1} \right\rangle_p$ the gravimeter plates are incorporated in the transition region of a molecular beam electric resonance apparatus. $\Delta J = 0$, $Dm_J = \pm 1$ Stark transitions in a polar molecule are induced in separated regions of $\mathscr{E}_{RF}$ between plates 1 and 2. If the Stark energies are small compared with the rotational energy of the molecule, the Stark transition frequency is given by $\nu_{STARK} = k \left\langle \mathscr{E}_{DC}^{2} \right\rangle_B$, where k is a function of the molecular constants and quantum numbers and $\left\langle \mathscr{E}^{2} \right\rangle_B$ is the average of the square of the electric field at the location of the molecular beam between the regions of $\mathscr{E}_{RF}$. Assuming that $\left\langle \mathscr{E}_{PL}^{2} \right\rangle_B = \left\langle \mathscr{E}_{DC}^{2} \right\rangle_p$ (which is not strictly so because of the fringing field and, for only one molecular beam, because of nonparallelism of the plates) we can save the force equation and get

$$\nu_{STARK} = \frac{8\ k}{A} mg.$$

If m and A are constant, the g measurement becomes a frequency measurement

$$\frac{\Delta g}{g} = \frac{\Delta \nu}{\nu}.$$

This rudimentary description of the gravimeter only alludes to a host of problems which must be investigated first. Among these are:

1. Constancy of the gravitating mass and temperature dependence of the plate area.

2. Constancy of the relation between F_e and $\left\langle \mathscr{E}^{2} \right\rangle_B$. In particular, how does the relation vary with plate separation, tilt, and co-planarity of the gravitating plate and the guard plates? An experiment is now in progress to study these effects for various plate geometries and potential distributions.

3. Field homogeneity conditions necessary to see a resonance. Inhomogeneitics can arise from nonparallelism of the plates and the time dependence of ground noise. For example, it may be necessary to have a fast AC servo to hold the plate, and hence $\mathscr{E}_{DC}^{2}$, steady over the integration time of the servo that scans the resonance.

Stability of the Earth

Although no measurements have been reported of changes in g at a fixed point on the Earth (besides calculable and known effects such as the tides), it is likely that they exist, especially within the precision demanded for this experiment. In principle, the only multipole moment of the Earth's gravitational potential whose changes are not amenable to averaging over distributed gravimeter sites is the monopole. A catalogue of the mass changes that one can think of would yield as the largest contribution $\Delta g/g \sim 10^{-16}$/year from meteor influx. Estimates of changes in the Earth's radius are far more influential. Again, there are no measurements, and some theories predict expansion, and others, contraction. Jeffreys,[9] and MacDonald[10] are exponents of contraction caused by cooling which would result in changes in radius producing $\frac{\Delta g}{g} \sim +10^{-10} \rightarrow 10^{13}$ per year. Egyed[11] calculates for an expansion, together with continental drift, a change in radius that could result in a $\frac{\Delta g}{g} \sim -10^{-10}$ per year. To emphasize this sensitivity, one need only observe that a change of 0.3 mm in the radial position of the gravimeter corresponds to a $\frac{\Delta g}{g} \sim 10^{-10}$.

One change in the quadrupole moment can already be anticipated. The melting of the polar ice caps results in a $\frac{\Delta g}{g} \sim 10^{-10}$ per year at 45° latitude; however, it is zero at 30° latitude. Variations in the Earth's rotation rate are monitored to the precision necessary for the experiment.

Besides the Earth's radius, the other major unknowns are the magnitudes of local distortions and mass redistributions in the vicinity of a given site (the very high order multipole moments). Knowledge of this will set a limit on the number of sites necessary to establish a statistical estimate of the global g variation. We would endeavor, of course, to pick seismically inactive rock shields with small gravity anomalies. To our knowledge, the only measurements of secular earth distortion (except in regions of post-glacial uplift) have been made by the Benioff Strain seismometer at the Lamont Geophysical Laboratory site, in Ogdensberg, New Jersey, where a limit of $\frac{\Delta \ell}{\ell} < 10^{-8}$/month over a 200-ft length[12] has been set. It appears, however, that the limit is instrumental.

In order to have a handle on radius changes and to correlate local distortions with changes in g, it would be useful to have a stable strain seismometer associated with the gravimeter. We are, at present, engaged in the design and construction of a stabilized laser strain seismometer. Another necessary instrument is a stable tiltmeter, since the gravimeter is quadratically dependent on the angle between the plumb and the normal to the gravitating plate. This instrument is being constructed as part of senior thesis research.

Our first effort will be to build one gravimeter and search for the annual periodic change in g predicted by Dicke's scalar theory.

R. Weiss

References

1. P. A. M. Dirac, Proc. Roy. Soc. (London) A165, 199 (1938).

2. P. Jordan, Schwerkraft und Weltall (Friedrich Vieweg und Sohn, Braunschweig, 1955).

3. C. Grans and R. H. Dicke, Phys. Rev. 124, 1925 (1961).

4. W. H. Munk and G. J. F. MacDonald, The Rotation of the Earth (Cambridge University Press, London, 1960).

5. G. P. Woollard, Advances in Geophysics, Vol. 1, p. 281, 1952.

6. F. H. Newman and V. H. L. Searle, The General Properties of Matter (Edward Arnold Ltd., London, 5th edition, 1957).

7. R. H. Dicke, Rev. Modern Phys. 34, 110 (1962).

8. P. Jordan, Naturwiss. 48, 417 (1961).

9. H. Jeffreys, The Earth (Cambridge University Press, London, 4th edition, 1962).

10. G. J. F. MacDonald, Revs. Geophys. 1, 587 (1963).

11. L. Egyed, Nature 178, 534 (1956).

12. M. W. Major, G. H. Sutton, U. Oliver, and R. Metsger, Bull. Seismol. Soc. Am. 54, 295 (1964).