Resource Letter GI-1: Gravity and inertia

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This Resource Letter provides a guide to the literature on gravity and inertia. The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A indicates rather specialized or advanced material. An asterisk (*) indicates articles that we feel are especially useful or interesting; a double asterisk (**) indicates those articles to be included in an accompanying reprint book.

SALVIATI: ...but if this author knows by which principle other world bodies are moved in rotation, as they certainly are moved, then I say that that which makes the earth move is a thing similar to whatever moves Mars and Jupiter... If he will advise me as to the motive power of one of these movable bodies, I promise I shall be able to tell him what makes the earth move. Moreover, I shall do the same if he can teach me what it is that moves earthly things downward.

SIMPLICIUS: The cause of this effect is well known; everybody is aware that it is gravity.

Everybody is aware that gravity is a mysterious force that pulls things downward, is universal, and is somehow the key to understanding the universe. Everybody is also aware of the more subtle phenomenon of inertia, by which it is hard to move heavy bodies, or to stop them once they are in motion; inertia is also popularly felt to be mysterious and fundamental.

The popular ideas about gravity and inertia come partly from common experience and partly from scientific thought and speculation. Common experience teaches everyone that heavy bodies normally tend to move down and that heavy moving bodies are hard to stop, but says nothing about the cause of these effects. The mystery associated with them comes from centuries of philosophic and scientific speculation, and has only been partially resolved in this century. Today we would say that masses follow geodesic paths in the curved geometry of space-time, and that this is why heavy bodies move downward and planets follow the paths they do. The interpretation of gravity as geometry leads naturally to cosmology as a branch of gravitation theory, so that there is some justification for the popular notion of gravity being central to the understanding of the universe. Inertia is less well explained by reference to the influence of distant masses, or to electromagnetic mass.

Our word gravity and its more precise derivative gravitational come from the Latin word gravitas, from gravis (heavy), which comes ultimately from a still older root word hypothesized to have existed because of numerous cognates in related languages: for example, compare the Old English word grafan (grave), the Old Slavic pogreti (to bury), Sanskrit guru (weighty, venerable), and Greek barys (heavy, grievous) among others. These words have in common meanings of heaviness, importance, seriousness, dignity, grimness: the modern sense of a field of attraction did not appear until Newton's time. Indeed, for Galileo, Newton, and scientists up to this century, gravity was only an empty name for the phenomenon, a fact that they were well aware of.

Inertia has a somewhat more modern derivation. It may be traced to its Latin roots in + ars, hence iners, meaning unskilled or artless. Kepler first applied the word in a phys-
Both gravity and inertia have had central roles in the development of physical science, particularly in the discovery of the laws of motion and cosmology. In antiquity, the motion of falling bodies as understood by Aristotle was taken as evidence for the geocentric theory of the universe. As more precise observations of the motion of falling bodies and projectiles were made, it became apparent that some property internal to the body was necessary to account for its continued motion; the medieval theory of impetus came from this. Still more precise observations led to Galileo's discovery of the law of falling bodies and of inertia; finally, Newton extended the law of gravity to apply to the planets, and found the laws of motion to apply to them as well as to terrestrial objects. Now gravitation was evidence for the Copernican theory rather than the geocentric one.

Since Newton's time this history has repeated with variations. Better measurements revealed an anomalous motion of Mercury, which was not accounted for by Newton's theories. Einstein's general relativity accounted for this and other effects as well; the result being that the motion of Mercury is now generally regarded as being evidence against Newton, if not absolutely in favor of Einstein.

It would be premature to judge entirely in favor of general relativity or any other theory of gravitation. This is certainly the opinion of the many people doing experimental work to verify or disprove it. Testing modern gravitational theories is a difficult task, because the differences between predictions of the competing theories are usually small fractions of the total gravitational force, and on any laboratory scale the total gravitational force itself is very weak. Because gravity is such a weak force, scale is very important, and many experiments are only observational, as with planetary and stellar orbits; the laboratory-sized experiments that can be done, are necessary among the most sensitive, precise, and interesting in physics. This adds to the excitement of the field.

This resource letter lists references that are intended to summarize the status of gravitational experiments, and includes historically interesting, background, and current material. Some theoretical material is necessarily included, both as background and as part of the experimental papers, and we have excluded some related experimental topics as being not quite in the subject area. Interested persons may want to refer to the topics of black holes, gravitational radiation, gamma ray bursts, the object SS-433, supraluminal velocities, and others included in the general subjects of general relativity, cosmology, and gravitation. Many of the references were selected because they contain further references; these we have placed at the beginning of each section. Otherwise the order, if any, is chronological. We have tried to avoid duplication of material in related Resource Letters, which include "Resource Letter GR-1 on General Relativity" [Am. J. Phys. 36 (2), (1968)] and "Resource Letter RC-1: Cosmology" [Am. J. Phys. 44 (3), (1976)].

I. JOURNALS

The most recent published results on any scientific subject usually appear in journals; gravity is no exception. We have roughly grouped the journals below according to the frequency of appearance of articles on gravitational experiments, as determined from Physics Abstracts and citations. The first half-dozen journals account for a majority of early reports of experiments and results, and are also most often cited as references; still a significant number of important articles appear elsewhere.

- Physical Review Letters
- Astrophysical Journal
- Nature
- Physical Review D
- Astrophysical Journal Letters
- Physics Today
- Soviet Physics JETP
- General Relativity and Gravitation
- Annual Review of Astronomy and Astrophysics
- Proceedings of the Royal Society of London
- Nuovo Cimento C
- Nuovo Cimento B
- Nuovo Cimento Letters
- International Journal of Theoretical Physics
- Soviet Physics Usp.
- Acta Astronautica
- Scientific American
- American Scientist
- Astronomy and Astrophysics
- Annalen der Physik
- Annals of Physics
- Journal of Applied Physics
- Journal of the Physical Society of Japan
- Australian Journal of Physics
- Foundations of Physics
- Radio Science
- Physics Letters A
- American Journal of Physics
- QJR Astronomical Society
- I.A.U. Circular
- Acta Physica Polonica
- Soviet Astronomical Letters
- Laser Spectroscopy
- Applied Optics
- Instrumentation and Experimental Technique
- The Physics Teacher
- Physics Bulletin

II. CONFERENCE PROCEEDINGS

Conference proceedings and reports usually contain a lot of related material including review articles, research status reports, and descriptions of existing and proposed experiments. Consequently they make good references. The following proceedings contain the highest concentration of material on gravitation and inertia although much of it is highly specialized.

International Conference on Gravitation and General Relativity

There have been nine of these conferences at several locations. The latest is reported in

1. GR9 Abstracts of Contributed Papers for discussion groups: 9th International Conference on General Relativity and Gravitation (Friedrich Schiller University, Jena, DDR, 1980). (E)
Proceedings of the Enrico Fermi School of Physics
This school covers a variety of topics. Four courses of interest are
3. Experimental Gravitation (Course 56), edited by B. Bertotti (Academic, New York, 1974). (E)

Other Conferences

Texas Symposium on Relativistic Astrophysics
The latest of these symposia is reported in

III. TEXTBOOKS AND EXPOSITIONS
Most texts on the theory of general relativity include a section or two on experimental tests, and for the most part we have excluded them as being referenced elsewhere. The texts and expositions below either are largely about experiment, or discuss a lot of experiments, or are randomly selected.

16. Theory and Experiment in Gravitational Physics, C. M. Will (Cambridge University, Cambridge, 1981). This recent book presents techniques for analyzing experimental results and treats many experiments. (I)
17. Gravitation, C. W. Misner, K. S. Thorne, and J. H. Wheeler (Freeman, San Francisco, 1973). This comprehensive book contains, besides a development of theory, a description of the PPN formalism, which is often used to compare theories and experimental results, and a fairly complete discussion of experiments up to 1972. (E)
26. Gravity and Spacetime, H. C. Ohanian, A senior level text. (I)

IV. CURRENT RESEARCH TOPICS
The most active current research areas of experimental gravitational physics are the fields of pulsars and quasars, spacecraft tracking, gravitational wave detection, gravitational lens effects, orbital tests of general relativity, the equivalence principle, the gravitational constant, and elementary particle interactions with gravity. We begin by listing some fairly general review articles, then a breakdown by category of experiment, which is intended to include both historically interesting publications, important results, and a sampling of current papers.

A. General review articles
A fairly complete discussion of experiments up to 1973 is included as part of the material in Ref. 17. The following papers should be helpful for becoming familiar with the field since then. We have selected these according to quality and/or number of additional references they contain.

B. Astrophysical measurements

In addition to the basic division into theory and experiment, gravitational research may be further subdivided into astrophysical and laboratory measurements. The astrophysical measurements often determine the parameters of gravitational theories to good accuracy (usually in complete agreement with general relativity) in spite of the unknowns of dealing with natural bodies. The laboratory measurements give the added certainty of dealing with controlled circumstances at the expense of being rather difficult.

1. Deflection of starlight

This is one of the classical tests of general relativity but the field is by no means exhausted, as the following current research topics show. The original measurements (below) were by no means conclusive, as discussed in Ref. 46 and others. At present, precise measurement of the positions of radio objects such as pulsars gives the most exact measurements of starlight deflection.


The double quasar 0957 + 561A, B is widely regarded as due to an intervening gravitational lens. These are some recent reports.


2. Binary pulsar

Since its discovery in 1975 the binary pulsar (there are now at least two) has been recognized as potentially very important to gravitational theory. Because of the large masses involved and the closeness of the system, general relativistic effects such as perihelion advance should be greatly enhanced. Apparent energy loss of gravitational radiation has recently made this object an interesting topic.


60. "Gravitational Waves: an indirect confirmation," M. Lachieze-Rey, Recherche 10 (102), 776–7 (1979); describes indirect observation of gravitational waves by slowdown of binary pulsar—in French. (E)


C. Solar system experiments

These are experiments involving bodies in the solar system that are much more accessible than those outside; i.e., they can be “touched” either physically or by active instruments such as radar. This gives an even higher degree of confidence in the results, and allows detection of some effects that cannot be measured in objects at stellar distances. The subclass of experiments, using space probes either free-floating or “anchored” to planets, is providing some extremely sensitive variants of the classical experiments, such as signal retardation in a gravitational field. Precise tracking of spacecraft is providing some of the best estimates to date of many PPN parameters and has the potential for detecting gravitational waves.


1. Experiments involving planetary bodies


70. "The Viking Relativity Experiment," I. I. Shapiro, R. D. Reasenberg,
2. Perihelion advance of Mercury

Other bodies than Mercury are now included in this classical test of general relativity, including spacecraft—see Secs. IV C 3 and IV B 2. A major limitation at present is lack of knowledge of the details of the interior of the sun, which is not necessarily spherical and may cause a similar effect through its oblateness.


3. Spacecraft tracking experiments

Spacecraft can be tracked with phenomenal accuracy, so that the uncertainty in gravitational tests is due to nongravitational disturbances rather than quality of the measurement. Even the disturbances may be greatly reduced by using drag-free spacecraft or by placing the spacecraft on planets.


3.2. Control technology challenges for gravitational physics experiments in space," D. B. DeBra, J. Guidance Control 2 (2), 147–51 (1979); describes some of the technical problems with these experiments. [E]


D. Laboratory experiments

1. Tests of the equivalence principle

Being a postulate of general relativity, as well as of many other gravitational theories, the equivalence principle is a very important topic. The following papers are only a fraction of those available. See also Refs. 68, 69, 99, 163, 165, 114, and 109.

1.1. "What is the principle of equivalence?" H. C. Ohanian, Am. J. Phys. 45 (10), 903–9 (1977); a useful explanatory article that touches on most of the misunderstandings about equivalence. [E]

2. Principia, I. Newton (London, 1686); contains the description of Newton's pendulum experiments. [E]

2.1. "Versuche über die Kraft, mit welcher die Erde Körper von verschiedener Beschaffenheit anzieht," F. W. Bessel, Ann. Phys. Chem. (Poggendorf) 25, 401–8 (1832); the summary of Bessel's work with pendulums—in German. [E]

2.2. "Untersuchungen über Gravitation und Erdmagnetismus," V. von Echt, Ann. Phys. 59, 354 (1896); Eötvös' original article—in German. [E]


2.6. Experimental measurement of the equivalence of active and passive gravitational mass," I. B. Kreuzer, Phys. Rev. 169, 1007–12 (1968); a switch on the usual comparison with inertial mass. [E]


2.8. Verification of the equivalence of gravitational and inertial mass for the neutron," I. Koestler, Phys. Rev. D 14, 907–9 (1976); a classical experiment, which should be compared with the nonclassical experiments in Sec. IV D 10. [I]

2.9. Verification of the equivalence of inertial and gravitational mass," V. B. Braginsky and V. I. Panov, Sov. Phys. JETP 34, 464–66 (1971); a more thorough description is in Ref. 22. [E]

2.10. Eötvös Experiments with a Fluid Fiber," G. M. Keiser and J. E. Faller, in Ref. 8, a novel idea that removes many of the problems with vibrations. [I]

2.11. Equivalence Principle Tests in Earth Orbit," P. W. Worden, Acta Astronaut. 5, 27–42 (1978); contains an estimate of the sensitivity to be reached in orbit and one way to go about it. [I]


2. Gravitational red shift

The gravitational red shift was one of the three classical tests proposed by Einstein, but it is now regarded as a test of the Einstein equivalence principle rather than of general relativity. It is being replaced by the neoclassical test of the relativistic time delay (see Refs. 16 and 73).


3. Tests of Mach’s principle

The hypothesis that inertial effects depend on the influence of distant masses is variously regarded, and in fact has never been very precisely stated. Very little experimental work has been done on the principle itself; we have included some experiments that are otherwise hard to classify.
104. Die Geschichte und die Wurzel des Satzes von der Erhaltung der Arbeit, E. Mach (Calve, Prague, 1872), in German. (E)

105. The Science of Mechanics, E. Mach (Open Court, LaSalle, IL, 1960), Sec. 2 Vlf. (E)


113. Experimental implications of Mach's Principle, W. S. Cheung, University of Virginia, Master's thesis (unpublished), 1978; contains many references. (E)


4. Gravitational radiation

Detection of gravitational waves would be an excellent confirmation of general relativity, and efforts to detect them have grown enormously since Weber's original claim of discovery. The sensitivity of resonant detectors has increased with the use of cryogenic antennas and detectors as well as ultrahigh- Q materials, until several groups are claiming the sensitivity to see supernovae within the galaxy. Meanwhile other investigators are designing free-mass detectors of equal or greater potential sensitivity.


117. "Gravitational-radiation experiments," D. H. Douglass and V. B. Braginsky, in Ref. 18, p. 90-137. (E)


126. "Quantum nondemolition and gravity wave detection," W. Unruh, Phys. Rev. D19 (10), 2888-96 (1979); a review of various schemes for these techniques. (A)


129. "Local field and gravitational-radiation experiments," H. Hagiwara, J. Phys. Soc. Jpn. 48 (2), 685-6 (1980); discusses nonradiative components of local gravitational field as noise limit to gravitational radiation experiments. (E)


5. Stanford gyro reality experiment

This experiment seeks to verify the existence and magnitude of frame-dragging effect in Earth orbit.


136. Final Report on NASA Grant 05-020-019 to perform a gyro test of General Relativity in a satellite and develop associated control technology, edited by C. W. F. Everitt, W. W. Hansen Laboratory of Physics, Stanford University, Stanford, CA; this massive document has never been published, but it is the most comprehensive description of this experiment in existence. Copies are available at the above address. (I)


6. Twin-satellite experiment

Two satellites in the same orbit, but moving in opposite directions, allow a separation of relativistic effects from geophysical effects.


7. Measurements of G

Measurement of G was and is one of the most important gravitational measurements. Great ingenuity has been used to get the accuracy of measurement within a few parts in $10^7$.

141. "The Density of the Earth," H. Cavendish, Philos. Trans. R. Soc. 88, 469 (1798); the original experiment to "weight the earth." (E)


*143. "On the Newtonian Constant of Gravitation," C. V. Boys, Philos. Trans. R. Soc. A 186 (1), pt. 1, 1 (1895); a classic experiment of the..."
Cavendish type (E)
144. "Redetermination of the Constant of Gravitation," P. R. Heyl, Bur. Stand. J. Res. 5, 1243–90 (1930); using the period rather than the deflection of a Cavendish balance to determine G. (E)

8. Measurements of the time variation of G

Reference 11 contains a number of papers on this subject.

9. Inverse square law


10. Nonclassical experiments

Some very interesting experiments involving gravity and subatomic particles have been done recently.

E. Gravimetry and Gravimetric Devices

This letter covers mostly basic research on gravitation, but the many techniques used to measure gravity (some of which are very elegant) should not be ignored. Accordingly we have listed some interesting papers on gravity measurement of which we are aware.