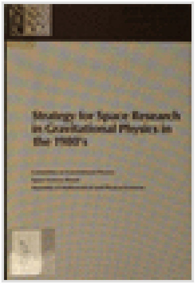

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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Foreword

This document is one of a series prepared by committees of the Space Science Board (SSB) that develop strategies for space science over the period of a decade. Several reports in this series have been completed. *Report on Space Science 1975* (Part II, Report of the Committee on Planetary and Lunar Exploration, which covers the outer planets); *Strategy for Exploration of the Inner Planets: 1977–1987*; *Strategy for Space Astronomy and Astrophysics for the 1980's* (1979); *Life beyond the Earth's Environment: The Biology of Living Organisms in Space* (1979); *Solar-System Space Physics in the 1980's: A Research Strategy* (1980); and *Strategy for the Exploration of Primitive Solar-System Bodies–Asteroids, Comets, and Meteoroids*: 1980–1990 (1980).

This document deals with a different aspect of science than those surveyed by earlier strategies, which were concerned with measurements of the environment of the Earth, the solar system, and the universe as a whole. The present study deals with the contribution that space measurements can make to understanding the nature of one of the four fundamental forces in the universe–gravitation. We are accustomed to thinking of studies in fundamental physics as being carried out in earthbound laboratories, often involving the highest-energy accelerators, but the force of gravity is so weak in comparison with the other forces that only space provides an environment sufficiently free from perturbations to make possible the extraordinarily sensitive measurements described in this report.

The report of the Committee on Gravitational Physics was approved by the Board at its meeting of April 1980. The Board appreciates the efforts of the Committee and particularly its Chairman Irwin Shapiro.

A. G. W. Cameron, *Chairman*
Space Science Board

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Summary

Gravitational physics is concerned with the fundamental theory of gravitation and its experimental verification. Although by far the weakest of the four known elementary-particle interactions, gravitation dominates the overall behavior of the universe. Applications in astrophysics of the relativistic theory of gravitation are broad and deep, encompassing such diverse subjects as the early history and ultimate fate of the universe, the properties of putative black holes, and the gravitational focusing of light by galaxies.

It is important to perform gravitational experiments at the ever higher limits of accuracy that evolving technology allows in order to detect and study new phenomena and to distinguish between theories of gravitation that differ at these levels. For example, our view of the universe would change profoundly if even a small admixture of a scalar field were detected in the gravitational interaction, now thought to be exclusively tensor in character.

Space offers many unique advantages for the study of gravitational phenomena. In space, necesssarily delicate apparatus can escape the disturbing influences of Earth. Further, space techniques allow instruments to be transported to the close neighborhood of the sun, where gravitational effects in the solar system are strongest. The space program has already played an important role in the development of gravitational physics and can play an even more pivotal role in the future with the development and use of more-sensitive instrumentation.

Gravitational experiments performed to measure relativistic effects have been limited mainly to observing the behavior of clocks, light rays, and test particles under the influence of massive bodies like the sun and Earth.

Our proposed strategy involves a broadening of these experiments through measurements in space of entirely new phenomena, extension of previous measurements to substantially higher levels of accuracy, and improvements of instrumentation to attempt to detect gravitational waves.

I. RECOMMENDATIONS

For the present decade, we propose tests of gravitational theories through experiments in space that are technically and economically feasible and that either measure previously undetected effects or improve significantly upon previous measurements. We also propose development of advanced instrumentation that will make possible new types of experiments in the following decade.

Our recommendations for experiments in the 1980's are divided into two classes, based on cost. The first class involves experiments that either require a dedicated spacecraft or have a major impact on a spacecraft; the second class contains experiments that either rely solely on ground-based measurements or represent small additions to spacecraft devoted primarily to other goals. Within each class, the recommendations are listed in priority order with the highest rank first; interclass ratings are virtually meaningless in view of the wide disparity in required resources. A third class of rank-ordered recommendations contains our proposals for development of advanced instrumentation.

Class 1 (a) Test the relativistic prediction of the dragging of inertial frames by rotating masses

The relativistic theory of gravitation predicts the existence of a gravitational analog of the magnetic field—the "mass-current" effect of rotating matter that results in a "dragging" of inertial frames about the rotating mass. One consequence of this predicted effect is the precession with respect to directions defined by distant stars of the spin axis of a gyroscope in orbit about a massive rotating body. No manifestation of this frame dragging has ever been observed. It would be a most fundamental contribution to physics to verify its existence and measure its strength.

The best-developed means to measure frame dragging is to place a gyroscope in earth orbit and monitor the precession of its spin axis that would be due to the effect of the earth's rotation. Results in accord with the general theory of relativity would provide a firm base for this aspect of the theory and give confidence in its use in models for various astrophysical phenomena involving massive rotating bodies. Reliable results incompatible with general relativity would constitute a major landmark in experimental physics.

A gyroscope is predicted to partake of another, larger and distinguishable, precession owing simply to its being in orbit about a massive body. This prediction of general relativity, also not yet observed, could be tested at the same time as the mass-current effect, and to much higher fractional accuracy, by orbiting several differently oriented gyroscopes in the same spacecraft.

Class 1 (b) Measure the gravitational quadrupole moment of the sun

Knowledge of the gravitational quadrupole moment of the sun is essential for the proper determination of relativistic effects on the orbits of the planets. This quadrupole moment causes an advance of the perihelion of the orbit of Mercury, for example, which is virtually indistinguishable from the relativistic contribution to the advance. The latter effect affords the best present means of measuring the nonlinearity in the superposition of gravitational potentials and for this reason is of special importance. A measurement with an uncertainty of 10^{-8} of the (dimensionless) coefficient J_2 that represents the sun's quadrupole moment would allow a more than tenfold improvement in our ability to separate the relativistic contribution from the measured advance of Mercury's perihelion. Such a measurement would also provide a fundamental constraint on models of the interior of the sun, especially its rotation.

It is possible to measure J_2 to within 10^{-8} through radio tracking of a spacecraft that passes within about 4 solar radii of the sun's center, provided the spacecraft is equipped with a suitable drag-compensation system to correct for nongravitational accelerations. It may also be feasible to measure J_2 to this accuracy through several years of radio tracking of a spacecraft in a suitable orbit about Mercury. The potentially far higher accuracy of radio tracking compared with that of the currently used passive radar tracking could enable the effects of J_2 to be separated from the other influences on Mercury's orbit.

Class 1 (c) Measure the nonlinear effect of gravitational potentials on the rate of a clock

The general theory of relativity predicts that a clock will appear to run more slowly in a region of stronger gravitational potential. This prediction has already been verified. However, it is important to check it with substantially higher accuracy to determine the extent to which a clock's running rate is affected by the nonlinearity in the superposition of gravitational potentials. Prior experiments were insensitive to this nonlinearity.

The predicted nonlinearity could be checked with under 10 percent uncertainty by placing a very stable frequency standard (instability under 1 part in 10^{15} for averaging times of a few hundred seconds to a few days), like the one proposed to measure J_2, on a spacecraft that passes close to the sun. Such a frequency standard, together with suitable modifications to the spacecraft's radio tracking system, would also enhance the sensitivity of attempts to detect gravitational waves during the cruise of the spacecraft to the sun.

Class 2 (a) Determine the relativistic contributions to the orbits of the moon and inner planets

The inner solar system forms the best available laboratory for measuring relativistic effects of gravitation. Measurements within this system will likely provide for years to come the prime experimental underpinning for any theory of gravitation because the orbits of the moon and planets display varied and detectable manifestations of relativistic gravitation. These include the curvature of space caused by the sun, a possible breakdown of the principle of equivalence for massive bodies, and the nonlinear superposition of gravitational potentials. In addition, a small but important change with time of the universal "constant" of gravitation could be discernible as a variation in a planetary orbital period when measured on an atomic time scale; if present, such a variation would have a profound influence on our perception of the evolution of the universe and its contents.

Radio ranging to the Viking lander, laser ranging to the retroreflectors on the moon, and radar ranging to the planets can all provide data with ever-increasing sensitivity to such relativistic and cosmological effects. Measurements with these modern space techniques should be made at every feasible opportunity since our ability to isolate the relativistic and cosmological contributions to the orbital motions increases with the time span covered by the measurements. By the same token, these measurements would be an extremely valuable legacy to leave for future generations.

Class 2 (b) Attempt direct detection of gravitational waves

The detection of low-frequency gravitational waves, such as might be produced by formation of massive black holes and collisions between them, can best be attempted with space techniques. Earth-based experiments will be ineffective in searches for these waves because of interference from seismic noise and especially variations in gravity gradients.

Detection of these waves would be a momentous event, opening a new window on the universe and allowing us to determine whether gravitation is truly a field phenomenon and, if so, of what type.

Spacecraft placed for other purposes in heliocentric orbit far from the earth should be equipped with instrumentation as sensitive as possible to the effects of gravitational waves. The best present means for the detection of these waves is through the unique signature they would impart to the Doppler shift of the radio signals used to track spacecraft. These signals are currently limited in their usefulness by the corrupting effect of interplanetary plasma on the 2-GHz frequency "uplink" signal now in standard use, along with the 2- and 8-GHz downlink signals. The substitution of an ~8-GHz uplink signal, for which the technology has already been developed, would yield more than a tenfold increase in sensitivity of the Doppler tracking system to the effects of gravitational waves. A further increase would follow the later introduction of dual-band tracking signals on the uplink matched to those on the downlink.

Most estimates of the likely strengths of gravitational waves bathing the Earth, in the spectral band to which the Doppler tracking signal would be sensitive, place them below detectability even with the improved systems. Although technical impediments to continued increases in sensitivity are severe, no relevant fundamental limitation is known. It thus seems prudent to test new instrumentation at successive stages of improvement that change the system sensitivity by an order of magnitude or more. Further, nature may hold a surprise in store: an astrophysical source of gravitational radiation of far greater strength than anticipated.

Class 3 Develop advanced instrumentation

Future experimental progress in gravitational physics depends on the development of more-powerful instrumentation. Such development therefore forms an essential ingredient of our strategy. Our highest-priority instruments for development are (a) a radio tracking system with about two orders of magnitude greater immunity to plasma effects and correspondingly greater accuracy in ranging than the present system and (b) an optical interferometer for deployment in space, with a capability to measure relative positions of tenth-magnitude or brighter stars with an uncertainty of 1 μsec of arc.

The improved radio tracking system would allow a several order-of-magnitude increase in the accuracy of measurements of various relativistic effects of gravitation if the system were used on a planetary lander or suitable orbiter and would also further improve the sensitivity of the tracking system for detection of gravitational waves. The optical interferometer would allow detection of a post-post-Newtonian effect of gravitation for the first time and would also allow determination of the kinematic behavior of stars in our Galaxy with vastly increased accuracy and, possibly, detection of other planetary systems.

We also recommend study of advanced optically linked detectors in space that preliminary estimates indicate might well achieve the sensitivity needed to detect gravitational waves.

II. CONCERN

One implication of this proposed strategy is of particular concern: the difficulty of coordinating spacecraft missions that involve experiments from disparate disciplines. For many gravitational experiments, a dedicated spacecraft is unwarranted and unnecessary. Missions shared between disciplines appear eminently sensible in making the best use of increasingly rare and costly opportunities for space experiments. Mechanisms should be devised to allow such sharing to yield maximum scientific return. These are needed especially when a mission is devoted primarily to one discipline and involves a small complement of experiments from others.

In summary, the strategy that we propose is designed to broaden the experimental foundation of the relativistic theory of gravitation and to attempt direct detection of gravitational radiation. However, like the oft-stated goal of understanding the origin and evolution of the universe, it is easier to state than to achieve. The effects of relativistic gravitation are incredibly small, but the heroic efforts required to detect them are justified by the fundamental importance of the results.

2
Introduction

Gravitation is central to physics and astronomy. To demonstrate this centrality we describe briefly the development of gravitational theory, the recent advances in the understanding of the relation between gravitation and other branches of physics, and some applications of relativistic gravitation in astrophysics. We also discuss the need for experimental tests of the relativistic theory of gravitation.

I. HISTORICAL BACKGROUND OF GRAVITATIONAL PHYSICS

The mysterious motions of heavenly bodies provided the intellectual challenge that stimulated the early development of science. The introduction by Copernicus of the heliocentric system 500 years ago started a virtually exponential growth in scientific achievement. Kepler, with his development of the laws of planetary motion within this system, and Galileo, with his insights into motion, gave Isaac Newton the tools to unlock the secret hidden in centuries of painstakingly gathered positions of celestial bodies: combination of the laws of motion with the hypothesis of universal gravitation.

Mathematicians, too, were inspired by celestial dynamics. The names of Bessel, Gauss, Euler, Lagrange, Laplace, and Poincaré each figured prominently in parallel developments of dynamics and mathematics. The creation of perturbation theories and other entirely new mathematical techniques, still in use today, was stimulated by the problems arising from the science of gravitation founded by Newton.

The mind of Albert Einstein was also directed to the problem of gravitation, but from a deeper level. Einstein gave an entirely new view of the structure of the world and an extraordinary insight into the nature of gravitation. His general theory of relativity is perhaps the most brilliantly original contribution to scientific thought. Einstein had the genius to think of the space-time continuum as shaped entirely by the distribution of matter and energy within it and to develop the appropriate equations to give a quantitative basis for this association.

Although Einstein's niche as a genius was made forever secure by the famous eclipse expedition of 1919, which confirmed the predicted gravitational deflection of starlight by the sun, many of the other consequences of his theory were left unexplored for more than a quarter of a century. The attention of physicists was directed mainly inward toward the atom, rather than outward toward the universe. Experimental physicists lost interest in gravitation since no further significant tests of the general theory of relativity seemed feasible, and theoreticians were mostly preoccupied by the exciting developments in the world of microphysics.

A resurgence of interest in Einstein's theory occurred in the late 1950's and early 1960's. The interest of theorists was sparked in part by dramatic discoveries in astrophysics, the interest of experimentalists by the post-World War II flowering of technology. Yet, even today, gravitational physics differs from almost all other branches of physics in at least two curious respects. In other branches, experiment and theory develop hand in hand; for a short time one leads, and then roles reverse. In many cases, experiments have provided the stimuli for major advances. In gravitation, the experimental part of the discipline lags well behind the theoretical; black holes are, as it were, out of sight of experimentalists. The explanation for the lag is simple: the technical difficulties impeding significant experiments remain awesome, although not insurmountable. Gravitational physics as a consequence is also set apart in regard to development of fundamental theories. In other branches of physics, a new theory is usually developed only when the limit of validity of the old appears, from experiment, to have been reached or exceeded. In gravitation, new theories are being developed continually, despite there being no credible experimental evidence indicating that the realm of validity of general relativity has been exceeded. There are basically two reasons for such developments: (1) General relativity is a classical theory and must, at some level, be supplanted by a quantum theory of gravitation. However, the technical obstacles seem so severe that no theoretically acceptable (consistent, renormalizable) quantum field theory of gravitation has yet been constructed, despite enormous effort. (2) Relativistic effects of gravitation are so difficult to measure and, hence, have provided so few checks on general relativity that alternate classical theories have been developed both to determine and to clarify the significance of any experimental verifications, or refutations, of general relativity.

II. RECENT DEVELOPMENTS IN GRAVITATIONAL THEORY

Current activity in theoretical astrophysics is especially intense; the general theory of relativity is at its core, a basic tool for calculation and for speculation alike. The possible collapse of matter within an event horizon to produce a black hole is perhaps the most dramatic predicted consequence of general relativity. The birth of the universe may have brought forth a froth of tiny black holes, and accompanying larger-scale inhomogeneities may have been the trigger for the formation of galaxies. Black holes may also serve as the engines underlying the prodigious amounts of energy observed emanating from quasars, the most distant objects known in the universe. Closer to home are similar topics and problems that ultimately involve general relativity; among these are stabilities of rapidly rotating dense stars and relativistic effects in strongly interacting binary star systems and in supernova collapses.

This burst of activity has yielded profound insights into the properties of black holes and of physical phenomena that may occur in their vicinity. Perhaps most startling has been the application of concepts from thermodynamics and quantum field theory to physical phenomena occurring in regions of space-time, where curvature is significant. These developments have led to the respective association of the temperature and entropy of a black hole with its (inverse) mass and invariant area, as well as to the identification of quantum processes of creation and annihilation of pairs of elementary particles that can take place near the horizon of a black hole and lead to its evaporation. The synthesis thereby created between the previously disparate disciplines of gravitation, thermodynamics, and quantum theory constitutes a major theoretical advance. However, this synthesis is not complete. There is no general theory from which all of these concepts follow; the relation between gravitation and quantum theory remains enigmatic. At the present level of development, the thermodynamic and quantum processes are assumed simply to take place on the background stage provided by the classical space-time metric of general relativity. Moreover, none of the predictions from this partial synthesis has been verified experimentally. In fact, although there are tantalizing hints from a variety of astronomical observations that black holes are indeed present in the universe, the evidence is far from conclusive.

Theoretical speculations stemming from elementary-particle physics have also incorporated gravitation in a potentially profound manner. These ideas indicate that the four known forces of nature, which under normal laboratory conditions appear to us to have vastly different strengths, may be of comparable strength at very high energies, 10^{19} GeV and higher, or, equivalently, on very small spatial scales, of the order of the Planck length of about 10^{-33} cm and smaller, where quantum gravitational effects are expected to be important. These and other recent speculations have relit the interest of theoretical physicists in unified field theories, once out of favor. Such "grand unifications" of the fundamental interactions of nature, based on gauge theories of elementary particles, go well beyond the unification of Einstein's dreams.

III. APPLICATIONS OF RELATIVISTIC GRAVITATION IN ASTROPHYSICS

Applications based on concepts of gravitation span an enormous dynamic range in astrophysics—from an instant about 10^{-36} sec after the "big bang," when the universe was intensely hot and exceedingly compact, to an epoch more than 10^{36} sec later, when the universe might exist as a very extended tenuous and cold entity composed in significant measure of gravitational radiation. Here we discuss some of these applications in decreasing order of the size scale involved.

Cosmology

One important consequence of general relativity, recognized by Einstein himself, was the possibility of an expanding universe. This possibility was confirmed as reality with observations in the late 1920's of the recession of distant galaxies. The basic question of whether the universe is open, and will expand forever, or closed, and will eventually contract, is still not answerable definitively from observations, although present evidence leans toward a fate of continued expansion for the universe.

This big-bang model of a homogeneous, isotropic, and now expanding universe, based on Einstein's field equation, is used in almost all cosmological calculations. For example, in combination with a grand-unification theory of the strong, weak, and electromagnetic interactions, the big-bang model allows one to calculate the specific entropy of the universe, as reflected in the ratio of the number density of photons to that of baryons. The value obtained, of the order of 10^9, although uncertain by at least a few powers of 10, is still in remarkable agreement with estimates from observation and implies that the baryon number density of the universe may not be arbitrary but rather an inevitable consequence of the laws of nature and the high temperature of formation of the universe.

Energy Sources of Quasars

Quasars radiate prodigious amounts of energy and thereby present one of the deepest enigmas in modern astronomy. Gravitation, through the action of a massive rotating body, may be the source for this energy. Consider, for example, quasars at the centers of one of the most striking structures in the universe, giant double-lobed radio sources. For some objects the double structure has been observed to persist over a range of six orders of magnitude in size, from parsecs to megaparsecs, with an alignment that is preserved over this entire range. Observations have also revealed some quasars with radio-visible components appearing to separate at relative speeds more than twice that of light. The components from successive outbursts from these quasars usually appear along the same position angle on the sky. Thus, in both examples, quasar cores seem to maintain a memory of direction, in the former case often up to 10^8 years.

One explanation for this memory over cosmological time scales involves a massive, rotating black hole at the center of the quasar. A number of mechanisms have been suggested by which matter and energy can be extracted from opposite ends of the axis of this central power station to fuel the radio sources and to supply the enormous energies that they radiate. Current speculations involve complex processes in a disk of gas accreting onto the rotating hole. The fact that the collimation of material is along the spin axis is thought to involve to a significant degree the relativistic dragging of inertial frames—the prediction of general relativity that a massive rotating body will "drag" an inertial frame.

That black holes are at the core of such astrophysical systems is the "best bet" of many theorists; the odds may nonetheless be long: All the smoke seen so far is consistent with other origins for the fire. But whatever the actual details, it seems likely that the bulk of the energy fueling the gigantic double-lobed radio sources depends on the rotation of a central condensation and that frame-dragging may well play an important role.

Masses of Galaxies

An intriguing consequence of the general theory of relativity is the prediction that mass focuses light. The properties of such gravitational lenses were investigated first by Einstein, almost half a century ago. Since then, they have remained mostly theoretical curiosities—until 2 years ago. In the early spring of 1979, nearly on the centennial of Einstein's birth, two quasars were discovered 6 sec of arc apart on the sky with virtually identical optical spectra and red shifts—identical to within the small measurement errors of a few parts in 10^4. Several months later a foreground elliptical galaxy, the brightest member of a rich cluster, was discovered, presumably acting as a gravitational lens and forming these images. Very-high-angular-resolution radio observations have been made to discern the shapes of the images and to discover whether there is a third image, as would be expected for a transparent gravitational lens.

A main goal is to use the properties of the image to place quantitative constraints on the mass distribution of the lens galaxy. Heretofore, galactic masses were mostly determined indirectly with large uncertainties. Now, for the first time, the relativistic deflection of light will be applied to this problem. Moreover, the application is important: knowledge of the masses of galaxies is basic to the solutions to a variety of astrophysical problems. Indeed, our knowledge of the mean density of the universe, and its ultimate fate, depends on such determinations. The main cloud on the horizon complicating the interpretation of the images of the gravitational lens is the presence of the other nearby foreground galaxies in the cluster that may also exert important influences on the positions and shapes of the images.

More such gravitational lenses will doubtless be discovered, especially as fainter and fainter objects are studied in the era of the space telescope. Thus, the analysis of gravitational images may well become a widely used tool for extragalactic astronomy.

Masses of Stars

Although, at present, the gravitational lens effect cannot be used to determine masses of individual stars, there are situations in which other relativistic effects of gravitation can be used to estimate stellar masses. For strongly interacting condensed stars in binary systems, the relativistic advance of the periastron can be used to provide a constraint on the masses of the stars. This technique has, in fact, already been used effectively for the estimation of the masses of a pulsar and its companion in a binary system.

Supernova Collapse

Many of the major questions in astrophysics concern collapse phenomena, as in supernova explosions. These events are widely thought to be responsible for the formation of heavy elements in the universe, for the regulation of temperature and density over a large part of the interstellar medium, and for the creation of pulsars and perhaps even of black holes. But the physical processes occurring inside supernovae are not well understood and are incredibly difficult to observe. Even neutrinos are thought to be absorbed and scattered so strongly that essential information about collapse cannot be obtained from them. Gravitational waves, on the other hand, carry away detailed information about the bulk behavior of matter during the collapse;

their detection may therefore yield unique information essential to our understanding of the internal dynamical processes that take place during supernova explosions.

IV. EXPERIMENTAL VERIFICATION OF THE THEORY OF GRAVITATION

Although general relativity is an everyday tool of the theoretical astrophysicist, its experimental verification rests on meager evidence. But physics is, in its deepest sense, an experimental science. The theoretical foundations must be checked as accurately as possible. Every theory devised may be expected to have limits of validity. Where will the classical theory of general relativity break down? Clearly, at the quantum limit. Crucial questions are: Does the theory hold to this limit, or does it break down in some portion of the classical domain? No one knows. There exist opinions and guesses. But the history of science shows such guesses to have been unreliable. For example, in the eighteenth and early nineteenth centuries, no one predicted that Newton's theory of gravitation would be inadequate to explain the orbital motion of the planet Mercury. Although a deviation was found in the mid-nineteenth century, it was not until almost 70 years later that a theory was devised to explain the deviation satisfactorily.

A prudent program therefore demands that experimental checks be made when significant ones are possible. But what tests are significant? The answer must, perforce, be subjective. We consider tests of previously undetected or unmeasured gravitational phenomena, especially if they might have astrophysical consequences, to be of the highest importance. Improved accuracy of measurement of effects already detected can also be of great significance, especially if the accuracy can achieve a level in which higher-order (e.g., post-post-Newtonian) predictions can be tested. It is important to obtain quantitative checks of general relativity primarily because of their bearing on the fundamental law of gravitation, and also because, if verified, the theory can be used with confidence in astrophysics.

The space program offers many opportunities for the performance of significant experiments in this decade and for the development of instrumentation for experiments for the next decade. We discuss several here as illustrations.

General relativity is based on the fundamental principle of equivalence, which asserts, in its so-called weak form, that gravitational and inertial mass are equivalent. Is this a universally valid principle? Or does it, too, break down at some level of accuracy in some region of physical conditions? In particular, does gravitational binding energy contribute equally to gravitational and inertial mass? These questions can be addressed usefully through accurate monitoring of the motions of the moon and inner planets, possible only with space techniques.

One of the more unusual predictions of the general theory of relativity is the dragging of inertial frames. According to the theory, an angular momentum vector transported in free fall about a rotating mass will precess. This predicted precession will be dependent on the rotation, an effect of gravitation akin to that of magnetic fields created by current loops. However, this effect of rotation on local inertial frames is so weak in the solar system that it has never been observed. Does it occur? Only with a space experiment does it appear feasible to answer this question reliably.

In general relativity the (dimensions) constant of gravitation is a universal constant of space-time. But some cosmologies have been developed in which the value of this "constant" varies with atomic time, such that the ratio of the electrostatic to the gravitational force between charged elementary particles remains equal to the age of the universe, expressed in atomic units. Comparisons of gravitational clocks with atomic clocks have set some bounds on any such possible variation, but not yet at the level required either to lend support to, or to rule out, many of these cosmological theories. Continued measurements of planetary motion with space techniques could provide definitive answers.

Gravitational waves, first predicted to exist by Einstein, have not yet been detected directly. Do they exist, and do they travel with the speed of light, and exhibit the two states of polarization predicted? Again, measurements in space should provide answers.

The remainder of this report is devoted primarily to a review of the current status of experimental research in gravitation and to a discussion of our proposed strategy for research in this decade.

3
Status of Current Research

Theoretical research in gravitation has far outdistanced experimentation. Yet significant experimental advances have been made, especially in the last decade and primarily through the space program. Here we present a theoretical framework within which we discuss the status of experiments in gravitation. We also treat gravitational radiation—possible astrophysical sources and possible means of detection.

I. TESTS OF THEORIES OF GRAVITATION

In gravitational physics, the invention of new theories has not been stimulated by the challenge of unexplained experimental facts but rather by the challenge of developing alternative theories to general relativity that are also in agreement with existing experimental facts. Such developments are not futile exercises but rather tend to show the potential richness in nature and, in addition, to sharpen our ability to design crucial experiments and to understand their physical significance. For historical as well as intrinsic reasons, however, general relativity is the theory of gravitation almost always used in applications. The applications, in turn, almost always involve an astronomical setting, since, in the laboratory, gravitation is rarely strong enough for a relativistic effect to be detected, let alone to be of importance.

Framework for Interpreting Experiments

General relativity makes two distinct statements about the nature of gravitation:

(a) Gravitation can be described as a Riemannian curvature of space–time with the laws of physics for all nongravitational interactions having the same form in the local Lorentz frames of curved space–time as in the flat space-time of special relativity. This statement characterizes Einstein's bold generalization of the principle of equivalence and is often called the metric hypothesis because, according to it, the space–time Riemannian metric is the mathematical embodiment of gravitation. All theories of gravitation that share this hypothesis are called metric; those that violate it are called nonmetric.

(b) The curvature of space–time is determined, through a field equation, by the energy, momentum, and stress of all matter and nongravitational fields contained in space–time. Gravitation in this view is an intrinsically nonlinear phenomenon; the field equation alone allows the equations of motion for particles to be deduced from it. This characteristic stands in sharp contrast to Newtonian theory in which the field equation and the equations of motion are separate postulates. Other metric theories of gravitation differ from general relativity by the manner in which space–time curvature is generated.

Experimental tests of general relativity can correspondingly be separated into two categories: tests of the metric hypothesis, such as facets of the principle of equivalence, and tests of the properties of space–time curvature, such as the orbits of light rays and test particles. The theoretical significance of these experiments is usually evaluated by contrasting the predictions of general relativity with those of other theories. One can thereby better discern what aspects of the theory are being probed by any given experiment. This approach is, of course, only one of many possible ways to analyze experimental tests of general relativity.

Most gravitational experiments involve measurements of the space–time curvature produced by the solar system. The solar system has three special properties in this regard: (a) its gravity is everywhere very weak: the dimensionless ratio of the gravitational potential to the square of the speed of light is always 10^{-5} or smaller; (b) the square of the ratio of the speed of each source of significant gravity to that of light is under 10^{-7}; and (c) the ratios of the internal stress energies of all bodies to their respective rest energies are also under 10^{-5}. These three conditions guarantee that Newton's theory of gravitation will provide the same predictions as general relativity to within about 1 part in 10^5 for the structure of the sun and to within about 1 part in 10^6 for experiments confined to the exterior of the sun. Thus, the goals of most such experiments have been to measure deviations from Newtonian theory, i.e., post-Newtonian or relativistic effects of gravitation whose fractional magnitudes are about 10^{-6} or somewhat less. Of course, Newton's theory of gravitation is confirmed daily by all, and these confirmations represent as well triumphs of relativistic theories of gravitation. On the other hand, higher-order relativistic deviations from Newtonian theory, of magnitude of the second and higher powers of 10^{-6}, are also predicted to exist in the solar system, but these are not discernible in present experiments. Thus, the post-Newtonian level suffices for most of our discussion.

The structure of metric theories of gravitation can be clarified by analogy with electromagnetic theory. Gravitation is described by a four-dimensional metric of space–time and electromagnetism by a four-dimensional tensor for the electromagnetic field. However, one often gains insight and computational power by utilizing a special global reference frame to decompose the four-dimensional quantities into separate spatial and temporal components. For example, in such a decomposition, the electromagnetic field splits into electric and magnetic parts. Similarly, the gravitational field, or metric tensor, separates into three parts: an electric-like field, a magnetic-like field, and a part that represents the curvature of space.

In the Newtonian limit of any metric theory of gravitation, the magnetic-like field and space curvature vanish; the much stronger electric-like field reduces to the Newtonian gravitational acceleration. In the post-Newtonian regime, a rich variety of new phenomena appear, such as the dragging of inertial frames, the gravitational deflection of light, and the perihelion advance of planetary orbits—manifestations, respectively, of a magnetic-like gravitational field, of space curvature, and of the nonlinear superposition law for Newtonian potentials. To express clearly the consequences of these different post-Newtonian phenomena and the differences between the predictions for each from different metric theories, one can use the parameterized-post-Newtonian (PPN) formalism. With it, all metric theories can be expressed in a common framework in a special coordinate system. In particular, explicit reference is removed to all "auxiliary" scalar, vector, or tensor fields that are utilized in some metric theories to generate part of the space–time curvature. In this special coordinate system, the three basic "fields"—electric-like, magnetic-like, and space curvature—are expressed in terms of potentials whose coupling has strengths that generally vary from one metric theory to another and that can be expressed in terms of ten dimensionless parameters.

Thus, each theory can be characterized, at this level, by the numerical values of its PPN parameters; and each solar-system experiment can be characterized by a predicted result, dependent on one or more of these parameters. Probably the most important parameters are γ and β; these describe, respectively, the amount of spatial curvature generated by a unit rest mass and the amount of nonlinearity in the superposition of Newtonian gravitational potentials. There is also one parameter that describes the amount of any "preferred-location" effect, three that describe the amount and kind of "preferred-frame" effects, and five (four distinct from those already listed) that describe the amount and nature of violations of global conservation laws for total energy-momentum. By definition, each member of the last subset vanishes for "fully conservative" theories. An eleventh parameter, $\dot{G}/G$, introduced to describe any fractional time rate of change of the constant of gravitation, depends more on cosmology than on a metric theory of gravitation. For general relativity, γ and β are unity and all other parameters vanish. Although the PPN formalism has its limitations, it has served admirably as a framework to incorporate a large number of theories of gravitation and to stimulate the invention of new experiments.

Status of Tests

The experimental tests of general relativity undertaken in the solar system consist of validation of the principle of equivalence and of the predicted effects of gravitation on the behavior of clocks, light rays, and mass points. We discuss these in turn.

PRINCIPLE OF EQUIVALENCE

In his approach to the theory of gravitation, Einstein did not seek to explain the equivalence of gravitational and inertial mass but instead elevated it to the status of a principle and proposed a generalization stating that, locally, gravitation and acceleration are indistinguishable. The most accurate experimental tests of this principle have been confined to the "mass-equivalence" form.

Laboratory experiments on small bodies to determine whether the ratio of inertial to (passive) gravitational mass is the same for all bodies, independent of size or composition, were the concern of even nonphysicists back at least as far as the fifth century. At that time, Ioannes Grammaticus recorded the existence of this equivalence in colloquial terms. Quantitative verification has steadily improved over the past few hundred years.

Improvements made by Eötvös in the beginning of the twentieth century enabled the principle to be established to a few parts in 10^8 for a wide range of materials. His four-order-of-magnitude improvement made by elegant but simple modification of standard apparatus is, in itself, a beautiful tribute to the possibilities for fundamental experiments in physics.

Two independent modern versions of the Eötvös experiment were performed in the last two decades. In the first, the equivalence of inertial and (passive) gravitational mass was verified to a few parts in 10^{11}. In the second, verification to 1 part in 10^{12} was reported; however, this experiment is so extremely delicate and difficult to perform that it has remained unchecked by independent researchers.

These experiments imply that to high accuracy the nuclear, the electromagnetic, and even the weak interactions contribute equally to gravitational and inertial mass. But does *gravitational* binding energy contribute equally?

Here the experimental picture is quite different. The ratio of the gravitational binding energy to the total mass-energy varies with the square of the characteristic length of a body. For objects usable in a laboratory, only about 1 part in 10^{23} of the total mass-energy is contributed by the gravitational binding energy, some 11 orders of magnitude smaller than the minimum effect detectable with laboratory experiments. Thus, for the gravitational binding energy, important theoretically because it involves the nonlinear character of gravitation, there is little hope of obtaining experimental evidence from an Earth-based laboratory. Space techniques must be used. The sizes of the test bodies must be increased to a planetary scale to be useful, and three or more such bodies are needed. Were only two available, a violation of the principle of equivalence could not be distinguished from a rescaling of the mass of one of the bodies with respect to that of the other; no means exist, other than orbital behavior, for the determination of these masses.

Our mastery of space has enabled an accurate test to be performed with the Earth-moon-sun system. Emplacement on the lunar surface of optical corner-reflectors by the Apollo astronauts has allowed us to distinguish whether the moon and the Earth fall toward the sun with the same acceleration. Any anomalous difference in these accelerations would manifest itself in a corresponding monthly variation in the Earth-moon distance, now determined from laser measurements to within about 25 cm. The measurements set stringent limits on any anomalous behavior and establish that at least 98.5 percent of the gravitational binding energy of the moon contributes to both its gravitational mass and its inertial mass. To this accuracy, therefore, it has been verified that all ordinary mass energy, including that due to gravitational self-energy, gravitates in the same manner. This result constrains a combination of PPN parameters; for the special case of fully conservative metric theories without preferred frame or location effects, it implies that the linear combination $4\beta-\gamma-3$ vanishes to within 0.015. Some metric theories predict a violation of the principle of equivalence for massive bodies because, in these theories, only part of the mass due to gravitational self-energy gravitates, although the principle is obeyed for the contributions to mass from all other forms of energy. The class of such theories has thus been sharply curtailed by this result from the lunar laser ranging experiment.

CLOCK BEHAVIOR

One of the most celebrated predictions of general relativity concerns the effect of changes in gravitational potential on the rate of a clock and on the frequency of an electromagnetic signal (red shift). A given clock is predicted to appear to run more slowly than an identical clock located in a region in which the Newtonian gravitational potential is of lower magnitude. The most precise laboratory verification of the red-shift prediction was obtained a decade and a half ago and utilized the Mössbauer effect in which the recoil momentum on emission or absorption of gamma radiation from a single nucleus in a crystal is shared by the whole crystal, thus allowing the formation of extremely narrow spectral lines. By a velocity compensation of the change in frequency of the gamma rays over a vertical distance of 25 m, it was possible to verify this prediction to about 1 percent of the predicted change.

By far the most impressive experiment to test the effect of gravitation on the rate of a clock was performed by the placement of a hydrogen-maser frequency standard on a rocket that traveled on an orbital arc with a 10,000-km maximum altitude. In this experiment, a sophisticated radio communication link was employed to circumvent ionospheric effects in order to compare accurately the rate of the hydrogen-maser standard in orbit with corresponding masers on the ground. The measured red shift agreed with the prediction to within the uncertainty of about 1 part in 10^4, the most accurate relativity experiment yet performed with space techniques.

LIGHT DEFLECTION

Light rays are predicted by general relativity to be deflected by massive bodies, in part from the action of the electric-like component of the gravitational field (a direct consequence of the principle of equivalence) and in equal part as a consequence of space curvature.

The deflection of light by the sun was dramatically verified by the eclipse expedition team in 1919 and catapulted Einstein to world fame. But Earth-based observations of total eclipses were less successful in achieving quantitative verification of the predicted deflection. These measurements are severely limited both in accuracy and in the opportunity to make them and were largely supplanted by radio-interferometric techniques, starting in the late 1960's. Simultaneous measurements at two radio-frequency bands can enable the effects of the solar corona to be reduced to a benign level. As a result, the uncertainty of the verification of the predicted 1.75 sec of arc deflection for rays grazing the solar limb was decreased from about 25 percent to about 1 percent, implying that γ is unity to within about 2 percent.

SIGNAL RETARDATION

General relativity also predicts that the transit times of light signals traveling between two points will be increased if a massive body is placed near the path of these signals. There is no contradiction between this predicted "slowdown" and the concept of the constancy of the speed of light: an observer freely falling will always measure the same value for the speed of light in his or her neighborhood, independent of the observer's location in space-time. However, a "global" measurement of the round-trip time of light rays propagating between two points will be greater the nearer a massive body lies to the path of propagation, owing, as for the deflection, in part to the principle of equivalence and in equal part to space curvature. Further, the contradiction between light propagation being slowed down and mass particles being speeded up near massive bodies is more apparent than real. Mass particles, too, are predicted to appear to slow near massive bodies provided their speeds approach closely enough that of light.

The increase of the round-trip times of light or radio signals propagating between planets, due to the direct effect of solar gravitation, is predicted by general relativity to be a maximum of about 250 μsec for ray paths that graze the limb of the sun. This prediction was verified first through measurement of echo times of radar signals bounced from the surfaces of the inner planets. More recently, the increased accuracy obtainable with measurements of the round-trip times of radio signals sent to the Viking spacecraft has enabled the uncertainty to be reduced from the 4 percent obtained with radar to approximately 0.1 percent, an order of magnitude higher accuracy than yet achieved for the deflection measurement. The results are again in accord with general relativity to within their uncertainty, i.e., γ appears to be unity to within 0.002.

PERIHELION ADVANCE

The anomalous advance of the perihelion of the orbit of the planet Mercury, noted in the mid-nineteenth century, provided the first hint that Newtonian theory was not adequate for a description of the dynamics of the solar system. This advance, subsequently determined to be 43 sec of arc per century, was an elegant confirmation of Einstein's theory. Because this effect increases secularly, the improvement from use of modern radar observations of Mercury for the past decade, over the results obtained from several hundred years of optical observations, has not been so dramatic. At present, radar observations of Mercury yield an uncertainty of 0.5 percent in the determination of the "anomalous" perihelion advance, a twofold improvement over the results from optical observations. A serious impediment to the proper interpretation of this advance is posed by our uncertainty about the magnitude of the contribution of the solar gravitational quadrupole moment, which has never been measured directly.

The relativistic contribution to the perihelion advance depends not only on space curvature but also on the nonlinearity of the superposition law for the gravitational potential and on preferred-frame and location effects. If one assumes that the contributions of the solar quadrupole moment and of possible preferred-frame and location effects are negligible, the measurements demonstrate that for fully conservative theories the combination $(2 + 2\gamma - \beta)/3$ of PPN parameters is unity to within 0.5 percent.

Aside from Mercury, only for Mars and for the asteroid Icarus have the relativistic advances been detected with any useful accuracy; the results agree, to within the 20 percent uncertainties of the determinations, with the values predicted by general relativity.

Have not measurements of the signals from the pulsar in a close binary system made obsolete any concern with the perihelion advances of planetary orbits? The periastron advance of the orbit of this pulsar is about 4.2 degrees per year, about 35,000 times larger than the relativistic advance for the orbit of Mercury. Unfortunately, measurement of this advance for the pulsar serves primarily to determine a function of the masses of the individual components of the binary system. At present, these masses cannot be determined independently with any useful accuracy. Thus, this binary system is not now useful as a laboratory to test the predictions of general relativity for periastron advance.

GRAVITATIONAL CONSTANT

A deep question of physics concerns possible variations with time of certain "constants" of nature. General relativity assumes that the constant of gravitation is a universal constant, independent of both spatial location and time. The possibility that this constant varies with time is based in part on the so-called "large numbers hypothesis." This hypothesis stems from the fact that the ratio of the electrostatic to the gravitational force between an electron and a proton, about 10^{39}, is approximately equal to the age of the universe expressed in atomic units. Is this near equality a mere coincidence confined to the present epoch? If one assumes instead that it is of fundamental significance, independent of epoch, then since the age of the universe is a function of time, some other quantity must also vary with time. It has been proposed, therefore, that the gravitational interaction, as measured against the electromagnetic, may be weakening with time. Any such effect should be detectable by measurement on an atomic time scale of the time kept by a gravitational clock. For this purpose, the orbit with the shortest period should provide the best probe, all other aspects being the same. Because of problems with lunar tides, however, Mercury is a better object to observe for this purpose than is the moon. No reliable evidence has yet been found that indicates any changing of the gravitational constant. A reliable limit on the fractional magnitude of any such change is about 1 part in 10^{10} per year. Several cosmological models, however, predict changes at the level of 1 part in 10^{11} per year, or below, and are thus neither substantiated nor refuted by present experimental evidence.

Table 1 summarizes the results from these experiments in the solar system,

TABLE 1 Summary of Solar-System Tests of Theories of Gravitation

Measured Effect	Resultant Constraint	Comment
Comparison between clock in ballistic trajectory and clock on ground	$\frac{\text{measured change}}{\text{predicted change}} = 1.0000 \pm 0.0001$	Test of metric hypothesis
Bound on any non-Newtonian monthly variation in the Earth–moon distance	$4\beta - \gamma - 3 = 0.001 \pm 0.015$[a]	Test of relative contributions of gravitational binding energy to inertial and to (passive) gravitational mass
Deflection of radio waves by gravitational field of sun	$\gamma = 1.01 \pm 0.02$	Test of amount of spatial curvature generated by unit mass
Increase of echo time of radio signals sent from Earth to Mars, due to gravitational field of sun	$\gamma = 1.000 \pm 0.002$	Test of amount of spatial curvature generated by unit mass
Relativistic contribution to advance of perihelion of Mercury's orbit	$(2 + 2\gamma - \beta)/3 = 1.003 \pm 0.005$[a]	Test of combination of amount of spatial curvature generated by unit mass (γ) and nonlinearity in superposition of Newtonian gravitational potentials (β); contribution to advance of gravitational quadrupole moment of sun is assumed to be negligible
Bound on any "anomalous" acceleration of longitude of Mercury's orbit	$\lvert \dot{G}/G \rvert \leq 1.5 \times 10^{-10}\ \text{yr}^{-1}$	Test of constancy of "constant" of gravition, G

[a]For simplicity in the presentation of results, we have neglected the implied constraints on PPN parameters concerned with violations of global conservation laws and with preferred frame and location effects.

at present our main laboratory for measurements of relativistic gravitational phenomena. However, it may well be that the basic laboratory for testing theories of gravitation will eventually evolve to encompass more remote astronomical systems, where the intensity of the gravitational fields encountered will yield a wider harvest of measurable relativistic effects. The pulsar already discovered in a tightly coupled binary star system perhaps foreshadows that transition.

II. GRAVITATIONAL RADIATION

Just as electromagnetism has its wave aspect, so too should gravitation: both have been formulated with apparent success as field theories. Based on general relativity, Einstein showed over 60 years ago that gravitational waves should exist, and he discussed some of their basic properties. In all metric theories, gravitational waves are described as "ripples" in the curvature of space–time that propagate away from the source at the speed of light. What are the likely sources of gravitational radiation that might be detected? It is clear that a "Hertz" experiment, the detection of gravitational radiation from the motion of massive bodies in the laboratory, is hopelessly beyond our present capability. Because of the principle of equivalence and the conservation laws that apply to mass and momentum, variations in quadrupole or higher moments are necessary to generate gravitational waves, according to general relativity. Virtually nothing was known about sources of such radiation from outside the solar system when serious efforts were made in the 1960's to develop apparatus suitable for its detection. In the past decade, stimulated by that work, substantial progress has been made in identifying and characterizing possible astrophysical sources of gravitational waves, and truly remarkable progress has been made in improving the methods for their detection. There still remains a significant gap between present instrument sensitivity and theoretical estimates of the likely intensity of gravitational radiation impinging on the Earth. Yet progress has been so rapid that the gap may well be bridged within a decade or two. If nature is holding a surprise in store in the form of levels of radiation intensity far higher than expected, perhaps from unsuspected sources, then detection may be possible within a shorter period.

Here we discuss first the types and characteristics of gravitational waves that are thought to pass through the solar neighborhood and then the status of the development and use of instrumentation for their detection.

Astrophysical Sources of Gravitational Waves

Because matter is electrically neutral on macroscopic scales, cosmic electromagnetic waves are typically an incoherent superposition of emissions from huge numbers of individual electrons. By contrast, the fact that all objects have positive mass prevents macroscopic gravitational shielding and causes the strongest predicted gravitational waves to come from bulk motions of large conglomerates of matter. The waves should be especially strong when both the velocities of the emitting matter are near the speed of light and the density is so high that internal gravitational effects are relativistic. Dynamical motions of curved empty space alone could also generate strong waves as in a collision between two black holes.

Relativistic motions of bulk matter and strong gravitational fields are central to most current speculations about the behavior of supernovae and about violent activity in galactic nuclei and quasars. Gravitational waves from such events should carry detailed information about these objects. Furthermore, although the sources of the gravitational waves will typically be buried beneath vast layers of obscuring matter, these waves should emerge virtually unaltered—without absorption, scattering, or distortion. By contrast, electromagnetic waves and, for supernovae, even neutrinos lose most of their information en route. Thus, gravitational waves should serve as a probe of violent phenomena in the centers of collapsing stars, in quasars, and in galactic nuclei—phenomena that can be studied only poorly, and perhaps not at all, by electromagnetic waves and neutrinos.

As an example of the information that gravitational waves might carry, consider a collision between two black holes. The final value of the dimensionless amplitude h, which describes the effect of the waves on the space-time metric, would differ from the initial value. This difference could tell us reliably whether the source, initially or finally or both, consisted of two or more bodies moving at high speed relative to each other—in this case two black holes in the initial state. The time dependence of h observed at the beginning—the form of its initial rise, its peak value, and the difference between its initial and final values—depends on the impact parameter and relative velocity of the collision and on the orientation of the observer relative to the collision. The time dependence that would be observed later consists of damped oscillations produced by pulsations of the final coalesced black hole, with the damping time and frequency being determined by the mass and angular momentum of the final hole, which in turn determine almost all of its other properties.

The characteristics of gravitational waves that might be reaching the Earth have been the subject of serious speculation for almost a decade. What are their spatial and temporal attributes? Unfortunately, the answers to such questions are still uncertain. For discussion, it is convenient to classify gravitational waves into three categories: (a) the stochastic background—the sum total of the overlapping gravitational radiation from very distant sources in the universe; (b) burst events—short-lived events that produce distinguishable gravitational waves such as from supernova explosions and collapses of relatively nearby galactic nuclei; and (c) periodic sources—sources that produce periodic waves such as binary stellar systems and nonspherical oscillations of single stars. We discuss each category in turn, focusing particular attention on those wave frequencies between about 10^{-2} and 10^{-4} Hz to which space observations in the 1980's would be most sensitive.

A stochastic background of gravitational waves may exist, for example, as a result of the formation of black holes from stars born before galaxies formed or of the big-bang explosion in which the universe presumably originated. It is conceivable that such a stochastic background could be so strong that its energy density in one or two special decades of frequency is adequate to close the universe, leading, say, at a frequency near 10^{-3} Hz to a root-mean-square amplitude h of the order of 10^{-15}. It would have a profound effect on cosmology were the universe found to be closed, or nearly closed, by the energy density of its gravitational radiation. Of course, the stochastic background could be many orders of magnitude weaker: we are simply ignorant of both the distribution of distant events in space and time and the efficiency with which these events may have produced gravitational radiation.

Broadband bursts are predicted to result from a variety of phenomena and to have characteristic durations ranging from $\sim 10^{-4}$ to $\sim 10^{4}$ sec. Such burst radiation could arrive in the solar system as often as once per month with amplitudes as large as $h \sim 10^{-13}$ at a wave frequency of $\sim 10^{-3}$ Hz, without violating any widely accepted beliefs about the nature of gravitation or about the astrophysical structure of the universe. This radiation could result from the creation of black holes with masses between 10^{6} and 10^{8} solar masses in galactic nuclei and quasars or from collisions between such supermassive holes. Conventional models for these phenomena predict, however, that the strongest bursts would be several orders of magnitude smaller than this "maximum" value and that the interval between such bursts could be far, far longer.

At the higher wave frequencies of $\sim 10^{2}$ to 10^{4} Hz, where ground detectors now operate, bursts may come from supernovae, from the final decay and collision between elements of a binary system, and from neutron-star corequakes, if they exist. The frequency of occurrence of these bursts is also a topic of speculation. One of the most tightly constrained estimates, the frequency of occurrence of supernova explosions within our Galaxy, is bounded between about one per decade and two per century. But there is as yet no early warning system. We also do not know the fraction of energy released in such explosions in the form of gravitational radiation. The theoretical simulation of these very complex events is exceedingly difficult to carry out accurately.

Periodic gravitational waves should be produced by binary star systems, rotating neutron stars and white dwarfs, and pulsations of white dwarfs that may follow nova outbursts. Standard calculations based on general relativity indicate that of the binary systems with known properties, the strongest of the gravitational waves that reach the earth will have $h \leq 10^{-20}$ in the range of wave frequencies between $\sim 10^{-3}$ and 10^{-4} Hz. Here one can calculate accurately, from the observed optical characteristics of a binary stellar system, not only the expected amplitude but the direction, phase, and polarization of the waves. But, owing to the perversity of nature, this radiation is very weak. Other periodic systems in our Galaxy, however, may lead to values of h at the earth perhaps as much as an order of magnitude larger. At the higher wave frequencies of $\sim 10^{-1}$ to 10^{2} Hz, the amplitudes of gravitational radiation are expected to be less than $\sim 10^{-21}$ and $\sim 10^{-26}$ for oscillating white dwarfs and rotating neutron stars, respectively.

To summarize, we are not able to predict with much confidence the strengths of the gravitational waves that pass the Earth, except perhaps in the case of certain binary star systems for which the effects are very weak. Only observational searches can give us reliable information.

Characteristics of Gravitational Radiation

The existence of gravitational radiation is almost universally accepted on theoretical grounds. One of the most fundamental properties of such radiation is its velocity of propagation. In general relativity, this velocity is the same as that of light, but in many other metric theories, it differs fractionally by $\sim 10^{-7}$. It is conceivable that the velocity could depend on the frequency of the radiation. Any such differences might be measurable by comparing the arrival times for light and for gravitational radiation from short-duration events, such as supernova explosions.

Another critical property of gravitational radiation is its polarization. General relativity predicts that there are two states of polarization, both transverse and different from each other by a 45-degree rotation. Detection of these two states, and only these, could verify that the gravitational field is governed by an elementary particle of zero rest mass and spin 2. By contrast, within the class of metric theories of gravitation, six polarization modes are allowed for weak gravitational waves; three are transverse, one is longitudinal, and two are mixed. A scalar–tensor theory, for example, allows three—the two of general relativity plus a third (spin-zero) transverse mode. Polarization experiments may therefore turn out to be the most severe tests of theories of gravitation.

Gravitational radiation can also be described by its polarity (i.e., monopole, dipole, or quadrupole). In the theory of general relativity, quadrupole is the lowest-order polarity represented. Conservation of energy and momentum and the principle of equivalence prevent monopole and dipole radiation. However, in some metric theories, including those that involve "prior geometry," dipole and even monopole radiation is permitted. The differences in the implications for various astrophysical processes that produce gravitational waves can be significant. For example, in a binary system with small separation between stars, the rate of decay of the orbit will usually depend importantly on the lowest-order polarity present in any gravitational radiation.

Indirect Detection of Gravitational Waves

One of the most stimulating discoveries of the last decade was the detection of a pulsar in a tight binary system, the mutual orbital period being a mere 8 hours. Because pulses from this pulsar are each of short duration, approximately 10 msec, and highly repeatable in structure, timing their arrivals has been possible with an accuracy of some 50 μsec. The determination of the orbital properties has been accomplished with comparable accuracy. In particular, the measured decrease in orbital period or, equivalently and more sensitively, the measured quadratic gain with time in orbital position, compared with predictions based on the assumption of a constant orbital period, provides tantalizing evidence for the existence of gravitational radiation since the orbital period is expected to decrease as a "back reaction" from the loss of energy radiated as gravitational waves. Indeed, a decrease in orbital period of about 3 parts in 10^{12} has been observed since discovery and agrees, within its present uncertainty of about 20 percent, with the expected value, based on the general theory of relativity and on the inference from the same observations of the masses of the components and of the relevant orbital properties of the system. Continued observations will lower this uncertainty. Some other theories of gravitation already appear to be ruled out by these observations because these theories predict a greater energy loss in the form of dipole radiation, strictly forbidden in general relativity by the principle of equivalence. Clouding this triumph somewhat, however, is the present lack of unequivocal evidence about the nature of the companion to the pulsar, about mass loss from the system, and about the possible existence of other, massive and distant, bodies in the "binary" system. Of course, the presence of additional bodies would eventually become known when their effects on the higher time derivatives of the changes in orbital period became apparent. If with more information, all of these uncertainties prove benign in their consequences, then the measured decrease in orbital period will provide powerful evidence for the existence and strength of gravitational radiation.

Search for Direct Evidence of Gravitational Waves

The first Earth-based detector for gravitational waves was completed in the late 1960's. This detector, a metal cylinder about 1 m in length, can be considered as two test masses connected by a spring. The spring does not influence the amplitude of the response to a gravitational wave but helps to reduce the noise at the ~10^3-Hz resonant frequency of the bar. Detectors of this "first-generation" type were all at room temperature and were improved sufficiently by the mid-1970's to reach a level of sensitivity of $h \sim 10^{-15}$, in the sense that a (power) signal-to-noise ratio of 10 would result from a signal of that strength at the resonant frequency. Such a level, however, was far above the expected amplitudes of gravitational waves in this frequency range, and no waves were in fact detected. Nevertheless these investigations spurred interest in the field, and, in a large number of laboratories around the world, construction began on cooled-bar antennas for the detection of gravitational waves. The sensitivity of such instrumentation is developing rapidly. Within the next few years, the sensitivity of these "second-generation" detectors to gravitational waves is expected to be about one hundredfold better than that of the uncooled bars, corresponding to a ten-thousandfold improvement in energy sensitivity to gravitational waves in the kilohertz range.

Another approach being developed for detection of gravitational waves utilizes "almost" free masses, each suspended as a pendulum, with laser ranging between them. This scheme has the advantage that the response of the instrument is broadband above the pendulum frequency. Although the laser system is less developed, it is expected to reach a sensitivity at least comparable with that of a resonant bar but in the frequency range down to about 30 Hz.

Overall, ground-based instruments for the detection of gravitational radiation seem limited to the detection of those waves whose frequencies exceed about 30 Hz, a limit set by seismic noise and gravity gradients at the surface of the Earth.

Spacecraft microwave tracking systems may be used in an attempt to detect very-low-frequency gravitational radiation. Such radiation, passing through the solar system, would cause the Earth and a spacecraft to oscillate relative to each other. The fractional effect of the gravitational radiation on the frequency of the microwave tracking signal will be proportional to *h* for pulses of radiation short compared with the round-trip propagation delay of the tracking signals. Each of these gravitational-wave pulses will impart a characteristic "three-pulse" signature to the microwave signal with specific relations among the three that depend only on the distance between the Earth and the spacecraft and on the direction of propagation of the gravitational wave relative to the Earth–spacecraft direction. The three pulses are introduced by the impingement of the gravitational wave on the Earth during transmission of a microwave tracking signal, on the spacecraft during the transponding of a signal, and on the Earth during reception of a signal. This system has its highest sensitivity to gravitational radiation in the spectral region from about 10^{-4} to 10^{-2} Hz, limits set in part by signal-to-noise considerations.

The existing tracking system is, at best, sensitive at a signal-to-noise ratio

TABLE 2 Gravitational Radiation: Sample Comparison between Estimated Strengths of Astrophysical Sources and Present Instrument Sensitivity

Type of Radiation	Frequency of Wave (Hz)	Amplitude of Wave: Theoretical Estimate[a]	Amplitude of Wave: Instrument Sensitivity[b]	Amplitude of Wave: Ratio of Theoretical Estimate to Instrument Sensitivity	Comment
Stochastic	10^{-3} 10^{3}	6×10^{-17} 6×10^{-23}	3×10^{-14} 10^{-17}	2×10^{-3} 6×10^{-6}	Theoretical estimate is based on energy density of stochastic radiation equal to 1% that of "closure" density for universe; energy spectral density assumed to be uniformly distributed between zero and value of frequency indicated. Observations assumed to extend over this bandwidth and over time interval of 10^6 sec
Burst	10^{-4} 10^{3}	10^{-15} 10^{-21}	10^{-13} 10^{-15}	10^{-2} 10^{-6}	Theoretical estimate at each frequency is based on sources distributed over a volume large enough for estimated event rate to be one per year. Lowest-frequency source is assumed to be formation of 10^8 solar mass black hole in center of galactic nucleus; highest-frequency source is assumed to be supernova collapse. "Duty cycle" of observations, ratio of event duration to mean time between events, was considered in calculation of instrument sensitivity
Periodic	10^{-4} 6×10	10^{-20} 3×10^{-27}	3×10^{-15} 3×10^{-19}	3×10^{-6} 10^{-8}	Low-frequency source is binary-star system, i Boo; high-frequency source is Crab pulsar. Observations assumed to extend over 10^6 sec in both cases

[a] In many cases the actual amplitude could differ from the estimated value by several or more orders of magnitude. For example, the entries for a stochastic background could be somewhat larger or many orders of magnitude smaller.
[b] Sensitivity as of early 1980, defined as a (power) signal-to-noise ratio of 10 or equivalent for low-duty-cycle observations.

of 10 only to gravitational waves with dimensionless amplitude $h \sim 10^{-13}$ and only for observations of spacecraft very near the antisolar direction, where the disturbances from the solar wind are minimized. At present, the utility of this system for detecting gravitational waves is limited by its transponder, which can receive from the Earth only the relatively low radio frequency of 2.2 GHz; hence, the tracking signal is highly susceptible to plasma perturbations. Measurements near and far from solar opposition with the Doppler tracking system on the Viking and Voyager spacecraft have confirmed that plasma fluctuations in the interplanetary medium provide by far the main limitation on achievable sensitivity for detecting gravitational radiation. Methods to overcome this and other limitations are discussed later.

For the three types of gravitational radiation—stochastic, burst, and periodic—the present state of theoretical understanding and instrument sensitivity is given in Table 2, where we compare estimates of the strengths of gravitational waves arriving at the Earth from various astrophysical sources with estimates of current instrument capabilities.

In sum, the challenges posed by the prospect of detecting gravitational waves have spurred innovation in a wide variety of technologies related to high-precision measurements and to suppression of unwanted noise. Optimism in this search must, however, be tempered by the severe difficulties in the development of instrumentation of sufficient sensitivity to detect gravitational waves reliably. The remaining challenges are extraordinary. Sustained efforts for a decade or more will be required for success.

4
Strategy for Research in the 1980's

I. INTRODUCTION

Gravitation, although by far the weakest of the four fundamental interactions known in nature, exerts the dominant influence on the behavior of large agglomerations of matter and on the structure of the universe. What is the correct theory of gravitation? More specifically, what are the limits of validity of general relativity? Are its predictions of gravitational-wave phenomena reliable, and can we thus open a new window on the universe through the detection and study of these waves? These are some of the fundamental questions that can be addressed, if not definitively answered, through the space program.

The strategy we propose for making significant advances in this decade depends on a delicate interplay of the sometimes conflicting factors of scientific importance, technical capability, and cost. In developing this strategy, we also considered the likely importance of both the experiments and the technology to other disciplines and to applications.

In the remainder of this chapter, we discuss in more detail the assumptions underlying our strategy, our specific recommendations, our concerns, and our overall conclusion.

II. ASSUMPTIONS

Gravitational physics is a discipline in which space measurements can substantially increase the depth to which fundamental questions can be pursued. In view of the extreme weakness of gravitation, non-Newtonian effects cannot be observed except close to large masses or through highly accurate measurements or both. Space techniques allow us to get close to the sun and to escape the many perturbations that affect delicate experimental apparatus on the Earth. The sharply reduced size of gravity gradients and the near absence of index-of-refraction perturbations in space are of major importance. Free-fall conditions make possible measurements of the gravitational effects of rotating massive bodies, and the very long measurement distances available in space magnify linearly the size of appropriate gravitational-wave displacements. Space techniques also allow us to utilize the inner planets of the solar system as a family of nearly ideal test bodies that are only weakly perturbed by nongravitational forces and that have orbits of different eccentricities and solar distances.

Three interrelated assumptions underlie our strategy. The first is the major importance of non-Newtonian gravitational effects in other parts of the universe and in the early stages of its development. The existence and characteristics of these effects must therefore be checked and measured carefully if we are to have reasonable confidence in the predictions from the relativistic theory of gravitation. For example, at present there is absolutely no theory-independent evidence for even the existence of magnetic-like gravitational effects such as the dragging of inertial frames by rotating massive bodies.

The second assumption is the uniqueness of the information about the universe and about fundamental physics that gravitational waves can provide. Observations of gravitational waves could tell us about random gravitational radiation that may have been created when the universe was young, about events that occur in the cores of supernovae, and about the growth of large black holes that may inhabit the centers of some galaxies. Gravitational waves, once detected, may also be used to study fundamental physical problems: Do they indeed travel at the speed of light? Are their polarization properties those of a spin-2, zero-rest-mass field as demanded by general relativity? Another major reason for emphasis on gravitational radiation is the possible link it provides to the basic question of whether black holes really exist. Although theoretical arguments for their existence are strong, nature may have found a way to prevent matter from collapsing behind an event horizon. Detailed analysis of gravitational waves could establish whether they originated from black-hole phenomena.

Our third assumption is the possibility of a breakdown in the general theory of relativity at levels that could be observed through precise measurements of the behavior of clocks, light rays, and massive bodies in the solar system. Some non-Newtonian effects on orbital properties accumulate with time and can therefore reach substantial amplitudes; for example, the contribution of the nonlinear part of the gravitational interaction causes an oscillatory variation in the distance between the Earth and Mercury for which the envelope increases linearly in amplitude by about 20 km per year. Any variation of gravitational time with respect to atomic time would have a profound impact on cosmology; a change in the gravitational constant of 1 part in 10^{11} per year would cause an oscillatory variation in the Earth–Mercury distance, with the amplitude increasing quadratically with time, with an acceleration of about 12 m per year per year. Anomalous secular changes in other elements of the orbits of the inner planets could also be detected from observations extended over suitably long periods, if such changes exist.

The present uncertainty in the solar gravitational quadrupole moment will limit the usefulness of many of these solar-system tests of the gravitational interaction. It is therefore of great importance that this quadrupole moment be determined with high accuracy. In particular, a determination of the dimensionless coefficient J_2 of the second zonal harmonic ("quadrupole moment") of the sun's gravitational potential with an uncertainty of 10^{-8} would ensure that the interpretation of solar-system measurements as tests of gravitational theory would not be impeded for the foreseeable future by lack of knowledge of the sun's gravitational field. Such a determination can be made only with space techniques.

III. RECOMMENDATIONS

In developing our specific recommendations we assessed the importance of each type of measurement for furthering our understanding of gravitation, the relative costs and technical merits of ground-based and space-based approaches, and the opportunities for space measurements.

We divide our recommendations for experiments into two classes, based on cost, and consider the more costly first. This first class consists of experiments that either require a dedicated spacecraft or have a major impact on a spacecraft mission. The second class involves either solely ground-based measurements or experiments that would be carried piggyback aboard spacecraft devoted mainly to other goals. Our recommendations within each of these classes are listed in order of priority. For each recommendation we indicate what should be done, why, and, where appropriate, how. Interclass comparisons are omitted as unimportant because of the large differences in the resources involved. Many of the experiments recommended are independent in the sense that the successful completion of one is not a prerequisite for another; sometimes the recommendations are almost inseparable, as in the case of observations and corresponding data analyses.

In a third class of recommendations, we discuss, in order of priority, advanced instrumentation proposed for development or study in the 1980's—instrumentation essential for later experiments. We also recommend the development of auxiliary instruments applicable to several types of space experiments in gravitational physics. Finally, in a fourth section, we make some brief comments on the role of theoretical research in gravitation.

Spacecraft Experiments

DRAGGING OF INERTIAL FRAMES BY ROTATING MASSES

The prediction of general relativity that rotating masses "drag" inertial frames should be tested through quantitative measurement. Such an experiment appears to be the only feasible means to verify the existence of a magnetic-like effect of gravitation.

The influences of gravitation on the behavior of light rays and massive bodies have been tested only in regard to the gravitation produced by a static, spherically symmetric, mass distribution. These solar-system experiments have thus probed only space-curvature effects and gravitational analogs of electric fields, as explained in Chapter 3. The effect of rotation, which breaks the spherical symmetry, is to couple directly the orbital and spin motions to produce magnetic-like effects. Such predicted coupling has been far too small to be detectable in experiments so far performed.

This prediction of frame dragging is of fundamental importance in the theory of general relativity: Just as the principle of equivalence requires that all test particles undergo the same acceleration under the same circumstances, independent of their masses, so does this principle require that all test gyroscopes under the same circumstances undergo the same precession, independent of their spin angular momenta. Thus, we may associate this precession solely with the behavior of a local inertial frame and consider that a rotating massive body "drags" this frame into rotation with respect to a frame far from the rotating body, the frame of the "fixed" stars.

Frame dragging is, of course, also predicted by the PPN formalism; the magnitude of the drag is linearly dependent on the space-curvature parameter γ and on a parameter that allows for "preferred-frame" effects. Although experiments sensitive both to space-curvature effects and to possible preferred-frame effects have verified the predictions of general relativity to rather high accuracy, as outlined earlier, we feel it unwise to rely solely on this *indirect* verification of the existence and magnitude of frame dragging. This magnetic-like manifestation of gravitation is of such fundamental theoretical importance as to demand direct observation and measurement.

Frame dragging would have several observable consequences. For example, the orbital angular momentum vector of a test particle in orbit about a massive spinning body would precess about the spin angular momentum vector of the massive body. The effect predicted by general relativity is, of course, not large; precession for a test particle or satellite moving about the earth at an altitude of about 800 km is expected to be about 0.2 sec of arc per year, the precise value depending on the spin angular momentum of the Earth and on the mean distance between the test particle and the Earth. This effect is the predicted gravitational analog of the electromagnetic coupling of the orbital motion of an electron in an atom to the dipole magnetic field of the nucleus.

The spin axis of a gyroscope in orbit about a rotating massive body would also turn with respect to the "fixed" stars. This precession results from the predicted spin-spin coupling between the orbiting gyroscope and the rotating massive body. In this second manifestation of "frame dragging," the axis of the gyroscope, if in a low-altitude polar orbit about the Earth, is predicted by general relativity to precess by approximately 0.05 sec of arc per year. Here, the magnitude depends not only on the mean altitude of the orbit but also on the angle between the spin vector of the Earth and the orbital angular momentum vector of the gyroscope—for a polar orbit, the magnitude is half that for the equatorial orbit. This precession is the gravitational analog of the precession of the spinning charged body in the field of a magnet. In atomic physics, the spinning charged body is an electron and the magnet a nucleus with spin; this magnetically induced spin-spin coupling is responsible for the hyperfine splitting of energy levels in atoms.

Aside from the effects of the rotation of the massive body, there is a further precession due solely to the orbiting of a gyroscope about a massive body. This "geodetic" precession is much larger than that due to the spin of the massive body for the usual situations encountered in the solar system. For a gyroscope in orbit about the Earth, the geodetic precession is predicted by general relativity to be approximately 7 sec of arc per year, about one hundredfold larger than the value for the spin-spin coupling. The geodetic precession can be thought of as composed of two parts, with the second contributing half as much as the first. The first is due to the curvature of three-dimensional space caused by the massive body that changes the values of locally measured angles compared with those measured with respect to the fixed stars. The second part is attributable to the gravitational analog of the spin-orbit coupling of an electron in an atom. This coupling contributes one half of the fine structure of atomic spectral lines; the other half, due to the Thomas precession, is absent for a gyroscope in free fall but would be present were the gyroscope locally accelerated as in a laboratory on Earth.

The geodetic precession has also not yet been unequivocally detected. A quantitative measurement of it would be a valuable contribution to the experimental foundations of any theory of gravitation. The geodetic and the frame-dragging precession are distinguishable experimentally, as they are predicted, except for special cases, to take place in different "planes."

None of these gravitational effects, neither the spin-spin coupling nor the orbit-spin coupling nor the orbit-mass (space-curvature) coupling, has ever been detected in the solar system, let alone quantitatively measured with useful accuracy.

An experiment that measured the dragging of inertial frames due to a spinning mass would be a landmark in physics—the first evidence of a magnetic-like effect of gravitation. If the result were quantitatively in accord with predictions, it would give confidence in the applicability, at least to the level of accuracy reached, of the relativistic effects of mass rotation. For example, frame dragging appears, in principle, to provide the only means for direct measurement of the angular momentum of the sun, a fundamental constraint on models of the solar interior. Also, as mentioned in Chapter 2, the concept of frame-dragging plays an important role in current speculations concerning the extraordinarily long-term memory of direction exhibited by the cores of powerful extragalactic radio sources.

If, on the other hand, a frame-dragging experiment were to reliably disprove general relativity's predictions of frame dragging, it would be a towering achievement. One difficulty, in either case, would be in checking the result through repetition; the fiscal barriers are so high that it is doubtful verification or refutation could follow quickly.

There appear to be two feasible approaches to the measurement of frame dragging. One is through placement in Earth orbit of very precise gyroscopes; the other is through placement of two Earth satellites in counterorbiting polar orbits and the accurate measurement of the relative precession of their orbital angular momentum vectors. The extraordinary technology needed for the gyroscope experiment has been under development over the past decade and a half. The possibility of counterorbiting satellites has received less attention; it appears to require two separate launches and the development of new tracking systems. Even if this second approach proved feasible, its total cost would likely be substantially higher than for the first and will not be discussed further here.

The first approach, as currently envisaged, involves four identical gyroscopes (two pairs orthogonally oriented) and a reference telescope, all fabricated from fused quartz and operating at a temperature of about 1.6 K within a liquid helium vessel capable of maintaining such temperatures for over a year. Each gyroscope would consist of a very round, very homogeneous quartz sphere almost 4 cm in diameter, coated with a superconducting niobium film and electrostatically suspended in vacuum. Each gyroscope would be spun to a speed of nearly 200 revolutions per second and would be expected to lose only one quarter of 1 percent of its initial spin rate during the course of a year because of the very low, 10^{-9} Torr, pressure maintained within the vessel.

Each gyroscope rotor has to be round to better than 1 part in 10^6 and homogeneous to within a few parts in 10^7. The homogeneity requirement is caused by the need to reduce (a) the mass-unbalance torque caused by nongravitational forces acting on an object whose center of mass and center of geometry do not coincide and (b) the gravity-gradient torque due to the interaction of the quadrupole moment of the rotor with the gradient of the Earth's gravitational field. The extreme requirements on roundness and homogeneity pose a need for a sophisticated system to monitor the changes in direction of the spin axis of each gyroscope. At the heart of the concept of the experiment, in fact, is the determination of the change in direction of the spin vector of the gyroscope by observation of its London moment, the magnetic moment created by the currents induced in the superconducting niobium coating when the ball is spun. These changes in direction of the spin axis, and hence of the London moment, can be determined by measuring the consequent changes in field in a set of orthogonal superconducting current loops. These measurements would be made with superconducting-quantum-interference-device (SQUID) magnetometers. A capability to detect a change in angle of 1 msec of arc has already been demonstrated in the laboratory with this technique. The use of the London moment to monitor the spin axis of the gyroscope is a critical reason for operating the equipment at liquid helium temperatures. Other reasons include increased mechanical stability and ease of magnetic shielding.

The proposed fused-quartz reference telescope is a folded Schmidt Cassegrainian system of nearly 400-cm focal length and about 14-cm aperture. The physical length of the telescope is only about 35 cm, and its optical components are in direct contact with each other to achieve maximum stability. The whole spacecraft would be slowly rolled about the telescope axis to average out certain torques and to modulate the sought-for precession signal at a known frequency. The observed reference star would be a bright object with known proper motion and would be located near the plane of the celestial equator. Rigel appears a good choice; its proper motion with respect to an inertial frame seems to be known to within a few milliseconds of arc per year.

In addition to a pointing control system, the proposed spacecraft would have a translational control system to reduce the mean residual nongravitational accelerations on the gyroscopes to about 10^{-7} cm per second per second. The translational controller, or drag-compensation system, would be referred to an inertial "drag-free" proof mass.

The design goal of the experiment should be to achieve a measurement of the frame-dragging precession and the geodetic precession to about 1 percent and 0.01 percent, respectively, of the effects predicted by general relativity. The limiting error source may be the knowledge of the proper motion of the reference star. If so, future improvements in the determination of the proper motion would allow the results of the experiment to be refined.

It appears technically infeasible to measure the frame-dragging precession in the laboratory; the requirements on the gyroscope are too severe. For example, the reduction of the mass-imbalance torque to a harmless level for a gyroscope not in free fall requires sphericity and homogeneity tolerances several orders of magnitude finer than for a gyroscope in space. In fact, this requirement is one of the major reasons for performing the experiment in space.

Once developed and tested in space, this gyroscope should also find use in applications for which a compact, ultraprecise pointing system is required.

GRAVITATIONAL QUADRUPOLE MOMENT OF THE SUN

The dimensionless coefficient J_2 of the second zonal harmonic of the gravitational potential of the sun should be determined with an uncertainty of 10^{-8} or less.

Lack of knowledge of J_2, as mentioned earlier, is the major limiting factor in the interpretation of the advance of the perihelion of Mercury. If J_2 is determined to within 10^{-8}, the next limitation will be about one order of magnitude smaller and is set by the uncertainty of the fractional difference in the principal equatorial moments of inertia of Mercury. This difference introduces a secular term in the perihelion advance of the orbit through the resonance coupling of Mercury's spin and orbit.

Two approaches to the measurement of J_2 appear feasible. One involves a spacecraft that passes within a few solar radii of the sun's surface and the other a spacecraft in a suitable orbit about Mercury. Both determinations would depend on the separation of the signature of J_2 from other effects on the radio-tracking signals. For a solar probe there would be far less masking by the signatures of other effects; for a Mercury orbiter the required technology is better developed. For a solar probe, a system is needed capable of compensation for nongravitational accelerations ("drag") at least at the level of 10^{-7} cm per second per second, especially in the spectral range between 10^{-5} and 10^{-4} Hz, which corresponds to the period of time the spacecraft would spend near the sun. A "drag-free" system was used successfully in earth orbit in the early 1970's and maintained compensation at the level of 10^{-8} cm per second per second until the gas supply was exhausted, after several years. A similar system is proposed for use in the gyroscope experiment. For the solar-probe experiment, further development of the drag-free system is required because of the harsher environment near the sun: one must deal with the potentially serious charging effects of cosmic rays on the proof mass and with the more severe thermal problems, as well as with the need to accommodate other experiments that may involve time-varying mass distributions. The requirements on the tracking system are also more severe for the solar probe since the crucial signals must pass through the solar corona. However, it appears likely that with an uplink at a radio frequency near 8 GHz, these latter requirements can be met.

If a Mercury orbiter were used to determine J_2, at least several years of very-high-accuracy radio tracking would be required to reduce the uncertainty in the estimate of J_2 to the level of 10^{-8}. Such extended tracking of a Mercury orbiter would also reduce substantially the uncertainty in our knowledge of any variation with time of the gravitational constant.

In addition to its importance for testing general relativity, a determination of J_2 could be of great significance for our understanding of the interior of the sun. Various contemporary models of the solar interior yield values for J_2 that span the range from about 5×10^{-7} to 10^{-8}, even ignoring the possibility of rapid internal rotation. Because essentially no measurements exist bearing directly on the solar interior, the constraint provided by a measurement of J_2 could have a profound influence on our concepts of the interior, perhaps even on our view of the solar-neutrino problem.

NONLINEAR EFFECTS OF GRAVITATIONAL POTENTIALS ON CLOCKS

The predicted effect on clock behavior of the nonlinearity in the superposition of (Newtonian) gravitational potentials should be measured.

All past measurements of nonlinearity in the superposition of gravitational potentials have involved the dynamical motions of test bodies such as Mercury, whose perihelion shift revealed the level predicted by general relativity, a value of the PPN parameter β consistent with unity. A clock experiment would probe this nonlinearity in a different physical context and would check whether, at this nonlinear level, gravitation can be represented by a metric theory. If the clock experiment yields a value reliably different from unity, then metric theories cannot provide acceptable descriptions of gravitation. If the clock and the dynamical tests of this nonlinearity give consistent results, then, at least at this level, metric theories and, in particular, general relativity would be adequate.

Deploying an oscillator, with instabilities of 1 part in 10^{15}, or less, for averaging times of the order of a few hundred seconds to a few days, on a spacecraft with a drag-compensation system that passes near the sun, could allow β to be estimated with an uncertainty under 10 percent. This oscillator, or clock, experiment could be combined with the experiment to measure the gravitational quadrupole moment of the sun. During a several-year cruise toward the sun, the availability of an on-board ultrastable oscillator and a suitable microwave tracking system would also offer an improved sensitivity for the attempt to detect gravitational waves, discussed below.

The additional technology required for this gravitational red-shift experiment concerns the refinement of existing instrumentation for ensuring reliable operation in space for the necessary time intervals. Oscillators of the hydrogen-maser type have already been operated in the laboratory for long periods of time with nearly the required stability characteristics; even the earlier model carried aloft in a rocket demonstrated stability characteristics only an order of magnitude shy of the desired ones. Continued development should thus yield the necessary improvements for spaceborne oscillators.

Ground-Based and Piggyback Experiments

ORBITS OF THE MOON AND INNER PLANETS

The relativistic contributions to the orbits of the moon and inner planets should be determined as accurately as technically feasible with ground-based observations.

The inner solar system forms the best available laboratory for testing relativistic effects of gravitation. Measurements of the relative positions of the moon and planets can now be carried out with exquisite accuracy, uncertainties being as low as 1 part in 10^{11} in some cases. These positions contain information on the extent of the validity of the principle of equivalence for massive bodies, on the extent to which the strength of the gravitational interaction might be changing with respect to that of the electromagnetic interaction, and on the extent of the nonlinearity of the superposition of (Newtonian) gravitational potentials. The significance of these facets of gravitation was discussed in Chapter 3.

Such measurements of the dynamics of the solar system, made with modern instrumentation, could be an extremely valuable legacy to leave to future generations of scientists. Many relativistic orbital effects accumulate with time. Hence, in the future, scientists could combine their data with those obtained in the present era and reap more sensitive tests of the fundamental theories of gravitation. Further, measurements made now with higher accuracy than that of their interpretation are not necessarily wasted. Future improvements in the interpretation may improve the utility of the data. Examples abound. Thus, the limitation on the interpretation of planetary radar observations as tests of gravitational theories is not now provided by the signal-to-noise ratio but rather by the as yet uncharted topography of the observed planets. Future developments of accurate topographic maps, combined with knowledge of the radar scattering laws and of the planet spin vectors, will allow past observations to be interpreted to their full inherent accuracy. Similarly, future improvements in star catalogs will enable the observations of the differential positions of planets and stars to be interpreted with higher accuracy.

Particularly shining examples of the importance of such legacies mark the development of gravitational physics—from the observational work of Tycho Brahe and its use by Kepler to the work of many generations of observational astronomers that enabled Leverrier in the mid-nineteenth century to detect deviations in the orbit of Mercury from the predictions of the Newtonian theory of gravitation.

Of course, one need not be concerned only with future generations. Even within the confines of a single generation the whole is, in effect, greater than the sum of its parts: analysis of the total available data set can enhance the reliability and accuracy of any single test of a theory of gravitation. Moreover, data obtained during one space mission might be virtually worthless in themselves but, when combined with data taken in another, might be of great interest. Consider as a simple, albeit artificial, example, the measurement over a one-year time interval of the perihelion position of the orbit of Mercury with an uncertainty of 0.002 sec of arc. Such data would yield little improvement in the determination of the advance of the perihelion position. However, in combination with another round of such measurements made a decade later, the original data could yield a tenfold more accurate value for the advance.

We now discuss in detail the opportunities in this decade for carrying out precise measurements in the inner solar system and their likely impact.

VIKING RANGING Measurements of the distance or range, from Earth to Viking Lander 1 on Mars should be made at least once per week, except when the tracking signals pass too close to the sun to obtain useful data.

This range can be measured with uncertainties as low as 3 to 5 m near opposition, by far the highest fractional accuracy currently achievable in solar-system measurements. To extract the full scientific content from such an opportunity requires at least weekly observations in order to be able to distinguish reliably all the different physical effects that contribute to the observable range; these effects have different and sometimes variable signatures.

If continued through this decade, these measurements would allow any change in the gravitational constant of 1 part in 10^{11} per year or larger to be detected reliably, could provide a test of the principle of equivalence for gravitational binding energy for the sun–Mars–Jupiter system with an uncertainty of under 1 percent, and would allow the relativistic contribution to the perihelion advance of Mars to be determined with under 10 percent uncertainty. Further, the concomitant improvement in the orbit of Earth would improve significantly the accuracy of the interpretation of the Earth-based observations of Mercury, discussed below.

These ranging observations would also provide other results: an estimate of the precession constant of Mars to within about 10 percent and, with other data, its moments of inertia; determinations of variations in the rate of rotation of Mars, if at all similar to Earth's; and improved determinations of the masses of the Jovian system and of the four largest asteroids. Combined with measurements of diameters, these latter mass estimates will allow reliable densities to be determined for these asteroids.

In summary, it would appear to be unconscionable not to take full advantage of this unique opportunity to range accurately to the Viking lander on Mars.

RADAR RANGING Measurements with radar of the range between Earth and the other inner planets should be made at every feasible opportunity.

Such measurements are most important for Mercury; being closest to the sun and in a very eccentric orbit, it plays a pivotal role in all dynamical tests of the relativistic behavior of massive bodies in the gravitational field of the sun. Radar measurements of the range between Earth and Mars are least important for gravitational physics so long as ranging observations of the Viking lander continue.

The importance of these radar measurements for tests of theories of gravitation has already been stressed. Here we add only that through continual monitoring of the orbital motion of Mercury, the bound on any possible change in the gravitational constant will decrease with the inverse five-halves power of the total time span of the measurements. Without any allowance for statistical improvement through averaging of random errors, one can still envision this limit to decrease with inverse square of the time interval spanned because the orbital phase, or longitude, undergoes accelerated change proportional to any rate of change of the constant of gravitation. The limit on accuracy that can be foreseen from lack of knowledge of other relevant physical quantities is about 1 part in 10^{14} per year and stems from the uncertainty in our knowledge of the mass loss of the sun. This limit will not become a serious concern for quite some time.

The uncertainty in the determination of the total advance of the perihelion position of Mercury decreases with the inverse three-halves power of the time interval spanned by ranging measurements. This position, as mentioned earlier, is sensitive to a nonlinearity in the superposition of gravitational potentials in the electric-like component of the space–time metric for the sun and is thereby of especial importance. Unfortunately, the separation of the relativistic contribution from the total is already limited by a lack of knowledge of the contribution of the solar gravitational quadrupole moment. Although this latter contribution is certainly separable in principle, the correlation is so high that, in practice, the accuracy of separation is severely limited. It is for this reason that an independent determination of the solar quadrupole moment is of such great importance to gravitational physics.

Sustained high-accuracy measurements of the echo delay of radar ranging signals transmitted from Earth to the inner planets can be accomplished at present only with the NASA-supported radar facilities at the Arecibo Observatory in Puerto Rico and at the Goldstone Tracking Station in California. The main limitation on the utility of such data for tests of relativistic gravitational effects has not been measurement accuracy but rather measurement sparsity and the unknown topography of the target planets. The frequency of measurements should be increased. Further, currently available techniques should be used, where possible, to measure the topography with an accuracy comparable with that of the measurements themselves. The radar method of delay-Doppler interferometry has been developed so that the three coordinates of some observed points on a target planet can be measured simultaneously. In addition, repeated measurements at widely separated times of the echo delay to the same point on a target planet's surface can be made to provide "closure" from which the effects of topography can be largely eliminated with, of course, the loss of one degree of freedom from the set of measurements to each given point. The topographic maps obtained with the altimeter on the Pioneer Venus Orbiter can also be used to within their resolution and coverage limitations to correct the Earth-based radar measurements for the effects of topography.

Radar observations of asteroids, when within range, should also be made, as they serve to probe better the gravitational perturbations of other asteroids and, hence, to reduce the uncertainty in the interpretation of solar-system measurements due to our currently inadequate knowledge of the mass distribution of the asteroid belt.

LASER RANGING Laser ranging to the optical corner reflectors on the moon should be continued throughout the decade. It would be desirable to use two or more sites on Earth to separate better the contributions to these ranges of the relativistic effects from the motions of Earth about its center of mass.

These ranging measurements, each now having an uncertainty of about 10 cm, could allow an almost tenfold improvement in the test of the principle of equivalence for massive bodies, i.e., for the nonlinear regime where gravitational binding energy contributes. The contribution of the geodetic precession to the change in direction of the orbital angular momentum vector of the moon could also be determined from these data to within about 10 percent of the predicted effect; however, this accuracy is far lower than is expected to be achievable with the gyroscopes discussed earlier. Additionally, these laser-ranging data should allow a separation of the effects of the tides on the orbit of the moon from those of a possible change in the gravitational constant, but here the level of accuracy possible in the next decade will be at least an order of magnitude lower than for the gravitational clock provided by an inner planet.

Laser observations are also useful for a variety of applications in selenophysics and geophysics such as the determination of the lunar gravitational field, earth rotation and polar motion, and tidal dissipation within the moon and within Earth.

ORBITER RANGING Measurements of the range between Earth and any spacecraft in orbit about a planet ought to be made at regular intervals throughout the lifetime of the spacecraft.

The accuracy of ranging to a planetary orbiter, interpreted as equivalent ranges to the center of mass of the planet, can far surpass that achievable with ground-based radar observations. Thus the opportunity for ranging to planetary orbiters should be seized for all the reasons adduced above for continued radar observations of the planets. For example, spacecraft with suitable ranging transponders in orbit about Venus could provide measurements of especial importance for the determination of any possible change with time of the gravitational constant.

Finally, we emphasize the important interrelationship between planetary- and lunar-ranging measurements. For illustration, consider the effect of accurate lunar-ranging observations on the interpretation of the radar and spacecraft measurements of the ranges to the inner planets. Through the determination of the geocentric orbit of the moon, which is directly reflected in the motion of Earth about the Earth-moon barycenter, and through improved determination of certain elements in the orbit of this barycenter, lunar laser-ranging measurements reduce the "masking factors" that tend to limit the accuracy with which relativistic parameters can be determined from the planetary-ranging measurements. This masking arises from correlations between estimates of the relativistic parameters and the other, "nuisance" parameters on which the observations also depend. Inclusion of the lunar-ranging data in the analysis serves to reduce these correlations significantly. Of course, this reduction of correlations works both ways: the planetary observations, too, aid the analysis of the lunar data. Thus, the contribution of any given set of measurements must be judged, not in isolation but in regard to its effect on deductions from the ensemble of measurements, past as well as future. It is for this essential reason that each feasible opportunity for ranging to the moon and planets should be seized.

DATA ANALYSIS All of these determinations of relativistic effects in the solar system require extremely intricate calculations. To interpret measurements to the level of their intrinsic accuracy requires calculations of the theoretical values of observables, like round-trip times of radio signals propagating between planets, to a fractional accuracy of about 1 part in 10^{12}. The consequent need to incorporate all manner of classical effects, concerned with the motions of and about the centers of mass of Earth and the target body, leads to computer programs with upwards of 100,000 Fortran statements. Verification of the reliability of such enormous programs is practically impossible. It would appear that only two sets of software, each developed completely independently, can serve as an adequate check on reliability. It therefore seems important that at least two separate groups be involved in the evaluation and analysis of these data, which can yield such very sensitive tests of theories of gravitation. This conclusion is only reinforced by the fact that the measurements in becoming evermore accurate will be requiring comparable improvements in the theoretical model with the consequent increasing complexity of the necessary software.

GRAVITATIONAL RADIATION

Spacecraft to be placed in orbit well beyond the Earth-moon system for other purposes should also be instrumented for best use in attempts to detect gravitational waves. This instrumentation should at least include an ~8-GHz uplink signal in addition to the normal, coherently related, ~2- and ~8-GHz downlink signals. (Uplink refers to the path of the signal from the earth to the spacecraft and downlink to the path from the spacecraft back to Earth.)

Pairs or triplets of such spacecraft, widely distributed about the solar system, could be especially useful if observed simultaneously so that the signatures of gravitational waves could be distinguished far better from sources of noise. Data collection appropriate for the search for gravitational waves should be concentrated near solar opposition, where the effects of interplanetary plasma fluctuations are least, and at times when the spacecraft are not executing translational or orientational maneuvers that could each introduce noise into the spacecraft motions.

The present Doppler tracking system has an ~2-GHz uplink signal and coherent ~2- and 8-GHz downlink signals; its sensitivity to low-frequency gravitational radiation is such that a wave in the frequency band $\sim 10^{-2}$ to $\sim 10^{-4}$ Hz and with dimensionless amplitude $h \sim 10^{-13}$ might be detected reliably (see Table 2). The main limitation on sensitivity is provided by fluctuations in the interplanetary plasma that cause time-varying changes in the frequency of the relatively low-frequency uplink tracking signals. The use of an 8-GHz frequency for the uplink signal would enable an immediate improvement by a factor of more than 10 to be made in the system sensitivity for detection of gravitational waves.

The detection and study of gravitational waves from space is an enticing prospect, as discussed at length in Chapter 3. The discovery of any gravitational radiation from space would be an event of enormous scientific significance, surpassing even that of the first detection of x rays from beyond the solar system. Nonetheless, despite the great uncertainty in the theoretical estimates of the strength of such waves impinging on the solar system, it appears rather unlikely that their levels will be sufficient to be detected, even with the addition of an x-band uplink to the Doppler tracking system.

It is clearly a gamble to do experiments with a system whose sensitivity is apparently lower than necessary to detect the phenomenon sought. It would certainly be unwarranted to propose a dedicated spacecraft for this purpose. In view of the importance of the goal of detecting gravitational waves and the possibility of their being of unexpectedly large amplitude, it does seem warranted, however, to make small additions to planned spacecraft for the purpose of searching for these waves. The gamble is not foolish when the investment is modest; the added expense would probably be under 1 percent. Moreover, if this goal of detection is to be attained eventually, one should proceed in reasonable steps. A one-order-of-magnitude increase in system capability at a small fractional cost is such a step when, as here, there is a potential for further developments that could continue to yield substantial increases in sensitivity.

It is necessary to utilize space for the search for gravitational waves with frequencies well under 1 Hz because, as mentioned earlier, seismic noise and local mass motions on Earth seem to provide a low-frequency cutoff at about 30 Hz for entirely Earth-based detection systems.

Other benefits that would accrue from use of a higher-frequency uplink signal include the ability to (a) study the solar corona closer to the surface of the sun and (b) return data obtained by spacecraft near superior conjunction with lower error rates and from larger communication distances.

Advanced Instrumentation

Significant experiments in gravitation require instrumentation at the very forefront of measurement technology. Therefore continued experimental progress in gravitational physics depends crucially on the development of advanced instrumentation. Here we describe each instrument whose development or study we recommend and the reasons for each recommendation.

RADIO TRACKING SYSTEM

A radio tracking system should be developed to allow phase-stable, dual-band uplink and downlink communication and to support ranging signals with a bandwidth of up to 50 MHz.

The dual-band, dual-link system could involve the standard ~2- and 8-GHz radio signals or, if feasible, signals at higher frequencies. This system could be used on spacecraft in deep space to increase significantly the immunity to plasma of the Doppler tracking system compared with that attainable with the use of an ~8-GHz uplink and a dual-band downlink. With the improved system, the limit on the stability of the radio tracking signal for the approximately 1000-sec time scales of interest for the detection of gravitational waves would likely be set by the effects of the troposphere, which is essentially nondispersive at radio wavelengths and might introduce noise at a level equivalent to $h \gtrsim 3 \times 10^{-15}$. The use of other techniques, such as spacecraft-to-spacecraft tracking, which would avoid the troposphere, could further increase system sensitivity. Overall, with present technology, it appears possible to reduce the threshold for reliable detection of low-frequency gravitational waves to at least $h \sim 10^{-15}$.

The proposed wideband ranging system could allow a two-orders-of-magnitude or more improvement in various tests of general relativity, depending on the deployment of the spacecraft. The full inherent centimeter accuracy of such a ranging system could only be utilized for a spacecraft landed on the surface of a planet like Mars or Mercury. This accuracy can be achieved without high power through use of bandwidth synthesis as is routinely done in radio interferometry. Development of the wideband ranging system now would ensure its availability when another planetary lander mission is planned. Nearly the full accuracy could also be utilized on a spacecraft in orbit about a planet. In fact, a small ranging subsatellite could be developed and deployed by the main spacecraft into a planetary orbit appropriate for the determination of both interplanetary distances and the low-degree terms of the gravitational fields of the host planet.

If landers with this wideband ranging system were deployed on the surface of Mars or Mercury, it would also be possible to detect tectonic motions, if as large as on Earth, and monitor polar motion and small variations in rotation rate.

A wideband ranging system could, in addition, be of importance as an all-weather, high-accuracy system for inexpensive tracking of earth satellites whose orbits must be determined precisely. One such example is a satellite used to measure the heights of ocean surfaces with a radar altimeter to determine the geoid as well as the dynamical effects of wave motions in the oceans.

OPTICAL INTERFEROMETER

Technology should be developed for an astrometric optical interferometer to be placed in Earth orbit.

This instrument could be used to measure, for the first time, a post-post-Newtonian effect of gravitation: the effect on the bending of starlight due to a nonlinear contribution of the sun's gravitational potential to the curvature of space. (In the advance of the perihelion of a planet, the post-Newtonian effect involving β is also due to a nonlinear contribution but to the electric-like part of the gravitational field.)

A feasible instrument, based on present technology, could consist of a set of crossed Michelson interferometers with 1-m-diameter mirrors, separated by

10 m. The relative position of any pair of tenth-magnitude or brighter stars, separated by 90 deg on the sky, could be measured with this instrument to within 1 μsec of arc from observations of a few minutes' duration.

Other astrophysical applications of this instrument include refinement of the cosmic distance ladder through more accurate (parallax) determinations of the distances to the lowest rungs, construction of an accurate kinematic map of the Galaxy, and a significant potential for detection of planetary companions to stars through the effects on the stars' proper motions.

OPTICAL HETERODYNE SYSTEM

The feasibility of an optical heterodyne system, deployed in space to detect gravitational waves, should be investigated.

Although the sensitivity of the present radio heterodyne system for tracking spacecraft can be increased substantially, as mentioned, it is inherently far more susceptible than an optical system to the effects of interplanetary plasma. Because the deviation from unity of the index of refraction of a plasma varies approximately inversely with the square of the frequency of the electromagnetic waves, optical systems are virtually immune to plasma "noise" and, in principle, present an attractive alternative. Preliminary studies indicate that an optical heterodyne tracking system, to provide pairwise electromagnetic coupling between three or more spacecraft, may eventually be capable of achieving a sensitivity sufficient to detect gravitational waves with $h \lesssim 10^{-21}$ in the frequency range below ~30 Hz, where Earth-based detectors seem to be infeasible. But no detailed analysis of this system or of others that might be competitive, such as an optical interferometer system or an infrared heterodyne system, has yet been carried out. To assess properly their potential, we recommend that studies of such systems be undertaken, with emphasis on such aspects as achievable transmitter powers, telescope sizes, and pointing accuracies (including the effects of aberration); efficacy of transponders and shielding systems; and importance of gravity-gradient disturbances. Such studies should take advantage of experience gained with similar ground-based systems being developed to detect gravitational waves with frequencies greater than ~30 Hz. If sensitivity to fractional strains of the order of 10^{-21} appears attainable with a space system, it would deserve prime consideration for development and possible use in the 1990's.

AUXILIARY INSTRUMENTS

Most space experiments in gravitation would benefit from the development of auxiliary instrumentation. Here we discuss two such types of instruments. The development of other instruments, of at least equal importance, such as drag-compensation systems and ultrastable oscillators, was already discussed in the context of proposed experiments.

TROPOSPHERIC CALIBRATION SYSTEM Research should be initiated to develop methods and then instrumentation for calibration of the electrical pathlength of the troposphere.

The uncertainty of the propagation delay of radio signals passing through the troposphere poses the most fundamental limit on the accuracy of radio tracking of spacecraft from Earth. This uncertainty is due mainly to water vapor that is not in hydrostatic equilibrium. An accurate calibration system, if one could be developed, would improve the sensitivity of searches for gravitation waves and would also allow more-accurate interpretation of ranging measurements to be made. The calibration may be approached either directly or indirectly. At the moment, the indirect possibility appears the more promising. In searches for gravitational waves, this possibility can perhaps be realized through the inclusion on the spacecraft of a highly stable oscillator to control its transmitter directly. This configuration would permit multiple-link radio communications between spacecraft and ground that could be used to distinguish, through time-correlation analysis, between effects of the troposphere and of gravitational waves on the spacecraft tracking signal. This correlation analysis might also offer some additional immunity to the effects of fluctuations in the interplanetary plasma.

For ranging, as well as for the search for gravitational waves, water-vapor radiometers that monitor the brightness temperature of the atmosphere at two frequencies in the 20- to 30-GHz region may be useful because of the high correlation between the brightness temperature and the electrical pathlength of the atmosphere.

CRYOGENIC TECHNOLOGY Further development of cryogenic technology should be undertaken for use in space.

Cryogenic technology is seeing increasing application in space projects, the gyroscope experiment and the infrared telescope facility being two examples. Recent improvements in the stability of laboratory oscillators have involved cryogenic technology; its extension to space will allow improvement in all gravitational experiments that depend on stable frequency standards or clocks in orbit. An Eötvös experiment might also be performed with cryogenic apparatus in Earth orbit, where the accuracy in testing the equivalence of inertial and (passive) gravitational masses might exceed that achieved on Earth's surface by several orders of magnitude. A gravitational-wave detector in space, and radio transponders too, might well profit from an advance in cryogenic technology through use of very low-noise cooled receiver systems.

Components for cryogenic technology, such as valves highly resistant to leakage and strong materials of low thermal conductivity, require advanced development to produce the desired low-vibration, large-capacity, very-low-temperature, closed-cycle systems.

Theory

Theoretical studies in gravitation are of several kinds: (a) development of the general mathematical and physical consequences of theories of gravitation, (b) identification of new experiments for testing such theories or for detecting gravitational waves, (c) evaluation of the feasibility and accuracy of possible experimental techniques, and (d) determination of the theoretical significance of experiments in gravitation.

NASA has traditionally supported theoretical studies relating directly to space experiments in gravitation. This support has been quite fruitful and has led to the creation of the parametrized-post-Newtonian formalism and of a framework for evaluation of the significance of tests of the metric hypothesis. In addition, the signficance of lunar laser ranging and of geophysical experiments to test theories of gravitation was clarified. The origin of the "quantum limit" for gravitational-wave detectors has been analyzed, and a new class of experimental techniques has been proposed for circumvention of this limit. These techniques may herald a major advance in precision measurements, although much more development is required before their potential can be assessed reliably.

Often these studies have yielded as much benefit for Earth-based experiments as for space-based ones; sometimes more. This situation is unavoidable because of the close theoretical interlock between these two types of experiments.

The general health of theoretical research in gravitation thus seems excellent, and we recommend that support be continued in the future at the same level as in the past.

IV. CONCERNS AND CONCLUSION

We note here several of our concerns regarding the overall strategy for gravitational physics for this decade, and then our conclusion.

Organization

Many experiments in gravitational physics require a space platform but often do not require exclusive use of this platform. Efficient deployment of resources thus dictates cooperative missions with multiple purposes. Unfortunately, in the past, the needs of gravitational-physics experiments in cooperative missions have often not been accorded sufficient priority for their full potential to be realized; this low priority has been inconsistent with their fundamental importance to science. Broader perspectives are needed. In particular, explicit recognition should be given of the need for full cooperation between disciplines, starting with the planning phase and continuing through completion of the mission, even when one discipline claims a large majority of the experiments. Cooperative missions with experiments from different disciplines are especially important in view of the increasing cost and rarity of deep-space experiments.

Innovation

Experimental research in gravitation is at the cutting edge of science and requires broad extension of the armamentarium of modern technology to produce significant results. In general, such impetus for improvement in technology comes from the challenge to make measurements of fundamental importance. Meeting this challenge draws talent of the highest caliber. The complexity of the challenge usually requires the coordinated effort of a team for periods of a decade or more to produce the desired major advance in instrumentation. This driving force of fundamental science may, in fact, be a crucial ingredient for technological innovation. Especially in view of the widely perceived national need to maintain a rapid pace in innovation, we urge that NASA foster such teams of high talent for instrumentation development in gravitational physics. Those that make excellent progress should not be disbanded, except for the gravest of reasons. We are mindful not only of the fact that once disassembled a group can in practice not be re-assembled but also that the precedent set by disbanding such a group will make it more difficult in the future to convince talented people to engage in similar developments.

Coordination

Significant support for gravitational physics is provided by the National Science Foundation (NSF), primarily for Earth-based experiments and for general theoretical studies. However, the separation between ground and space experiments, and between either and theory, cannot, and should not, be complete. Continued coordination and cooperation between NASA, NSF, and other relevant agencies is necessary to ensure adequate support to maintain and improve the health of the discipline.

Conclusion

We conclude that the space program offers opportunities for experimental advances that will strengthen greatly the foundation for our understanding of the basic phenomenon of gravitation, so central to physics and astronomy. The strategy outlined here for the decade of the 1980's represents a vigorous continuation of this quest for a deeper knowledge of gravitation.