RESOURCE LETTER

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This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course contents in specified fields. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455. Reprints: When ordering request Resource Letter GI-1. Enclose 35 cents per copy (not in stamps) together with a stamped and self-addressed envelope and send to: Executive Office, American Association of Physics Teachers, Graduate Physics Building, SUNY at Stony Brook, Stony Brook, NY 11794.

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

Galileo Galilei, *Dialogue Concerning the two Chief World Systems* (University of California, Berkeley, CA, 1974), translated by Stillman Drake.

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 *gravitation* 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 physical sense, but not with the modern meaning: he used it only for bodies at rest. Galileo discovered the law of inertia, but did not name it. Newton gave the word *inertia* its modern sense in the *Principia*: "A body, from the inert state of matter, is not without difficulty put out of its state of rest or motion. Upon which account, this *vis insita* may, by a most significant name, be called *vis inertiae*, or force of inactivity... ."

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, 3° background 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

2. **Evidence for Gravitational Theories (Course 20)**, edited by C. Møller (Academic, New York, 1961). (E)
3. **Experimental Gravitation (Course 56)**, edited by B. Bertotti (Academic, New York, 1974). (E)
4. **Isolated Gravitating Systems in General Relativity (Course 67)**, edited by J. Ehlers (North-Holland, Amsterdam, 1979). (I)
5. **Physics and Astrophysics of Neutron Stars and Black Holes (Course 65)**, edited by R. Giaconni and R. Ruffini (North-Holland, Amsterdam, 1978). (I)

Other Conferences

6. **Proceedings of the International School of General Relativistic Effects in Physics and Astrophysics: Experimental and Theory (3rd Course)**, edited by R. Ruffini, J. Ehlers, and C. W. F. Everitt (Max Planck Institute für Physik and Astrophysik, Munich, 1977). (E)
7. **Proceedings of the First Marcel Grossman Meeting on General Relativity**, edited by R. Ruffini (North-Holland, Amsterdam, 1979). (E)
8. **Proceedings of the Second Marcel Grossman Meeting on General Relativity**, edited by R. Ruffini (North-Holland, Amsterdam, 1981). (E)
9. **Proceedings of the International Symposium on Experimental Gravitation, Pavia, 1976**, edited by B. Bertotti (Academia Nationale dei Lincei, Rome, 1977). (E)
10. **Proceedings of the Conference on Experimental Tests of Gravitation Theories** edited by R. W. Davies (California Institute of Technology, Pasadena, 1970) (JPL TM 33-499). (E)
11. **Proceedings of the workshop meeting on the measurement of Cosmological Variations of the Gravitational Constant**, edited by L. Halpern (University of Florida, Gainsville, 1978). (I)
12. **Proceedings of the Einstein Centenary Summer School, Perth, Australia**, edited by C. Edwards (Springer-Verlag, Berlin, 1980). (E)
13. **International Astronomical Union Symposium No. 64: Gravitational Radiation and Gravitational Collapse**, edited by C. DeWitt-Morette (Reidel, Boston, 1974). (E)

Texas Symposium on Relativistic Astrophysics

The latest of these symposia is reported in

14. **Proceedings of the 9th Texas Symposium on Relativistic Astrophysics** edited by J. Ehlers, J. J. Perry, and M. Walker (New York Academy of Science, New York, 1980). (I)
15. **4th General Conference of the Eurpoean Physical Society** (Trends in Physics, York, England, 1978). (E)

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)

18. **General Relativity: An Einstein Centenary Survey**, edited by S. W. Hawking and W. Israel (Cambridge University, Cambridge, 1979), contains many papers of current interest. (E)
19. **Gravitation: An Introduction to Current Research**, edited by L. Witten (Wiley, New York, 1962). (E)
20. **Gravitation & Cosmology: Principles and Applications of the General Theory of Relativity**, S. Weinberg (Wiley, New York, 1972). (E)
21. **Physical Experiments with Test Bodies**, V. B. Braginsky [Nauka, Moscow (NASA TT F-672) 1972]. This book describes advanced experimental techniques, particularly in gravitational physics. (E)
22. **Measurements of Weak Forces in Physics Experiments**, V. B. Braginsky and A. B. Manukin, edited by D. Douglas (University of Chicago, Chicago, 1977). A continuation of the theme begun in *Physical Experiments with Test Bodies*, with particular emphasis on very small forces. (E)
23. **Sources of Gravitational Radiation**, edited by L. Smarr (Cambridge University, Cambridge, 1979). (I)
24. **Topics in Theoretical and Experimental Gravitation Physics**, edited by V. DeSabbata and J. Weber (Plenum, New York, 1977). (I)
25. **Physics & Contemporary Needs**, edited by Riazuddin (Plenum, New York, 1980). (E)
26. **Gravity and Spacetime**, H. C. Ohanian. A senior level text. (I)
27. **Gravitational Curvature: An Introduction to Einstein's Theory**, T. Frankel (Freeman, Oxford, England, 1979). (E)
28. **On the Path of Albert Einstein**, edited by A. Perlmutter and L. F. Scott (Plenum, New York, 1979). An undergraduate text. (E)
29. **General Relativity and Gravitation**, edited by G. Shaviv and J. Rosen (Wiley, New York, 1975). (E)
30. **Theoretical Principles in Astrophysics and Relativity**, edited by N. R. Lebovits, W. H. Reid, and P. O. Vandervoort (University of Chicago, Chicago, 1978). (I)
31. **Space, Time and Gravitation**, A. S. Eddington (Cambridge University, Cambridge, 1920). Still the best popular exposition of general relativity. (E)

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.

32. **"Experimental Relativity,"** R. H. Dicke, in *Relativity, Groups, and Topology*, edited by C. DeWitt and B. DeWitt (Gordon and Breach, New York, 1964).
33. **"Comparison of theory and observation in general relativity,"** L. I. Schiff, in *Relativity Theory and Astrophysics. I. Relativity and Cosmology*, edited by J. Ehlers (American Mathematical Society, Providence, RI, 1967). (I)

34. **"Einstein on the Firing Line," C. M. Will, Phys. Today **25** (10), 23–29 (Oct. 1972). This relativity accessible article discusses the PPN framework for testing gravitational theories. (E)

35. **"Theoretical Frameworks for Testing Relativistic Gravity. IV. A Compendium of Metric Theories of Gravity and their Post-Newtonian Limits,"** W. T. Ni, Astrophys. J. **176**, 769–796 (1972). (I)
36. **"Laboratory experiments to test relativistic gravity,"** V. B. Braginsky, C. M. Caves, and K. S. Thorne, Phys. Rev. D **15**, 2047–68 (1977). (E)

37. **"Relativistic Experiments in Gravitational Fields," V. N. Rudenko, Sov. Phys. Usp. **21** (11), 893 (1978). (E)

38. **"Experimental Tests of General Relativity,"** C. M. Will, Proc. R. Soc. London **368**, 1732, 5–8 (1979). (E)

39. **"Experimental Verification of the General Theory of Relativity," V. L. Ginzburg, Sov. Phys. Usp. **22**, 514–527 (1979). (E)

40. **"Status of Experimental Gravitation,"** B. Bertotti, in *Recent Developments in Gravitation*, NATO Advanced Study Institutes Series B, Vol. 44, edited by M. Levy and S. Deser (Plenum, New York, 1979), p. 3. (E)

*41. **"Gravitation, Relativity and Precise Experimentation,"** C. W. F.

Everitt in Ref. 7. (E)

42. **"Astronomical Tests of General Relativity,"** J. R. Shakeshaft, Observatory **99** (1031), 122–3 (1979). (E)
43. **"Experimental Tests of General Relativity: Past, Present and Future,"** C. W. F. Everitt, in Ref. 25, Vol. 4. (E)
44. **"The Confrontation between General Relativity and Experiment,"** C. M. Will, in Ref. 14, p. 307. (I)

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.

45. **"A determination of the deflection of light by the Sun's gravitational field,"** F. W. Dyson, A. S. Eddington, and C. Davidson, Philos. Trans. R. Soc. **220**, 291 (1920). (E)
46. **"Experiments on Gravitation."** B. Bertotti, D. R. Brill, and R. Krotkov, in Ref. 19, p. 1–48. (E)
47. **"Principle of Equivalence and the deflection of light by the Sun,"** R. P. Comer and J. D. Lathrop, Am. J. Phys. **46** (8), 801 (1978). (E)
48. **"A Measurement of the gravitational deflection of radio waves by the sun,"** J. M. Hill, Mon. Not. R. Astron. Soc. **153**, 7P–11P (1971). (E)
49. **"Solar gravitational deflection of radio waves measured by very-long-baseline interferometry,"** C. C. Counselman III, S. M. Kent, C. A. Knight, I. I. Shapiro, T. A. Clark, H. F. Hinteregger, A. A. Rogers, and A. R. Whitney, Phys. Rev. Lett. **33**, 1621–23 (1974). (I)
50. **"Testing Relativity in the desert: The Texas–Mauritania eclipse expedition,"** R. Matzner, Phys. Teach. **13** (4), 215–22 (1975). (E)
51. **"Measurement of the solar gravitational deflection of radio waves in agreement with general relativity,"** E. B. Fomalont and R. A. Şramek, Phys. Rev. Lett. **36**, 1475–78 (1976). (E)
52. **"Sensitivity of laboratory tests of gravitation beyond the geometrical optics limit,"** A. M. Grassi Strini, G. Strini, and G. Tagliaferri, Phys. Lett. A (Netherlands) **72** (6), 476–8 (1979); describes light deflection experiments in the laboratory. (I)

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

53. **"Evidence for the presence of a gravitationally-lensed secondary image,"** N. Sanitt, Mon. Not. R. Astron. Soc. **174** (1), 91–103 (1976); an early report of another object. (E)
54. **"0957 + 561A, B twin quasistellar objects or gravitational lens?"** D. Walsh, R. F. Carswell, and R. J. Weymann, Nature **279**, 381 (1979). (E)
55. **"Radio Studies of the Double QSO 0957 + 561A, B,"** G. G. Pooley, Nature **280** (5722), 461–4 (1979). (I)
56. **"Multiple-mirror telescope observations of the twin QSO's 0957 + 561A, B,"** R. J. Weymann, F. H. Chaffee, M. Davis, N. P. Carleton, D. Walsh, and R. F. Carswell, Astrophys. J. Lett. **233** (2), pt. 2, L43–6 (1979). (I)

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.

57. **"Discovery of a Pulsar in a Binary System,"** R. A. Hulse and J. H. Taylor, Astrophys. J. Lett. **195** (2), pt. 2, L51–3 (1975). (E)
58. **"Further observations of a binary pulsar PSR 1913 + 16,"** J. H. Taylor, R. A. Hulse, and L. A. Fowler, Astrophysics. J. Lett. **206** (1), pt. 2, L53–8 (1976). (E)
59. **"Measurement of general relativistic effects in the binary pulsar PS1913 + 16,"** J. H. Taylor, L. A. Fowler, and P. M. McCulloch, Nature **277**, 437 (1979). (I)
60. **"Gravitational Waves: an indirect confirmation,"** M. Lachieze-Rey, Recherce **10** (102), 776–7 (1979); describes indirect observation of gravitational waves by slowdown of binary pulsar—in French. (E)
61. **"Progress report on the binary pulsar 1913 + 16,"** L. A. Fowler, J. M. Cordes, and J. H. Taylor, Aust. J. Phys. **32** (1-2), 35–41 (1979). (I)

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 extra 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-flying 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.

62. **"Solar-System tests of General Relativity," R. D. Reasenberg and I. I. Shapiro, in Ref. 9, p. 143–60. (E)

63. **"The Problem of Comparing the observation results with the Theoretical data to check on Relativistic effects in the solar system,"** V. A. Brumberg and A. M. Finkel'shtein, Sov. Phys. JETP **49** (5), 749 (1979). (A)
64. **"Tests of theories of gravity in the solar system,"** J. P. Richard, in Ref. 29, p. 169–88. (E)

1. Experiments involving planetary bodies

65. **"Tests of General Relativity using astrometric and radiometric observations of the planets," J. D. Anderson, M. S. W. Keesey, E. L. Lau, E. M. Standish, Jr., and X. Newhall, Acta Astronaut. **5**, 43–61 (1978). (E)

66. **"Testing General Relativity with laser ranging to the Moon,"** R. Baierlein, Phys. Rev. **162**, 1275–88 (1967). (E)
67. **"The lunar laser ranging experiment,"** P. L. Bender, D. G. Currie, R. H. Dicke, D. K. Eckhardt, J. E. Faller, W. M. Kaula, J. D. Mulholland, H. H. Plotkin, S. K. Poultney, E. C. Silverberg, D. T. Wilkinson, J. G. Williams, and C. O. Alley, Science **182**, 229–38 (1973). (E)
68. **"New Test of the Equivalence Principle from Lunar Laser Ranging,"** J. G. Williams, R. H. Dicke, P. I. Bender, C. O. Alley, W. E. Carter, D. G. Currie, D. H. Eckhardt, J. E. Faller, W. M. Kaula, J. D. Mulholland, H. H. Plotkin, S. K. Poultney, P. J. Shelus, E. C. Silverberg, W. S. Sinclair, M. A. Slade, and D. T. Wilkinson, Phys. Rev. Lett. **36** (11), 551–54 (1976). (I)
69. **"Verification of the Principle of Equivalence for massive bodies,"** I. I. Shapiro, C. C. Counselman III, and R. W. King, Phys. Rev. Lett. **36** (11), 555 (1976); describes laser ranging of the moon. (E)
70. **"The Viking Relativity Experiment,"** I. I. Shapiro, R. D. Reasenberg,

P. E. MacNeil, R. B. Goldstein, J. P. Brenkley, D. L. Çain, T. Komarek, A. I. Zygielbaum, W. F. Cuddihy, and W. H. Michael, Jr., J. Geophys. Res. **82**, 4329 (1977); describes preliminary results. (E)
71. **"Viking Relativity Experiment: Verification of Signal Retardation by Solar Gravity,"** R. D. Reasenberg, I. I. Shapiro, P. E. MacNeil, R. B. Goldstein, J. C. Breidenthal, J. P. Brenkle, D. L. Cain, T. M. Kaufman, T. A. Komarek, and A. I. Zygielbaum, Astrophys. J. Lett. **234** (3), pt. 2, L219–21 (1979); 14 months of data confirms signal retardation effect from solar gravity to 0.1%. (I)

2. Perihelion advance of Mercury

Other bodies than Mercury are now included in this classic 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.

72. **"The Relativity Effect in Planetary Motions,"** G. M. Clemence, Rev. Mod. Phys. **19**, 361–4 (1947); includes references to prior measurements of this effect. (E)
73. **"Mercury's Perihelion Advance: Determination by radar,"** I. I. Shapiro, G. H. Pettengill, M. E. Ash, R. P. Ingalls, D. B. Campbell, and R. B. Dyce, Phys. Rev. Lett. **28**, 1594 (1972). (I)
74. **"The oblateness of the Sun and relativity,"** R. H. Dicke, Science **184**, 419–29 (1974). (E)
75. **"Solar oblateness, excess brightness, and relativity,"** H. A. Hill, P. D. Clayton, D. L. Patz, A. W. Healy, R. T. Stebbins, J. R. Oleson, and C. A. Zanoni, Phys. Rev. Lett. **33** (25), 1497–500 (1974). (A)
76. **"The oblateness of the Sun,"** H. M. Goldenberg and R. H. Dicke, Astrophys. J. Suppl. **27**, 131–82 (1974). (A)

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.

77. **"Application of DSN Spacecraft Tracking Technology to Experimental Gravitation,"** J. D. Anderson, J. Spacecraft Rockets **16** (2), 120–5 (1979). (E)
78. **"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)
79. **"Experimental test of General Relativity using time-delay data from Mariner 6 and Mariner 7,"** J. D. Anderson, P. B. Esposito, W. Martin, C. L. Thornton, and D. O. Muhleman, Astrophys. J. **200**, 221–33 (1975). (I)
80. **"Detecting a gravitational radiation background using spacecraft Doppler tracking,"** R. W. Hellings, Phys. Rev. Lett. **43** (6), 470–3 (1979). (E)
81. **"Tests of gravitation theories using space probes,"** W. Davidson, Int. J. Theor. Phys. **17** (8), (1978). (E)
82. **"Relativity Experiments with Clocks,"** R. F. C. Vessot, Radio Sci. **14** (4), 629–47 (1979). (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.

83. **"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)
84. **Principia**, I. Newton (London, 1686); contains the description of Newton's pendulum experiments. (E)
85. **"Versuche Uber die Kraft, mit welcher die Erde Körper von verschiedner Beschaffenheit anzieht,"** F. W. Bessel, Ann. Phys. Chem. (Poggendorf) **25**, 401–8 (1832); the summary of Bessel's work with pendulums—in German. (E)
86. **"Untersuchungen über Gravitation und Erdmagnetismus,"** R. von Eötvös, Ann. Phys. **59**, 354 (1896); Eötvös' original article—in German. (E)
87. **"Experiments on gravitation,"** P. Zeeman, Verh. D. Akad. Wet. **26**, 451 (1918); careful weighings establish the equivalence principle. (E)
88. **"Beiträge zum Gesetze der Proportionalität von Trägheit und Gravität,"** R. von Eötvös, D. Pekar, and E. Fekete, Ann. Phys. (Leipzig) **68**, 11 (1922); in German. (E)
*89. **"The Equivalence of Inertial and Passive Gravitational Mass,"** P. G. Roll, R. Krotkov, and R. H. Dicke, Ann. Phys. **26**, 442 (1964); in our opinion the best experiment done so far. (E)
90. **"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)
91. **"An Eötvös Experiment in Earth Orbit,"** P. K. Chapman and A. J. Hanson, in Ref. 10, p. 228; proposes a method of testing equivalence in Earth orbit. (I)
92. **"Verification of the equivalence of gravitational and inertial mass for the neutron,"** I. Koester, Phys. Rev. D **14**, 907–9 (1976); a classical experiment, which should be compared with the nonclassical experiments in Sec. IV D 10. (I)
93. **"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)
94. **"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)
95. **"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)
96. **"The optical isotropy of space and its relation to the equivalence principle,"** O. N. Naida and Ya. A. Smaorodinskii, Sov. Phys. JETP **49** (4), 585 (1979). (I)
97. **"A Test of the Equivalence Principle using a Space-Borne Clock,"** R. F. C. Vessot and M. W. Levine, Gen. Relativ. Gravit. **10** (3), 181–204 (1979); reports a test to $\eta = 2\times10^{-4}$ using a clock in a space probe. (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).

98. **"On experimental tests of the general theory of relativity,"** L. I. Schiff, Am. J. Phys. **28**, 340–3 (1960). (E)
99. **"Eötvös experiment and the gravitational red shift,"** R. H. Dicke, Am. J. Phys. **28**, 344–7 (1960). (E)
100. **"Apparent Weight of Photons,"** R. V. Pound and G. A. Rebka, Phys. Rev. Lett. **4**, 337–41 (1960). (E)
101. **"The Gravitational Redshift in the Solar Spectrum,"** J. W. Brault, Bull. Am. Phys. Soc. **8**, 28 (1963). (I)
102. **"Effect of gravity on gamma radiation,"** R. V. Pound and J. L. Snider, Phys. Rev. B **140**, 788–803 (1965). (I)
103. **"New Measurement of the Solar Gravitational Redshift,"** J. L. Snider, Phys. Rev. Lett. **28**, 853 (1972). (I)

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.Vff. (E)
106. **"On the origin of Inertia,"** D. W. Sciama, Mon. Not. R. Astron. Soc. **113**, 34 (1953). (E)
107. **"A search for anisotropy of inertial mass using a free precession technique,"** R. W. P. Drever, Philos. Mag. **6**, 683–7 (1961). (I)
108. **"Mach's Principle and experiments on mass anisotropy,"** V. W. Hughes, in *Gravitation and Relativity* (Benjamin, New York, 1964), p. 106–20. (E)
109. **"Mach's Principle and Equivalence,"** R. H. Dicke, in Ref. 2. (E)
110. **"Search for evidence of a preferred reference frame,"** R. J. Warburton and J. M. Goodkind, Astrophys. J. **208**, 881 (1975). (I)
111. **"Gravity and Inertia in a Machian Framework,"** J. B. Barbour and B. Bertotti, Nuovo Cimento **38b** (1), 1 (1977). (I)
112. **"Specific Consequences of Mach's Principle,"** J. D. Nightingale, Am. J. Phys. **45** (4), 376–9 (1977); a theoretical discussion of the Machian effects to be expected in general relativity. (I)
113. **Experimental implications of Mach's Principle**, W. S. Cheung, University of Virginia, Master's thesis (unpublished), 1978; contains many references. (E)
114. **"Experimental test of the Equivalence Principle,"** B. V. Vasilev and E. V. Kolycheva, Sov. Phys. JETP **48** (1), 4 (1978). (I)
115. **"Improved laser test of the isotropy of space,"** A. Brillet and J. L. Hall, Phys. Rev. Lett. **42**, 549–52 (1979). (I)

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 desigining free-mass detectors of equal or greater potential sensitivity.

116. **"Gravitational-Wave Astronomy," R. Giffard and J. A. Tyson, Ann. Rev. Astron. Astrophys. **16**, 521–54 (1978). (E)
117. **"Gravitational-radiation experiments,"** D. H. Douglass and V. B. Braginsky, in Ref. 18, p. 90–137. (E)
118. **Present Status of Gravitational-wave Experiments**, V. B. Braginsky and K. S. Thorne, Cal. Tech. OAP-609 (unpublished). (E)
119. **"Evidence for discovery of gravitational radiation,"** J. Weber, Phys. Rev. Lett. **22**, 1320–4 (1969). (E)
120. **"Gravitational Radiation detector observations in 1973 and 1974,"** M. Lee, D. Gretz, S. Steppel, and J. Weber, Phys. Rev. D **14**, 4 (1976); a summary of the observations by Weber's group. (E)
121. **"Initial operation of the $M = 390$ Kg Cryogenic Gravitational wave antenna,"** E. Amaldi, C. Cosmelli, S. Frasca, I. Modena, G. V. Pallottino, G. Pizella, F. Ricci, P. Bonifazi, F. Bordoni, V. Ferrari, U. Giovanardi, V. Iafolla, B. Pavan, S. Ugazio, and G. Vannaroni, Nuovo Cimento C Ser. 1 **16** (6), 497–509 (1978). (I)
*122. **"Ultimate Sensitivity Limit of a Resonant Gravitational wave antenna,"** R. Giffard, Phys. Rev. D **14** (10), 2476–86 (1977). (I)
123. **"Quantum limits on resonant-mass gravitational-radiation detectors,"** J. Hollenhorst, Phys. Rev. D **19**, 1669 (1979). (I)
124. **"Tunable 'free-mass' gravitational wave detector,"** R. V. Wagoner, C. M. Will, and H. J. Paik, Phys. Rev. D **19** (8), 2325–9 (1979). (E)
125. **"Gravitational Wave Detectors,"** R. W. P. Drever, J. Hough, J. R. Pugh, W. A. Edelstein, H. Ward, G. M. Ford, and N. A. Robertson, Proc. R. Soc. London **368** (1732), 11–13 (1979); describes separated mass detectors. (E)
126. **"Quantum nondemolition and gravity wave detection,"** W. Unruh, Phys. Rev. **D19** (10), 2888–96 (1979); a review of various schemes for these techinques. (A)
127. **"Pulsar timing measurements and the search for gravitational waves,"** S. Detweiler, Astrophys. J. **234** (3), pt. 1, 1100–4 (1979); arrival time of pulsar pulses sets limits to long-period gravitational waves. (E)
128. **"Gravitational Radiation from the Crab nebula at 60.2 Hz,"** K. Oide, H. Hirakawa, and M. K. Fujimoto, Phys. Rev. D **20** (10), 2480–3 (1979). (I)
129. **"Local field and gravitational-radiation experiments,"** T. Suzuki and 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)
130. **"On the measurement of a weak classical force coupled to a quantum-mechanical oscillator. I. Issues of principle,"** C. M. Caves, K. S. Thorne, W. P. Drever, V. D. Sandberg, and M. Zimmermann, Rev. Mod. Phys. **52**, 1341–92 (1980). (I)
131. **"Elastooptical antenna for detection of Gravitational Radiation,"** G. R. Boyer, B. F. Lamouroux, B. S. Prade, and J. Y. Vinet, Appl. Opt. **19** (3), 382–5 (1980). (I)
132. **"Low-Noise Temperature Gravitational Radiation Antenna–Transducer System,"** D. G. Blair and A. G. Mann, Nuovo Cimento **61** (1), (1981). (A)

5. *Stanford gyro relativity experiment*

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

133. **"Possible new test of general relativity theory,"** L. I. Schiff, Phys. Rev. Lett. **4**, 215–7 (1960). (E)
134. **"The Gyroscope Experiment. I. General description and analysis of gyroscope performance,"** C. W. F. Everitt, in Ref. 3. (E)
135. **"A Superconducting Gyroscope to test Einstein's General Theory of Relativity,"** C. W. F. Everitt, Proc. Soc. Photo-Opt. Instrum. Eng. **157**, 175–88 (1978). (E)
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)
137. **"Effects of the motion of particles with spin in Gravitational fields,"** E. N. Epikhin and N. V. Mitskevich, Sov. Phys. JETP **22** (5), 554–6 (1979). (A)

6. *Twin-satellite experiment*

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

138. **"Relativity Mission with two counter-orbiting polar satellites,"** R. A. Van Patten and C. W. F. Everitt, in *Astrodynamics 1975, Vol. 33, Advances in the Astronautical Sciences* (American Astronomical Society, San Diego, 1976). (E)
139. **"Possible experiment with two counter-orbiting drag-free satellites...,"** R. A. Van Patten and C. W. F. Everitt, Phys. Rev. Lett. **36** (12), 629–32 (1976). (E)
140. **"Relativistic Effects on Earth Satellites,"** L. Cugusi and E. Proverbio, Astron. Astrophys. **69** (3), 321–5 (1978). (I)

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 10^4.

141. **"The Density of the Earth,"** H. Cavendish, Philos. Trans. R. Soc. **88**, 469 (1798); the original experiment to "weight the earth." (E)
142. **"On a determination of the mean density of the earth and the gravitation constant by means of the common balance,"** J. H. Poynting, Philos. Trans. R. Soc. A **182**, 565 (1891); a careful adaptation of a chemical balance.
*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)
145. **"Determination of the gravitational constant G,"** R. D. Rose, H. M. Parker, R. A. Lowry, A. R. Kuhlthau, and J. W. Beams, Phys. Rev. Lett. **23**, 655–88 (1969). (E)
146. **"Finding a better Value for G,"** J. W. Beams, Phys. Today **24** (5), 34–40 (1971); rotating the experiment averages external noise. (E)

8. *Measurements of the time variation of G*

Reference 11 contains a number of papers on this subject.

147. **"Gravitational constant: Experimental bound on its time variation,"** I. I. Shapiro and W. B. Smith, Phys. Rev. Lett. **28**, 1594–97 (1971). (E)
148. **"Possibility of measuring the time dependence of the gravitational constant,"** V. B. Braginsky and V. L. Ginzburg, Sov. Phys. Dokl. **19**, 290–1 (1974). (I)
149. **"Limit on the secular change of the gravitational constant based on studies of solar evolution,"** C. W. Chin and R. Stothers, Phys. Rev. Lett. **36**, 833–5 (1976).
150. **"Is Gravity getting weaker?"** T. C. Van Flandern, Sci. Am. **234** (2), 44–52 (1976). (E)
151. **"E&M vibrating system for observation of small periodic mass variations,"** V. I. Panov and V. N. Frontov, Instrum. Exp. Tech. (USSR) [Prib. Tekh. Exsp.] **22** (1), pt. 2, 217–20 (1979); a servoed beam balance for constancy of mass—$\Delta m/m = 3\times 10^{-12}$ in 8000 sec. (I)
152. **"Limits to the expansion of Earth, Moon, Mars, and Mercury and to changes in the gravitational constant,"** M. W. McElhinny, S. R. Taylor, and D. J. Stevenson, Nature **271**, 316 (1978). (E)
153. **"Dynamic measurement of matter creation,"** R. Ritter, Nature **271**, 228 (1978). (I)
154. **"Experimental searches for gravitational effects outside General Relativity,"** R. Ritter, in Ref. 8. (I)

9. *Inverse square law*

155. **"Why do we believe Newtonian gravitation at laboratory distances?"** D. R. Long, Phys. Rev. D **9**, 850–1 (1974). (E)
156. **"Experimental Examination of the Gravitational Inverse Square Law at laboratory dimensions,"** D. R. Long, Nature **260** (5550), 417–8 (1975). (E)
157. **"Cavendish Experiment at large distances,"** V. I. Panov and V. N. Frontov, Sov. Phys. JETP **50** (5), 852–56 (1979). (I)
158. **"Proposed Null expt. to test inverse square law of gravity,"** A. P. Mills, Jr., Gen. Relativ. Gravit. **11** (1), 1–11 (1979); describes a null Cavendish experiment using a fluid filled resonator excited by deviations from $1/R^2$ force. (E)
159. **"New Null experiment to test the inverse square law of gravitation,"** H. J. Paik, Phys. Rev. D **19** (8), 2320–4 (1979). (I)
160. **"Dynamical test of the law of gravitation,"** H. Hirakawa, K. Tsubono, and K. Oide, Nature **283** (5743), 184–5 (1980); tests using quadrupole interactions. (I)
161. **"An experimental determination of the gravitational constant at distances around 10 meters,"** Hsou-Tao Yu, Wei-Tou Ni, Chin-Cheng Hu, Fa-Hsing Liu, Chia-Hsiang Yang, and Wu-Nan Liu, Chin. J. Phys. (Taiwan) **16** (4), 201–2 (1979); a simple test of the $1/R^2$ law of gravity at short distances using a gravimeter, swimming pool, and oil tank. (E)

10. *Nonclassical experiments*

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

162. **"Experimental comparison of the gravitational force on freely falling electrons and metallic electrons,"** F. C. Witteborn and W. M. Fairbank, Phys. Rev. Lett. **19**, 1049–52 (1967). (E)
163. **"The role of Equivalence in Quantum Mechanics,"** D. Greenberger, Ann. Phys. **47** (1), 116–26 (1968). (E)
164. **"Observation of gravitationally induced quantum interference,"** R. Colella and A. W. Overhauser, Phys. Rev. Lett. **34** (23), 1472–4 (1972). (E)
165. **"Experiments to determine the force of gravity on single electrons and positrons,"** W. M. Fairbank, F. C. Witteborn, J. M. Madey, and J. M. Lockhart, in Ref. 3. (I)
166. **"Magnetic Field effects on Dynamical diffraction of neutrons,"** A. Zeilinger and C. G. Shull, Phys. Rev. B **19** (8), 3957–62 (1979). (A)
167. **"The Role of Gravity in Quantum Theory,"** D. M. Greenberger and A. W. Overhauser, Sci. Am. **242** (5), 66 (1980); a description of some experiments on the effect of gravity on neutron interference. (I)
168. **"Neutrons, Gravity and Quantum Mechanics,"** R. Colella and A. W. Overhauser, Am. Sci. **68**, 70 (1980). (I)

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.

169. **"Gravitational Spectra from direct measurements,"** C. A. Wagner and O. L. Colombo, J. Geophys. Res. **84** (B9), 4699–712 (1979). (I)
*170. **"Development of Gravity Pendulums in the 19th century,"** V. F. Lenzen and R. P. Multhauf, in Contributions from the Museum of History and Technology, U. S. National Museum bulletin 240, Smithsonian Institution, 1965, paper 44, p. 301–348. (E)
171. **"Relative gravity measurements using precision pendulum equipment,"** Geophys. **5**, 176–191 (1940). (E)
172. **"Recent developments in the absolute measurement of gravity,"** A. H. Cook, Bull. Geodis. **44**, 34–59 (1957). (E)
173. **A Cryogenic Gravimeter**, W. A. Prothero, Ph.D. Thesis, University of California at San Diego, La Jolla, CA (unpublished) (1967). (I)
174. **"Generation and detection of dynamic gravitational-gradient fields,"** R. Forward and L. R. Miller, J. Appl. Phys. **38** (2), 512 (1967); describes a dynamic gravity gradient detector of great sensitivity. (I)
175. **"The influence of barometric pressure fluctuations on gravity,"** R. J. Warburton and J. M. Goodkind, Geophys. J. R. Astron. Soc. **48**, 281–92 (1977); this publication is more available than Ref. 173 and describes measurements with a superconducting gravimeter. (I)
176. **"Electronic Cooling of Resonant Gravity Gradiometers,"** R. Forward, J. Appl. Phys. **50** (1), 1–6 (1979); describes more recent work on the device in Ref. 170. (I)