# Charles H. Townes

1915–2015

BIOGRAPHICAL *Memoirs*

*A Biographical Memoir by*
*P. Buford Price*
*and Reinhard Genzel*



NATIONAL ACADEMY OF SCIENCES

# CHARLES HARD **TOWNES**

*July 28, 1915–January 27, 2015*

Elected to the NAS, 1956

*By P. Buford Price and Reinhard Genzel*

## Early Life and Graduate Studies

Charles Hard Townes, co-recipient of the 1964 Nobel Prize in Physics for his co-inventions of the maser and laser, died peacefully on January 27, 2015 in Oakland, California at the age of 99. Charles Townes ('Charlie' to his family, friends and close colleagues) was born on July 28, 1915, in Greenville, South Carolina, the fourth of six children of Henry Townes, a small-town lawyer, and Ellen Hard. Charlie grew up on a farm, and often emphasized that his interest in science and nature started there, when he (and his older brother Henry, who later became a well known entomologist) explored the woods and streams around their home. He was a brilliant student with wide interests, including entomology and ornithology. He graduated from the local high school in 1931 when he was 15. He attended the local college, Furman University, and in 1935 received undergraduate degrees in both physics and modern languages, *summa cum laude*, as valedictorian. He was curator of the college museum and a member of the band, glee club, swimming team and newspaper staff.

Charlie pursued graduate studies in physics at Duke University in Durham, North Carolina, after being turned down by the California Institute of Technology (Caltech). On receiving a masters degree from Duke in 1936, he again applied to Caltech. After interviews with the faculty, this time he was accepted at Caltech, and he did his PhD research under W.R. Smythe in 1937-39 on the separation of isotopes and on the determination of their nuclear spins. After his PhD in 1939, he took a position at AT&T Bell Laboratories in Manhattan, New York, to understand secondary electron emission from surfaces bombarded with ions. During World War II Charlie was assigned to work on radar-based aircraft bombing systems. These projects included an ill-fated short-wavelength (1.25cm) radar system, which turned out to be impractical because of atmospheric water vapor absorption. However, Charlie gained valuable technical knowledge for his later career and was awarded a number of patents in related technology.

After the war Charlie became interested in using microwaves for molecular spectroscopy, which he foresaw both as a powerful new tool for the study of the structure of atoms and molecules and as a potential new basis for controlling electromagnetic waves. Bell Labs gave him permission to build an innovative laboratory effort, utilizing some of the techniques and hardware of the wartime radar work.

Charles and Frances Townes as newlyweds.
(Photo courtesy U.C. Berkeley Space Sciences Laboratory.)

While at Bell Labs he met and married his beloved wife and partner of 74 years, Frances Brown.

## Columbia: Development of the first maser

On the initiative of Nobelist Isidor Rabi, Charlie moved uptown in 1948 from Bell Labs to Columbia University, as Associate Professor of Physics. Two years later, he became a Full Professor, and from 1952 to 1955 was the head of Columbia's Physics Department. He also lectured abroad, financed by Guggenheim and Fulbright fellowships.

Beginning in 1946 (at Bell Labs) with studies of the inversion transitions of the $NH_3$-molecule (which will re-occur as a key theme in several later phases of his research), Charlie and his students and postdocs carried out breakthrough studies on molecular structure, as well as on spins and quadrupole moments of atomic nuclei. This research culminated in the seminal 1955 textbook *Microwave Spectroscopy* by Charlie and his postdoc and brother-in-law, Art Schawlow (1981 Nobel Prize in Physics for his work on laser spectroscopy). Since many molecules have their rotational transitions at millimeter, sub-millimeter and infrared wavelengths, one of Charlie's goals was to push spectroscopic techniques to ever shorter wavelengths. However, a lack of electronic oscillators owing to the small size of resonant cavities made progress difficult. This is where Charlie had the general idea of exploiting atomic and molecular transitions as natural, high quality oscillators. A system of such atoms/molecules with an inverted state population,

Charlie told the story of how he conceived the solution to these problems in a 'Eureka' moment sitting one morning on a bench in Washington's Franklin Park in 1951.

in conjunction with wave amplification by stimulated emission could then in principle provide intense sources of microwave radiation. Stimulated emission was known as a theoretical concept since Einstein's 1917 paper, and a number of physicists had previously considered the possibility of exploiting it in experiments. Inversion population had been demonstrated in the experiments of Lamb & Retherford (1950) and Purcell & Pound (1951). However, a practical demonstration of substantial gain useful for applications in a microwave source had not been obtained. This was mainly because of inherent losses in the apparatus.

**Townes as a young man.** (Photo courtesy U.C. Berkeley Space Sciences Laboratory.)

Charlie told the story of how he conceived the solution to these problems in a 'Eureka' moment sitting one morning on a bench in Washington's Franklin Park in 1951. By employing a 'Paul' quadrupole focuser (invented by the German Nobelist Wolfgang Paul) to generate an intense beam of $NH_3$ molecules in the excited state of one of the inversion transitions and feeding this beam through a resonant cavity, whose highly conducting walls helped to supply the necessary positive feedback, Charlie was convinced that a device with substantial gain could be developed. And indeed Charlie with student James Gordon and postdoc Herb Zeiger reported the successful operation of the first $NH_3$ oscillator in 1954. The extremely narrow line width and high coherence immediately demonstrated the enormous potential as oscillator, amplifier and precise clock. Charlie dubbed the device that he had successfully constructed at Columbia the "maser" i.e., a device which operated by the principle of "Microwave Amplification by Stimulated Emission of Radiation." Serber and Townes then pointed out that the maser was the prototype of all quantum-limited amplifiers, whose sensitivity is ultimately limited only by the uncertainty principle for number and phase. Independently and at about the same time, Alexandr Prokhorov and Nikolay Basov at the Lebedev Institute in Moscow also proposed a maser device operating on a similar design. Ten years later, in 1964, Charlie Townes shared the Nobel Prize in Physics with these two colleagues "for fundamental work in the field of quantum electronics which has led to the construction of oscillators and amplifiers based on the maser-laser principle."

## Development of the Laser: who was first?

The new emerging field of maser research started to expand rapidly. The first solid state, tunable maser was demonstrated by Nicolaas Bloembergen (Nobel Prize 1981) in 1956, a year when Charlie and his family spent a sabbatical in France and Japan. To Charlie, the most interesting big next step was the development of "optical masers" or "lasers" ("light amplification by stimulated emission of radiation"). In 1958, Townes and Schawlow showed in a theoretical paper that optical masers could be constructed by embedding the active medium of inverted states in an open, Fabry-Perot type resonator, and coupling out the light in one of the resonator modes. The Townes & Schwalow work resulted, through Bell Laboratories, in a joint 1960 patent on optical and infrared masers, which featured some of the most exciting utilizations of the fundamental maser idea. At about the same time, Columbia graduate student Gordon Gould (a student of Nobelist Polykarp Kusch and familiar with and interested in the work of the Townes group) also contributed some ideas to the maser and laser. He later claimed that he had independently (and before Townes & Schawlow) conceived of the Fabry-Perot resonator concept. This led to an unfortunate three-decade long court fight against the Townes-Schawlow patent. Charlie devoted a chapter in his book, *How the Laser Happened; Adventures of a Scientist* to Gordon Gould's fight for patent rights.

Theodore H. Maiman, a physicist with a PhD from Stanford, then built the first successful laser from a ruby crystal in 1960 at the Hughes Research Laboratory in Malibu, California, with an expenditure of only $50,000. This was followed in the same year by the uranium solid-state laser (Peter Sorokin and Mirek Stevenson at the IBM Thomas J.Watson Research Center), and by the He-Ne laser (Ali Javan, William Bennett Jr. and Donald Herriott at Bell Labs). It is noteworthy that all these developments were carried out in industrial laboratories, probably as a result of their larger and more concentrated resources as compared to University groups.

To date, more than a dozen Nobel Prizes have been awarded for work done with lasers. Lasers are incorporated into consumer electronics, communication devices and optical fibers, surveying equipment and printers, light shows and laser pointers. Lasers are used to cut metal, slice through tissue during surgery, trap atoms, and even initiate nuclear fusion. At the time of writing the commercial applications of the maser/laser have become a 10 billion dollar per year industry. The laser has become a household word for millions of people and is an excellent example of how basic research can create technology that influences humanity at large.

As Charlie emphasized often, he was drawn to new, unexplored territories of scientific inquiry. Once he had done the initial exploring, he was quite happy to move on and leave the new playing grounds to others.

Townes himself went on to use masers for radio astronomy and lasers for infrared astronomy and interferometry, and he promoted their use in areas as diverse as precision timekeeping—the atomic clock—and extraterrestrial communication (Townes & Schwartz 1961).

## The government advisor

As Charlie emphasized often, he was drawn to new, unexplored territories of scientific inquiry. Once he had done the initial exploring, he was quite happy to move on and leave the new playing grounds to others. So he did in 1955, when he left microwave spectroscopy, and so he largely did in the early 1960s when he moved his attention away from the laser and its many applications.

After the 1957 'Sputnik shock' Charlie felt a strong duty to help his country. He decided to spend 1959-1961 in Washington as Vice President of the Institute for Defense Analysis (IDA). There he founded (and later became a member of) the JASON group, scientists advising the US government and military on scientific and technical issues. Over the years Charlie had many important roles as government advisor. He was a member of the Apollo-Program Advisory Committee to NASA, helping President Kennedy and NASA to overcome the scientific community's significant doubts about and opposition to the manned space program. He was a member of the Science Advisory Committee to four US Presidents, and was active in the Pugwash arms-control discussions with the Russians. In the early 1980s he chaired the MX Missile Basing Committee under President Reagan.

Charlie was an effective Chair of committees. One of us (BP) served on one such Board, called the Space Science Board. That Board usually met in one of the rooms in the building of the National Academy for one 3-day weekend, typically 3 times per year. Charlie very effectively worked with the committee and typically achieved productive results.

## Townes at MIT and U. C. Berkeley

After his time at the IDA, the Townes family moved in 1961 to Boston and Townes became Provost of MIT. While much of his time and energy were taken up by science administration and continuing work for the government (on the Apollo and Presidential Science Advisory committees), Charlie continued research and became interested in the new field of nonlinear optics. With his graduate students Elsa Garmire and Ray Chiao, Charlie discovered stimulated Raman and Brillouin scattering, self-trapping of light beams and self-steepening of light pulses in nonlinear material innovations. 1964 brought the announcement and fame of the Nobel Prize, including a memorable personal meeting of Charlie and Frances Townes in Stockholm with the Peace Prize Laureate of that year, Martin Luther King Jr.

In the mid 1960's Charlie decided to return to full-time basic research and change location and fields again, in part because his bid to become the next MIT President had failed: luckily so for basic research. This time it was to be California and astrophysics. University of California President Clark Kerr had learned that Townes was considering leaving MIT. He offered Charlie a very prestigious position as "University Professor," which allows its recipient to do teaching and research at any of the U. C. campuses. Charlie decided to make Berkeley his new home. Its Physics Department provided him generous space on the fifth floor of the then recently constructed Birge Hall, with a mix of offices and labs adjacent to the Campanile and with a magnificent view of the San Francisco Bay and the Golden Gate Bridge. He moved to Berkeley in 1967.

Charlie had toyed with the idea of taking up radio astronomy as early as 1945. Together with his students (one of whom was Arno Penzias, who later shared the Nobel Prize for the discovery of the Cosmic Microwave Background) and colleagues at the Naval Research Lab, Charlie put his first tunable ruby maser in 1956 to good use as a sensitive amplifier for radio astronomy. In a paper for the 1957 General Assembly of the International Astronomical Union, he laid out a detailed list of interesting radio and millimeter transitions of atoms and molecules that might be detectable in space. This paper initially had little impact within the astronomical community but in hindsight was a prescient preview of the field of astronomical molecular spectroscopy, which would soon start blooming.

Charlie and his Berkeley colleague Jack Welch (along with graduate student Al Cheung, postdoc Dave Rank and engineer Doug Thornton) pioneered this development by detecting in 1969 the first polyatomic interstellar molecules, $NH_3$ and $H_2O$. These

Above: Townes receiving the Nobel Prize.
Right: Townes with Princess Sybilla of Sweden. (Photos courtesy U. C. Berkeley Physics Department.)

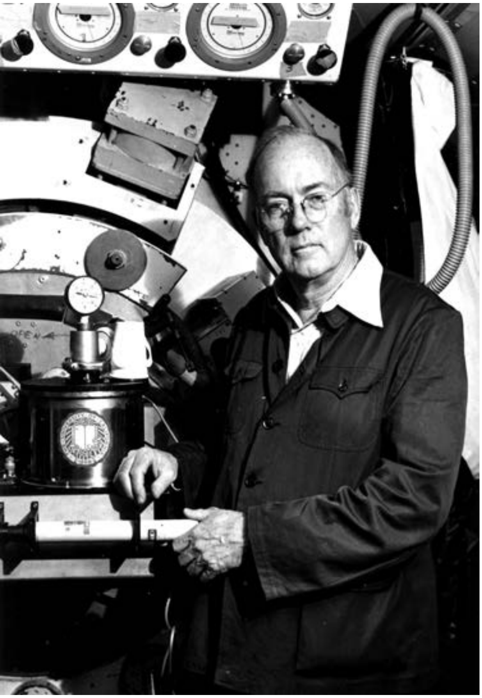
Townes, 2009, on a park bench similar to the one where he conceived the solution to the problems of stimulated emission from a microwave source.
(Photo courtesy U. C. Berkeley Physics Department.)

discoveries reflect back to Charlie's earlier work in New York. The detected interstellar $NH_3$ lines were the same 1.25cm inversion transitions that he had studied at Bell Labs in 1946 and that he had used for the first maser at Columbia in 1954. In the case of $H_2O$ the 1.35cm transition discovered was the same that had made the wartime short-wavelength radar impractical. Even more remarkable was the finding that the $H_2O$ line emission that the team detected turned out to be a "natural" cosmic maser, amplifying the vacuum zero-point fluctuations as a travelling-wave system. While diatomic molecules, such as CH, CN and OH had previously been discovered in diffuse interstellar clouds, the detection of $H_2O$ and $NH_3$ (soon followed by $H_2CO$ and many more complex molecules, including organic molecules that are the basis of life) demonstrated that interstellar clouds are much denser and colder than previously thought. As a result of the high volume and column densities of (molecular) hydrogen and dust in these "molecular clouds", many species of molecules can form and are protected against the diffuse ultra-violet radiation. We now know that the presence of dust and molecules is critical for the formation of stars, as they can cool interstellar gas to low temperature, such that gravity can overcome thermal motions.

The desire to detect the rotational lines of additional molecules motivated the development of mid- and far-infrared, airborne spectroscopy by Charlie and his group. Since water vapor in the Earth's atmosphere prevents much of the 30-300μm radiation from penetrating to the ground, observations have to be largely carried out from above the tropopause, by high-flying aircraft, balloons or satellites. To detect the faint infrared signals in the presence of the strong atmospheric and instrumental thermal background radiation, instruments have to be cooled to liquid helium temperature and special, low-noise semiconductor detectors have to be employed. For these reasons, Charlie and his team (graduate students Dan Watson and John Lugten, postdocs John Storey, Reinhard Genzel, Michael Crawford and Gordon Stacey, engineer Walt Fitelson) developed a twin, 50-200µm scanning Fabry-Perot spectrometer for the NASA Kuiper Airborne Observatory that led to the detections and detailed investigations of a number of molecular (OH, CH, $NH_3$, CO) and atomic (OI, CII, OIII, NIII) lines in the Galaxy as well as in extragalactic interstellar media. The development of this system also profited from novel, sensitive germanium photoconductive detectors, which had just been developed in Berkeley by Charlie's colleagues Paul Richards in the physics department and Eugene Haller in the material sciences department. As such the instrument's success is an example of another strength of Charlie's work throughout the years, namely to be broad-minded and ready to exploit novel developments over a wide range of fields. The pioneering far-infrared studies of the Townes group in the late 1970s and early 1980s were a forerunner of the expanding new field of far-infrared astronomical spectroscopy on space telescopes in the next three decades.

Townes with Reinhard Genzel.
(Photo courtesy U. C. Berkeley Physics Department.)

Another important highlight of his Berkeley astronomy research was the detection of rapidly moving ionized gas clouds at the center of the Milky Way. This work, based on the development of a Fabry-Perot spectrometer at 10µm (with his students Thomas Geballe, Eric Wollman, John Lacy, Sara Beck and Eugene Serabyn, and postdoc Dave Hollenbach), provided the first dynamical evidence for a mass concentration there of about four million times the mass of the Sun. By 1982 Charlie and his team were fairly certain that this object likely was a massive black hole, whose existence in galactic nuclei had been proposed in 1971 by the British theoretical astrophysicists Donald Lynden-Bell and Lord Martin Rees, following the discovery of the luminous distant quasars. Detailed studies of orbiting stars with ever better resolution and precision (by one of us and his group (RG), as well as a group at UCLA around Andrea Ghez) have since fully confirmed and much strengthened Charlie's conclusion, such that the


Townes in front of the far-infrared spectrometer onboard the KAO.

compact mass concentration in the galactic center is now considered to be the best evidence in favor of the existence of black holes as predicted by the Einstein/Schwarzschild/Kerr theory of gravitation.

A final example of these remarkable Berkeley astrophysics years is the development of mid-infrared spatial interferometry, which kept Charlie busy over more than three decades, and until a few years ago. Extrapolating radio interferometry techniques to a wavelength of 10 µm, and replacing electronic oscillators by infrared $CO_2$ lasers, Charlie used this novel technique to resolve and map the continuum and line mid-infrared emission from planets and dusty stars at a level of detail far surpassing that possible even with the largest ground-based telescopes. This pioneering effort (with students Albert Betz, Michael Johnson and Edmund Sutton) initially (in the 1970s) used the two siderostats of the Kitt Peak McMath solar telescope. In the 1980s Charlie and his team (student John Monnier, postdocs William Danchi, Manfred Bester and Peter Tuthill, engineers Walt Fitelson, Bob Weitzmann and physicist Ed Wishnow) were then funded to develop a dedicated Infrared Spatial Interferometer (ISI) at the UC Berkeley Space Sciences Laboratory, consisting of three 1.7m diameter, movable telescopes for spatial interferometry. With the ISI operating on Mount Wilson near Los Angeles starting in the late 1980s, the Townes team were able resolve the fine structure of dust and molecules around giant dusty stars, and demonstrate the presence of distinct dust shells, as well as non-spherically symmetric dust components. Over an 18-year period, they were able to detect and track changes in the size of the red supergiant star Betelgeuse.

## Life with Frances

Frances Townes, age 100 as of this writing, came from northern New Hampshire. Her father was in the paper manufacturing business and had come from Portland, Maine. He was brought up as a Congregationalist. Her mother was a liberal southern Episcopalian from an aristocratic Atlanta background. Her parents were well-to-do, and she went to boarding school, and then spent a year in Paris at the Sorbonne and a year in Florence where she learned Italian. She then studied at Smith College, and got a job at International House in New York City. While working there, she arranged outings such as a ski trip in Vermont, where she met Charlie. He had finished his PhD at Caltech and had started his job with Bell Labs. After several outings together, they got engaged in the summer of 1940 and married on May 4, 1941. Charlie and Frances made a happy couple and Frances played a central role throughout his life. The two of them spent summer periods and holidays on their farm in Goffstown, N. H. They had four daughters, Linda Townes-Rosenwein, Ellen Townes-Anderson, Carla Townes-Kessler and Holly Townes. There are six grandchildren and two great grandchildren. Charlie was devoted to his family.

**Charles and Frances with family.** (Photo courtesy U. C. Berkeley Space Sciences Laboratory.)

In Berkeley Frances was very engaged in the fate of the many homeless of the city. She persuaded members of her church (First Congregational of Berkeley) to provide food, clothing, and bedding for poor people in a sheltered area adjacent to their church.

## Science & Religion

Charlie also was a deeply spiritual person. He was an active member of the local church communities wherever he lived and he strongly felt that science and religion are not in opposition but constitute different but related routes for exploring and understanding the universe. He was often asked to speak about how he was able to rationalize Christianity with science. His short answer was that they are united by common goals: science seeks to discern the laws and order of our universe; religion seeks to understand the universe's purpose and meaning, and humankind fits into both. "Understanding the order of the universe and understanding the purpose of the universe are not identical," he acknowledged in a paper for the IBM *THINK* magazine in 1966, "but they are not

**A happy gathering of friends at the Berkeley Faculty Club in 2014: Buford Price, Sylvia McLaughlin** (founder of the Save the San Francisco Bay movement), Jo Ann Price, Julian Evans (then British Consul to San Francisco), Peter Sibley (attorney), Frances, and Charlie. (Photo courtesy U. C. Berkeley Physics Department.)

very far apart." Calling himself a Protestant Christian, Townes saw science and religion as compatible, saying there was little difference between a scientific revelation, like his maser brainstorm, and a religious one.

Charlie interpreted the recent discoveries relating to the Big Bang and the structure and evolution of the universe (cosmology), as well as the remarkable "fine-tuning" of the fundamental constants and of the properties of the solar system required for the existence of humankind in this universe (the "anthropic principle") as an indication in favor of the presence of an intelligent planning. He also argued eloquently that many "scientific truths" are based on faith and/or postulates that as such cannot be "proven." His optimistic vision was that science and religion in the future might converge to one coherent framework. He explained and discussed his views in a number of articles, as well as in interviews (e.g. an interview with Nobelist Harry Kroto on the occasion of his 90th

Townes with Pope John Paul II.
(Photo courtesy U. C. Berkeley Space Sciences Laboratory.)

birthday in 2005: http://www.vega.org.uk/video/programme/114).

To his great surprise, in 2005 the Templeton Foundation awarded Charlie a 1.5 million dollar prize on the basis of his talks on his beliefs and his rationalization of religion and science. In 1987, investor and philanthropist Sir John Templeton established the prize to "reward interdisciplinary research about human purpose and ultimate reality," with a stipend always set to have a value greater than that of the Nobel Prize. It recognizes those who, throughout their lives, have sought to advance ideas and/or institutions that will deepen the world's understanding of God and of spiritual realities.

Charlie considered himself a curious, exploring naturalist; "I like to explore new things, and I like to push things" (Townes, 1997, *Ann. Rev. Astr. Ap.*). When he was seen in his lab or office on a Saturday, he would say that he was not working, he was "just having fun," and he really meant it. He also loved nature, taking every opportunity on a trip or at an observatory to go out and watch birds. Even in his late eighties, Charlie was still reasonably fit, and one of us (BP) would sometimes see him walking on trails in Tilden Park in the Berkeley hills.

His levelheadedness, fairness, optimism, and humanity were rooted in a remarkable combination of spirituality, curiosity, and civility. Townes had a great influence on scientific education. He supervised the doctoral research of 68 students, about half while he was at Columbia and half after he moved to Berkeley. Of his students, Arno Penzias shared a Nobel Prize with Robert Wilson for the discovery of the cosmic microwave background radiation.

To his colleagues and students, Charlie was a role model and a revered mentor. He was a "southern gentleman." He deeply cared for his students. The intensity and vibrancy in his research group was legendary, driven by Charlie's relentless curiosity and boundless energy. It was an enormous privilege to be a member of the "Townes Group." This was demonstrated again recently, when many Townes group members of the Columbia, MIT, and Berkeley periods met in summer 2015 in Berkeley for a two-day symposium in honor of Charlie's 100th birthday.

To learn more about the lives of Charlie and Frances, read their books *How the Laser Happened: Adventures of a Scientist* (1999), by Charlie, and *Misadventures of a Scientist's Wife* (2007) by Frances.

## HONORS AND AWARDS

Charlie was elected in 1956, at the early age of 40, to the National Academy of Sciences, and was later awarded its Comstock Prize and John J. Carty Medal. Shortly thereafter he was elected to the American Academy of Arts and Sciences and, in 1976, to the Royal Society of London. He was awarded many prizes, including the Rumford Premium; the Stuart Ballentine Medal of the Franklin Institute (twice); a Guggenheim Fellowship; Fulbright Lectureships at Universities of Paris and of Tokyo; the Mees Medal of the Optical Society of America; the Plyler Prize of the American Physical Society; NASA's Distinguished Public Service Medal; the Thomas Young Medal and Prize of the Institute of Physics and the Physical Society (England); the Wilhelm Exner Award (Austria); the 1979 Niels Bohr International Gold Medal; membership in the National Inventors Hall of Fame, 1976; South Carolina Hall of Fame; National Lectureships for Sigma Xi; Fermi International School of Physics in Italy; the Mendel Medal (Villanova Univ., 1999); Fellow of IEEE for life; foreign member of Russian Academy of Sciences, which awarded him the Lomonosov Medal in 2000; Presidency of APS, 1967; and many other honors, including in 1982 the National Medal of Science awarded him by President Ronald Reagan.

In addition to roughly 600 scientific papers, and the seminal book "Microwave Spectroscopy" he wrote two memoirs in book form, *Making Waves* (1995) and *How the Laser Happened: Adventures of a Scientist* (1999).

Partial list of honorary doctoral degrees and other honors awarded to Townes:

| | |
|---|---|
| Furman University, D. Litt. | 1960 |
| Clemson College, Sc. D. | 1963 |
| Wesleyan University, Sc. D. | 1963 |
| Columbia University, Sc. D. | 1963 |
| Swarthmore College, Sc. D. | 1963 |
| Polytechnic Institute of Milan, Dott. Ing. | 1964 |
| Worcester Polytechnic Institute, Sc. D. | 1964 |
| Amherst College, Sc. D. | 1964 |
| New England College, LL. D. | 1964 |
| University of Notre Dame, LL. D. | 1964 |
| University of South Carolina, LL. D. | 1965 |
| Augustana College, L. H. D. | 1965 |
| Hebrew University of Jerusalem, PhD | 1966 |

| | |
|---|---|
| Gustavus Adolphus College, Sc. D. | 1966 |
| Duke University, Sc. D. | 1966 |
| University of Alberta, LL. D. | 1966 |
| Yeshiva University, Sc. D. | 1967 |
| New York University, Sc. D. | 1967 |
| Mercer University, LL. D. | 1968 |
| Carnegie-Mellon University, E. Eng. | 1969 |
| Medical Univ. of S. Carolina, D. Med. Sci. | 1978 |
| Yale University, Sc. D. | 1988 |
| Legion d'Honneur (France) | 1959 |
| Stuart Ballantine medal Franklin Institute | 1962 |
| University of South Florida, L.H.D. | 1989 |
| University of Toronto, Sc. D. | 1989 |
| Ecole Norm. Superieure, Doc. Hon. Causa | 1994 |
| University of Pusan, Korea, Sc. D. | 1997 |
| Harvard Univ., Hon. Deg. Doc. of Science | 2001 |
| Hon. Doc. Humane Lett., Univ. Redlands | 2008 |
| Univ. Strathclyde, Scotland, Hon. Doc. Sci. | 2011 |

In addition to his more than 30 honorary science degrees and numerous endowed lectureships, three U. S. universities have named new science centers in his honor. In October 2008 Furman University in Greenville, South Carolina dedicated its $62.5 million facility as The Charles H. Townes Center for Science, and a reading room named for his wife Frances. The Charles H. Townes Laboratories for Optical Science and Technology at Clemson University in Clemson, South Carolina, was dedicated in 2008. The Townes Laser Institute at the University of Central Florida's College of Optics and Photonics in Orlando was dedicated in May 2007. For some years Charlie served as a member of the Pontifical Academy of Sciences, which advises the Pope.

## REFERENCES

Ekström, S. 2012. Grids of stellar models with rotation. I. Models from 0.8 to 120 solar masses at solar metallicity (Z = 0.014). *Astron. Astrophys.* 537:A146.

Genzel, R. and R. Chiao. 2015. Charles Hard Townes. *Physics Today* 68(6):64-65.

Genzel, R., F. Eisenhauer, and S. Gillessen. 2010. The Galactic Center massive black hole and nuclear star cluster. *Rev. Mod. Phys.* 82:3121-3195.

Hale, D. D. S., M. Bester, W. C. Danchi, W. Fitelson, S. H. Hossi, E. A. Lipman, J. D. Monnier, P. G. Tuthill, and C. H. Townes. 2000. The Berkeley Infrared Spatial Interferometer: a heterodyne stellar interferometer for the mid-infrared. *Ap. J.* 537:998-1012.

Lockwood, S., E. H. Wishnow, V. Ravi, W. Fitelson, W. Mallard, D. Werthimer, H. Mistry, G. Perrin, V. Coud´e du Foresto, S. T. Ridgway, B. Mennesson, C. Ruilier, J.-M. Mariotti, W. A. Traub, and M. G. Lacasse. 1999. Interferometric observations of R Leonis in the K band. First direct detection of the photospheric pulsation and study of the atmospheric intensity distribution. *Astron. Astrophys.* 345:221-232.

Maiman, T. 2000. *The Laser Odyssey: Creator of the world's first laser*. Vancouver, Canada: Laser Press.

Ravi, V. 2011. The non-uniform, dynamic atmosphere of Betelgeuse observed at mid-infrared wavelengths. *Ap. J.* 740:1-11.

Ravi, V., E. Wishnow, S. Lockwood, C. H. Townes. 2011. The Many Faces of Betelgeuse. *Astronomical Society of the Pacific* 448:1025. arXiv:1012.0377.

Reid, M. J. and K. M. Menten. 1990. A subarcsecond $H_2O$ maser shell surrounding a variable star. *Ap. J.* 360:L51-L52.

Tatebe, K. 2007. Observation of a burst of high-velocity dust from alpha-Herculis. *Ap. J.* 658:L103.

Tatebe, K., A. A. Chandler, E. H. Wishnow, D. D. S. Hale, and C. H. Townes. 2007. The nonspherical shape of Betelgeuse in the Mid-infrared. *Ap. J.* 670:L21-L24.

Templeton, J. M. 1987. *The Templeton Plan: 21 steps to personal success and real happiness*. West Conshohocken, PA:Templeton Press.

Townes, C. H. 1997. A Physicist Courts Astronomy. *Ann. Rev. Astr. Ap.* 35:xiii-xliv.

Townes, C. H. 1999. *How the Laser Happened: adventures of a scientist*. New York: Oxford University Press.

Townes, C. H. 2014. Recent observations of Betelgeuse and new instrumentation at the ISI. In *Resolving the Future of Astronomy with Long-Baseline Astronomy*. ASP Conference Series 487. pp. 337-343. San Francisco: Astronomical Society of the Pacific.

Townes, C. H., E. H. Wishnow, D. D. S. Hale, and B. Walp. 2009. A systematic change with time in the size of Betelgeuse. *Ap. J. Lett.* 697:L128-L129.

Townes, Frances. 2007. *Misadventures of a Scientist's Wife*. Berkeley, CA: Regent Press.

van Belle, G. T. 2009. Interferometric astrometry. *New Astrometry Reviews* 53:336-343.

van Belle, G. T., M. J. Creech-Eakman, and A. Hart. 2009. Supergiant temperatures and linear radii from near-infrared interferometry. *Mon. Not. R. Astron. Soc.* 394:1925-1935.

Wishnow, E. H., A. Leung, and H. P. Gush. 1999. Cryogenic multiple reflection absorption cell and Fourier transform spectrometer system for the far infrared, *Rev. Sci. Instrum*. 70:23-31.

Wishnow, E. H., W. Mallard, V. Ravi, S. Lockwood, W. Fitelson, D. Werthimer, and C. H. Townes. 2010. Mid-infrared interferometry with high spectral resolution. In *Optical and Infrared Interferometry II.* Edited by William C. Danchi. *Proc. of SPIE* 7734:773409.

## SELECTED BIBLIOGRAPHY

1939 Concentration of the heavy isotope of carbon and measurement of its nuclear spin. PhD Thesis. California Intsitute of Technology.

With W. R. Smythe. The spin of carbon thirteen. *Physical Review* 56:1210-1213.

1946 With F. R. Merritt. Water spectrum near one-centimeter wave-length. *Physical Review* 70:558-559.

The Ammonia spectrum and line shapes near 1.25-cm wave-length. *Physical Review* 70:665-671.

1949 With B. P. Dailey. Determination of electronic structure of molecules from nuclear quadrupole effects. *Journal of Chemical Physics* 17:782-796.

1954 With J. P. Gordon and H. J. Zeiger. Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of $NH_3$. *Physical Review* 95:282-284.

1955 With A. L. Schawlow. *Microwave Spectroscopy*. New York: McGraw-Hill.

With S. H. Autler. Stark effect in rapidly varying fields. *Physical Review* 100:703-722.

With G. C. Dousmanis and T. M. Sanders. Microwave spectra of the free radicals OH and OD. *Physical Review* 100:1735-1754.

With J. P. Gordon and H. J. Zeiger. The maser-new type of microwave amplifier, frequency standard, and spectrometer. *Physical Review* 99:1264-1274.

1957 Microwave and radio-frequency resonance lines of interest to radio astronomy. In *Radio Astronomy, Proceedings from 4th IAU Symposium. International Astronomical Union*. Edited by Hendrik Christoffel Van de Hulst. p. 92. Cambridge: Cambridge University Press.

1958 With A. L. Schawlow. Infrared and optical masers. *Physical Review* 112:1940-1949.

1961 With R. N. Schwartz. Interstellar and interplanetary communication by optical masers. *Nature* 190(4772):205-208.

1964 With R. Y. Chiao and B. P. Stoicheff. Stimulated Brillouin scattering and coherent generation of intense hypersonic waves. *Physical Review Letters* 12:592-595.

With R. Y. Chiao, and E. Garmire. Self-trapping of optical beams. *Physical Review Letters* 13:479-482.

1968 With A. C. Cheung, D. M. Rank, D. D. Thornton, and W. J. Welch. Detection of $NH_3$ molecules in the interstellar medium by their microwave emission. *Physical Review Letters* 21:1701-1705.

1969 With A. C. Cheung, D. M. Rank, D. D. Thornton, and W. J. Welch. Detection of water in interstellar regions by its microwave radiation. *Nature* 221(5181):626-628.

1971 With D. M. Rank, and W. J. Welch. Interstellar molecules and dense clouds. *Science* 174(4014):1083-1101.

1977 With R. W. Boyd. An infrared upconverter for astronomical imaging. *Applied Physics Letters* 31:440-442.

With E. R. Wollman, T. R. Geballe, J. H. Lacy, and D. M. Rank. NE II 12.8 micron emission from the galactic center. II. *Astrophysical Journal* 218:L103-L107.

1978 With E. C. Sutton, J. W. V. Storey, and D. L. Spears. Variations in the spatial distribution of 11 micron radiation from Omicron Ceti. *Astrophysical Journal* 224:L123-L126.

1980 With D. H. Lacy, T. R. Geballe, and D. J. Hollenbach. Observations of the motion and distribution of the ionized gas in the central parsec of the Galaxy. II. *Astrophysical Journal* 241:132-146.

1982 With D. H. Lacy and D. J. Hollenbach. The nature of the central parsec of the Galaxy. *Astrophysical Journal* 262:120-134.

1983 With P. T. P. Ho. Interstellar ammonia. *Annual Review of Astronomy and Astrophysics* 21:239-270.

1985 With D. M. Watson, R. Genzel, and J. W. V. Storey. Far-infrared emission lines of CO and OH in the Orion-KL molecular shock. *Astrophysical Journal* 298:316-327.

1987 With R. Genzel. Physical conditions, dynamics, and mass distribution in the center of the Galaxy. *Annual Review of Astronomy and Astrophysics* 25:377-423.

1991 With G. J. Stacey, N. Geis, R. Genzel, J. B. Lugten, A. Poglitsch, and A. Sternberg. The 158 micron C II line - A measure of global star formation activity in galaxies. *Astrophysical Journal* 373:423-444.

1994 With W. C. Danchi, M. Bester, C. G. Degiacomi, and L. J. Greenhill. Characteristics of dust shells around 13 late-type stars. *Astronomical Journal* 107(4):1469-1513.

1997 A physicist courts astronomy. *Annual Review of Astronomy and Astrophysics* 35:xiii-xliv.

2003 Karl Schwarzschild Lecture: The behavior of stars observed by infrared interferometry. In *The Cosmic Circuit of Matter*. Reviews in Modern Astronomy, Vol. 16. Edited by Reinhard E. Scheilicke. New York: Wiley.

2009 With E. H. Wishnow, D. D. S. Hale, and B. Walp. A systematic change with time in the size of Betelgeuse. *Ap. J. Lett.* 697:L128-L129.