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ROBERT HENRY DICKE
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A Biographical Memoir by

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Bob Dicke

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BOB DICKE CONTRIBUTED to advances in radar, atomic physics, quantum optics, gravity physics, astrophysics, and cosmology. The unifying theme was his application of powerful and scrupulously controlled experimental methods to issues that really matter. Though Bob sometimes had to hide his amusement at theorists he found poorly grounded in phenomenology, he did not hesitate to speculate where the experimental ground is thin; the condition was that there had to be the possibility of a measurement that could teach us something new. He wrote:

> I have long believed that an experimentalist should not be unduly inhibited by theoretical untidiness. If he insists on having every last theoretical T crossed before he starts his research the chances are that he will never do a significant experiment. And the more significant and fundamental the experiment the more theoretical uncertainty may be tolerated. By contrast, the more important and difficult the experiment the more that experimental care is warranted. There is no point in attempting a half-hearted experiment with an inadequate apparatus.[1]

Bob held some 50 patents, from clothes dryers to lasers. He recognized that two mirrors make a more effective laser than the traditional closed cavity of microwave technology. In the company Princeton Applied Research he and his students packaged his advances in phase-sensitive detection in the now-ubiquitous "lock-in amplifier." With its successors this probably has contributed as much to experimental Ph.D. theses as any device of the last generation. Bob predicted and experimentally showed that collisions that restrict the long-range motions of radiating atoms in a gas can suppress Doppler broadening. The physics is the same as that of Mössbauer narrowing of gamma-ray lines; it is used in the atomic clocks of the Global Positioning System. He contributed to the concept of adaptive optics in astronomy. He was among the first to recognize that the accepted gravity theory, general relativity, could and should be subject to more thorough tests. His series of gravity experiments mark the beginning of the present rich network of tests. He set forth the idea[2] of the anthropic principle that now plays a large part in speculation on what our universe was doing before it was expanding. Bob's visualization of an oscillating universe stimulated the discovery of the cosmic microwave background, the most direct evidence that our universe really did expand from a dense state. A key instrument in measurements of this fossil of the Big Bang is the microwave radiometer he invented.

Bob left us a challenge: discover whether or how laboratory physics is related to the universe at large. At the turn of the century Ernst Mach argued for such a relation, that distant matter determines local inertial frames. Mach's principle led Einstein to general relativity. In this theory the mass distribution does influence inertial motion, but it has no effect on local laboratory measurements. Bob felt Mach's principle likely expresses more than this, and he and Carl Brans[3] gave an example, a generalization of general relativity in which the expansion of the universe causes the strength of the gravitational interaction to decrease. Experimental advances in gravity physics ruled out their approach, but the theory reappears in superstring models. And we are left to wonder what to make of Bob's belief: "the laboratory, Earth and Solar System could not be isolated even in principle from the rest of the universe."[1]

PERSONAL HISTORY

Bob recalled his early life as follows:

> I was born in St. Louis, Missouri, in 1916, but my earliest recollections are of Washington, D.C., where my father worked for the U.S. Patent Office as a patent examiner. Later, when my father became a patent attorney for the General Railway Signal Corp., we moved to Rochester, New York. It was there, at an age of 5, that I had my first contact with the fascination of science. An old spectacle lens fell into my possession and I was both fascinated and puzzled by its behavior. Later my childhood scientific interests ran the usual course—mechanical gadgets, insect collecting, electricity, chemistry via a "chemistry set", microscopy via an inexpensive Sears microscope, astronomy—and I read everything scientific I could get my hands on.[1]

Bob entered the University of Rochester intending to major in engineering, it not having occurred to him that he might make a living as a physicist. He credits Lee A. DuBridge with attracting him to physics and Frederic Seitz at Rochester and E. U. Compton at Princeton University for brokering his transfer there as a junior. While at Princeton he published his first research paper, on a dynamical model of a globular star cluster as an ideal gas sphere.

Bob returned to the University of Rochester for graduate work in nuclear physics. There he courted Annie Currie; they were married in Rochester on June 6, 1942. Bob completed research for his Ph.D. degree at the University of Rochester in the spring of 1941. His topic, which he had selected, was one of the first experimental studies of inelastic scattering of protons. He recalled that "Professor DuBridge offered me a position as instructor in the department for the following fall (at the impressive salary of $1,800.00 for the academic year). I was happy to accept, but I didn't have a chance to serve. War rumblings were growing louder and Professor DuBridge had left to establish the Radiation Laboratory at MIT to develop microwave radar. A few months later he asked me to join the laboratory as soon as I could get my thesis finished. I arrived at MIT in September of 1941."[1]

A year later Annie joined Bob in Cambridge. She was not supposed to know about his classified research. Her first hint came from Bob's cousin Tom Kuenning, a pilot in the antisubmarine campaign off the New England coast. A storm during patrol forced Tom to land away from his base and, since the crew had no money, they had to stay with friends; Tom stayed with the Dickes in Cambridge. Over breakfast Tom remarked on the marvelous effect of the radar sets from the Radiation Laboratory.

The Radiation Laboratory also produced a brilliant crop of physicists, Bob notable among them for his imaginative and subtly effective approach to physics. Among the results was his microwave radiometer, which he took to Florida to demonstrate that humid air radiates strongly near 1-cm wavelength, and hence that humid air is a strong absorber at that wavelength. At the time this limited the push to shorter wavelength radar for better resolution. Bob found time for a little pure science, using his radiometer to measure the surface temperature of the moon and to show that the space between the stars could not be warmer than 20 degrees above absolute zero.[4]

After the war Bob returned to the Department of Physics at Princeton University. He brought his 1.25-cm radiometer, but he recalls that "as a very junior member of the physics department, I considered it rash to start doing astronomical research, and I could not develop any interest in the astronomy department. I realized only later that the physics department was tolerant and that it would have been proud to have the first radio astronomy in the country."[1] Instead of radio astronomy Bob spent the next decade on the rich physics of the quantum mechanical interaction of radiation and matter. The book on quantum mechanics by him and his former student James P. Wittke was published in 1960.[5] It was used in many graduate courses, and, we suspect, was consulted by a lot more teachers of quantum mechanics.

Beginning in 1955, Bob turned to gravity physics in a series of elegant and searching experiments and theoretical analyses that set the stage for today's active research community. Two of the authors (PJEP as a student and DTW as a postdoc) remember when his Gravity Group met on Friday evenings; we complained but attended because the physics was too fascinating to miss. He probably knew we called ourselves "Dicke birds"—it fit his quiet good humor, which kept us from taking ourselves too seriously, while always remembering that we had better take the physics very seriously.

Bob was among the most imaginative of physicists. One sensed this in personal interactions, by his close attention, and support for work on anything of substance in biology, geology, astronomy, physics, or any of the other sciences. Discussions with Bob tended to leave one feeling that science is a wonderful adventure that one could join.

Bob Dicke was elected to the National Academy of Sciences in 1967. Among his many prizes and awards were the National Medal of Science (1971), the Comstock Prize of the National Academy of Sciences (1973), and the NASA Medal for Exceptional Scientific Achievement (1973). He was a member of the National Science Board from 1970 to 1976. Bob was appointed to the Princeton University Department of Physics in 1946, served as chair from 1967 to 1970, moved to emeritus in 1984, and kept active in research until prevented by physical problems, including Parkinson's disease. He and Annie loved and supported each other, and Bob followed developments in science until his last moments. He is survived by Annie and their children: Nancy Dicke Rapoport, John Robert Dicke, and James Howard Dicke.

PROFESSIONAL HISTORY

At the Radiation Laboratory Bob was assigned to the Fundamental Developments Group under Harvard's Ed Purcell. As one of the young stars of the Radiation Laboratory, he invented chirped radar, coherent pulse radar, and monopulse radar, all of which came into widespread use after the end of World War II. He also invented the magic tee microwave junction and the microwave radiometer, devices at the heart of radio telescopes. The flavor of Dicke's elegant contributions to microwave radar comes through clearly in *Principles of Microwave Circuits*,[6] one of the classic volumes of the Radiation Laboratory Series. Characteristically, Bob was the first to make systematic and potent use of symmetry principles and scattering matrix ideas from nuclear physics to analyze waveguide junctions and other microwave devices.

Back at Princeton after the war Bob used the microwave skills he had acquired at the Radiation Laboratory to make fundamental measurements in physics. With excellent taste, he started to measure the fine structure of the $n = 2$ level of hydrogen, but on learning that Willis Lamb was already working hard on that problem with the resources of the Columbia Radiation Laboratory, Bob turned to other challenges. Unswayed by careless assumptions of others that because the g-value of free electrons could not be measured in an atomic beam machine there was some fundamental reason the g-value could not be measured at all, Bob began to generate free electrons by photoionization of sodium atoms with circularly polarized light. Unaware of Kastler's work in Paris, Bob and his student Bruce Hawkins[7] carried out one of the first optical pumping experiments—on a beam of sodium atoms.

Bob understood how important narrow spectral linewidths are to precision spectroscopic measurements. He soon realized that gas-phase collisions, often a source of line broadening, could be an advantage in the right circumstances, since sufficiently rapid randomization of the thermal velocity vector would eliminate the Doppler broadening of the line.[8] Bob and his students showed that this collisional narrowing is particularly effective for the 0-0 "clock" transitions of hydrogen and the alkali-metal atoms.[9] Further development of these ideas by Tom Carver and others led to fabulously stable atomic clocks. Bob wondered about applications of these narrowing ideas to other spectral regions, but it remained for R. Mössbauer to show that at sufficiently low temperatures the Doppler broadening of certain gamma-ray lines could be eliminated by the same physics.

Fascinated by coherent microwave radiation from pulse-excited ammonia molecules, Bob conceived of the phenomenon of superradiance, where properly phased atomic systems can radiate with great intensity in narrow pencil-shaped beams.[10] Characteristically, Bob made the concept of superradiance clear to a large audience with apt and quantitative analogies to the high-gain antennas he understood so well from his work at the Radiation Laboratory. Many years later a beautiful series of experiments in the infrared by Mike Feld and colleagues[11] at MIT confirmed the striking properties of superradiant systems that Bob had foreseen.

During sabbatical leave at Harvard in 1954-55 Bob turned to the experimental and theoretical basis for gravity physics. At the time the Eötvös experiment showed that test bodies of different composition have the same gravitational acceleration to a few parts in 10^{9}. That was a guide to Einstein's general relativity: A gravitational acceleration may be transformed away by going to an accelerating coordinate frame. There were three tests of Einstein's theory. First, it agreed with the measured rate of advance of the orbit of the planet Mercury, 42.56 ± 0.94 arc seconds per century faster than Newtonian theory.[12] This was an impressive success, but Bob was to emphasize that it depended on the mass model for the Sun. Second, the relativistic deflection of light by a mass concentration is twice the Newtonian value. The deflection of starlight by the Sun arguably was detected and consistent with relativity; the accuracy was at best 10%. Third, in a static mass distribution the fractional shift of the wavelength of light is proportional to the gravitational potential difference through which the light moves. The redshift was detected in spectral lines from surfaces of white dwarf stars, consistent with the theory to perhaps 30%.[13] The contrast to the present range and precision of the experimental basis for gravity physics is striking.

Among his gravity experiments Bob was most proud of the modern Eötvös experiment and the solar oblateness measurement as a probe of the solar interior. The Eötvös experiment monitored the difference of gravitational accelerations of test masses in a torsion balance. The balance is triangular, to suppress tidal torques, with two aluminum weights and one gold. The orientation of the balance is measured by a light beam reflected by an optical flat to intersect a wire vibrating at 3,000 Hz. A servo system electrostatically torques the balance to null the fundamental period in the light passing the wire. A difference of gravitational accelerations of aluminum and gold toward the Sun would cause the feedback voltage to the electrodes to vary with the orientation of the balance relative to the Sun. This elegant experiment showed the fractional difference of gravitational accelerations of aluminum and gold is $(1.3 \pm 1.0) \times 10^{-11}$, an improvement of two orders of magnitude. It is no slight to Eötvös's magnificent achievement to say the modern error budget is more reliable.

The oblateness experiment is another memorable example of effective design of an experiment to test a bold hypothesis, that the test of general relativity theory from the rate of precession of the perihelion of the orbit of the planet Mercury may be compromised by the departure from a spherical mass distribution in the Sun.[14] This would be reflected in the shape of the solar surface. By the time of the first oblateness measurements the experimental tests of gravity theories were much improved, in large measure because of Bob's work and example, and they favored general relativity (as they still do). But it was characteristic that, having set out to make this important test, Bob pushed it to the limit for a ground-based observation. With his former students Jeffrey R. Kuhn and Kenneth G. Libbrecht the experiment was improved and moved from Princeton to Mount Wilson (above Pasadena). Observations there suggested the oblateness varies from year to year.[15] Now, measurements from the Solar and Heliospheric Observatory satellite, above the blurring of the atmosphere, show the oblateness is close to what would be expected from the mean rotation of the solar surface,[16] indicating the departure from a spherical mass distribution is not a serious factor in the precession of Mercury's perihelion. Bob's former colleagues Henry Hill, Kuhn, and Libbrecht are among those who have established that the solar interior indeed is a dynamic system but not in the way Bob imagined.

While Bob was involved in the demanding Eötvös and oblateness experiments he and his students were producing many other tests of gravity physics. Here are examples with dates of Ph.D. awards. James W. Brault (1962) showed that the gravitational redshift of the solar spectrum is 1.05 ± 0.05 times the predicted value. The Doppler shifts that compromised previous measurements were suppressed by the use of a strong line that originates high in the atmosphere. Kenneth C. Turner (1962) improved the Kennedy-Thorndike bound on the variation of an oscillator frequency with velocity relative to a preferred frame, perhaps one defined by distant matter. The fractional difference of frequencies of two oscillators with relative velocity $\delta\mathbf{u}$ that are otherwise identical may be expressed as $\delta f / f = 2\mathbf{u} \bullet \delta\mathbf{u} / c^2$, where $\mathbf{u}$ is the velocity relative to the preferred frame. The Kennedy-Thorndike bound[17] is $u = 10 \pm 10$ km s^{-1}. The Mössbauer effect with the gamma-ray source and absorber on opposite sides of a centrifuge gave $u < 900$ cm s^{-1}. James E. Faller (1963) obtained an absolute measurement of the local acceleration of gravity, to an accuracy of 7 parts in 10^7, by using one element of an optical interferometer as the freely falling object. Lloyd Kreuzer (1966) tested the universality of the ratio r of active to passive gravitational masses for a solid floating in a liquid. At neutral buoyancy the passive mass distribution is independent of the position of the solid in the liquid. If the ratio r were different in the solid and liquid the gravitational field produced by the active mass distribution would depend on the position of the solid. Kreutzer's limit (for Teflon floating in a mixture of methyl bromide and trichloroethelene) is $|r_1 - r_2| < 4 \times 10^{-5}$ at 68% confidence. With the discovery of the thermal background radiation it became of great interest to improve the measurements of the helium abundance, to compare to the predicted production in the early universe. The helium abundance in a star affects its luminosity for given mass; the mass measurement requires improved orbital elements in older binary stars, which are likely to have closer to primeval abundances. Work on improving measurements of the angular separations of close binary stars commenced with David R. Curott (1965) and Dennis J. Hegyi (1968), and concluded with William Wickes's (1972) interferometer, which is capable of measuring separations as small as 0.2" with experimental error of about 0.008".

Bob's largest experimental collaboration grew in part from his remark (and later independently that of Kenneth L. Nordtvedt) that, if the strength of the gravitational interaction were a function of position, the gravitational acceleration of a body massive enough to have a significant gravitational self-energy would differ from that of a nearly massless test particle. Nordtvedt[18] analyzed the effect in an extension of the parameterized formulation of metric gravity theory. In 1960 Bob with William F. Hoffman and Robert Krotkov showed that an optical corner reflector offers a good way to get precision distances to an artificial satellite. In 1969, at the first moon landing, the astronauts set out a rack of 100 corner reflectors designed to reflect a pulsed laser beam from Earth. The time delay gives a precision distance that can be used to test the Nordtvedt effect, among other uses. The results, under the early leadership of Bob's former student Carroll Alley, now significantly restrict the spatial variation of the gravitational interaction.

Bob's role in the discovery of the thermal background radiation is legendary, and legends tend to beguile even those personally involved. Bob wrote[1]:

> There is one unfortunate and embarrassing aspect of our work on the fireball radiation. We failed to make an adequate literature search and missed the more important papers of Gamow, Alpher, and Herman. I must take the major blame for this, for the others in our group were too young to know these old papers. In ancient times I had heard Gamow talk at Princeton, but I had remembered his model universe as cold and initially filled only with neutrons.

Many have wondered how Bob could have forgotten Gamow's work. The last sentence in this quote agrees with all we know: Memory can fail. For example, when work began at Princeton on a Dicke radiometer to search for thermal cosmic radiation we had to remind Bob that he had measured a significant bound on its temperature two decades earlier. In the second sentence of this quote Bob may be referring to an unpublished paper by one of us on light element production in a hot Big Bang cosmology, written before we knew Gamow already had worked out the key physics. Our paper[19] interpreting the radiation as a fossil of the Big Bang referred to the "$\alpha\beta\gamma$" paper. This was inappropriate; Gamow had not yet taken account of the effect of the mass density in thermal radiation on the rate of expansion of the universe through the epoch of light element production. We also referred to a later paper by Alpher, Follin, and Herman[20] that gives a close to modern treatment of the centrally important evolution of the neutron-proton ratio and notes that the predicted hydrogen-to-helium ratio is in the range 1:7 to 1:10 by number, in line with astronomical data. This certainly was one of the most important of the earlier papers. We did miss the most important of all, by Gamow,[21] which set forth the now standard picture for light element production. By 1971 we had the story straight.[22]

Bob arrived at the idea of a hot Big Bang by considering element destruction rather than formation. He favored an oscillating universe as a way to understand what the universe was doing before it was expanding. There has to be a provision for removal of stars and the heavy elements they produce from the last cycle. Bob noted that, if the bounce were deep enough to blueshift starlight from the last cycle to above MeV energies, the radiation would thermalize and could evaporate stars and heavy elements. He persuaded

P. G. Roll and one of us (DTW) to build a Dicke radiometer to look for the thermalized starlight, which would be adiabatically cooled by a large factor since elimination of the heavy elements. News of this experiment led Arno A. Penzias and Robert W. Wilson to realize that the excess noise temperature in a radio telescope at the Bell Laboratories might be extraterrestrial. And cosmology dramatically advanced.

WE ARE DEEPLY GRATEFUL to Annie Dicke for her guidance to Bob's early life in science and society.

NOTES

1. R. H. Dicke. A scientific autobiography. Unpublished manuscript on file in the Membership Office of the National Academy of Sciences, 1975.

2. R. H. Dicke. Dirac's cosmology and Mach's principle. *Nature* 192(1961):440-41.

3. C. Brans and R. H. Dicke. Mach's principle and a relativistic theory of gravitation. *Phys. Rev.* 124(1961):925-35.

4. R. H. Dicke, R. Beringer, R. L. Kyhl, and A. B. Vane. Atmospheric absorption measurements with a microwave radiometer. *Phys. Rev.* 70(1946):340-48.

5. R. H. Dicke and J. P. Wittke. *Introduction to Quantum Mechanics.* Reading, Mass.: Addison-Wesley, 1960.

6. C. G. Montgomery, R. H. Dicke and E. M. Purcell. *Principles of Microwave Circuits.* Massachusetts Institute of Technology Radiation Laboratory Series, vol. 8. Lexington, Mass.: Boston Technical Publishers, 1964.

7. W. B. Hawkins and R. H. Dicke. The polarization of sodium atoms. *Phys. Rev.* 91(1953):1008-1009.

8. R. H. Dicke. The effect of collisions upon the Doppler widths of spectral lines. *Phys. Rev.* 89(1953):472-73.

9. J. P. Wittke and R. H. Dicke. Redetermination of the hyperfine splitting in the ground state of atomic hydrogen. *Phys. Rev.* 96(1954):530-31.

10. R. H. Dicke. Coherence in spontaneous radiation processes. *Phys. Rev.* 93(1954):99-110.

11. N. Skribanowitz, I. P. Herman, J. C. MacGillivray, and M. S.

Feld. Observation of Dicke superradiance in optically pumped HF gas. *Phys. Rev. Lett.* 30(1973):309-12.

12. G. M. Clemence. The relativity effect in planetary orbits. *Rev. Mod. Phys.* 19(1947):361-64.

13. D. M. Popper. Red shift in the spectrum of 40 Eridani B. *Astrophys. J.* 120(1954):316-21.

14. R. H. Dicke. The Sun's rotation and relativity. *Nature* 202(1964):432-35.

15. R. H. Dicke, J. R. Kuhn, and K. G. Libbrecht. Is the solar oblateness variable? Measurements of 1985. *Astrophys. J.* 318(1987):451-58.

16. J. R. Kuhn, R. I. Bush, X. Scheick, and P. Scherrer. The Sun's shape and brightness. *Nature* 392(1998):155-57.

17. R. J. Kennedy and E. M. Thorndike. Experimental establishment of the relativity of time. *Phys. Rev.* 42(1932):400-418.

18. K. Nordtvedt. Equivalence principle for massive bodies. I. Phenomenology. II. Theory. *Phys. Rev.* 169(1968):1014-25.

19. R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson. Cosmic blackbody radiation. *Astrophys. J.* 142(1965):414-19.

20. R. A. Alpher, J. W. Follin, and R. C. Herman. Physical conditions in the initial stages of the expanding universe. *Phys. Rev.* 92(1953):1347-61.

21. G. Gamow. The origin of the elements and the separation of galaxies. *Phys. Rev.* 74(1948):505-506.

22. P. J. E. Peebles. *Physical Cosmology*, pp. 125-29, 240-42. Princeton, N.J.: Princeton University Press, 1971.

SELECTED BIBLIOGRAPHY

1946

The measurement of thermal radiation at microwave frequencies. *Rev. Sci. Instrum.* 17:268-75.

With R. Beringer. Microwave radiation from the Sun and Moon. *Astrophys. J.* 103:375-76.

1953

The effect of collisions upon the Doppler width of spectral lines. *Phys. Rev.* 89:472-73.

With W. B. Hawkins. The polarization of sodium atoms. *Phys. Rev.* 91:1008-1009.

1954

Coherence in spontaneous radiation processes. *Phys. Rev.* 93:99-110.

1960

With W. F. Hoffman and R. Krotkov. Precision optical tracking of artificial satellites. *IRE Trans. Mil. Electron.* MIL-4:28-37.

1961

Dirac's cosmology and Mach's principle. *Nature* 192:440-41.

With C. Brans. Mach's principle and a relativistic theory of gravitation. *Phys. Rev.* 124:925-35.

1962

With P. J. E. Peebles. Cosmology and the radioactive decay ages of terrestrial rocks and meteorites. *Phys. Rev.* 128:2006-2011.

1964

With P. G. Roll and R. Krotkov. The equivalence of active and passive gravitational mass. *Ann. Phys.* 26:442-517.

1965

With P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson. Cosmic blackbody radiation. *Astrophys. J.* 142:414-19.

1968

Scatter-hole cameras for X rays and gamma rays. *Astrophys. J.* 153:L101-L106.

1974

With H. M. Goldenberg. The oblateness of the Sun. *Astrophys. J.* 27(supple.):131-82.

1975

Phase-contrast detection of telescope seeing errors and their correction. *Astrophys. J.* 198:605-15.

1976

With J. G. Williams et al. New test of the equivalence principle from lunar laser ranging. *Phys. Rev. Lett.* 36:551-54.

1979

With P. J. E. Peebles. The Big Bang cosmology—Enigmas and nostrums. In *General Relativity, an Einstein Centenary Survey*, eds. S. W. Hawking and W. Israel, pp. 504-17. Cambridge: Cambridge University Press.

1987

With J. R. Kuhn and K. G. Libbrecht. Is the solar oblateness variable? Measurements of 1985. *Astrophys. J.* 318:451-58.