Department of Physics

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Experimental and Theoretical Investigation of Gravitation

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Gravitation physics This research under the leadership of Professor R. H. Dicke is directed primarily to the improvement of the observational basis of relativity. This requires a close interplay between theory and experiment and a substantial part of the research is theoretical. Owing to the great weakness of gravitation, laboratory-bound experiments of the traditional type are virtually useless, astrophysics, geophysics, and space physics being the chief sources of new data. Because of the wide-ranging character of this search for basic information, not infrequently results of more general interest are obtained.

At the end of the academic year, 1965, the research group consisted of 4 professors, Dicke, Goldenberg, Roll and Wilkinson; a research staff member, Peebles; and research associate D. Curott. Some 10 - 12 students, graduate and undergraduate, were associated with the group in some capacity during the past year. Two Ph. D. degrees were granted. The following is a list of papers published or accepted for publication during the academic year 1964-65.

Publications

R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson Cosmic Black-Body Radiation to be published Astrophysical Journal (July, 1965)

R. H. Dicke Icarus and Relativity to be published, Astronomical Journal (1965)

R. H. Dicke The Equivalence of Inertial and Gravitational Mass to be published in the Proceedings of the 2nd Texas Conference on Relativistic Astrophysics

R. H. Dicke and P. J. E. Peebles Gravitation and Space Science to be published Space Science Reviews, (1965)

R. H. Dicke The Secular Acceleration of the Earth's Rotation Chapter in Proceedings of the Conference on the Earth-Moon System, 1964 (to be published)

R. H. Dicke Stellar Evolution with Varying G Chapter in NASA Conference on Stellar Evolution, 1964 (to be published)

R. H. Dicke The Theoretical Significance of Experimental Relativity Gordon and Breach (1965). Reprinted from Relativity, Groups and Topology, C. De Witt et al eds. Gordon and Breach 1964.

C. Callan, R. H. Dicke, and P. J. E. Peebles Cosmology and Newtonian Mechanics Am. J. of Phys. 33, 105 (1965)

R. H. Dicke The Weak and Strong Principles of Equivalence Ann. of Phys. 31, 235 (1965)

P. J. E. Peebles Are the interiors of Jupiter and Saturn hot? Chapter in The Origins and Evolutions of Atmospheres and Oceans, John Wiley and Sons, Inc. (1964)

P. J. E. Peebles The Big Planets Science and Technology 32 (Nov., 1964)

P. J. E. Peebles The Structure and Composition of Jupiter and Saturn, Astrophys. Jour. 140, 328 (1964)

C. T. Murphy and R. H. Dicke The effects of a decreasing gravitational constant in the interior of the earth Proc. of the American Philosophical Society 108, 224 (1964)

Governmental Support The research work of the group is supported by a research grant from the National Science Foundation and by a research contract with the Office of Naval Research of the United States Navy.

The principle research activities of the group during the past year clustered about the following problems:

1) Solar oblateness experiment
2) Solar oblateness theory
3) The earth's rotation
4) Solar eclipses
5) Isostatic rebound
6) Pendulum
7) Hot universe (theory)
8) Helium formations
9) Stability and galaxy formation
10) 3 cm radiometer
11) X-Ray stars
12) Cosmology and infrared from distant galaxies

Most of these are discussed briefly in the following section on:

Principle Results and Future Planning

Solar Oblateness — Goldenberg and Dicke

A slightly oblate sun would imply oblate surfaces of gravitational potential about the sun, in turn affecting the motion of the planet Mercury. This effect is almost indistinguishable from the famous relativistic rotation of the perihelion of Mercury. Until the oblateness is measured with an accuracy better than 1 part in 10^4, the relativistic check (the only potentially accurate check presently available) is uncertain to 20%.

The telescope built specially for the purpose of measuring this oblateness has not yet generated a convincing set of numbers and it is planned to work actively on this problem through the coming summer.

Solar Oblateness Theory   Peebles and Dicke

The solar oblateness experiment is properly accompanied by some theoretical astrophysical considerations. First, assuming that the sun is found to be oblate, what will this imply about the solar interior? Second, are there any theoretical arguments which would tend to rule out the conjecture of an oblate sun?

With regard to the first question, it was originally suggested that a solar oblateness would result if the solar interior were rotating more rapidly than the surface layers. If the inner 2/3 by radius of the sun were rotating with a 36 hour period it would introduce a 10% change in the rate of precession of the perihelion of Mercury. This discrepancy would be of the right magnitude to compensate for the effects of a long range scalar interaction, with $\omega = 4$. The sun could be prolate rather than oblate if there were a very large toroidal magnetic field. This possibility would require a very large, perhaps unreasonably large, toroidal field strength of the order of 10^6 gauss to produce appreciable deformation of the solar surface.

The question of whether the assumed differential rotation would have been preserved over the lifetime of the solar system was investigated in some detail. It was shown by us that the torque arising from this assumed differential rotation due to laminar viscous drag would be very small, amounting to only 10^{30} dyne-cm. It was also shown that this is just the torque exerted on the solar surface due to the expanding solar atmosphere, the solar wind. That is, if all other damping effects in the solar interior could be neglected, it would be concluded that the sun could very well have an appreciable differential rotation, and that the differential rotation in fact would be needed to explain the rotation rate of the solar surface.

Three other damping processes which might introduce additional torques between the solar surface and a faster rotating solar interior were considered by Peebles.

First, any magnetic field threading from the solar interior to the surface could provide very large damping torques. It was shown that if the magnetic torques are to be less than 10^{30} dyne-cm in a differentially rotating sun, the on-axis general magnetic field of the sun must be less than .02 gamma at the pole. The magnetic field strengths observed at the pole are of the order of one gauss, and appear to alternate in sense on alternating sunspot cycles. Thus, the observed fields could only be surface fields, for otherwise they could not change so rapidly, and we have little idea how large the general solar magnetic field might be.

Second, if the differential rotation gave rise to turbulence, it would cause torques much larger than the torque calculated on the simple laminar flow model. However, the region of differential rotation must be below the convective zone, and here, the temperature gradient being less than the adiabatic gradient, horizontal flow tends to be stable. The problem of discussing this stability is complicated by the compressability of the medium. A transformation was found to a simpler, incompressable flow problem, which has already been solved. From this a stability condition was obtained, and it was shown that the assumed differential rotation in the sun should be stable a short distance below the bottom of the convective zone.

Finally, differential solar rotation might give rise to quite appreciable meridional circulation currents, the currents being particularily large in the region where the gradient of the angular velocity of rotation is largest. This could be important as a means for carrying angular momentum from the solar interior to surface, thus increasing the torque required to maintain the differential rotation. The meridional circulation problem was solved on the assumption that the angular velocity of the material within any given shell is a constant, independent of latitude. However, this is an artificial problem because any meridional circulation would cause the angular velocity to vary with latitude. We have not yet solved the more realistic problem in which angular velocity is a function of latitude as well as radius. More work is required before we will know whether the meridional circulation carries appreciable angular momentum.

The present conclusion from this work is that the torque arising from the assumed differential rotation appears to be just enough to balance the torque due to the solar wind. A possible exception is the meridional circulation current, and further work is required on this point.

If the sun is found to be oblate, it will raise a host of new questions about the sun. Assuming the oblateness is due to differential rotation, it would imply that the general on-axis solar magnetic field is extremely small, and we would like to be able to understand how this could be so. Also, further work is required to understand whether differential rotation and the associated meridional circulation currents near the solar surface could give rise to any observable surface phenomona.

<u>The Earth's Rotation</u> Dicke

It is known that the presence of a scalar component in gravitation would imply that there should be a gradually decreasing strength of the gravitational interaction, in turn implying a gradual slowing of planetary motion (compared with the earth's rotation). This is equivalent to a gradual increase of the earth's rotation referred to a planetary time scale. The expected effect is not excessively small. We decided to make a serious attempt to use 3000 years of astronomical data to determine the acceleration of the earth's rotation subtract the tidal slowing effect, and estimate the various geophysical factors affecting the earth's spin. An extended study of this type was carried out during the fall of 1964.

The writer has never encountered a fundamental physical problem drawing from a wider range of disciplines. A knowledge of classical accounts of ancient eclipses is essential for a determination of the acceleration averaged over a long time span. Astronomy, geophysics, and physics, all are involved.

This study exhibited the effect in question but it cannot be ascribed with certainty to the presence of a scalar field. A long chapter for a book on the earth-moon system was written, based on this work.

D. Curott is presently analyzing the accounts of ancient Chinese eclipses in a desperate attempt to improve the observational basis for the determination of the effect of sea-level fluctuation on the earth's rotation.

Solar Eclipses   D. R. Curott

A detailed study of ancient solar eclipses is nearing completion and is expected to yield important consequences for geophysics as well as relativity. Analysis of eclipse records provides the most accurate measure of the average secular deceleration of the earth's rotation. The earth retardation is predominantly tidal in origin but a small acceleration component may be present since the rotation is measured in Ephemeris Time. A decreasing E. T. due to a secular decrease of the gravitational constant is predicted by the Brans-Dicke Relativistic Theory.

Conventional analysis of the ancient records contains large systematic errors which are eliminated in the present re-examination. Additional eclipses from Chinese antiquity have also been researched and included.

Interesting byproducts for the historian are strong conclusions concerning authenticity and chronology of the eclipse records.

Pendulum Experiment D. R. Curott

Construction and instrumentation for a precision pendulum gravimeter was completed and data was obtained and analyzed. The design of this particular instrument was motivated by the need for an improved gravimeter with excellent long term stability and short term precision in order to improve the upper limits upon the intensity of scalar gravitational radiation.

Disturbing mechanical noise from the building substantially reduced the precision from that inherent in the instrument. The characteristics of this device were very encouraging but operation at an isolated site is suggested by these experiences.

Cosmic Black-Body Radiation (Theory) Peebles and Dicke

One of us (R.H.D.) has suggested that the implication of a matter filled universe created de novo some 7×10^9 years ago could be avoided by assuming that the universe is oscillating, periodically passing through a highly contracted state of high temperature. This would have associated with it thermal radiation of the same high temperature. As an effect of the general expansion, this thermal radiation would be cooled until today it might be only a few degrees. It could not readily exceed 40 ^{o}K in temperature of the mean energy density would be too great for the observed maximum space curvature. Peebles has shown with an argument based on helium abundance that, within the framework of General Relativity, and for a matter filled oscillating universe, it should exceed 10 °K. This radiation seems to have now been found at a temperature of 3.5 °K by Penzias and Wilson of the Bell Telephone Laboratories. The low temperature presents a problem but it has been shown that with the Brans-Dicke cosmology the temperature could be substantially lower without violating Peebles helium criterions. The group working on the cosmic black-body radiation problem consists of Peebles, Roll, Wilkinson, and Dicke.

Helium Formation P. J. E. Peebles

Dicke, Peebles, Roll and Wilkinson have suggested that if the universe is evolving, it should have been filled with thermal, black body radiation, the fireball from the big bang. These general considerations say nothing about the present temperature of this radiation. I have been able to place a very useful restriction on the temperature by considering some of the thermonuclear reactions which would have taken place during the big bang. These reactions lead to the formation of helium, and it has been shown that the colder the universe the greater the fraction of hydrogen burned to helium. Thus, from an upper limit on the amount of helium which reasonably could have been produced we have a useful limit on temperature conditions in the universe. Assuming the conventional general relativity theory, the limit is very restrictive. With a radiation temperature of 3 °K the mean density of matter must be a factor of 20 below the estimated density in galaxies.

The work has been completed and submitted for publication to the Physical Review.

Further progress depends on two important questions. First, what is the abundance of helium in the very old stars? Second, what is the mean density of matter in the universe, including matter in galaxies, extragalactic material bound in clusters, and extragalactic material outside clusters? Further theoretical work on this second question is planned.

Stability and Galaxy Formation P. J. E. Peebles

Stability problems arise, in different ways, in two cosmological problems. First, we know that the matter in the universe is concentrated in galaxies, while the galaxies are found in groups, and in clusters containing many hundreds of galaxies, and perhaps also in clusters of clusters. We have shown that this very inhomogeneous distribution of matter very likely resulted from a gravitational instability strongly influenced by the presence of black body radiation.

Second, we know that despite this very inhomogeneous distribution of matter, it appears nevertheless that in the average over sufficiently large distances the universe is strikingly regular, isotropic and homogeneous. These detailed statistical observations extend to a distance of about one quarter of the radius of the visible universe. Now the gravitational instability applies also over these large distances, and the problem here is to understand how the universe could have preserved its regularity in the face of this gravitational instability.

Considerable progress has been made in understanding the first problem, the origin of galaxies and clusters of galaxies. It appears that the black body radiation issuing from the big bang plays a central role in the formation of galaxies. It determines the masses of pregalactic systems formed through a Jeans stability effect. Second, it determines the radii of the system by fixing a critical epoch for the first appearance of gravitationally bound systems. Thus, the fairly uniform nature of the galaxies is made explicable without having to assume very detailed initial conditions on the expanding universe. Reasonable values for the masses and radii of the pregalactic systems are obtained if the present radiation temperature is about 3 °K.

This work has been completed, and submitted for publication in the Astrophysical Journal.

Work is still in progress on the second stability problem, concerning the meaning of large scale regularity of the universe. A few tentative conclusions can be drawn. First, in the case of the large scale structure of the universe, we have shown that radiation does not provide a smoothing effect to counteract the gravitational instability. The observed large scale regularity of the universe could only be due to very regular initial conditions. This raises difficulties with either the big bang or the oscillating universe cosmologies.

It might be that the universe originated at a finite time in the past as the singular infinite density state which appears in the cosmological models. However, unless this universe was quite cold, it appears that thermal fluctuations should have perturbed the system enough to have quite destroyed its regularity by the present epoch. This is unacceptable, for the universe is quite regular, and we believe that it could not have been cold.

This difficulty could be avoided if we were willing to assume that the universe originated as a very regular, finite density state. This is philosophically unappealing, for we would prefer to believe that, if the universe had a beginning, it began with a bang.

The problem of considering the beginning, as a physical process, is avoided if we assume that the universe is oscillating, and always has been oscillating. The difficulty again is with stability. An oscillating universe appears to be unstable. A preliminary analyses of the instabilities and smoothing processes to be found during one cycle, from a highly contracted expanding state to a highly contracted collapsing state, indicates that the net result of the cycle is a growth of the irregularities. However, we do not know how to describe a nonsingular connection between collapsing and expanding phases, and we do not know whether this connection might not entail some additional smoothing.

At present it is an open question whether the universe could be eternal, and oscillating. We feel it is important to devote more work to this problem. The two outstanding questions we would like to resolve are first, the nature of the instabilities in an oscillating universe, and second, the nature of the bounce from collapsing to expanding phases in an oscillating universe.

3 cm Radiometer P. G. Roll and D. T. Wilkinson

Elsewhere in this report are discussed the reasons why one might expect the universe to be filled with black body radiation with a characteristic temperature of a few degrees Kelvin (see R. H. Dicke and P. J. E. Peebles). Since September, 1964 we have been constructing a microwave radiometer which is designed to search for this thermal radiation at a wavelength of 3 centimeters. This radiometer is of the conventional "switched" type in which the input to the receiver is alternately connected to the antenna and to a reference load whose temperature is accurately known. In this way the receiver is periodically (about 400 times a second) calibrated against a known source of radiation.

The experiment differs from conventional radio-astronomical measurements principally in requirement for a precisely-known source for absolute calibration. A few key parts of the instrument are discussed below.

Antenna. The antenna is of a somewhat unconventional horn type. It was fabricated in the Palmer Laboratory machine shop and, in contrast to the large antennas of most radiotelescopes, it can easily be carried by one man. We have added wavetraps and shielding flares to the horn in order to minimize the backlobes of the radiation pattern and, thus, avoid ground radiation. This would be a serious problem at most radiotelescope facilities. Testing of the horn antenna is nearly complete and we now regard this problem as essentially solved.

Plumbing and Switch. Since we are interested in absolute measurements of the incoming radiation, care must be taken to understand the reflection and absorption properties of the waveguide components which channel the radiation into the receiver. Thus, a test bench has been assembled to check each part before it is attached to the radiometer. The switch is a critical component and has been made by modifying a commercially built ferrite Faraday rotation switch in such a way as to give a plane of symmetry through the device.

Reference Source. The reference source consists of an accurately calibrated waveguide attenuator, for inserting a known amount of radiation into the waveguide, and a matched waveguide termination which is cooled to 4.2 ^{o}K with liquid helium. Both of these components have been built and are now under test. Many of the problems encountered here are unique as most radio-telescopes do not measure absolute radiation levels and, therefore, do not need a calibrated laboratory source.

Receiver. The receiver is conventional and has been assembled, for the most part, from commercial components. Lock in techniques are used to separate the signal from the receiver noise at the output. Signals representing a temperature change of 0.1 ^{o}K have been detected in a few minutes against a receiver noise level of about 2000 ^{o}K.

At present we are in the last stage of testing and assembling the parts of the radiometer. We will soon begin preparing our observing site (the roof of Guyot Hall), and hope to be observing by mid-summer.

Cosmology and the Infrared Radiation Background due to Distant Galaxies

P. J. E. Peebles

A possible new cosmological experiment has been considered. It is based on the fact that the light from very distant galaxies is shifted down into the infrared. If the intensity and spectrum of this infrared background could be measured, it would yield important new information on the large scale structure and geometry of the universe, and on the evolution of galaxies. The observation must be carried out above the atmosphere. It was concluded that with available techniques it should be possible to observe with more than adequate accuracy the expected intensity in the range 10 - 25 μ . The background due to stars and zodiacal light should be unimportant at these wavelengths. The preliminary theoretical discussion of this experiment has been completed, and will be submitted for publication.