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ROBERT B. LEIGHTON

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A Biographical Memoir by

JESSE L. GREENSTEIN

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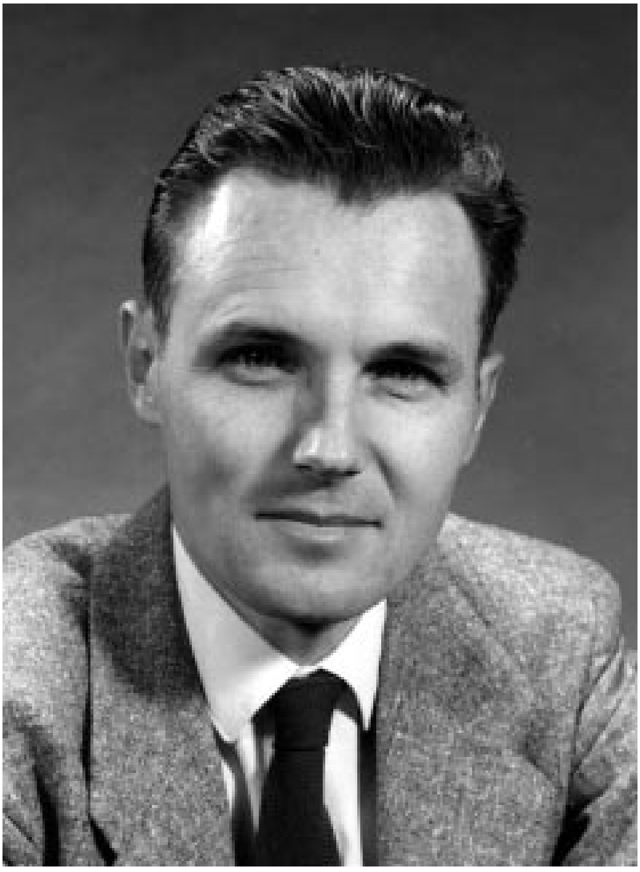

Photo by Harvey, Pasadena, California

R B Leighton

ROBERT B. LEIGHTON

September 10, 1919–March 9, 1997

BY JESSE L. GREENSTEIN

ROBERT B. LEIGHTON, William L. Valentine professor of physics emeritus at the California Institute of Technology, was a remarkably ingenious physicist and astrophysicist. He found no instrumentation problem too difficult, especially if it might open a new part of the electromagnetic spectrum to observation. If he found an inexpensive solution, he would build the apparatus in his spare time, for use by others and by himself.

Bob Leighton built, improved, and used cloud chambers to identify and measure new products of cosmic ray collisions. He explored the decay modes of mu-mesons and recognized several of the "strange" particles when particle physics was at its beginning. His subject matter evolved from physics to astrophysics as he helped astronomy take on its modern shape. Leighton worked in solar astronomy, improving old instruments on Mount Wilson. With them he discovered the five-minute body oscillation of the Sun by superposing two Doppler photographs of the same area taken in rapid succession, one a negative and one a positive of the other. In a similar way he studied the Sun's magnetic fields, using the difference in Zeeman shifts between photographs taken with opposite senses of polarization.

To discover sources of infrared radiation (a moribund subject) distant from Earth, he built an automated telescope with a 62-inch epoxy mirror. That survey discovered thousands of cool stars and cold dust clouds. He became part of the first team to observe the surfaces of planets from space, using low bit-rate television. Near the end of his career he designed and built inexpensive 10-meter radio telescopes of the highest quality for work at submillimeter wavelengths. His goal was always to look and to understand.

Leighton was an excellent teacher, his textbook *Principles of Modern Physics* (1959) being a longtime favorite undergraduate text. He was at the center of the recording, transcribing, and editing of the *Feynman Lectures on Physics* (1963-65), which represented three years of introductory physics as taught in Richard Feynman's unique sense of the word "introductory." Leighton wrote the final draft of the published text. Leighton had an American do-it-yourself personality, which worked successfully at the far edge of scientific difficulty. His career was spent entirely at Caltech, and he became one of its ornaments. An outstanding physicist, engineer, inventor, and builder, he carried with him a nineteenth-century independence and originality. But he was also a twentieth-century astrophysicist, who opened new regions of the electromagnetic spectrum. He retired from teaching in 1985 and from research in 1990. He died in a sanitarium after five and a half years of a slow neurological illness.

YOUTH

Leighton was born in Detroit, where his father made precision dies for an automobile company. After moving to Seattle the family broke up, and his father returned to Detroit. His mother moved to downtown Los Angeles, where she became the breadwinner, eventually as a chambermaid in a Los Angeles hotel. Leighton's childhood is defined by his hardworking mother and by experiments with an electric train, erector set, and clocks. His mother brought him up carefully, supplied him with mechanical toys, and most importantly, backed his education. He remembered studying the motor and drive gears of a merry-go-round. He took trains and clocks apart and discovered how a left- and a right-handed screw differed. His mother remarked that a clock he had disassembled needed to be reassembled, which he did.

At eight, Leighton won a movie-theater game involving Baby Ruth and Abba Zabba candy bars, reasoning that the smaller bars should (and did) contain the prize-winning red ribbons. He fondly remembered the schoolteacher at Starr-King elementary school, who gave him an informal intelligence test that permitted him to skip third grade. He rode his bicycle to Los Angeles junior high schools, some of which have since vanished under freeways. At Berendo High School, which still survives, he did well in science, algebra, mechanical drawings, and shop, but poorly in music and Latin. He corrected each deficiency by purchasing used texts for study, an early example of the self-education that was to become a defining personal characteristic. When asked to teach an unfamiliar course, he bought and studied related texts, worked problems, and prepared lecture notes.

As a child, he skated from school across Los Angeles to its public library, where he read mathematics and astronomy. In an interview[1] he referred to the library as "the Los Angeles Public Library, God bless them."[2] A new world of science and technology was opened at "that great high school," the John H. Francis Polytechnic in central Los Angeles. There he learned practical and theoretical electrical engineering in a laboratory full of steam engines, motors, and generators. While its chemistry was unsurpassed, the physics of pulleys and strings failed to inspire him.

In 1932 Leighton bought a five-dollar telescope to study the Moon, Jupiter and its satellites, star clusters, and an occultation of Venus. He met George H. Herbig, who would become a leading astronomer at the Lick Observatory. Herbig was active in amateur astronomy and instilled in Leighton an interest in instrument building. How did these budding astronomers observe the wonders of the sky near the central city? Poly was excellent, and in fact, an American Chemical Society contest there proved decisive. Charles Wilts,[3] Leighton, and another Poly student won one-year scholarships to their choice of colleges. Because the Great Depression had made the scholarship unusable, Leighton's mother urged him not to work for money, but to register for another high school year. He began independent study of a book called *Practical Calculus for Home Study* and mastered the calculus. After taking a course in photography, Leighton visited Carl D. Anderson at Caltech to take a picture for the Poly student newspaper. Anderson showed Leighton his cloud-chamber laboratory and the room in which the 200-inch mirror was being polished and tested.[4] Leighton registered at Los Angeles City College in engineering, where he found good and tough instruction—and more mathematics. In his second LACC year, he found the "new" atomic physics exciting. Encouraged by his instructor Ralph Winger, he took the transfer examination and entered Caltech as a junior in 1939. His fifty-eight-year career was spent at Caltech, and he was happy to be nowhere else.

THE CALIFORNIA INSTITUTE OF TECHNOLOGY

Caltech was a remarkable place, and some of its most remarkable instructors at that time were William V. Houston (soon to be president of Rice College), William H.

Pickering (Jet Propulsion Laboratory), Frederick C. Lindvall (engineer), and Paul S. Epstein (quantum mechanics theorist), Carl D. Anderson (Nobel laureate), and William R. Smythe. Smythe[5] gave the difficult course on classical electricity and magnetism, while Epstein taught theoretical thermodynamics. Every student who hoped for graduate school had to pass an oral exam on all such courses. Leighton "slogged through" Smythe's senior electromagnetism course, getting C, B, and A in successive terms. The undergraduate curriculum emphasized the solution of difficult problems, which students had to turn in weekly. It required that students learn all the physics and applied mathematics, which they might never use. For Leighton it supplied basic familiarity with all of physics, much of which he did use, especially in the design of new instruments.

Leighton lived at home as an undergraduate, helping support his mother and himself. Partly because of work habits from youth, he admitted to remaining somewhat nonsocial most of his life. He worked hard on the high-voltage transformer and on Kellogg Laboratory's electrostatic generator, both generating high-energy X rays. For a Los Angeles doctor he built a small electrostatic generator to treat cancer. With World War II, Caltech faculty and students joined the military effort, designing and manufacturing rockets and rocket launchers. Leighton found new ways of being original, creating rocket launchers for navy aircraft and an air-to-ground missile to attack German V-1 sites. His friend Charles Wilts devised an elegant retrofiring-rocket antisubmarine technique. The faculty machined cordite and ballistite, filled metal casings, inserted shaped-charge detonators, and test fired rockets. Rockets went into massive production in Pasadena and at the Jet Propulsion Laboratory, and thousands of tons of explosives were trucked safely through city streets. The principal investigator was Dean Earnest C. Watson, who carried the heavy administrative load, and William A. Fowler was the executive.

The war essentially stopped graduate education, but Leighton finished research for his Ph.D. in 1947 after his thesis advisor W. V. Houston had left for Rice. The thesis, completed under Epstein, concerned the specific heat of face-centered cubic crystals. After a good deal of mathematical theory, he needed to perform certain integrations; he built and weighed a three-dimensional model of the functions required by the crystal's geometry. His thesis constituted a significant advance and was published in *Physical Review*. It taught him that he was not a theoretical physicist. "The way I solved the theoretical problem was to go into the shop and build something concrete." After acquiring knowledge of a new field from the course on nuclear physics of Fowler, Leighton included his elegant lecture notes in his own later text *Principles of Modern Physics*. He and Fowler formed an enduring friendship, as he did with Tommy Lauritsen. Leighton's second marriage was to Lauritsen's widow. His daily life included talking physics at picnic-style lunches, parties for his students, and viewing stars and planets through his homemade telescope.

PHYSICS WITH ANDERSON

Leighton received offers from Rice University and Ramo-Wooldridge, but he stayed at Caltech. There Carl Anderson invited him to join the cosmic-ray cloud-chamber laboratory, where the effects of nuclear collisions were being studied. The numbers, N(E), of cosmic rays from space (largely protons) having energies, E, above a hundred MeV obey the power law, log N(E) proportional to $-\Gamma$ x log E (with $\Gamma \approx 2.7$). In the 1940s particle accelerators provided collisions up to only a few MeV. Anderson used a cloud chamber, evacuated except for some vaporizable liquid, within a magnetic field. When a cosmic ray arrived, it might interact with a particle in the cloud chamber and the external counters would trigger expansion. The vapor condensed on the tracks, forming droplets with varying density; the tracks thus visualized were photographed. From the curvature and length of the tracks, the direction of spiraling and the thickness of droplets, the charge, energy, and mass of the incident, and emergent particles were all computable. Neutrinos left no track, but they were identifiable by the imbalance of the energy equations. Banks of Geiger counters with progressively more complex coincidence and anti-coincidence circuits above and below the chamber resulted in only complete events being photographed. Records by the thousands were searched for unexpected particles, and one could only wait for an extremely energetic cosmic ray to collide. J. J. Thomson discovered the electron in 1897, and Anderson found its anti-particle, the positron, in 1932. Chadwick discovered neutrons in 1932 and antineutrons in 1955. Most anti-particles were found when the Berkeley bevatron started to operate. The particle zoo was also being filled by events in cloud chambers.

Leighton's first success in Anderson's laboratory was the decay mode of the mu-meson.[6] In 1935 Yukawa suggested that nuclear forces resulted from nucleons exchanging mesons. Anderson and Neddermeyer had found a particle of intermediate mass (near 200 MeV) common in cosmic-ray collisions and called it the mesotron, or mu-meson (shortened to muon). The muon provided Leighton with a hunting ground in the cloud chambers, which he steadily improved. The muon lived only a short time in the chamber; it emitted an electron having energy over a considerable range, as occurred in beta-decays. Two invisible partners[7] were needed to balance the energy equation, which were neutrinos sharing the energy lost by the electron. The Caltech group studied 134 such events occurring completely within the chamber, where previous experimenters had seen only a few. Their muon unfortunately proved not to be the particle of Yukawa's theory, but Leighton explored its properties thoroughly. Having the intermediate mass (106 MeV) and either a negative or positive electron charge, it ultimately produced a neutrino, an anti-neutrino, a positron, and an electron. The meson's life of 2×10^{-6} sec gave it a long range (because it interacted only weakly with matter) and made it the most common cosmic-ray secondary. In 1947 they explored the pi-meson, which has a single electron's (plus or minus) charge and a mass of 140 MeV.

Two odd tracks from high-energy cosmic rays in cloud chambers had been ascribed to V-particles and were classified as hooks and forks at Manchester University. The Caltech cloud chamber studies of many higher energy cosmic rays yielded similar complex events; some are illustrated in Leighton's textbook. He recognized the decay modes[8] and computed the masses, lifetimes, and energies of such strange particles, or hyperons (1950). Among these were k-mesons and lambda, theta, and xi particles, some with masses exceeding a thousand electrons. Most exciting were those with masses of 2,600 electrons, exceeding that of the proton! None of these experiments, which occupied Leighton for seven years, were costly. They required larger chambers and more complex shielding by anti-coincidence circuits, and improved detectors. One waited patiently for important events to occur, and the nature of the power law dictated when high-energy cosmic-ray events arrived. Leighton built a chamber that ran unattended for days on mile-high Mount Wilson and ultimately provided two dozen hooks and forks identifiable by their decay modes, charge, and mass. Leighton and collaborators determined the natures of such strange particles, at times in consultation with theorist Robert Christy.

Thus were the inhabitants of the particle zoo first recognized.

Leighton designed and built the first cloud chamber, suspended from a free-flying balloon at high altitudes, where there were fewer cosmic-ray secondaries. But by 1955 Berkeley physicists had powerful accelerators, which also made pi's, mesons, and hyperons. The race for strange events was won by the machines, although they could not match the 10^{19} or 10^{20} eV particles found (although rarely) among the cosmic rays. His collaborators began to work with big machines, while E. G. Cowan continued to look in vain for the fractionally charged particles, or quarks. Leighton finished his work on cosmic rays with study of the xi's decay into a neutral lambda—a meson—and then into a proton and another meson. The particles and anti-particles observed in cloud or bubble chambers, photographic emulsions, and scintillators are classified as either baryons (heavy), mesons (mid-weight), or leptons (light). Their strong and weak interactions were put into systematized form by the theoretical work of M. Gell-Mann and R. Feynman in 1958. Thus, particle physics has depended both on laboratory discoveries and on their theoretical analysis.

THE SUN

Leighton was an individualist who was quite unwilling to join the large teams on accelerators. From childhood on, his work kept leading him into completely new directions, the first being the revival of solar astronomy. In 1906 George Ellery Hale started astronomical observations on Mount Wilson and built ever more powerful instruments to observe the Sun. At 5,000 feet above Pasadena, the mountain proved useful for both solar and stellar observations. Good seeing, which meant that the atmosphere was stable against convection, lasted much of the night and persisted after dawn, when the sunlit mountain began to heat the atmosphere. Hale's discoveries included the magnetic fields in sunspots and the systematic changes in their field strength and polarity. He found the chromosphere, a hot, ever changing, emission line region, and invented the Zeeman analyzer and the spectroheliograph. During Hale's long illness (he died in 1938), solar work declined to the daily routine of mapping sunspots and taking spectroheliograms in H-alpha and calcium K to study the chromosphere. Leighton was a friend of the stellar spectroscopist Olin C. Wilson and the two scientists who later became directors, Ira Bowen and Horace Babcock. While working on Mount Wilson on cosmic-ray physics, Leighton began observations with the 60-inch reflector, for which he built an automatic guider with dynamic stabilization. He obtained excellent pictures of Mars and Jupiter, but in his oral interview[1] he felt these pictures "a little tainted . . . but it was fun to do because I had the technical problem of how to hold the image steady because that was the thing you needed to make progress."

In 1956 Leighton applied a new technique on the 60-foot solar tower, adapted from an idea of Fritz Zwicky, a physicist turned astronomer—the use of differential photography. Take two matched photographs of a galaxy, one through a blue filter and one through a red filter. Then carefully superpose the positive of one picture on the negative of the other. If the photographic processes were fully linear and the exposures well balanced, the regions of average color in the galaxy would cancel out and appear neutral gray. But a highly colored blue region could show up as light and red regions as dark in the composite photograph. Although differential photography was non-linear and its processing nonobjective, it gave a quick, rough photometric and colorimetric map of the region. A similar idea is now based on modern electronics and uses a solid-state, charge-coupled silicon device that is linear. Two exposures in two differing fluxes, a readout and rapid subtraction follow. Or a long exposure of an object may be followed by one of equal length on nearby blank sky. Subtraction corrects for pixel-by-pixel sensitivity variations. The picture chip, which now often contains 2048x2048 pixels, may be exposed in two or more colors, and is linear over a large range of fluxes.

Leighton's experiments on the Sun were strongly supported by Ira Bowen, former Caltech physics professor and then director of the combined Mount Wilson and Palomar observatories. During 1957-59 Leighton altered Hale's spectroheliograph to produce simultaneous two-dimensional photographs of the solar surface in an absorption line and then correlate brightness and radial velocity on Doppler shifted pictures. An alternate procedure involved two photographs through a Zeeman analyzer, in an absorption line whose Zeeman components were shifted in wavelength by magnetic field, thus correlating magnetic field and brightness in each picture element. His experiments produced the first significant advances in solar physics since Hale. Leighton improved the 60-foot solar tower and, based on its output, physics graduate students Robert Noyes and Alan Title went on to successful careers in solar astronomy. Seeing within our atmosphere limits the smallest picture element resolvable on the Sun and, if the early morning seeing is at best one arc second, that cell is 750 kilometers.

Absorption lines are produced in a reversing layer at lower temperature than where the continuum is formed. Moving outwards, a low-density region is found in the chromosphere, reaching 35,000°K and producing emission lines. Solar activity is best observed in such emission and is driven by gases with moving magnetic fields driven from below. A long-slit, high-resolution spectrogram covers many picture elements simultaneously, making absorption lines wiggle.

Doppler velocities on the Sun's surface differ between adjacent rising and falling cells by a few km/sec. The same area photographed a few minutes later has lines with apparently uncorrelated wiggles. Granulation (the pattern of varying brightness) has bright, hot parts that are born, rise, cool, and die after a few minutes. Between the granules cooler falling darker material is found. But Leighton was the first to recognize that the spatial and velocity patterns of granules recurred at identical spots on the surface. They repeated in patterns surviving many such five-minute cycles as did magnetic fields. The five-minute surface oscillations merely followed periodic oscillations driven from deep in the interior. Leighton[1] told his student Bob Noyes, "I know what you're going to study for your thesis. The Sun is an oscillator with a period of 300 seconds." Later observations in emission lines revealed another organization on a much larger scale, convection cells accompanied by horizontal streaming like those in a boiling pot. This unexpected pattern, now called supergranulation, was confirmed by Martin Schwarzschild of Princeton, who used a balloon to lift a telescope above the terrestrial bad seeing. Leighton's discovery of both large and small periodic patterns on the Sun marked the birth of the two subjects, helioseismology and astroseismology. Observations around the world now provide solar brightness data continuously. The thousands of such periodicities observed result from deep oscillations at almost all possible periods and help determine the density, temperature, and composition of the Sun.

A limit to the study of such time-variable phenomena was bad seeing starting soon after sunrise. Leighton led a site survey supported by a small National Science Foundation grant. The best location discovered, in 1960, was the north shore of nearby Big Bear Lake. The water surface extending north-south did not overheat after sunrise, so the beam of sunlight remained undisturbed. When my own Caltech astronomy group entered on the study of the Sun in 1963, Harold Zirin was appointed from the University of Colorado. Zirin established Big Bear Solar Observatory just as Leighton's interests were changing. His last paper on the Sun, "A Magneto-Kinematic Model of the Solar Atmosphere," gave a partial explanation in 1968 of some of the long-term cycles of magnetic phenomena that Hale had found fifty years earlier. Rapid advances in data gathering came with the solar telescope at Big Bear, which from the beginning was designed for the new sophisticated electronic, solid-state instruments. With long-lasting good seeing they measured, subtracted, and recorded multiple pairs of both velocity and Zeeman images,[9] photographing granules, prominences, and flares. The telescope was in the forefront of observational solar astronomy for thirty years.

STUDIES OF THE INFRARED AND THE PLANETS

Leighton's interest in broadening the spectral regions used by astrophysicists concentrated in the early 1960s on the infrared. While a few celestial sources had previously been found to emit thermal radiation between 1 and 3 micron wavelengths, few of them seemed cool enough to justify attempts to observe their further infrared. Leighton started infrared work on with Gerry Neugebauer,[10] a new assistant professor of physics. There had been no theoretical preduction of success. They merely decided to find "what was out there" by a surveying the entire accessible sky in the infrared. The survey required a large mirror in a short-focus telescope. Fortunately, new infrared detectors had been developed for military uses (in heat-seeking missiles) and were available for scientific use. The whole-sky infrared survey required that it be an automatic one. Nearby Mount Wilson had suitable altitude, and Los Angeles produced little infrared contamination. Planetary wizard, Gerald Kuiper, had already demonstrated that large parabolic mirrors of epoxy resin could be made by spin-casting. Leighton slowly and smoothly rotated a tub of liquid epoxy mixture, at a speed such that its upper surface formed the paraboloid of revolution of the required focal length. As the epoxy reacted, it congealed into the smooth 62-inch-diameter paraboloid required. Its surface was accurace enough to produce a useful small image. Leighton designed, helped cut, and form the metal parts for the mounting in the physics shop. He helped build the mountain shelter, with roll-off roof, that was erected by the young members of the new infrared community.[11] Telescope and sky emitted thermal radiation at room-temperature. The telescope vibrated twenty times per second, so as to "chop" alternately between the sky plus object (i.e., signal plus noise) and nearby blank sky (noise). This greatly reduced the effect of the thermal background. The differences in infrared and photoelectric signals were synchronously recorded on a chart drive, together with the positions of the object.

The goal had been to find "what was out there." The automated survey from 1965 to 1968 detected 20,000 sources and published results for one-third.[12] Each source was measured three times by a detector covering from 1 to 3 microns that was peaked at 2.2 microns. In addition to the thousands of cool red M giants so identified, many extraordinarily cool dust nebulae were discovered. The first was NML Cygni, a newly formed, high-luminosity star immersed in an opaque envelope of gas and dust from which it was still contracting. The nuclear radiation absorbed is re-emitted in the far infrared, with energy distribution characteristic of the dust's low temperature. Neugebauer[12] says, "The very first night . . . we detected the reddest, most extreme source that we found in the three years of surveying. It was typical of Bob's good luck—good luck he worked hard to have." Many cool dying stars ejected their own shells, which acted as infrared converters. The Orion emission-line nebula contained young stars being born. A new universe of important objects was thus opened for study with large telescopes, including the Palomar 200-inch. Later, the helium-cooled Infrared Astronomy Satellite (of which Neugebauer was the leader) further widened the study of the very coolest of sources. A most important Infrared Astronomy Satellite (IRAS) discovery were the high-luminosity infrared galaxies, whose very bright nuclei had remained shrouded in dust envelopes from which they formed. These re-radiated most strongly at 60-100 microns. Infrared IRAS galaxies and quasars include some with the largest cosmological red shifts presently known. The 62-inch telescope is at the Smithsonian Institution's National Air and Space Museum in Washington, D.C.

With Gerry Neugebauer and his planetary science collaborators Bruce Murray and Robert P. Sharp, Leighton entered the space age with a vengeance. *Mariner IV* was going to Mars, and in timely fashion the group made the successful proposal to add TV imaging. The experiment, built by the Jet Propulsion Laboratory, was lightweight, but its telemetry was seriously limited by the low rate at which information could be transmitted to Earth. Twenty-one TV frames were taken rapidly on closest approach to Mars, stored on tape, and transmitted at a few bits per second to Earth, later in flight. A first major discovery was that Mars resembled the moon in having impact craters, once having suffered violent bombardment. A thin Martian atmosphere had sporadic dust storms. The surface features showed mostly low contrast. The atmosphere was largely CO_2 at a density one-tenth the one previously estimated by earthbound observers. From the vapor pressure and temperature, Leighton found that Martian polar caps must be frozen CO_2 at 150°K and not water ice. He remained associated with the TV photography from *Mariner VI* and *Mariner VII* and from the *Viking* lander. Each view of Mars, in fact, displayed a quite different landscape, one that was either featureless, or chaotic, volcanic, or had impact craters. Long deep gullies remained from what resembled ancient flows of what may have been water, water now apparently absent. The planet's surface has had a long and complex history.

FURTHER CHANGES

In the late 1960s there were changes in the courses Leighton taught and in the new devices he built. His main teaching remained the required undergraduate course in relativity, quantum mechanics, and atomic and nuclear physics. For it he wrote an excellent text entitled *Principles of Modern Physics* (1959). However, the legendary Dick Feynman became the center of a large new teaching project. Pressure from Matthew Sands (an accelerator designer) on both Feynman and Leighton resulted in Feynman's series of unusual undergraduate lectures. While possibly at too high a level for freshmen, Dick's lectures pleased the faculty, many of whom attended regularly. Feynman thought profoundly about the subject matter of his lectures, viewing each as if it were a new discovery needing to be examined from different viewpoints. Leighton attended and taped the lectures from 1963 to 1965. The tapes were transcribed and edited, leading to publication of the three-volume series *The Feynman Lectures on Physics* (in 1965). Leighton said that Feynman was "possibly the one person in the world who knew more about how everything in the universe worked than anyone else on Earth at that moment." Leighton and Feynman were close personal friends, enjoying talk about physics; Leighton's son Ralph entertained them musically and later became

Feynman's musical and book-writing companion. Neugebauer says, "He provided inspiration for people at Caltech, ranging from undergrads to senior faculty . . . A whole crop of people at Caltech got their beginning with Bob, or carried out projects that Bob thought of, or thought would be good to do." Leighton served as division chairman (1970-75) following Robert F. Bacher and Carl D. Anderson in that post.

Leighton's thoughts were about how to build an infrared mirror twice as large. But doubling an epoxy mirror's diameter was dismissed as impractical, if it was to work in the near infrared. What, instead, about the structure that was needed to support a large mirror from behind? Large, rigid, lightweight three-dimensional structures were being used by radio astronomers partly because their longer wavelengths demanded only looser tolerances on surface accuracy. The surface precision needed could be attained. Using the computer language FORTH and only a modest computer, Leighton carefully designed the components of a three-dimensional, rear-mounting structure made of posts, tubes, and joints. Three posts met at each joint; posts were fabricated in only a few standard lengths that could be manufactured with high accuracy. The stresses expected under gravity predicted an acceptable surface accuracy. At wavelengths of a millimeter to a few centimeters, molecular lines of interstellar gas (including isotopes) had been discovered, using small dishes. Observation at submillimeter wavelengths with large dishes and interferometry at millimeter waves became Leighton's two new goals. A practical aperture was 10 meters (six times the size of his infrared telescope). This would increase both the signal strength and the angular resolution. An aluminum-honeycomb, parabolic front surface of mesh floated on the newly designed lightweight, three-dimensional support structure and was driven in altitude and azimuth to follow objects in the sky.

With Caltech's own funds Leighton built a prototype 10-meter dish in the cavernous shop where the 200-inch mirror had been ground and polished, and where the billion-volt electron synchrotron had later operated. The dish became in 1975 the first submillimeter-wavelength dish for what was to become the six-element interferometer at Owens Valley Radio Observatory. The interferometer observations resolved structural detail in the distribution of molecular gas and dust clouds in our galaxy, and in peculiar active external galaxies. The molecular lines present gave information on the compositions, on the chemical processes in interstellar matter, and on radial velocities. Modern low-noise receivers were then incorporated as the dishes were improved. A four-element interferometer, started in 1979, eventually became the present six-element Owens Valley Radio Observatory interferometer, which was renamed[13] in honor of Bob Leighton in 1997. The best of the dishes, a single well-instrumented 10-meter, federally funded dish, was erected on Mauna Kea in Hawaii. Its 4,000-meter altitude reduces both absorption and the thermal emission of the residual atmosphere; its 84 fine-mesh panels have a surface accuracy such that the dish is usable down to a wavelength of 350 microns. The Mauna Kea 10-meter telescope, in fact, nearly overlaps the wavelengths seen from space with the IRAS helium-cooled telescope. Leighton collaborated with radio astronomers and graduate students in their large teams. A few joint publications are found among the last references. Uniquely interesting were studies of CO, both locally in gas clouds and in remote extra-galactic nebulae.

Why did he concentrate so much on pioneering instrumentation? Some of this interest must refer back to his stimulating education in engineering at public schools like Berendo and John H. Francis Polytechnic high schools and Los Angeles City College. It is encouraging to realize how a poor boy could, at one time in our city's life, obtain superb skills in an urban environment. In one of his taped[1] interviews he recalls his father's boast about the accuracy of factory dies he made for Detroit automobile manufacturers, four inches in diameter and their surfaces smooth to 0.0003 inch. Leighton then further recalled with pride his own 400-inch-diameter dishes, accurate to 0.0001 or 0.0002 inch in pointable structures floating on an air-film bearing. He said, "Without any instruction from him, I must have had it in my genes. He, no doubt, endowed me with the right DNA to have the interest. It's all part of a pattern. . . ." It had proved a most successful pattern for Leighton's life work. He combined affection for physics with a love of nature. He was a natural catalyst, mentor, and teacher. His telescopes were unique. A self-made man, he was interested in putting old instruments to new uses, in finding "what was out there."

Among his honors was staff membership in the Mount Wilson and Palomar (later the Hale) observatories from 1963, and the Owens Valley Radio Observatory (1976-1985), as well as the chairmanship of the Division of Physics, Mathematics, and Astronomy of the California Institute of Technology from 1970 to 1975. He was a member of the American Physical Society, American Astronomical Society, American Association of Physics Teachers, National Academy of Sciences (where he was a member of the Space Science Board and received the Watson Medal in 1988), and a fellow of the American Academy of Arts and Sciences (from which he received the Rumford premium in 1986). He received the Space Science Award from the American Institute of Aeronautics and Astronautics for the *Mariner* television experiments in 1967 and the NASA Exceptional Scientific Achievement Medal in 1971. The six-component millimeter-wave radio telescopes at the Owens Valley Radio

Observatory, used together as an interferometer, have been given his name.[13]

NOTES

1. Most quotations are from the California Institute of Technology Oral History Project *Interviews with Robert B. Leighton* by Heidi Aspaturian (Caltech Archives, 1995). This provided some of my anecdotes, for which I am grateful. These describe well both his early schooling and early science, but give little of later family life. He was married twice and had two surviving sons. The oral history mirrors his recollections and were recorded from October 1986 to February 1987. His memory was failing and he gave few dates. His memory of science seems to have been excellent. No early papers, reprints, or pictures exist in the archives at Caltech or the National Academy of Sciences.

2. The downtown Los Angeles Library presented a symposium and exhibit in Leighton's honor soon after his death. His family has given major support to the library, making a substantial gift in his honor and funding a children's educational project.

3. Charles Wilts became a professor of electrical engineering at Caltech and an expert Sierra Club rock climber.

4. Work on the mirror in Pasadena was not finished until 1948, when it was transferred to the Palomar Observatory dome. There it was tested, sky photographs taken and measured, and the mirror retested repeatedly until the repolishing in the dome produced the correct figure. The telescope went into operation in 1951 and is named in honor of George Ellery Hale.

5. Smythe asked during an oral examination "what functions naturally appear in a boundary-value solution for a condenser, one of whose plates was shaped like a Maltese cross, the other an ellipse?" I sympathized with my new astronomy graduate students who sometimes had to repeat some undergraduate physics courses. Yet, when I worked with former Caltech student Leverett Davis, Jr., in 1951 on the light scattered by spinning, elongated interstellar dust grains, Leverett remembered and found one of his Smythe problems, which gave the polarizability of an ellipsoid. While apparently different from one I had from Max Born's *Optik*, the two answers proved to be the same after substantial manipulation.

6. This particle had a mass intermediate between the electron

and the proton and was called the mesotron at Caltech by Anderson and Neddermeyer, who first saw it in 1936.

7. The spectra of the neutrinos were published by Leighton, Anderson, and Seriff in 1949 and by Seriff, Leighton, Hsiao, Cowan, and Anderson in 1950.

8. Collaborators were Alford, Anderson, Bjornerud, van Lint, Sorrels, Trilling, and York.

9. See the profusely illustrated book by Harold Zirin (who directed the Big Bear Solar Observatory) *Astrophysics of the Sun* (Cambridge University Press, 1988).

10. Gerry's career was delayed by Army service as a lieutenant at the Jet Propulsion Laboratory.

11. Among them was Caltech undergraduate Jerry Nelson, who later became the chief designer of the Keck 10-meter telescopes on Mauna Kea in Hawaii.

12. Final data are contained in *The Two-Micron Survey, a Preliminary Catalog* with G. Neugebauer, published as NASA SP-3047.

13. This and other quotations come from various speakers at a taped memorial service for Leighton held at Caltech's Athenaeum, June 2, 1997. Brief articles from that event (by Charles Peck and Gerry Neugebauer) are in *Eng. Sci.* 60(1997):38-40.

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