Editorial note to:

R. H. Dicke, The Theoretical Significance of Experimental Relativity

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Abstract

In the mid-1950s the experimental study of gravity physics was close to inactive. Robert Dicke saw the need and opportunity to employ advances in technology to improve the classical tests and add to them. His book, “The Theoretical Significance of Experimental Relativity,” and the preceding lectures on which it was based, describes how he was going about it in his Gravity Research Group. There was theoretical motivation for some of his experiments. Others followed the experimentalists’ mantra: if an experiment of possible physical interest can be done better, then do it. It was the start of what has grown to be the rich subject of experimental gravity physics.

Keywords Experimental studies of gravity · Eötvös experiment · Classical tests of relativity · Gravitational redshift · Microwave background · Lunar laser ranging

Bob Dicke’s first large project in gravity physics was a repetition of the Eötvös experiment. Dicke admired the precision of Eötvös’s measurements of Earth’s gravitational field, and the test of the gravitational equivalence principle, but Bob had far better tools. Eötvös used a telescope to observe the orientation of his torsion balances. He had to stand back to avoid disturbing the balance, even by the tidal field of his own mass. Dicke’s electronic detection allowed him to seal the balance in a vacuum chamber and place it under ground in a space capped by a thick layer of insulation. Eötvös compared the responses of different test masses to the accelerations of Earth’s gravity and rotation. Dicke looked for the diurnal variation of the torque on the balance if gold and aluminum do not fall toward the Sun at the same

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gravitational acceleration. That synchronous detection eliminated the problem of setting a zero and offered a check: a real signal would follow the Sun. Eötvös could not shield against daily variations in conditions. Dicke had ample isolation.

Dicke's setup for the Eötvös experiment is worth considering. Three test masses, one gold and two aluminum, were suspended from the triangle shown at the top toward the left of Figure 2 in this "Golden Oldie" paper. Use of three masses reduces sensitivity to tidal fields of passing masses. The lens to the right of the triangle, in the "optical lever telescope," brings light passing through a narrow slit to a parallel beam that is reflected by an optical flat on the side of the triangle. The same lens brings the reflected light back to a focus, an image of the slit, at the black dot labeled "oscillating wire." The wire is parallel to the image of the slit. The wire oscillates in the direction normal to the slit. If the reflected beam arrives at the focus slightly off center of the oscillation then more light passes to the photomultiplier as the wire swings to one side than the other. This means the photomultiplier output has a sinusoidal component at the frequency of oscillation of the wire. The "bridge oscillator" to the right in the figure produces a sine wave signal that drives the wire and also goes to the "lock-in amplifier" below it. This amplifier multiplies the photomultiplier output by the sine wave. The "filter circuit" averages the product. That smooths out noise at all frequencies other than the bridge oscillator, leaving a measure of how far the light beam is off center at the wire. The sign depends on the direction the light is off from center. The "drift compensator" to the left in the figure forces this mean signal to zero by adjusting the electrostatic potential difference across the "feedback electrodes" on each side of the gold test mass. That potential difference in this feedback system is Dicke's measure of the torque on the balance.

Dicke announced a two and a half magnitude improvement in precision. Eötvös's experiments were wonderfully carefully done, but I recall Dicke worrying about how far to credit Eötvös's actual sensitivity.

Dicke's graduate student, Jim Brault, used a variant of this elegant feedback method to measure the gravitational redshift of light from the surface of the Sun. Earlier attempts had been frustrated by Doppler distortions of absorption line shapes by motions in the Solar atmosphere. Brault was able to probe the very center of the sodium line that forms well up in a more stable part of the solar atmosphere. He showed that the line shape very near its center is close to symmetric, a good sign that the center is not corrupted by turbulence. Dicke mentions this experiment in "Theoretical Significance ...". I do not know why Dicke showed Brault's result before correction for a known and measured instrumental asymmetry. The corrected measurements in Brault's thesis look much better. Brault's conclusion was that "the ratio of observed red shift to the theoretical value is found to be $1.05 \pm .05$." He did not publish, maybe because Pound and Rebka were already working on a laboratory detection based on the Mössbauer effect. They stated the same precision in their first paper.

A year or so after publication of "Theoretical Significance ..." Dicke's Gravity Research Group members, including Rainer Weiss, a visitor, showed how to improve the sensitivity of Lacoste-type spring gravimeters by the same feedback method that held the Eötvös balance in place. That greatly improved the gravimeter. They took examples to the University of California, San Diego, where they were used to

monitor Earth motions, as in earthquakes. That grew to the present Global Seismographic Network that monitors the effects of storm surges, underground explosions, and the like. Weiss told me that the LIGO detection of gravitational waves “uses many thousands of such feedback systems.”

Dicke’s first use of this lock-in amplifier technique, during war research at the MIT Radiation Laboratory, was in his microwave radiometer. He used the radiometer to measure atmospheric emission and absorption, for development of radar at shorter wavelengths. A decade later, Dicke’s radiometer was used in the Gravity Research Group to search for and then measure the properties of the cosmic microwave background radiation, which proves to be remnant from the early stages of expansion of the universe.

It may come as no surprise that Dicke led the formation of a company, Princeton Applied Research, to produce lock-in amplifiers. I am told they were widely used. But although Dicke’s name is so closely associated with synchronous detection he credited the idea to a 1941 paper by Walter C. Michels and Norma L. Curtis [2]. They in turn credited it to still earlier thinking [1].

I have focused on synchronous detection because it illustrates the ingenuity of what the Gravity Group was doing. Other experiments used other techniques, as reviewed in “Robert Dicke and the Naissance of Experimental Gravity Physics, 1957–1967” [3].

Dicke liked theory, though he tended to laugh at ideas, including some of mine, that have no discernible relevance to experiments. Dicke’s introductory remarks in “Theoretical Significance” and his explanation of the importance of the Eötvös experiment, show a brilliant experimentalist’s thinking about the theoretical meaning of measurements. He liked the question Eddington and Dirac raised in the 1930s: why is gravity so much weaker than electromagnetism? He particularly liked Dirac’s thought that the strength of gravity is so small because it has been decreasing for such a long time. I think this was at least in part because the idea invited so many tests, in the laboratory and in exploration of the evidence to be found in geology and astronomy. The latter range from the historical records of eclipses, which test the theory of the motion of the Moon, to observational consequences of the evolution of the universe, to tests of the idea that local physics is quite unrelated to the rest of the universe. It inspired Dicke’s work to have arrays of optical corner reflectors placed on the Moon. The Lunar Laser Ranging Program still reports bounds on the rate of change of Newton’s gravitational constant. The bounds now are well below what Dirac and Dicke were considering.

Dirac’s and Dicke’s ideas inspired my PhD thesis, on the possibility that the fine-structure constant is decreasing, though more slowly than gravity. I of course looked at empirical tests, mostly from radioactive decay ages based on decay rates that would change if the fine-structure constant changed. I also built a theory that could reconcile this evolution with the constraint from the Eötvös experiment.

In “Theoretical Significance” Dicke reviews thoughts he and I had been exploring about possible violation of Lorentz symmetry. Already in the 1957 Chapel Hill “Conference on The Role of Gravitation in Physics” Dicke mentioned ongoing experiments in his group to test sensitivity of local physics to motion relative to the

universe. His interest in this certainly shows in “Theoretical Significance ...” The search for violation of Lorentz symmetry still fascinates.

Dicke was not alone in using new technology to test old ideas about gravity. Robert Pound used the Mössbauer effect to check the gravitational redshift. Charles Townes used his masers to test Lorentz invariance. But Robert Dicke created a group for the systematic empirical examination of gravity. It led the way to the present rich tradition of experimental gravity physics.

Robert Henry Dicke—a brief biography

By M. A. H. MacCallum

Robert Dicke was born in St. Louis, Missouri, on May 6, 1916. His family soon moved to Washington, D.C., where his father was a patent examiner, and later to Rochester, New York. He took his bachelor’s degree at Princeton University, graduating in 1939, having earlier begun at the University of Rochester in engineering, and his doctorate in nuclear physics at Rochester, completing in 1941. He then became a staff scientist at the MIT Radiation Laboratory, directed by his graduate adviser Lee DuBridge, relinquishing an offer of a faculty post in Rochester.

The MIT laboratory played a key role in the development of radar, and Dicke himself invented a number of devices, the most important probably being the one mentioned above by Jim Peebles and the “Dicke radiometer” used in radio astronomy. He showed his interest in astronomy by using this instrument to detect microwave radiation from the Sun and Moon, and he set an upper bound of 20K on “radiation from cosmic matter at the radiometer wave-lengths.”

In 1946 he joined the faculty at his *alma mater*, Princeton, becoming Cyrus Fogg Brackett professor of physics in 1957, Albert Einstein Professor of Science in 1975 and Emeritus Professor in 1984. He died, in Princeton, on March 4th, 1997.

In his first decade on the Princeton staff he focused on quantum physics, in particular atomic spectroscopy, and formulated a quantum theory of coherent emission of radiation such as is now produced by lasers. One of his 50 or so patents was granted in 1958 for an infrared laser.

His early contributions to experimental gravitation are described above and in the accompanying republished paper, and more extensively in [3]. The thousand-fold improvement in the Eötvös experiment is well known in the relativity community, as are two other works among his 1960s papers.

One of those is the theory of gravity introduced in the paper that appeared as appendix 7 to this Golden Oldie. There are still many papers using [Jordan]–Brans–Dicke theory as an example of an alternative to general relativity, although it would be experimentally viable only if the deviations were very small. The theoretical work stimulated the lunar laser ranging tests of gravity [4], and Dicke’s work on solar oblateness [5], the need for the latter work also featuring in the Golden Oldie.

The other is the interpretation, together with Peebles, Roll and Wilkinson [6], of the excess noise in Bell telephone microwave communications experiments. The

receivers had serendipitously detected radiation from the hot early stages of expansion of the universe. (Dicke et al. were unaware that the possible significance of the Bell experiments had been independently recognized the year before by Doroshkevich and Novikov – see [7] – and had overlooked previous theory papers by Gamow and others). Dicke et al. having heard of the observations of Penzias and Wilson [8], the two papers appeared side by side. Dicke's group members' own experimental results appeared soon afterwards.

Dicke continued to take part in or lead valuable gravity experiments after 1964/1965: an account of these was given by Happer et al. [10].

Among several awards and honours [9, 10], Dicke was awarded the U.S. National Medal of Science in 1970 and the Comstock Prize of the National Academy of Sciences in 1973.

He had married Annie Currie, who had been born in Cumbria in the north of England, in 1942 and they had three children, Nancy, John and James (to whom we are indebted for permission to republish the accompanying paper).

(Note: this biography has been culled from online sources, including Wikipedia, mostly written anonymously, as well as the obituaries by Bruce Partridge [9] and Happer et al [10]. More on his work in areas other than gravity can be found there.)

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