MANAGEMENT AND OPERATIONS
WORKING GROUP FOR SHUTTLE ASTRONOMY

REPORT OF THE SUB-PANEL ON RELATIVITY AND GRAVITATION

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1. History of Sub-Panel

This report is a summary of the deliberations and the recommendations of a Sub-Panel of the Management and Operations Working Group in Shuttle Astronomy commissioned by Dr. Nancy G. Roman of NASA Headquarters to consider the role of the space program in the field of experimental relativity and gravitation.

The panel members are Professors Peter Bender of the University of Colorado and the National Bureau of Standards, Charles Misner of the University of Maryland, Robert V. Pound of Harvard University and Rainer Weiss of M.I.T., chairman.

The panel met 4 times during 1975, and at several of the meetings it was joined by visitors interested in the field. The visitors were Dr. Rudolf Decher of NASA Huntsville, Dr. Nancy Roman, NASA Headquarters, Professors James Peebles of Princeton University, Irwin Shapiro of M.I.T. and Kip Thorne of Cal Tech.

The report introduces the reader to the fundamental problems in experimental relativity and gravitation and then follows with sections on various areas in the field. Each section reviews the present status of research and brings forward suggestions where the space program may have an impact.

2. Introduction

Gravitation is at the same time the dominant force in the universe for matter in the large as well as the weakest known fundamental interaction in nature. Gravitation opened the era of modern science with Newton's remarkable insight that the force that keeps us from falling off the earth is also responsible for the motion of the planets. The Newtonian description of gravitation is certainly adequate, in a practical sense, in the weak gravitational fields we encounter in our neighborhood--earth and sun. However, it has long been recognized, since the advent of special relativity in 1905, that Newtonian gravitation cannot be a complete description of the gravitational interaction. In this century, many relativistic theories of gravitation have been formulated, of which the Einstein Theory of General Relativity is the best known, and in the opinion of many physicists the most likely to be correct. The fact that this remains only an opinion rather than a conviction rests primarily in the paucity of experimental evidence for relativistic theories of gravity.

The small amount of experimental evidence does not reflect disinterest but rather the experimental difficulties encountered in measuring the extremely small effects of relativistic gravitation in the weak fields available to us and the uncertainties in estimating the often much larger perturbing effects of other interactions. The first order relativistic corrections are of magnitude GM/rc^2; on the earth this quantity is approximately 10^{-9}, on the surface of the sun approximately 10^{-6}. Even though there are often formidable difficulties in carrying out measurements of relativistic gravitational effects, they are of profound importance both as they allude to the description of the physics in strong gravitational fields which may be encountered in astrophysics and cosmology and, in the deepest sense, as they further our understanding of one of the fundamental physical interactions of nature. Research in gravitation is indeed a frontier of basic science.

Progress in experimental relativity is closely tied to advances in technology and the discovery of new astrophysical phenomena. Several highlights in the history of the field in the last decades illustrate this well. The first reliable measurements of the gravitational Red Shift were made in the 1960's using the Mössbauer effect, which offered sources of unprecedented narrow spectral width. The development of low noise receivers, powerful microwave sources, and large antennas enabled interplanetary radar to become a tool to measure the excess relativistic time delay of electromagnetic waves in the gravitational field of the sun. The discovery of quasi stellar radio sources and the development of refined radio interferometers have led to the most authoritative measurements of the relativistic bending of light by the sun. X ray astronomy, in concert with identifications made by optical astronomy, may have uncovered evidence for highly condensed states of matter--black holes--the ultimate singularities of the gravitational interaction. Radio astronomers have discovered a pulsar with a close compact companion in orbit about each other. Providing that the system is "clean"--negligible tidal interactions, low gas densities, small magnetic interactions--it may provide measurements of relativistic gravitational effects in moderate fields as well as evidence for gravitational radiation damping.

The space program has already made contributions to the study of gravitation and experimental relativity in several ways: through the placement of corner reflectors on the moon for precision ranging, ranging to interplanetary spacecraft and the X ray astronomy survey. In our opinion, the space program can make significant and quite possibly unique advances in gravitation and experimental relativity by providing:

1) Means for carrying out astrophysical observations over the entire electromagnetic spectrum.
2) Means for using the solar system as a laboratory to measure relativistic gravitational effects with precision as well as to test fundamental principles.
3) Low acceleration and low noise environments for delicate laboratory style relativity experiments in orbit.

3. Fundamental Issues in Relativity and Gravitation

Conceptual questions touching gravitation theory can be organized under three headings: (1) Is Einstein's theory of gravity basically correct? (2) If so, what are the limits of that theory? and (3) What natural phenomena will it help us see?

(1) In discussing the validity of Einstein's general relativity, the question is most often phrased in a quite detailed way

which assumes that matter can be subject to gravitational influences only to the extent these are describable by a spacetime metric. Within this limit ("metric theories") two areas have been extensively studied: post-Newtonian effects and gravitational waves.

Some metric theories could be indistinguishable from general relativity (GR) in post-Newtonian order, but give rise to gravitational waves of polarizations different from GR polarizations. Thus if and when detectable sources of gravitational waves are found, a number of polarization experiments should be considered.

At present the comparison of GR with other metric theories (including the Brans-Dicke theory) is systematized by the parameterized post-Newtonian (PPN) formalism. Here the spacetime metric in the solar system is expanded in a series such as

$$g_{00} = 1 - 2\Sigma \frac{Gm}{rc^2} + 2\beta(\Sigma \frac{Gm}{rc^2})^2 + \cdots\cdot$$

$$g_{0\alpha} = \frac{7}{2} \Delta_1 \Sigma \frac{Gmv_\alpha}{rc^3} + \frac{1}{2} \Delta_2 \Sigma \frac{Gm(\vec{v}\cdot\vec{r})r_\alpha}{r^3c^3} + \cdots\cdot$$

$$g_{\alpha\beta} = -(1 + 2\gamma\Sigma \frac{Gm}{rc^2})\delta_{\alpha\beta} + \cdots\cdot$$

where the sums are over all gravitationally significant masses m. The parameters β, γ, Δ_1, Δ_2 are all unity in GR, but may differ in other theories. The observational challenge is to measure these parameters, and thus narrow the class of theories to those that predict the observed values. The number of terms which appear in the series is limited by symmetry considerations. The most important "symmetry," Einstein's equivalence principle, gives the "metric theory" limitation, and further symmetries (such as energy and momentum conservation) reduce the unknowns (in a post-Newtonian context) to five or ten numbers usually called β, γ, α_1, α_2, α_3, ζ_1, ζ_2, ζ_3, ζ_4, and ζ_w. (The Δ_1, Δ_2 above are combinations of these.)

Within the PPN formalism, experiments can be compared according to their cost-effectiveness in measuring the parameters to high accuracy, with first priority given to β and γ which may differ from their GR values without violating any simple symmetry; second priority then goes to α_1, α_2 and ζ_w which can be "anomalous" without violating energy or momentum conservation, and lower priority to α_3, ζ_1, ζ_3, ζ_4 and $\zeta_2 - \zeta_w$ which can have non-zero values while still preserving the equivalence principle.

But is gravitation a metric theory? Must all gravitational actions on matter be mediated by a metric? Some aspects of this fundamental question have been explored theoretically. It is known, for instance, that to the extent that matter can be idealized as point particles interacting electromagnetically, then either Eötvös type experiments, or Red Shift experiments, can in principle detect non-metric gravitational behavior. So also could any intercomparison of PPN experiments: inconsistencies between two different experiments designed to measure the same PPN parameters could be cited as evidence of the "non-metric" nature of gravity. Unfortunately no criterion is yet known for selecting the most apt intercomparisons for this purpose.

As a consequence it is premature to compare the relative merits of different experiments solely on the basis of their ability to determine a specific PPN parameter. It is at this stage in the development of experimental relativity safer to consider experiments that "appear" to measure different physical effects as different even though the results could be interrelated through the PPN formalism.

But does not spacetime geometry play at least some role in gravity theory? This is certainly a central question in asking whether Einstein was basically right with GR. For this qualitative question, a qualitative observational or experimental response appears to be possible, i.e., do black holes really exist? For among theories which have been scrutinized in this respect, it appears that those which avoid having black holes do so by depriving the gravitation field of its role as giving the unique or basic metric on spacetime.

Another feature which seems to be characteristic of GR (and other highly geometrical gravitation theories) is the prediction of singularities; but observational programs with this focus have not been formulated, in contrast to the fact that singularities have been the focus of much of the best theoretical work in the past dozen years.

General relativity exemplifies not merely a tendency to associate gravity with spacetime geometry, but also a still deeper prejudice to consider gravity as a field, i.e., as a potentiality for a spacetime region to exert physical influences that cannot be assigned to any material substance there, and to serve as a "life-support" vehicle for physical influences long weaned from their progenitors. Only electro-magnetism has been adequately shown by qualitatively convincing evidence to have this field character, in spite of the fact that numerous entities are routinely cast in that mold by theorists. The observation of freely propagating gravitational waves would make gravity a second clear example of a field. This would be comforting empirical support for a broad generalization that now rests too heavily on theorists' inability to imagine any inequivalent way to satisfy the (firmly based) demands of special relativity.

(2) Suppose that GR or some other gravitation theory can be established as competent for descriptions of the solar system, black holes, gravitational waves, and most of cosmology. It would still not be a well-understood theory until its limits of applicability were established. The

limitations of general relativity are frequently considered, and parallel questions inhere in other theories. Empirical guidance on these limits appears distant, but would be momentous if it could be provided. One anticipated limit is quantum gravity. How could one detect a graviton or otherwise demonstrate empirically the need for a quantized gravitational field? Or could the classical gravitational field arise from some very different microstructure, i.e., could we have gravitational waves without having a graviton?

Another possible limit of gravitation theory is posed in cosmology. Will a theory of gravity display the class of all possible universes (as Maxwell's theory describes all possible TV signals): And then is the choice to rest with the astrophysicist, or with the drama critic? A few astrophysical attempts have been made to rationalize the choice of initial conditions, but major progress would probably have an empirical component whose nature cannot even be specified yet.

(3) What natural phenomena require a refined gravitational theory for their description and study? Where should GR (or contraGR) be applied? What facts of nature will gravity theory open to our view? These are the observational questions which would remain even when the theory is no longer in doubt. Thus suppose black holes are certainly allowed by theory. One still must ask whether,

and in what quantities and sizes, the evolving Universe has managed to produce them. Similarly for sources of gravitational waves. Discovering the origins of the Universe will no doubt proceed using gravity theory (with other physics) to the same degree that discovering the structure of the nucleus proceeds using quantum mechanics. At present cosmological nucleosynthesis is the main example of this.

There may even be a relation between local physics and the large scale structure of the Universe. As one example, it has often been suggested that the dimensionless constants in nature are not an accident but rather related in a yet unknown way to the average properties of the Universe. Another example is that small magnitude large angular scale anisotropies in the remarkably uniform cosmic microwave background radiation might relate to local PPN experiments with a potential to detect preferred frame effects.

4. Solar System Measurements of Relativistic Gravitational Effects

The planets, their satellites, artificial spacecraft and the photon are test bodies that probe the gravitational field of the sun under almost controlled conditions. The precision measurement of the motion of these objects is in our opinion still the most profitable method of measuring relativistic gravitational effects. Measurements of orbits is of course an old science having been the cornerstone in developing Newtonian gravitation; however, the new techniques of precision angular and in particular range and rate measurements have added truly a new dimension to solar system astronomy. Position measurements to the inner planets are now made regularly to a few parts in 10^{10} of an astronomical unit, the position of the moon to a few parts in 10^{10} of the earth-moon distance.

a) Planetary Ranging Experiments

Accurate distance measurements from the earth to other planets can be made by several methods. One is to determine the transit time for electromagnetic waves to a transponder aboard a planetary orbiting spacecraft. A second method is planetary radar, where the transit time to the region near the sub-earth point usually is measured. A third approach is to make use of the transponder in a spacecraft which has landed on the planetary surface or of retroreflectors placed on the surface. Fourth, distance measurements can be made to artificial planets in solar orbit, which consist of spacecraft shielded from the perturbing effects of radiation pressure and the solar wind.

The two main limitations in using planetary orbiter data to determine the distance to the planet as a function of time are the basic measurement accuracy for the transit time to the transponder and the problem of finding the orbit of the spacecraft with respect to the planetary center of mass. For the

Mariner 9 Mars orbiter mission the transit time accuracy when Mars was near the sun was limited mainly by uncertainties in the integrated electron density along the signal path. Fluctuations of up to 800 meters due to the solar corona were observed near the sun. A second transponder frequency besides S-band would have increased the accuracy dramatically. Away from the sun the problem of determining the spacecraft orbit may have been the main limitation, although drifts in the transponder time delay due to temperature and signal level changes and to variations in the electrical components also may have affected the results.

Much improved dual-frequency transponders for future missions are now available. The accuracy capability is one meter or better, although some improvements in the ground system and in the antenna calibration are needed to make use of this capability. Future improvements to the 10 cm level are feasible for relatively modest costs and for little increase in spacecraft weight or power. The main constraints on future missions probably will come from the need to minimize perturbations on the spacecraft orbit due to thrust from unbalanced gas jets and to atmospheric drag near periapsis if the periapsis altitude is too low.

For planetary radar the main limitation at present comes from uncertainty in the planetary topography. The basic distance measurement accuracy with the upgraded Arecibo antenna at S-band or Goldstone at X-band is about 10 meters. Large numbers of elevation parameters are solved for in analyzing the data in order to reduce the topographic effects. Another approach is to concentrate the observations at times when a given region is at the sub-earth point. This "closure point" approach may make possible planetary distance measurements which can test gravitational theory at the 10 meter level. The number of opportunities for obtaining such closure points is largest for Mars, next largest for Venus, and smallest for Mercury.

The Viking mission includes S-band transponders on the Mars landers as well as both S-band and X-band capability on the orbiters. In principle the planetary rotation will give two coordinates of the lander with respect to the center of mass from short period range changes and the third coordinate from longer period changes. However, in practice the amount of transponder time for the lander will be small. Also, it is not clear whether the necessary X-band ground equipment to make use of the dual-frequency orbiter capability will be used in tracking the Viking spacecraft. Thus little can be said concerning the probable Mars distance measurement accuracy for the Viking mission.

The examples of landed apparatus which has helped considerably in studying planetary system dynamics are the optical retroreflectors placed on the lunar surface by Apollo and Luna missions and the ALSEP transmitters which are being used in differential VLBI work. Laser distance measurements to the lunar retroreflectors already have given evidence that the equivalence principle holds to 3% or better for the gravitational self-energy of the earth. Accurate information is being obtained on the difference in mean motion between the moon and sun, as well as between the moon and its perigee. The differential VLBI measurements with the ALSEP's are giving accurate ties between the angular position of the moon and extra-galactic radio sources.

An "artificial planet" mission would have the advantage that high eccentricity and accurate tracking could be combined. A preliminary study of such a mission called the Solar Orbiting Relativity Experiment has been carried out by ESRO, but efforts were shifted later to considering a possible Mercury orbiter mission instead. The main limitation for the artificial planet approach is the high mission cost and limited lifetime. With planetary orbit determinations any secular effects continue to build up with time, and the information from earlier missions or measurements can be combined with recent data to improve the accuracy. With a spacecraft in solar orbit the integration time is limited by the lifetime of the system for canceling out non-gravitational orbit perturbations and by the accuracy of that system.

It is important to emphasize that the combination of accurate distance measurements to Mercury, Venus, Mars, and *the Moon over a period of perhaps a decade is likely to give a much stronger check on theory than if each mission or each planet is considered separately. For this reason, we believe that the establishment of a Planetary Dynamics Test Project is highly desirable*. Under this Project the value of obtaining accurate range data on a particular mission or of obtaining improved planetary radar observations would be judged in terms of the resulting increased strength of the entire planetary dynamics data bank for testing gravitational theory. The present strategy where the benefits of improved distance measurement capability are considered primarily in terms of the payoff from the single mission for which a proposal is made demonstrably does not meet this goal. *The charting of the solar system with accuracies as high as a part in 10^{12} in the 1980's is a legacy which NASA can and should leave for future generations*.

Error analysis results available so far include mostly covariance analyses for range data to either Mars or Mercury. The parameters solved for frequently are two of the PPN parameters β and γ, the quadrupole moment J_2 for the sun, the rate of change of the gravitational constant $\dot{G}$, $GM_{\odot}$, and orbital parameters. Improved analyses are needed in which range data to all three of the other inner planets are included, and in which either additional PPN parameters or other "effects" parameters are considered. Also, allowances must be made for possible systematic measurement errors which may vary over times such as planetary orbital periods.

Despite the need for improved error analyses, it already is clear that very substantial improvements in our knowledge of gravitation can come from a comprehensive program of accurate planetary distance measurements. Much better determinations can be made of the time delay for electromagnetic waves passing near the sun, and of possible anisotropy in the time delay. Excellent progress is expected in determining whether the gravitational constant G is changing with time by looking for secular accelerations in planetary motions. Major improvements will be made in determining perihelion and nodal precession rates, short period non-Newtonian orbital terms, possible secular changes in semi-major axes and eccentricities, and deviations from Kepler's third law. The possible breakdown of the equivalence principle for astronomical bodies has been looked for with lunar distance measurements, and even stronger checks can be made with planetary distance measurements.

The related technique of differential VLBI measurements for the ALSEP transmitters on the moon and for planetary probes against distant radio sources also can contribute strongly. The combination of ALSEP differential VLBI results with lunar distance data can give a determination of geodesic precession, although not as accurately as may be possible with superconducting gyroscopes. The combination of differential VLBI results with planetary and lunar distance data permits a valuable check on whether an inertial frame determined by solar system measurements will rotate with respect to extremely distant galaxies.

1) Mercury Orbiter Mission

One special planetary mission which should be strongly considered in NASA's program on experimental relativity and gravitation is a Mercury orbiter. Although the cost of a Mercury orbiter mission with perhaps 30% to 50% of its payload dedicated to gravitational research is large compared with the cost of obtaining accurate dual-frequency tracking data on all other planetary orbiter missions in the next decade or two, the possible benefits also are very high. Such a mission probably would require a dual spacecraft approach, with the experimental relativity spacecraft having higher periapsis altitude, a shorter orbital period, reduced sensitivity to radiation pressure, and a longer mission lifetime than most other planetary missions. The first three requirements are due to the need for extremely accurate orbit determination, and the fourth to the strong improvement in the determination of secular gravitational effects with the length of the data base.

A preliminary study of a Mercury orbiter mission was carried out in 1973 by ESRO. In this study the orbit was assumed to be highly eccentric, with maximum and minimum altitudes of 25,000 km and about 500 km. A subsatellite for improving the orbit knowledge was discussed. A combined payload aimed at both planetary science and relativity was suggested, and the resulting added payload requirements led to the choice of orbit. A limited error analysis gave accuracies of only 1% for β and 0.3% for γ without the use of the subsatellite, but the uncertainty of knowing the spacecraft position with respect to Mercury's center of mass in this study was assumed to be 100 meters.

An additional computer calculation of the information obtainable from Earth-Mercury distance measurements has been carried out recently at JPL using covariance analysis. One range measurement per day with 10 meter accuracy was assumed, and the mission length was taken to be one year. Data within 5° of the Sun were excluded. β, γ, and J_2 for the Sun were estimated, as well as orbit parameters for each planet and one parameter equivalent to $GM_\odot$. The uncertainties in β, γ, and J_2 were 0.007, 0.0009, and 8×10^{-7}. However, a correlation coefficient of 0.97 for β and J_2 indicates that a linear combination of the two parameters is known to about 10 times higher accuracy. Another preliminary study of the Earth-Mercury distance problem done at JILA using a worst case analysis approach supports the JPL results.

It is important to note that the gravitational test sensitivity achievable in a Mercury orbiter mission should scale directly with the range measurement accuracy. It thus is necessary to look at what accuracy can be expected realistically for missions planned during the next few years. The Standard Spacecraft Transponder approach discussed at the First NASA Planetary Spacecraft Radio Science Coordinating Meeting at JPL on January 15, 1975, appears capable of 10 to 20 cm accuracy with reasonable integrating times, provided that substantially higher range code modulation frequencies are used. Additional work is needed on antenna and ground system stability and calibration procedures, but the necessary improvements seem feasible.

The other main limitation is knowledge of the spacecraft orbit around Mercury. Careful studies of the orbit determination problem are needed, but general considerations indicate that a roughly circular orbit with an altitude of perhaps 1000 to 2500 km should be determinable to about 20 cm with accurate tracking data. This expectation is based on comparisons with simulations for the Earth-orbiting Laser Geodetic Satellite (LAGEOS), for which routine orbit determinations at the 2 to 5 cm level are expected. The tracking accuracy and the geometry will be different and the radiation pressure much stronger, but no clear obstacles to achieving the desired accuracy are apparent if a favorable orbit can be obtained. The payload penalty for choosing a circular orbit of 1000 km altitude was quoted in the ESRO study as being about 30%.

In view of the above consideration, it appears that a dual-spacecraft Mercury orbiter mission with a 30 cm accuracy goal for determining the Earth-Mercury distance should be considered by NASA. Scaling from the JPL error analysis, such a mission would give accuracies for β, γ, and J_2 of 2×10^{-4}, 3×10^{-5}, and 3×10^{-8}. Clearly a Mercury orbiter mission with the suggested accuracy would constitute a major jump in our ability to test gravitational theory.

2) Close Solar Probe Mission

An additional type of mission which could play an important role in testing gravitational theory is a close solar probe. It has been suggested recently that a near encounter with Jupiter could be used to place a probe in a near-collision orbit toward the sun. Missions of this kind are being studied by the European Space Agency (ESA) and also by JPL. The problem of keeping the spacecraft temperature low enough to survive, at least until substantially after perihelion, is a serious one. The other main problems are reliable communications close to the sun and the short time available near perihelion for completing the experiments.

One mission studied by ESA had a perihelion distance of $4\ R_{\odot}$ and an over-the-poles trajectory. The probe would have successive heat shields directed toward the sun and a drag-free system or accelerometer for the radial direction to correct for non-gravitational accelerations. The main purposes are solar physics, such as measurements of plasma quantities inside the sonic point in the solar corona. However, a highly accurate measurement of the solar quadrupole moment and improved values for β and γ also could be obtained if accurate tracking is possible. A preliminary covariance study based on 2 mm/sec

Doppler tracking near the sun and one measurement per 100 sec gave accuracies of roughly 10^{-4} for β and γ and a few times 10^{-9} for J_2. The opportunities for gravitational tests in a mission of this kind deserve serious consideration if the tracking problem near the sun and the non-gravitational force problem can be overcome.

The strongest reason for interest in a close solar probe is the opportunity it would offer for measuring the gravitational Red Shift to second order in the solar potential. The first order shift at 4 $R_{\odot}$ is 0.5×10^{-6}, and the second order contribution is 5×10^{-13}. The elapsed time required for the spacecraft to change direction by 180° is 16 hr, and the clock stability required over this time is a few parts in 10^{15}. This is within the range already achieved by hydrogen masers, although the thermal problems would be much more severe for the solar probe. An additional requirement is a communications system capable of reading out the clock time to a few percent of the 14 nanosec time change due to the second order gravitational shift during the 180° direction change near perihelion. This requires the equivalent of a 10 cm or better ranging system. The problem of achieving such high accuracy very near the sun is substantial, and the question of whether a sufficiently accurate clock can be accommodated on a probe aimed mainly at solar problems is an open one. However, the benefits would be very large, since a check on the gravitational Red Shift to second order in the solar potential is regarded by many scientists as one of the most important gravitational measurements which could be done.

b) Deflection of Electromagnetic Waves by the Sun

Measurements of the deflection of electromagnetic waves by the gravitational field of the sun have in the past decade begun to yield precise values of this first order effect of relativistic gravitation. The relativistic bending is given by

$$\Delta\theta = \frac{4Gm_{\odot}}{Rc^2}\left(\frac{1+\gamma}{2}\right) = 1.75'' \frac{R_{\odot}}{R}\left(\frac{1+\gamma}{2}\right)$$

Early attempts at measuring the bending by comparing star fields around the sun during a total eclipse with the same field at night showed that the effect existed qualitatively. The measurements were dominated by systematic errors and plagued by short observation times; between 1919 and 1975 approximately 1/2 hour of observation was accumulated.

Definitive measurements have been made with radio interferometers by tracking the motion of several radio sources as they passed by the sun. The most recent observation by Fomalont and Sramek, using three colinear radio sources and S and X band receivers in a 35 km baseline interferometer, has measured the deflection to a precision of 1%, in agreement with the Einstein value.

Radio deflection observations employing transcontinental baselines (VLBI) have been carried out by Shapiro and Counselman, who have made measurements of the deflection to a few percent;

however, the ultimate accuracy of the VLBI technique has not been achieved. The reasons for this are twofold: first, the increased fringe sensitivity goes hand in hand with an increased sensitivity to phase fluctuations of the incoming radio wave due to atmospheric and coronal index variations, and second, the atmospheric index variations over such large baselines are uncorrelated. The noise results in temporary loss of the fringes. It is hoped that by improving the electronics, in particular the video bandwidths, to permit group delay measurements it will become possible to establish the deflection of light to 0.1% in the next few years.

The fundamental limits in radio VLBI deflection measurements are expected to be atmospheric index fluctuations for sources far from the solar limb and coronal index fluctuations near the limb. The refraction of the solar corona is proportional to λ^2 and can be removed in the steady state by using two radio wavelengths; the fluctuations in the corona, however, cause random phase fluctuations which are not completely correlated for the two wavelengths. A conservative estimate is that these effects will limit ground-based radio deflection measurements to the 0.1% level.

A ground-based optical experiment to observe the motion of stars around the sun in the daytime is being planned by Hill. The optical deflection is far less sensitive to the solar corona; however, atmospheric index fluctuations and more important scattering and flare in the telescope may limit the measurement to the 1% → 0.1% level.

The deflection of light is in one regard the cleanest of the first order effects of relativistic gravitation, as it is self-calibrating and furthermore does not require precision orbital information. Improvements in measurement should therefore directly yield more precise estimates of γ. At some stage, both space radio VLBI systems as well as optical interferometers, possibly on the moon, will be worth considering to gain the next several orders of magnitude in precision of γ.

c) The Gyroscope in Orbit

The late Professor Leonard Schiff, in about 1960, pointed out that, through the study of the pointing of the spin axis of an ultra-high quality gyroscope relative to the fixed stars, phenomena of relativistic origin should be made measurable. The orientation of the gyroscope would reveal changes, relative to the stars, of its local inertial coordinate frame. Two effects are measurable, the geodesic precession which is the gravitational equivalent of the Thomas-Fermi precession and the Lense-Thirring effect, the phenomena that a spinning source of gravitational field tends to drag along the inertial frame.

In principle the gyroscope studied could be on the ground. However, the support needed against gravity makes more difficult the achievement of the necessary freedom from extraneous drift. In free fall in orbit, the design problems are less severe and the higher orbital velocity results in a correspondingly larger rate of geodesic precession, which in Earth orbit would amount to about 7 seconds of arc per year. The Lense-Thirring component that arises from the rate of rotation of the earth, amounts to only 0.046 seconds per year. The eventual possibility of observing this second phenomenon is almost unique to the gyro experiment.

It is worth pointing out that neither of these rates of precession depends upon the spin rate or angular moment of the test gyroscope. Any other method capable of making observable the local inertial frame of the satellite would find these same motions relative to the "fixed stars."

A project to develop hardware possessing the necessary precision to carry out an experiment of this kind has been under way for about 15 years at Stanford University under the guidance of Professor William Fairbank. Among the advances needed in the state of the art were:

1) A gyroscope with an intrinsic drift rate lower by a factor at least 10^6 than that of the best inertial navigational gyroscope previously available.

2) A star telescope that can provide the directional reference to a star within a precision of 10^{-3} seconds of arc, without drift, over a year.

3) A means to sense, without drift and not producing torque reactions, the pointing of the spin axis of the gyroscope, to those same levels of accuracy.

4) Magnetic shielding able to remove extraneous magnetic fields from the environment of the gyroscopes, essentially to the level of the zeroth quantum state, to avoid this source of drift in the gyroscopes and sensors.

5) A servo-system for drag compensation of the satellite to maintain the net acceleration field acting on the gyros below about 10^{-9} g.

6) A Dewar to make practical the operation of the gyros, readout, and telescopes at the temperature of liquid helium for at least a full year, with means to avoid disturbances to the system from shifting center of gravity of the liquid, following the argument that only cryogenic methods can yield the required low system noise and drift.

In the fifteen years of development, much progress has been made by the team at Stanford and their collaborators at the Marshall Space Flight Center and elsewhere. They have developed gyroscopes in the form of 4 cm diameter spheres of fused quartz with a superconducting niobium coating. They are electrostatically supported by an active three-axis servo-system. Changes in pointing of the spin axis are to be read out by SQUID (superconducting quantum interference devices) magnetometers which link the lines of magnetic flux that result from the "London moment" of the spinning superconductor. When spun up in the superconducting state, a net circulating current is produced because the superconducting electrons do not partake in the spin-up directly. The resulting magnetic flux is not large and so exceptional sensitivity to flux changes is required in the sensors to detect reorientations of the axis, at the level of 10^{-3} seconds of arc. The star direction is to be observed and defined with a special split image telescope made entirely of optically contacted fused quartz. This construction and the use of low temperatures are aimed at obtaining the required low drift. Magnetic shielding of the system is to be accomplished by the use of superconducting shields with flux driven out by an ingenious expansion technique. The cryostat is so designed that the shielded gyro-telescope package can be inserted, already cold, into the main Dewar-satellite unit.

The design, as it has progressed so far, shows great ingenuity and sophistication. Nevertheless, many of the required performance levels cannot yet be demonstrated, and perhaps some will not be achievable in a ground environment. The eventual carrying out of this project could be aided in many ways by involvement with the space shuttle program, particularly as a way to make full-fledged tests of several of its components. It rates highly as a project of scientific and technical interest, but it is surely too soon to decide whether or not it should take full form under the present designs.

If and when the project becomes a full-fledged space experiment, the actual measurement must be carried out more than once to gain confidence in the result.

5. Tests of the Principle of Equivalence

The "principle of equivalence" was, for Einstein, a stepping stone that led him to his general theory of relativity from the "special" theory. In common with all other metric theories, the general theory predicts experimental results in agreement with those derived from the principle of equivalence, in particular, the universal proportionality of weight to mass and the gravitational "Red Shift."

a) "Eötvös" Experiments

Experiments to test the universality of the weight-to-mass ratio are known as Eötvös experiments, in recognition of the contribution made by R. von Eötvös in the years between about 1880 and 1920 toward a lowered limit to any departures from proportionality. R. H. Dicke in 1962 set an upper limit of 10^{-11} to the fractional difference of the mass-weight ratios of Al and Au, which Braginski, in the USSR, claims to have lowered to 10^{-12}, both by earthbound experiments.

Dicke's experiment was centered on a suspended platform, carrying carefully matched and balanced masses of differing constitution, able to twist about its suspension. Unless the masses all have a common mass-to-weight ratio, they would, in free fall follow different orbits in circulation about the sun, when given initial conditions of position and velocity. If they are to be restrained to move in fixed relative positions, forces must be supplied to them through the suspension. Such forces, if different for the different masses, in the plane transverse to the suspension, would show up as a torque needed to keep the suspension from twisting, and this would have a twenty-four hour period, as the earth rotates to modulate the components of the orbital velocity lying in that transverse plane. Detection of such a torque requirement would correspond to the determination of a departure from mass-weight proportionality.

An experiment in an Earth orbit could avoid the need for suspension and compare motions primarily determined by the Earth's gravity, about 1500 times stronger here than that of the sun. The period would be shorter by the number of orbits per day, too. Isolation from manmade and geophysical seismic disturbances would be another asset. Several experiments are being designed to attempt to take advantage of these improvements to be gained in orbit. None are very far advanced as yet. One of these, proposed and under study at Stanford University, plans to suspend two concentric cylinders of different materials as magnetically floated superconductors and then to measure the difference between the forces needed to keep them moving in fixed relative positions as they orbit about the Earth. Use of low temperatures sets correspondingly low levels to the inherent background noise (Brownian motion) and creep. A sensitivity to a violation of the mass-weight proportionality 10^3 to 10^5 times smaller than the present test limit is hoped for and the possibility that such a term in the total mass-energy of matter as originates in the weak interaction might be found to contribute a deviation is sometimes mentioned.

This experiment, like the gyroscope, is difficult to develop in the ground environment because of the much different requirements for support against the gravity of the Earth. The space shuttle could provide very useful test facilities for the components of such an experiment. It should be pointed out that, although the satellite environment does seem to offer the use of the field of the Earth as the driving force for the test, there is also a penalty in the sources of systematic error. The gradient of the field of the Earth is about 4×10^7 as large as that of the field of the sun and extraordinary precautions would be required to keep torques and force differences acting on the test objects from that cause from obtruding.

An issue that has received increased attention in the past few years is whether gravitation itself partakes in the universal proportionality of weight to mass. Specifically the question is, does the mass associated with gravitational binding energy have the same ratio of inertial to passive gravitational mass as that attributed to the other interactions in nature. The gravitational binding energy increases as the square of the mass and is appreciable only in large bodies--the sun, planets, and moon.

The LURE experiment has already set a limit of 3% to any violations of the principle of equivalence for gravitation, much improved limits can be set if the planetary dynamics test program is carried out. A specific proposal is to use the Sun, Jupiter, and an inner planet as the interacting bodies.

b) Red Shift Measurements

The other effect associated with the principle of equivalence is the gravitational Red Shift. Ground-based experiments have confirmed this effect to the level of 1% of the predicted value more than ten years ago. Currently investigations are under way toward the design of a ground-based experiment of the same type which may be able to reduce the uncertainty to 10^{-4} or even 10^{-5}. The plan there is to utilize a gamma-ray for which recoil free resonant absorption (Mossbauer effect) occurs but having a slightly better resolution than the ^{57}Fe used before but, more important, a lower energy. The lower energy renders more practical the entrapment of the radiation in a pipe by utilization of total external reflection at the walls at glancing incidence. By such means the vertical path and therefore the fractional shift can be increased with little increase in statistical uncertainty. Active pursuit of this project is attendant on the fabrication of an optimum source-absorber combination as well as development of an economical way to fabricate a light pipe of the required straightness, smoothness, and reflectivity.

A rocket probe carrying a clock in the form of a specially designed hydrogen maser is scheduled for launch by NASA in 1976. This NASA project is based at the Smithsonian Astrophysical Observatory under R. C. Vessot and at the Marshall Space Flight Center. The data from this experiment will be obtained during about 8000 seconds of flight by a radio link from the probe to ground stations. The very large Doppler effect resulting from the changing path length will be removed from the data by subtraction of one-half the frequency shift found in a two-way transponder link to the probe, using frequencies chosen to approximate in their average the ionospheric effects on the clock channel. It is not possible to rely upon the constancy of the maser frequency through the disturbances of the thrust phase of the rocket so the measured clock rates at different parts of the free fall part of the flight only will be compared. The project team estimate that the result will constitute a measurement of the gravitational shift to an uncertainty of 5×10^{-5} of the predicted value. The limits are shared equally by maser instability and phase shifts on the communication link due to ionospheric refraction.

An orbiting clock, particularly one in an eccentric orbit, offers higher accuracy and more redundancy in the measurement. The rocket probe was substituted for an earlier satellite project in the interest of economy. Recently a plan to adapt the Smithsonian maser to an orbiting satellite has been reactivated by Blamont and Israel from France, as a proposed project for the European Launcher Ariane, perhaps in 1980. Although it is clearly a much more expensive project than the rocket probe, the ability to observe the satellite on many successive orbits near perigee and apogee promises a more definitive result, whether the expected or an unexpected value were found. From the repetition of the observations, the proposers estimate the final errors to be ten times smaller than for the single shot probe experiment. An important aspect of the long-lived orbiting vehicle is that the uncertainties associated with the radio communication can be separated from the data by transmitting short timing pulses that represent accumulated time in the orbiting clock.

c) Other Clock Experiments

General relativity supposes that all clocks react in the same manner to changes of gravitational potential and that their relative rates remain constant throughout history, irrespective of the mechanisms on which their rates are based. In contrast, any changes in the relative strengths of the fundamental force laws of physics would show up when clocks depending on different weightings of them are compared. It is now possible to make clocks of sufficient precision to allow some such comparisons, and others, in particular laser clocks, appear to be on the verge of adequate development. The time-keeping of a hydrogen maser involves, to some degree, the strong nuclear force through the dependence on the anomalous part of the proton magnetic moment. An ammonia maser or laser clock, on the other hand, involves primarily the molecular and atomic structure factors, and therefore the electrical force. A quartz oscillator or superconducting cavity clock depends on solid state forces, again electromagnetic. A planet or satellite in orbit depends mainly on the gravitational force.

In the interest of revealing any possible differences, it is valuable to pursue the development of clocks based on the several distinct force laws, even if the best clocks are found to be of a single kind. Were they to be affected differently by, for example, gravitational potential, they might be observed to run differently even in an Earth-bound laboratory, as the Earth moves in an eccentric orbit around the sun. Even further into the future, if the state of clock development has advanced sufficiently, it is worth considering flying several types of clocks in the same spacecraft in a deep eccentric orbit about the sun to search for relative variations in clock rate.

One may, by invoking laws expressing the conservation of energy, demonstrate an interrelation between null results in experiments of the Eötvös type and possible violations of the gravitational Red Shift predicted from the principle of equivalence. If electromagnetic energy were not to react correctly under the principle, then one can argue that that part of the mass of materials that represents electromagnetic energy should violate the mass-weight proportionality, and produce a non-null result in the Eötvös test. This argument is not a compelling one for abandoning Red Shift tests at levels that seem to overlap the Eötvös experiments. Notwithstanding the great power inherent in arguments invoking the conservation of energy, such arguments can in fact be circular because they implicitly invoke a detailed model that does not admit unanticipated effects whereby energy balances can be maintained through other degrees of freedom not envisaged in the calculation.

d) Second Order Red Shift

One goal for the development of clocks of increased precision is the test of the effect of gravitational potential to the second order. Such tests as envisaged now in the maser in orbit around the Earth only hope to measure the effect, itself about 10^{-10} to a fractional precision of about 10^{-5}, still 10^{5} times larger than the second order effect. Even competing metric theories predict different values for the effect of gravity in the second order, and thus such a test can represent an important and worth while challenge. It seems unlikely that extension of the tests to second order will prove feasible without moving them into conditions where the first order effect is much larger than in Earth orbit, for example, in a near solar orbit or in orbit about Mercury. This means that the clocks will be required to perform under severely different environmental conditions. However at 5 solar radii the first order effect is 10^{-7} and therefore a clock with stability of 10^{-16} could be read down to 1% of the second order term. A measurement of the second order Red Shift in a close solar probe mission should be seriously considered.

6. Gravitational Radiation

All relativistic theories of gravitation predict gravitational radiation from dynamically changing systems of masses. The strength of the radiation, although not its polarization states, is theory independent. From dimensional arguments alone and the fact that the lowest order radiation terms can only be quadrupole-like, as there is no evidence for negative mass, the power radiated is approximately given by $P \approx \frac{G}{c^5} m^2 r^4 \omega^6$. m is the mass and r the radius of the moving system, ω the characteristic frequency of oscillation, G the Newtonian gravitational constant, c the velocity of propagation of gravitational waves. Gravitational waves are presumed to travel at the velocity of light, diminish in intensity with the square of the distance from the source, and in general relativity exert tidal or differential forces on matter transverse to their propagation direction. The tidal forces produce strains in free matter given approximately by

$$\frac{\Delta \ell}{\ell} \sim \left(\frac{G}{c^3} \frac{I_g}{\omega^2}\right)^{1/2}$$

where I_g is the intensity of the wave.

The gravitational interaction is the weakest in nature and this is reflected both in small power radiated into as well as miniscule effects produced by gravitational waves. The textbook example of the radiation by a spinning rod serves to illustrate this. A 10-ton rod of length 10 meters spinning at the breaking strength of 10,000 rpm, yields a gravitational strain of the order $\Delta\ell/\ell \sim 10^{-39}$ at a distance 10 wavelengths from the source at twice the rotation frequency of the rod.

At present gravitational wave research using terrestrial sources looks unpromising; the best hope is to detect gravitational radiation from astronomical bodies in fast motion.

Considerable theoretical work has now been done on estimating the intensities and frequency spectra of gravitational radiation incident on the earth from various astrophysical phenomena. Table I gives a sampling.

In the last few years searches for high frequency gravitational radiation using resonant bar antennas have set upper limits of $\Delta\ell/\ell \sim 10^{-17}$ on gravitational wave pulses incident on the earth with Fourier components in the kHz range. No gravitational radiation events have been positively identified. Although resonant bars give little information concerning the pulse shapes, these antennas will continue to be used as detectors in the search for gravitational wave pulses, as they have the useful property of storing the energy excited in the bar for a coherence time which permits integration of the displacement transducer noise. The minimum detectable impulsive strain in bars is given by

$$\left.\frac{\Delta\ell}{\ell}\right|_{\min} \sim \left(\frac{kT}{m}\right)^{1/2} \frac{1}{V_{\text{sound}}} \left(\frac{x^2(f)}{\langle x_{th}^2\rangle} \frac{\omega_o}{Q}\right)^{1/4}$$

k is Boltzmann's constant, T the temperature of the bar and m its mass, V_{sound} is the velocity of sound in the bar, $x^2(f)$ is the spectral density of the displacement transducer noise expressed in equivalent motion of the bar, cm^2/Hz, x_{th}^2 is the average thermal motion in the resonant mode of the bar with frequency ω_o and quality factor Q. In many cases the spectral noise density of the displacement transducer is proportional to

Table I

Source	Frequency Spectrum	In our galaxy $r \sim 10$ kpc		At distance of Virgo cluster $r \sim 10$ Mpc	
		Rate/Yr	$\Delta\ell/\ell$	Rate/Yr	$\Delta\ell/\ell$
Supernova explosions	10 kHz - 1 kHz	$10^{-1} \rightarrow 10^{-2}$	$10^{-17} \rightarrow 10^{-19}$	$10^{3} \rightarrow 10^{2}$	$10^{-20} \rightarrow 10^{-22}$
Pulsars	30 Hz → 1 Hz	Continuous	$< 10^{-24}$		
Formation of or collision of $10^{5} \rightarrow 10^{8}$ $m_{\odot}$ black holes in galactic centers	Periods 2 sec → 10 hours	?	$10^{-14} \rightarrow 10^{-18}$	$? \times 10^{4}$	$10^{-17} \rightarrow 10^{-21}$
Fast stellar binaries	Periods 40 min → 1 day	Continuous	$10^{-20} - 10^{-22}$		

the temperature so that the minimum detectable strain scales as $T^{1/2}/Q^{1/4}$.

In the next few years, the development of metal bars cooled to liquid helium temperature may extend the minimum detectable strain limits to $10^{-18} \rightarrow 10^{-19}$ and the further development of high Q long single crystal sapphire bars at low temperatures may extend the search to levels of $10^{-19} \rightarrow 10^{-20}$. At present, there is no obvious advantage to placing high frequency bars in space.

Ranging between free or almost free (loosely coupled) masses is another method of detecting gravitational waves. The principal feature of such antennas is the long baseline possible when using electromagnetic waves in the ranging. Baselines comparable to the gravitational wavelength or delay times approaching the period of the gravitational wave can be contemplated. If the noise sources in the antenna are independent of the baseline, the antenna strain sensitivity grows linearly with the baseline. Ranging antennas, being broadband, will be able to determine pulse shapes and furthermore may have application in searches for long period gravitational waves, periods of 1 sec to days.

One scheme is to Doppler range to a transponder on a drag-free satellite or a planetary orbiter or lander. The limiting strain sensitivity of Doppler ranging techniques, providing only a single body is being tracked, is given by

$$\frac{\Delta \ell}{\ell} > \frac{1}{\tau^{1/2}} \left(\frac{\pi}{\nu} \frac{\Delta\nu}{\nu} + \frac{kT}{P} \left(\frac{\lambda^2}{d_R d_T} \right)^2 \right)^{1/2}$$

Here $\Delta\nu/\nu$ is the relative frequency width of the local oscillator, assuming Gaussian phase fluctuations (Lorentzian power spectrum), ν the ranging frequency, τ the integration time, k Boltzmann's constant, T the effective noise temperature of the ranging receiver system, P the power transmitted by the transponder, and d_R and d_T the diameters of the receiving and transponder antennas. The first term is due to local oscillator instability, the second to noise in the receiving system. Random accelerations of the spacecraft and phase fluctuations due to the ionosphere and the solar corona have been neglected.

If tracking a single spacecraft, the dominant noise is due to oscillator instability. For example, if one uses X-band ranging and the hydrogen maser ($\Delta\nu/\nu \sim 10^{-15}$), the minimum strain measurable is

$$\frac{\Delta\ell}{\ell} \gtrsim \frac{3 \times 10^{-13}}{\tau^{1/2}}$$

As the frequency stability of the oscillator over the ranging delay time is the important factor--times of the order 10's of minutes for interplanetary distances--superconducting cavity oscillators $\Delta\nu/\nu \sim 10^{-17}$ or better still frequency stabilized lasers may be used. For example, a laser at $\lambda = 5 \times 10^{-5}$ Å frequency stabilized to $\Delta\nu/\nu \sim 10^{-16}$ allows measurement of

$$\frac{\Delta\ell}{\ell} \gtrsim \frac{3 \times 10^{-16}}{\tau^{1/2}}$$

Ranging antennas of this type require oscillator development.

Significant improvements are made if it is possible to track several objects at almost equal distances from the Earth. This arrangement exploits the property that in GR the gravitational wave strains are opposite, in two mutually orthogonal directions--expansion in one direction, contraction in the other. The ability to make differential strain measurements over almost equal-length baselines reduces the sensitivity to oscillator frequency instability by a factor $(\Delta d/d)$. d is the average distance of two spacecraft from the Earth while Δd is the difference in distance.

Another ranging antenna design is a self-contained interferometer. A design that has some promise but must be studied further is a Michelson interferometer mounted on a large frame placed in orbit around the Sun or at one of the stable Earth-Moon Lagrange points. The antenna masses, loosely suspended on the frame by field suspensions, serve as mirror mounts in multi-pass interferometer arms. A symmetric arrangement of interferometer arms placed along the sides of a square frame, each interferometer using adjacent legs, reduces many of the systematic noise terms.

At high frequencies the dominant noise is due to the amplitude shot noise in the detection of the interference fringes, expressed as an equivalent displacement spectral density

$$x^2(f) \sim \frac{e(1-R)^2 hc\lambda}{\pi^2 \epsilon P} \quad \mathrm{cm}^2/\mathrm{Hz}$$

R is the reflectivity of the mirrors, λ the wavelength of the illuminating source with power P, ε the quantum efficiency of the detector. For a 1-watt laser operating at 5000 Å with mirrors of 99.5% reflectivity and silicon photodetectors, $\varepsilon \sim 1/2$, $x^2(f) \sim 1 \times 10^{-32}$ cm^2/Hz. Smaller values are possible at microwave or mm wavelengths as mirror reflectivities can be much larger especially if superconductors are used; however, diffraction as well as long storage times in the interferometer arms may be undesirable.

At low frequencies, a host of noise sources due to stochastic forces are larger than the oscillator amplitude noise; the dominant and also not easily reduced noise appears to be the random forces of cosmic ray protons. An interferometer with 10^6 gm masses would experience a displacement spectral density of

$$x^2(f) \sim \frac{5 \times 10^{-37}}{\omega^4}$$

due to cosmic ray protons. Thermal noise coupled from the frame, suspension servo noise, radiation pressure noise are all smaller. Suspension periods of the order of 80 sec would make the oscillator amplitude noise and the stochastic force noise comparable. The minimum detectable strain is given by

$$\frac{\Delta \ell}{\ell} = \frac{1}{\ell\sqrt{\tau}}\left[\frac{e(1-R)^2 hc\lambda}{\pi^2 \varepsilon P} + \frac{F^2(f)}{m^2\omega^4}\right]^{1/2}$$

The first term is the oscillator amplitude noise, the second term is due to the stochastic forces expressed as a force spectral density $F^2(f)$ dynes^2/Hz, m is the suspended mass, ω the detection frequency, τ the integration time and ℓ the antenna baseline.

A sample calculation for such an antenna indicates that with a 1 km square, it would take about 10 days of integration to measure the estimated gravitational strain of $\Delta\ell/\ell \sim 10^{-21}$ from the fast stellar binary WZ sge at a 40-minute period, 10 days also to establish a $\Delta\ell/\ell \sim 10^{-24}$ limit for the Crab Pulsar NP0532 at 60 Hz. At the frequency of the Crab Pulsar the noise is dominated by the oscillator amplitude noise. The minimum pulse strain of 10^{-3} second duration measurable is $\Delta\ell/\ell \sim 3\times10^{-20}$. The integration times for fixed $\Delta\ell/\ell$ scales inversely as the square of the baseline.

Finally, if the Moon is ever revisited, the deployment of a working lunar gravimeter to measure both lunar tidal strains as well as the possible excitation of the Moon's normal spheroidal modes by low frequency gravitational radiation still seems to be worth while.

7. Search for Highly Condensed Objects--Black Holes

Black holes are expected to show themselves most readily as X-ray sources, but must then be distinguished from other compact objects (white dwarfs, neutron stars) primarily by their larger masses. The X-rays are generated by matter which is heated gravitationally as it accretes toward the collapsed object. A number of X-ray sources seem to fit this accretion disc model, with a normal companion star in a binary system supplying the accreting matter. In one case, Cyg X-1, this explanation of the X-ray emission, involving a black hole of mass near 10 $M_\odot$, seems the most natural interpretation. (More recently a black hole of mass near 10^3 $M_\odot$ in the center of the globular cluster NGC 6624 has been suggested as a possible explanation for short X-ray bursts from 3U1820-30.) X-ray observing programs, current and projected, include the search for black holes among their proper goals. It is particularly useful that the accretion disc models be developed and checked by observation. Current disc models have two components (inner and outer rings) which emit most strongly at different energies, and with different polarizations. Thus the technical requirements of interest for the black hole search include not only pointing accuracy (for optical identifications) but also spectral information, and the measurements of 1% to 3% polarizations. For black holes it is also of interest to verify small scale structure in the accretion discs. Thus time variations as short as 0.5 ms are of interest, and this requires large detector areas. Most of these needs are met by HEAO-A and HEAO-B, but some further development of polarization measures beyond those on OSO-I would be desirable.

Much more speculative is the idea that black holes of smaller masses, above 10^{-5} g, may have been formed in the big bang by the collapse of dense pockets of primordial radiation. Plausible theory suggests that creation of photon (and other particle) pairs spanning the horizons in these black holes would allow all below 10^{15} g to have evaporated by now. Larger masses have lower effective temperatures and thereby lose mass more slowly. Some would be reaching their endpoints now, emitting γ-rays for a short final gasp. Their numbers are limited observationally by the γ-ray spectrum above 120 MeV which does not fit this mechanism. But within this tolerable number one can hypothesize a population which could give bursts of 100 to 1000 MeV γ-rays that would be distinguishable from background γ's by their concentration in time or angle. Either positive or negative observations concerning such hard γ bursts would be very interesting if detector areas from 40 cm^2 up were employed (ref.: Page and Hawking, Caltech preprint OAP-430).

8. Cosmology and Gravitation

In the grandest sense, cosmology is also a study of gravitation as the gravitational field equations relate the spacetime geometry of the universe to the averaged matter density and pressure in the universe. The universe is, however, still so poorly understood that it is unreasonable to expect that observational cosmology will produce evidence favoring any particular theory of gravitation in the near future.

The challenge to observational cosmology is to determine the overall geometry of the universe and to develop a description of cosmic evolution. Pieces of the cosmological puzzle reside in several questions: Is the universe bounded or, asked in a different way, is there sufficient matter to gravitationally bind the universe? Is the universe indeed isotropic and homogeneous on a large scale or is there structure? Was there indeed a primeval explosion? When and how did galaxies form? These are some of the burning issues today.

Observational cosmology will benefit from the space program by at least two different styles of measurements using quite different types of instruments--large telescopes and special purpose small payloads. The ST operating above the atmosphere with a large aperture, high spatial resolution, precision pointing capability, and with spectral coverage from UV to mm waves, will address one class of cosmological problems. With the ST individual stars in galaxies more distant than the local group will become observable and thereby lend a great deal more confidence to the cosmic distance scale. It may also become possible to study the dynamics of nearby clusters of galaxies with sufficient precision to separate the components of the motion due to local gravitational forces from global effects, in an attempt to determine the cosmological spacetime geometry at moderate distances where evolutionary effects may be more easily understood. Clearly a major instrument in space such as the ST will be used to continue the program of Red Shift distance measurements which forms the cornerstone of observational cosmology. It can only be hoped that the improved "seeing" in space will help in unscrambling evolutionary effects. The ST will also enable extended studies of the isotropy of Red Shifts.

UV spectra of stars in other galaxies than our own would give new estimates of the primeval H/D ratio, a fundamental quantity in cosmological models.

This listing is by no means exhaustive but serves to indicate that an instrument such as ST will have profound implications for observational cosmology and indirectly on gravitation.

The absolute spectrum and the angular distribution of the diffuse background over the entire electromagnetic spectrum conveys information of the total energy content of the universe as well as the distribution of matter in the universe. Measurements of the diffuse background require both special purpose instruments and observing strategies to estimate the contribution from local sources. Full sky coverage is essential in all spectral regions.

The mm and sub mm region is of particular importance, as it includes the bulk of the energy in the 3°K cosmic background radiation alleged to be a remnant of the primordial cosmic explosion. Precision measurements of the spectrum require instruments above the Earth's atmosphere with low internal background and high side lobe rejection. Measurements of the large scale angular distribution of 3°K background radiation, made at several wavelengths, may reveal structure in the primeval explosion and should yield the velocity of the Earth relative to the reference frame determined by the expanding universe.

The diffuse background in the 1/2 mm to 1 μ region is not known and can only be determined by observation above the Earth's atmosphere. This spectral region may well be dominated by local sources, particularly radiation from zodiacal and interstellar dust. However, the emission from the earliest galaxy formation must fall in this part of the spectrum.

The search for a diffuse component in the X-ray sky is of importance to cosmology, as it may set limits on the amount of matter stored in the universe in the form of a low temperature plasma.

9. Summary and Recommendations

The space program can play a major role in the experimental study of gravitation and relativity, a fundamental frontier of research in physics, by:

1) Allowing observation of the universe over the entire electromagnetic and particle spectrum.
2) Permitting access to the solar system as a laboratory for the measurement of relativistic gravitational effects.
3) Making available quiet environments in spacecraft of low acceleration to execute delicate laboratory experiments.

Recommended Programs

NASA Planetary Dynamics Project

Precision measurement of the dynamics of the objects in the solar system and observation of the behavior of electromagnetic waves in the gravitational field of the Sun is, in our opinion, the single most important program to advance the understanding of relativistic gravitation. As the natural time scales are of the order of planetary orbital periods, the program by its very nature is a long term effort; no single measurement or unique mission can provide the complete description needed. Precision range, angular, and timing data evolved over a matter of decades will constitute a rich legacy to natural science provided by the space program.

A rational program is multifaceted and should include:

1) Vigorous and continuing support of radar ranging to the planets and the laser lunar ranging experiments.

2) The development of a dual-frequency NASA transponder with 10 cm ranging capability and its utilization on all planetary orbiter and lander missions as well as the upgrading of NASA tracking facilities for dual-frequency reception and transmission.

3) Allocation of enough time and budget for data acquisition to utilize fully ranging data from planetary orbiters and landers even after the prime objectives of the mission in other disciplines have been accomplished.

4) The strong support of data analysis, preferably involving two independent groups.

The above items have a low cost and should be considered as <u>an irreducible minimum program</u>. As this program falls under the purview of several parts of NASA, the Office for Applications of Space Technology, the Office for Data and Tracking, the Planetary Office and the Office for Astronomy and Relativity, a means for coordinating the activities of these offices is needed at a high level in NASA.

A more ambitious program would include, in addition to the foregoing, long-lived orbiter missions to the inner planets. In these missions, relativistic gravitational measurements would play a major role, dictating the choice of orbit and redesign of the orbiter to minimize random acceleration. A particularly attractive mission is a long-lived Mercury orbiter, as such a mission could in several years of observation yield vastly improved measurements of several of the parameters in relativistic theories of gravitation.

A close solar probe, preferably one that circumnavigates the Sun, should be seriously considered. Such a mission would afford substantial improvements in measurements of β and the solar gravitational quadrupole moment. Furthermore, if there is an effective SRT effort in clock development, this mission could also perform a measurement of the gravitational Red Shift to second order.

Supporting Research and Technology (SRT)

The full development of an experimental relativity and gravitation program in space requires, in addition, an expanded effort in supporting research and technology (SRT) to lay the groundwork for future space experiments in this field.

The ongoing effort to design a spaceworthy experiment to determine the geodetic precession and the Lense-Thirring effect by observation of an earth-orbiting gyro should be continued at a viable level but not at the exclusion of the study of other relativity experiments. The gyro experiment is not sufficiently developed at present to be considered in a flight program. If and when ready, several flights will be required to gain confidence in the results.

The feasibility of orbiting Eötvös experiments and large baseline antennas in space in order to search for long period gravitational waves should be studied.

An important technical effort which could be supported by NASA in an expanded SRT budget is the development of more stable frequency standards or clocks for use both in clock comparison experiments, as well as in a measurement of the second order gravitational Red Shift. Along with continued refinement of the hydrogen maser, the new technology of frequency stabilized lasers and superconducting cavity oscillators holds the promise of extending clock stabilities to the 10^{-16} level.