Rapport BIPM-83/1

THE NEWTONIAN GRAVITATIONAL CONSTANT :

An Index of Measurements
(1983 Edition)

George T. Gillies

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Bureau International des Poids et Mesures
Pavillon de Breteuil
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ABSTRACT

The Newtonian Gravitational Constant, "G", has probably been measured more often but, interestingly, with less precision than any other physical constant of fundamental importance. In an effort that has spanned more than a century to connect gravitation to the other forces of nature, over 200 experiments on G have been completed and reported; but many of them have not been reported in what would now be considered to be the open literature. This paper is a second, more complete attempt to carry MacKenzie's and Poynting's bibliographies forward from the 1800's to the present; and thereby include as many as possible of the experimental results on G that have been obtained since 1900.

I. Introduction

If one were to catalogue the tools of precision measurement, an unusually high number of the listings would claim as their genesis the precision measurement of the Newtonian Gravitational Constant, herein simply referred to as "G". These tools would include the torsion balance, the optical lever, the quartz fiber, synchronous detection techniques, ultra-high precision rotations and many others. Yet G stands alone as the only fundamental constant currently known to little better than one part in a thousand although there are three measurements claiming accuracies of one part in ten thousand. In parallel with these efforts to measure the absolute value of G, there has also been a wide variety of experiments aimed at linking the gravitational force to the other forces of nature. All such efforts to date have had the singularly unique result of demonstrating that gravity, indeed, stands alone - the last of the great classical mechanisms - in spite of its modernized presentation via general relativity.

Classical gravitational physics has been like this, and foreseeably will continue to be like this. The reason why is that, to this date, no one has succeeded in isolating sufficiently well the gravitational interaction between laboratory masses to the point where other disturbing forces or experimental uncertainties do not dominate the measurement, at least at levels above those at which other phenomena might be expected to occur.

*This is the Second Edition of this Index, the First Edition having been published in July 1982 as Rapport BIPM-82/9.

It is nevertheless both interesting and important to catalogue the large body of work done already in the hope that a thorough listing of the experimental facts concerning our knowledge of G will stimulate future work on this constant and the force that it governs.

Part of the motivation for this paper lies in the fact that much of the work on G was reported obscurely in spite of the fact that most experiments have been carefully designed and completed. It was, therefore, a challenge to extract from various libraries, archives and private collections the existing data that, when collectively viewed, will help to focus attention on just exactly what has been done and, more importantly, what has not been done in this field.

This work is meant to be a bibliography and, at present, only that. Owing to the unusually large number of references cited, any thorough discussion of all the results would have taken up more space than was available here. Nevertheless, there is a small amount of annotation provided in the following pages for each of the fourteen sections of the bibliography. The areas into which the papers have been classified are listed below:

1. Measurements of the absolute value of G and reports of important subsidiary technology.
2. Comments and reviews of measurements of G.
3. Measurements of gravitational permeability, absorption, and shielding.
4. Measurements of the local directive action of the gravitational force.
5. Measurements of the dependence of G on the physical state of masses.
6. Measurements of the dependence of G on the chemical state of masses.
7. Measurements of the dependence of G on temperature.
8. Measurements of the dependence of G on the radioactivity of masses.
9. Measurements of the dependence of G on the electromagnetic energy content of masses.
10. Measurements of the dependence of G on inter-mass spacing.
11. Measurements of the dependence of G on time.
12. Measurements of spontaneous matter creation (related to 11).
13. Measurements of the dependence of G on the state of quantization of the test masses.
14. Measurements of the anisotropies of G and of inertial masses.

There are about 960 references cited in these 14 sections. There is some duplication, as a few of the papers contain two or more experimental results each in a different area. Duplicate listings constitute about 5% (or less) of the total, however. The references are listed alphabetically in each section with a chronological sublisting for each author in each section. The order of the items in each of the references follows the ISO recommendations as closely as possible. Abbreviations for the journal titles follow the American Institute of Physics Style Manual wherever possible. For those journals not listed there, the abbreviations in the ISI* Current Contents indexes have been used. Those listings that have the author's name(s) marked with an asterisk have not been consulted at the time of this writing. References to entries in the various abstracting journals have not been given except for a few special cases where the abstracted article was judged to be published obscurely.

Not all of the listings in the Mackenzie (1900) and Poynting (1894) bibliographies were repeated here. Some, like those referring to the "Fr. Bertier" Controversy of the late 1700's/early 1800's, have little scientific merit and were omitted.

Sections 11 and 12 contain several references to instrumental papers in addition to those actually quoting significant results. In particular, the efforts at Princeton University, Massachusetts Institute of Technology, and the University of Virginia are listed in detail.

II. Experimental Studies and Critical Analyses of G

1. Measurements of the Absolute Value of G and Reports of Important Subsidiary Technology

The history of the measurement of the universal gravitational constant begins with geophysical studies of a related physical quantity: the mean density of the earth. These efforts started with attempts to measure the attraction of individual mountains, measurements of strata of the earth's crust as a function of depth in various mines, and they are continuing with measurements of the attraction of layers of water in large level-controllable lakes and in the oceans.

Chronologically, the torsion balance methods came next, and these gave the most reliable results until the advent of the torsion pendulum technique. The balance-beam methods were studied during the late 1800's, and today all three of these methods are being developed in experiments aimed at accuracies of one in 10^5.

Numerous miscellaneous methods have also been developed. These include resonant torsion pendulums, vertical pendulums, near zone gravity wave detector excitation, and long period horizontal pendulums. There have also been several proposed satellite determinations of G, but so far no such measurements have actually been made.

The early works on G, particularly those of Cavendish, Reich and Baily, have been reviewed frequently and the principal papers of these workers are summarized and paraphrased in most undergraduate textbooks on physics. There are, however, about 60 other determinations of G that are in the open literature. Some of these are well known too,

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particularly those of Boys, Poynting, Braun, Heyl and the Beams-Deslattes-Luther-Towler collaboration between the University of Virginia and the U.S. National Bureau of Standards.

Of the latest works, there are three that claim accuracies near one part in ten thousand. They are summarized in Table I. The agreement between the values is only fair, however, even at the 10^{-3} level.

Table I

Author	Year	Experimental Technique	$(G \pm \Delta G) \times 10^{11} m^3 kg^{-1} s^{-2}$
Facy, Pontikis	1972	Resonant Pendulum	6.6714 ± 0.0006
Sagitov et al.	1977	Torsion Pendulum	6.6745 ± 0.0008
Luther, Towler	1982	Torsion Pendulum	6.6726 ± 0.0005

All uncertainties quoted in Table I as well as that in the CODATA value below represent one standard deviation.

Even if ultimately measured in a drag-free satellite, where external horizontal gravity gradients would not influence the balance, measurements of G would still be limited by the uncertainties arising from density gradients in the materials used. This would probably occur somewhere between the 10^{-5} and 10^{-6} level. At that point, a totally different approach to the measurement of G will become necessary.

Our currently accepted value, the CODATA value, is from 1973:

$$G = (6.6720 \pm 0.0041) \times 10^{-11} \; m^3 kg^{-1} s^{-2}.$$

Mills (1979 - see section 10) has tabulated the results of the 22 most often cited measurements of G. There are several other works which are less well known but important nonetheless, and the results from these are entered in Table II. The most recent experiments listed there should be considered as work in progress, and not as a final result. Also, some of these measurements were not directed at G itself, but at a search for some variation in G, with the quoted result being a by-product.

Table II

Author	Year	Technique	$(G \pm \Delta G) \times 10^{11} m^3 kg^{-1} s^{-2}$	
Preston	1895	Pendulum decrement	7.16	
Barus	1919	Torsion balance	6.2	
Stern	1928	Resonant balance	6.6	± 0.5
Renner	1974	Torsion pendulum	6.670	± 0.008
Karagioz, et al.	1976	Torsion pendulum	6.668	± 0.002
Koldewyn, Faller	1976	Torsion pendulum	6.57	± 0.17
Spero	1979	Nulled torsion balance	6.70	± 0.19
Page, Geilker	1981	Torsion balance	6.1	± 0.4
Karagioz, et al.	1981	Torsion pendulum	6.5912	± 0.0016
Speake	1983	Beam balance	6.64	± 0.24

As a rather interesting aside, it should be noted that, since so many of the earliest measurements (those by Cavendish, Reich, Baily, among others) were done for the purpose of determining the mean density of the earth, this motivation has remained the classic justification for undertaking measurements of G. With a knowledge of the earth's density and its volume, one may estimate its total mass in kilograms. More recently, satellite ranging experiments have given us the "geocentric" gravitational constant directly : $G_g = GM_e$. The latest of these experiments, Ferrari, et al. (1980), has an uncertainty of only about 7×10^{-8}. This means that any increased accuracy in our knowledge of G will automatically give us M_e with a corresponding precision, and vice versa. A few of the recent measurements are catalogued in Table III.

Table III

Author	Year	Satellite	$(G_g \pm \Delta G_g)(km)^3 s^{-2}$	
Esposito	1979	Viking I	398600.5	± 0.1
Esposito	1979	Viking II	398600.65	± 0.20
Martin, Oh	1979	ATS 6	398600.36	± 0.12
Ferrari, et al.	1980	Lunar Orbiter 4	398600.461	± 0.026

2. Comments and Reviews of Measurements of G

There are four thorough reviews of the measurements of G: two dating to the late 1800's and two more recent ones. Poynting and, later, MacKenzie summarized the contemporary knowledge of G and, for that matter, all of gravitational physics, in books printed in 1894 and 1900, respectively. Sagitov (1969) recently published a similar work on G, although he omitted many references to experiments probably judged by him to be of secondary importance. Most recently, de Boer (1983) has contributed a review article which catalogues the recent major experiments and presents the results and uncertainties together on easily readable graphs. There are several other reviews of the experiments, and these are listed in the bibliography. It should be mentioned that each successive edition of the Encyclopedia Britannica articles on "Gravitation" contain interesting and relatively thorough sections on G that are very useful.

In addition to the review articles on G, there are a large number of papers, both old and new, that comment on or discuss certain measurements of G, propose new measurement techniques, or analyze probable experimental limitations. Some of these are worth consulting, since errors have occasionally appeared in the main papers of the principal investigators. The titles of the papers in this section of the bibliography usually indicate the relevance to a certain experiment or class of experiments.

3. Measurements of Gravitational Permeability, Absorption, and Shielding

Although not widely known, one of the most thoroughly researched aspects of gravitational physics is the question of the existence of a gravitational analogue to magnetic permeability. The pursuit of this question, i.e., the dependence of G on the density of the matter intervening between the interacting masses, began with a null result in the late 1800's. It continued until recent times, always with null results, but with ever-increasing accuracy. We now know that if gravitational energy is, in fact, absorbed by any intervening material, it occurs at a level such that, when measured in terms of G, the result is $(\Delta G/G)_{abs} < 10^{-16}$. Some theoretical analyses establish a lower limit several orders of magnitude below this, too.

At first these measurements were made by employing a Cavendish balance with a cylindrical screen separating the suspended dumb-bell from the attracting masses. Each screen was made of a different type of material, and all the materials had different densities. The screens were sequentially changed and the measurements of G subsequently made were analyzed for a resulting effect. Later, Majorana began a long series of experiments using a balance-beam and claimed to have found a result at the 10^{-11} level, but subsequent work by himself and others disproved this. The most sensitive measurements have been made in recent times by several workers studying the period shift in horizontal pendulums during a total solar eclipse. In every case, however, the results have been null except for the results of Allais and, later, Saxl and Allen which are seldom discussed.

Unless a new theory predicts a permeability effect substantially different from that empirically sought so far, it is difficult to see where the motivation would arise for new experiments in this area. This is especially so since recent gravitational analogues of electromagnetism predict that the "gravitational permeability of free space" is only $\frac{16\pi G}{c^2} \approx 10^{-26}$ m/kg (Forward, 1961), a very small effect indeed!

4. Measurements of the Local Directive Action of the Gravitational Force

Since so many properties of crystalline materials depend upon the direction of observation (e.g. refractive index, local density distribution, thermal conductivity, etc.), it seemed reasonable to question the constancy of G within crystalline materials as well. This was first done by MacKenzie, then later by Poynting although no anisotropy in the value of G was found in either case at $\approx 10^{-3}$ and 10^{-4} levels, respectively. Heyl did an exhaustive experiment in this area in 1924 and, by weighing crystals from each of the five non-isometric groups, was able to put a limit of $(\Delta G/G)_{ca} \approx 10^{-9}$, thereby effectively eliminating any doubt about it.

It has been suggested that one should not expect to find such anisotropies in general because they would lead to a violation of conservation of momentum. Nevertheless, the weakness of the gravitational force and the singular properties of some crystals made this, temporarily at least, an attractive area of research.

5. Measurements of the Dependence of G on the Physical State of Masses

This category is a rather general one, although it is possible to classify various types of experiments within it. Specifically, there have been measurements of G involving test masses and attracting masses of various geometrical shapes. For example, spheres, cylinders, rods, rings, and irregular masses have been used. In fact, a cylindrical configuration having the sphere-like field of a point source is presently under study. Attracting and test masses in the gaseous, liquid and solid state have been (or are being) studied, as well as masses which undergo a change of state during the experiment. In all cases, no departure from true constancy of G has been observed, at least within the levels of the experiments' precision. When one considers that the sun, a plasma, and its planets (gas, solid and liquid combinations) have orbits which conform precisely to the inverse square law (with only minor relativistic corrections), it is seen that this law is indeed well obeyed. The references cited here are representative examples of various types of experiments involving gases, liquids and solid masses of various shapes. Some of these citations are listed in other more appropriate sections of the bibliography, too.

6. Measurements of the Dependence of G on the Chemical State of Masses

This area of research is usually interpreted as being a test of the weak equivalence principle of General Relativity, i.e. a determination of the equivalence of gravitational and inertial mass. The various searches for a non-zero Eötvös ratio which test this equivalence are catalogued by Will (1981) and are not included here, except for a few special cases given below.

The earliest measurements in this area involved pendulums of the same mass but made of different materials. Eötvös and his contemporaries expanded this to include torsion balances and balance-beams which had masses of different materials attached to them and which oscillated in the time-varying field of the sun as measured at the surface of the earth.

Several workers studied the interesting question "Does G vary while the test mass undergoes a chemical reaction?" but, in all cases, equilibrated or reacting, null results have been obtained. This area has not been without controversy, however. C.F. Brush claimed to see a difference in pendulum periods between pendulums made of bismuth and those of zinc. His observations were ultimately explained by his failure to include the buoyancy of air in his calculations.

Although not strictly belonging to this category, the experiment of L. Kreuzer (1966), at Princeton, is included here because it has been interpreted by some as providing evidence for a variation of G over the elements of the periodic table. This claim was subsequently refuted, but caused some interest at the time.

7. Measurements of the Dependence of G on Temperature

Early in this century, there were three attempts to measure with balance-beams a dependence of G on the temperature of the attracting masses. They all produced null results but were nonetheless open to discussion. This was so for two reasons. First, there were well-known difficulties in experiments wherein two masses at different temperatures were used in a high-precision balance; and second, the unknown thermal profile of the earth immediately below the balance would seem to make an exact repetition of the experiment impossible, because any thermal dependence of gravity would presumably affect the earth's field too (and how can one control the temperature of the earth?).

Professor Shaw and his students, therefore, constructed a Boys-type balance in which the attracting masses could be heated. They measured G and analyzed their data in the form $G = G_0(1 + \alpha T)$. At first they found $\alpha \approx 10^{-5}\ °C^{-1}$. This result created great interest and several papers were written discussing it. A careful repetition of their original work showed, though, that after removing troublesome convection effects, $\alpha \leqslant 2 \times 10^{-6}\ °C^{-1}$, which effectively settled the issue in the negative. There do not seem to have been any other experiments following this one. Perhaps this is because it was realized that the large temperature difference between the earth and sun, when compared with the much smaller difference between the earth and moon, should have highlighted the existence of the effect. Instead, both orbits serve only to verify that the inverse square law is, in fact, independent of temperature. In questions of this type, however, scale factors may be important; and even though the balance-beam experiments (laboratory scale) in the earth's field produced null results at the 10^{-9} level, Shaw's experiment with isolated gravitational forces (also at laboratory scale) was 2 000 times less sensitive than either of theirs. So there may still, perhaps, be effects to be discovered.

The results of all the above experiments are given in Table IV.

Table IV

Author	Year	Technique	$\lvert \Delta G/G \rvert$ K^{-1}
Count Rumford	1785	Beam Balance	$< 3.3 \times 10^{-8}$
Poynting, Phillips	1905	Beam Balance	$< 10^{-10}$
Southerns	1906	Beam Balance	$< 10^{-8}$
Pettersson	1914	Beam Balance	$< 10^{-9}$
Shaw	1916	Torsion Balance	$\sim 10^{-5}$
Shaw, Davy	1923	Torsion Balance	$< 2 \times 10^{-6}$

8. Measurements of the Dependence of G on the Radioactivity of Masses

One very interesting area of research in this century has been the search for a connection between gravitation and what we now know to be the nuclear forces. Studies in this area have involved a wide variety of experimental techniques. Several famous physicists have worked in this area, including G. Sagnac, P. Zeeman, A. Compton and J.J. Thomson, each lending their own special expertise to this difficult problem.

Compton, for instance, produced a large and controllable pseudo-gravitational (centrifugal) field by rotating samples of radium at high speeds. He concluded that this did not affect the radioactivity by more than 10^{-3}. Thompson's uranium-pendulum experiment (carried out in more detail by Southerns) showed no gravitational coupling to the sample's radioactivity at the level of 5×10^{-5}. All other measurements also produced null results, except for that of R. Geigel who claimed to have seen a small weight change in a nonradioactive sample hanging on a sensitive balance when a radium salt sample was placed nearby. He interpreted this as an absorption of radioactivity which led to an increase in the gravitational potential energy of the nonradioactive sample. W. Kaufmann shortly thereafter, however, uncovered a thermal effect which explained the apparent weight change. No one since then has repeated Geigel's experiment.

9. Measurements of the Dependence of G on the Electromagnetic Energy Content of Masses

At the same time as the searches for a radioactivity-gravitational force coupling were under way, there was a parallel effort in progress aimed at finding an electromagnetic-gravitational coupling.

These searches typically involved weighing samples of steel in magnetized and unmagnetized states or charged and uncharged states.

The very much larger size of the electromagnetic forces always makes experiments of this kind very difficult, and careful attention must be paid to the shielding of undesirable electromagnetic couplings to the laboratory which would otherwise make the results ambiguous. In spite of this, null results were always reported.

At present, J.F. Woodward is repeating (with much higher precision) the early work of Faraday and Blackett in search of an electrogravitational effect, but it is not clear at this point what a positive result in these experiments would mean in terms of the value of G or the gravitational inverse square law. His preliminary results are included in this bibliography anyway, for the sake of completeness. The reference section of his paper refers the reader to citations of earlier work along that specific line.

10. Measurements of the Dependence of G on Inter-mass Spacing

The past decade has seen a great deal of research in this area, and most of the effort was motivated by the work of D. Long at Eastern Washington University. He claimed that an analysis of past measurements of the absolute value of G showed a distance dependence, which he later tested experimentally. His positive result produced great interest and motivated about ten groups to undertake experiments of their own, most of which now claim null results. The fundamental importance of this question has caused it to remain open, however, and both theoretical and experimental work will probably continue for some time to come.

Here too, experiments have been done on many scales of distance, ranging from 2 cm up to several kilometers. There have been analyses of the free oscillations of the earth in terms of how they might be influenced by a non-zero G(R); and on the still larger scale, the motion of the planets has been seen to confirm the inverse square law to an amazingly high precision (except for the previously mentioned relativistic corrections).

The majority of the latest experiments have been designed to be high sensitivity null measurements, although the early work of Mackenzie and, to some extent, that of Long instead involved measurements of the absolute value of G at two or more different mass spacings. While a workable scheme in principle, the absolute measurements are usually burdened with large drifts and metrological difficulties. This sometimes makes their results open to question.

Frank Stacey and his colleagues at the University of Queensland in Australia have undertaken a series of geophysical measurements in search of a non-newtonian component in the earth's gravitational field. A reanalysis of existing gravity data, Stacey (1983), has motivated them to do this, and their work is currently in progress.

Tests of the superposition principle as applied to gravitational fields also belong in this category. Work in this area is being done by G. Luther at the United States National Bureau of Standards (in progress), and also by P. Czipott and J. Goodkind at the University of California, San Diego (also in progress).

Finally, reviews of the G(R) measurements have been given by Hoskins, et al. (1983) and by Newman (in press) wherein the results have been tabulated and thoroughly discussed. Those interested in the overall status of this type of experimental search for non-newtonian effects are encouraged to consult these works.

11. Measurements of the Dependence of G on Time

Perhaps no other area of gravitation is of greater interest to theorists and cosmologists than the possibility of variations of G in time. There have been many theories calling for a time-varying G, each having its own implications on the behavior of matter and radiation at the early moments of the universe.

Here again, the experiments fall into three categories : laboratory, geophysical and astronomical. If such an effect exists, it is agreed that it must be very, very small; probably on the order of $\dot{G}/G \approx 10^{-11}$ year^{-1}. Few laboratory tests of any kind have been done at this level, and it is not surprising that the existing laboratory tests of this effect are limited at the level of $10^{-7} < \dot{G}/G < 10^{-8}$ year^{-1}. Several experiments with test masses have been proposed for both earth-surface and orbiting laboratories which should be sensitive to the predicted 10^{-11} year^{-1} changes, but none has yet been completed.

The geophysical tests have usually involved studies of the expansion of the earth or investigations of a paleobiologic type. While these provide corroborating evidence, they are not usually accepted as hard proof because of the many uncertain factors involved. Wesson's contributions are the most complete in this area, and his book "Cosmology and Geophysics" (1978) should be consulted for a thorough review of geophysical investigations of $\dot{G}/G$.

Van Flandern (1981, 1983) claims that all three astronomical tests of $\dot{G}/G$ are now yielding similar results; and that $\dot{G}/G \cong -(6 \pm 2) \times 10^{-11}$ year^{-1}. These tests include : (1) lunar laser ranging, (2) radar ranging of the inner planets, and (3) lunar occultation studies and determinations of the moon's orbit. The data from these three experiments have been coming in for several years now and have been carefully analyzed by several workers. The results for $\dot{G}/G$ from each of them have great importance, as each method poses an independent check on the other. Space limitations prevent a thorough presentation and discussion of these results here, but a recent paper by Van Flandern (1981) does this.

The results from other sources, including laboratory experiments and those derived from cosmological considerations, are listed in Table V. Although these areas are, at the moment, of secondary importance to the astronomical tests listed above, it is likely that sufficiently accurate data from all areas will have to be available and in agreement before the existence of a nonzero $\dot{G}/G$ is accepted.

Table V

Author	Year	Technique	$\lvert\dot{G}/G\rvert$ year^{-1}
Hoffmann	1962	Quartz pendulum gravimetry	$< 4 \times 10^{-8}$
Curott	1965	Quartz pendulum gravimetry	$< 6.2 \times 10^{-7}$
Weiss, Block	1965	Quartz spring gravimetry (drift limit, no firm result quoted)	$< 3.6 \times 10^{-6}$
Stephenson	1967	Reanalysis of Heyl's G measurements	$\sim 10^{-4}$ (periodic annually)
Newton	1968	Earth spindown	$\sim 10^{-10}$
Morganstern	1972	Flat space cosmology analysis	$\sim 10^{-11}$
Morganstern	1972	Closed space cosmology analysis	$\sim 3 \times 10^{-11}$
Eichendorf, Reinhardt	1977	Study of variations in the surface temperature of the earth	$(2.3 \pm 0.6)\times 10^{-11}$
Barrow	1978	Cosmological considerations	$(1.5 \pm 0.7)\times 10^{-12}$
Yang, et al.	1979	Analysis of nucleosynthesis data	5×10^{-13}
Lambeck	1979	Earth spindown	$(2.5 \pm 0.5)\times 10^{-11}$
Lapiedra, Palacios	1981	Planetary orbit studies	$< 7.5 \times 10^{-13}$
Rothman, Matzner	1982	Reanalysis of nucleosynthesis data	$< 1.7 \times 10^{-13}$

12. Measurements of Spontaneous Matter Creation

Most of the theories that call for a non-zero $\dot{G}/G$ also require the spontaneous creation of matter. This is usually the result of a gauge condition; or is in response to satisfying some phenomenological requirement, such as maintaining constant density in the universe. In a Machian universe, the value of the gravitational constant and processes like matter creation are presumably coupled in such a way that the value (or existence) of one affects the other. Therefore, it seemed appropriate to include the known experimental tests, tests in progress, and proposed tests of this effect, too.

In terms of categories, the $\dot{M}/M$ experiments are classifiable in the same way as the $\dot{G}/G$ experiments. There are substantially fewer of them, and only one laboratory experiment, that of S. Cohen and J. King, has yielded a result, which was null at the $\dot{M}/M = 10^{-23}\ s^{-1}$ level.

13. Measurements of the Dependence of G on the State of Quantization of the Test Masses

There have been two proposals for measuring G in terms of h, the Planck constant. These experiments, if ever done, will be the first direct tests of a quantum structure of the gravitational field. One indirect test by D. Page and C. Geilker has been carried out but is disputed.

14. Measurements of the Anisotropies of G and of Inertial Mass

The famous Hughes-Drever class of experiments all produced results which, to very high precision, showed that matter is evenly distributed in the universe. Dicke (1961) showed that they should be null measurements in principle, however.

Somewhat later, this question of large scale anisotropy in the universe arose again. This time, however, in the context of a variation of G with respect to direction on a universal scale. Warburton and Goodkind (1976) analyzed earth tide data taken with a superconducting gravimeter and found an effect not inconsistent with such a variation, but could not verify it due to uncertainties in the structure of the earth tides.

A room temperature, fedback torsion balance has been constructed at the Cavendish Laboratory for a similar investigation. It is, though, presently inactive.

Summary of Section II

For the most part, purely theoretical papers that discuss the possibility of variations in G (but do not set limits on it) have not been included. The goal here was to describe instead the "hard facts" so that all workers in the field could more easily assess the state of our knowledge.

The results of the different searches for variations in G are summarized in Table VI. Usually, the result claiming highest precision is quoted, although, where appropriate, a result typical of those in its class is given instead.

Some results entered in Table VI are dimensionless. In these cases, the authors listed had tried to set limits on some appropriate dimensionless scale factor. Their original results (where necessary) have been translated into the more familiar $\Delta G/G$ format for presentation here.

Table VI

Effect	Author	Year	Result ($\Delta G/G$)
Gravitational permeability or absorption	M. Caputo	1962	$\leqslant 6 \times 10^{-16}$
Directive action of gravitational force	P.R. Heyl	1924	$\leqslant 10^{-9}$
Dependence of G on physical and/or chemical states of matter	For a review, see C. Will	1981	$\leqslant 10^{-12}$
Temperature dependence via a Cavendish balance	P.E. Shaw, N. Davy	1922	$\leqslant 2 \times 10^{-6}\ {}^\circ C^{-1}$
Temperature dependence via a common balance	J.H. Poynting, P. Phillips	1905	$\leqslant 10^{-10}\ {}^\circ C^{-1}$
Gravitation/ radioactivity coupling	P. Zeeman	1918	$\leqslant 5 \times 10^{-8}$
Dependence of G on magnetization of matter	M.G. Lloyd	1909	$\leqslant 5 \times 10^{-12}$ Gauss^{-1}
Dependence of G on electrification of matter	L. Simons	1922	$\leqslant 1.2 \times 10^{-7}\ V^{-1}$
G(R)	R.E. Spero, et al.	1980	$(1 \pm 7) \times 10^{-5}$
$\dot{G}/G$ (Astronomical)	For a review, see T. Van Flandern	1981	$(-6 \pm 2) \times 10^{-11}$ year^{-1}
$\dot{G}/G$ (Laboratory)	W.F. Hoffmann	1963	$\leqslant 4 \times 10^{-8}$ year^{-1}
$\dot{M}/M$ (Laboratory)	S. Cohen, J.G. King	1969	$\leqslant 4 \times 10^{-23}\ s^{-1}$

III. Closing

As mentioned previously, this work is meant to be a resource bibliography, not a critical review of the status of each of the various areas treated here. It is hoped that the readers of this bibliography will benefit from the relatively comprehensive listing of references given here. Further, it is hoped that readers will respond with missing references if possible. This will be the only way that the "holes" can be filled, since the work to bring the bibliography to the present level has been more than one person should attempt alone.

As much useful information as possible has been put into each citation. References to work done in the Soviet Union are harder to get than most others. This is because there does not seem to be any direct exchange mechanism between Soviet libraries and Western libraries. Nevertheless, most of the important works published there have been obtained by the author and appropriately catalogued.

The references have been recorded at the BIPM using computerized word processors. This makes it possible to seek, sort and list them by author, date, journal and key word(s). The flexibility of this system makes this bibliography, in fact, a gravitational physics data base. Searches of it by non-BIPM personnel can be made under special arrangement.

English translations of some non-English articles in the bibliography (except those marked with an asterisk) are available from the author, also via special arrangement.

The addresses and telephone numbers of the research libraries that have been most helpful in this work are given below.

Library of the United States National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234
USA
(301) 921-2318

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U.S. Government Printing Office
Washington, D.C. 20402
USA
(202) 783-3238

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
USA
(703) 487-4650

The Library of Congress
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The author shall continue to add to this bibliography as more work on G is done in the future and as other previous reports are uncovered and made available.

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Some of the Russian names are transliterated one way by some publishers, and another way by others. In this listing, I have chosen to use the transliteration selected by the Eastern press authorities rather than those in the West, since this may be more in line with the individual author's wishes.

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