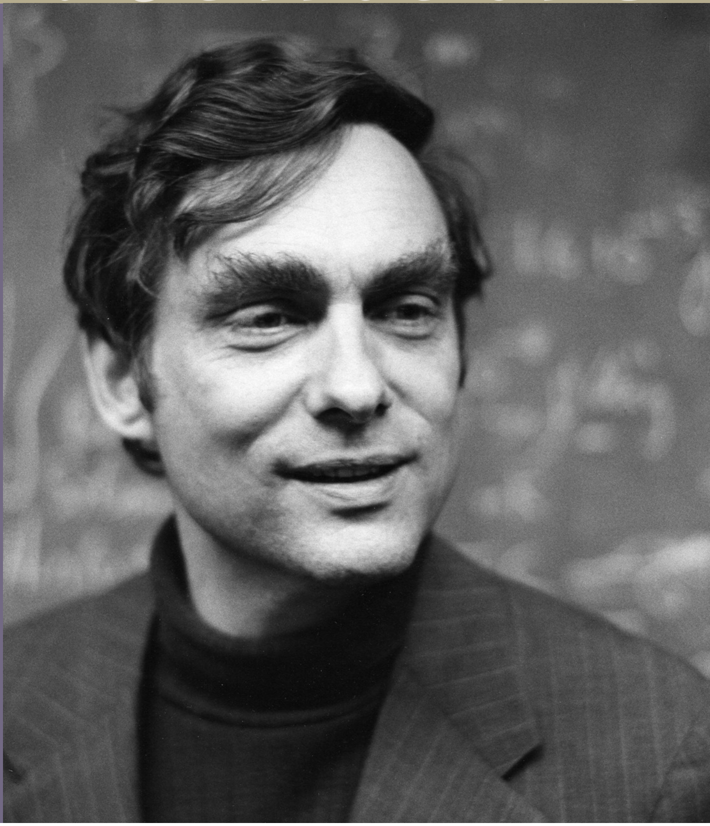
Patrick Thaddeus

1932–2017

BIOGRAPHICAL *Memoirs*



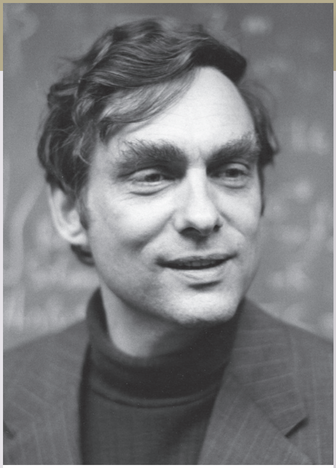
A Biographical Memoir by
James Moran

NATIONAL ACADEMY OF SCIENCES

PATRICK **THADDEUS**

June 6, 1932–April 28, 2017

Elected to the NAS, 1987



By James Moran

Patrick (Pat) Thaddeus was one of the founders of the field of astrochemistry and was largely responsible for recognizing that our galaxy is filled with a vast number of molecular clouds. Through combining his skills in laboratory spectroscopy and astronomical observation, Pat and his associates discovered a significant fraction of the known interstellar molecules, including organic rings, long carbon chains, and negatively charged ions. His ability to identify previously undetermined spectral lines was remarkable. He built a 1.2-m radio telescope with which he mapped the distribution of CO over an ever-increasing area in our galaxy, the Magellanic Clouds, and the nearby galaxy M31 over a period of 40 years. He also modeled the atmosphere of Venus and made an important early measurement of the temperature of the cosmic microwave background (CMB) that confirmed its blackbody nature. He was a tireless advocate for new instrumentation in radio astronomy.

The Early Years

Pat was born in the small village of Arden, Delaware, on June 6, 1932. Arden was a utopian community founded in 1900, based on the principles of the economist Henry George. All the land was held in common. It was a beautiful place and very neighborly. It was and remains an arts-and-crafts town, full of weaving and smithery and Shakespeare and fine furniture making. Victor Thaddeus, Pat's father, discovered Arden, built a house there, and married a local woman, Elizabeth Ross, granddaughter of two of the founders. Victor was a writer of biographies of great men, such as sculptor Benvenuto Cellini, Voltaire, Julius Caesar, and Frederick the Great, that were quite popular in their time. They had two children, Pat and Deirdre. Deirdre (Griswold) became an ardent communist and ran for the presidency of the United States in 1980 as the candidate of the Workers World Party.

Pat was a curious, high-spirited, and mischievous youngster, often suspended from school for truancy. His early home life was difficult. His parents divorced when he was seven, and his mother took him and his sister to live in Buffalo, New York. Missing his "native land" (as he used to tell the tale), he returned to Arden within a year to live with his father. He fondly recalled befriending German prisoners of war in the early 1940s as they worked in nearby fields. Pat was not a serious student, but he was interested in astronomy, and with the help of a middle school teacher, he built a reflector telescope and ground its mirror in the school shop. He spent many nights studying the night sky from Arden Common. He wasn't planning on going to college and had a fantasy of joining a mercenary army and fighting in the Congo. His father coaxed him into applying to the University of Delaware. He was accepted and entered in the fall of 1949. Much later, one of his high school teachers came across an article Pat had written in *Scientific American* and remarked that he would sooner have expected Pat to end up in prison.[1]

Pat graduated from the University of Delaware in 1953 with a degree in physics, then studied theoretical physics as a Fulbright Scholar at Oxford University. In 1955, he enrolled in a Ph.D. program at Columbia University. For his thesis under the supervision of Charles Townes (later a Nobel laureate), Pat measured the transition frequencies of a number of molecules with a maser-beam spectrometer that he built.[2]

While at Columbia, he met his future wife, Janice Farrar, a recent graduate of Barnard College who came from a distinguished literary family. By coincidence, Jan's father, John Farrar, was one of the founders of the publishing company Farrar and Rinehart,[3] which had published one of Victor Thaddeus' books. Her mother, Margaret Farrar, was a renowned crossword puzzle editor. She began as an assistant in 1924 to Arthur Wynne, the inventor of the crossword puzzle in 1924, and became the first editor of the *New York Times* crossword puzzle in 1942, a position she held for 26 years. Jan and Pat were married in 1963 after a short courtship.

In 1960, Pat took a National Research Council postdoctoral research fellowship at Columbia. In 1964, he joined the NASA Goddard Institute for Space Studies (GISS) as a research physicist. He continued his association with Columbia, where he had numerous teaching appointments and rose to the position of adjunct full professor. In 1986, he was recruited by then director Irwin Shapiro to move to the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. He was appointed professor of astronomy and also of applied physics at Harvard and concurrently as senior space scientist at the Smithsonian Astrophysical Observatory (SAO). He continued to work unabatedly until his retirement in 2014 from Harvard and in 2016 from SAO.

Research on Venus

In the late 1950s, a lively debate emerged in the astronomical community over the nature of Venus' atmosphere. Radio astronomical measurements at the time indicated that the brightness temperature of the planet was about 600 K at wavelengths longer than 1 cm and dropped rapidly to about 250 K at shorter wavelengths into the infrared. One theory was that Venus had a cool molecular atmosphere (optically thick at short wavelengths) and hot surface; or, alternatively, a hot ionosphere (optically thick at long wavelengths). Evidence tipped to the former model with the flyby measurements of Mariner 2 in 1962 and the *in situ* measurements of Venera 4 in 1967. Working with his first Ph.D. student, William Ho, and later Ph.D. students Irwin Kaufman, John Diamante, and John Moore, Pat made laboratory measurements of the high-pressure (many Earth atmospheres) line shapes of centimeter-wavelength transitions of CO_2, N_2, and other molecules and performed radiative-transfer calculations to model the spectrum semi-analytically in the transition region around 1-cm wavelength. This work was key to supporting the model of a cool, thick atmosphere composed primarily of CO_2. He ultimately wrote nine papers related to the atmosphere of Venus between 1964 and 1968.

The Cosmic Microwave Background

The discovery of the CMB in 1965 piqued his interest. He as well as George Field and Joseph Shklovsky (with Neville Woolf playing an important role as catalyst) independently speculated whether spectral lines of CN could be used to measure the temperature of the CMB. The CN line had been detected in the interstellar medium (ISM) in 1941 by Merrill, who measured its rotational excitation temperature to be 2.3 K. It was understood at the time that this temperature was determined by a combination of collisional excitation and the ambient radiation field. However, both of these processes were poorly understood, so no significance was attached to the result at the time.[4] With his optical experience limited to having built a reflecting telescope as a youth, Pat and students, John Clauser and Victor Bortolot, set out to see whether the previously observed pair of optical transitions of CN in the ISM could act as a reliable thermometer for the CMB. They realized that in the very-low-density environment, CN could be expected to be in equilibrium with the CMB. Using the Lick 120-inch telescope, they established the temperature of the CMB to be 2.78 ± 0.10 K at 2.6-mm wavelength, close to the modern value of 2.7255 K. For a long time, their measurement remained the most accurate short-wavelength anchor in the spectrum, proving the CMB to be blackbody in nature. Pat later mused,

> *My excursion into optical astronomy was short but it left an indelible impression. After many hours of exposure, the thrill of holding up a developed photographic plate…and seeing the faint, barely perceptible absorption lines of excited CN, knowing that it was a fingerprint of the universal radiation field filling all space, once as brilliant as the surface of the Sun, was an aesthetic and intellectual pleasure that I have never again experienced in research.*[5]

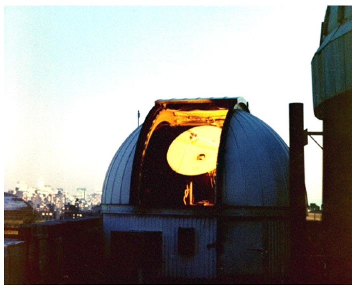
The idea for a space measurement of the CMB at wavelengths shorter than a millimeter was hatched in Pat's office with his postdoctoral fellow John Mather and others.[6] This ultimately led to the fabrication of the Cosmic Background Explorer (COBE) satellite and a Nobel Prize for Mather.

Interstellar Molecules

The study of radio astronomy began in 1932 when Karl Jansky identified radio emission from the central part of our galaxy. However, exploitation of spectroscopic observations of atoms and molecules in this region of the electromagnetic spectrum was slow to take hold. The frequency of the spin-flip transition of neutral hydrogen was fairly well known, and it was detected in 1951 at Harvard by Harold Ewen and Edward Purcell and quickly confirmed. It became a major research area in radio astronomy thereafter. But microwave spectroscopy began in earnest only after World War II, and in the 1950s, few accurate transition frequencies had been measured in the laboratory. By 1957, Charles Townes was advocating that searches for atoms and molecules would be a valuable area of research.[7] The ground-state lambda-doublet transitions of OH at 18-cm wavelength were searched for but not found. Following the first accurate lab measurements of these transitions by the Townes group at Columbia, they were readily detected in the ISM in 1963. However, it was widely accepted at the time that polyatomic molecules were unlikely to be detectable in the ISM because they would be easily photodissociated by interstellar UV radiation fields. That opinion changed when ammonia (NH_3), the first polyatomic molecule, was detected in 1968, followed by formaldehyde (H_2CO), the first organic polyatomic molecule, in 1969. It was appreciated that the density of spectral lines could be expected to increase rapidly with frequency because the electric dipole moments of rotational transitions scaled as the cube of the frequency. The floodgates opened when the first detection of a molecule in the millimeter-wavelength region, that of carbon monoxide (CO), was made with the NRAO 36-foot telescope at Kitt Peak National Observatory in Arizona. It was somewhat difficult to observe at millimeter wavelengths because of the absorption caused by the wings of water vapor transition in the submillimeter and infrared parts of the spectrum and the low sensitivity of the coherent receivers at the time.

Pat was one of the first to jump into this field, which was ripe for investigation. After a few successful detections of new molecules, such as silicon monoxide (SiO) and hydrogen sulfide (SH), he soon wearied of the intense competition among astronomers for telescope time with the 36-foot telescope and set out to find more accessible telescopes. Meanwhile, in 1970, the 5-m telescope operated by the Department of Electrical Engineering at the University of Texas (UT), largely for planetary observations, was moved to Mt. Locke in southwest Texas. It was renamed the Millimeter Wave Observatory (MWO) and became a part of the McDonald Observatory. Paul Vanden Bout, then on the faculty of the Department of Astronomy at UT, realized the need for partners to make the telescope effective as a spectroscopic instrument at millimeter wavelengths.[8] He formed a collaboration among UT, GISS with Thaddeus, Bell Telephone Laboratories (BTL) with Arno Penzias and Bob Wilson, and Harvard College Observatory (HCO) with Ed Lilley. GISS supplied the reference oscillators, BTL the mixers, and HCO the filter bank spectrometer. Pat and his students Marc Kutner, Ken Tucker, and Gordon Chin immediately set out to map the distribution of CO in the Orion Nebula. What they found was the first example of a so-called giant molecular cloud (GMC), vast regions of dense gas that we now know are the primary sites of star formation.

Realizing that thoroughly mapping such molecular clouds throughout the galaxy would take decades with the MWO or the Kitt Peak 36-foot telescope, Pat and his group, which included students Gordon Chin, Richard Cohen, and Hong-Ih Cong, decided to build their own small radio dish that they placed in the most unlikely of spots for astronomical observations: the center of Manhattan on the Columbia campus. Asked by a reporter how observations could be done there, Pat responded that at the frequency of their observations, "New York was as quiet as the day Henry Hudson came sailing up the river."[9] The so-called mini telescope was set to work day and night mapping the vast GMCs, which Pat likened to invisible thunderclouds hanging over the New York skyline. Within a few years, a second mini

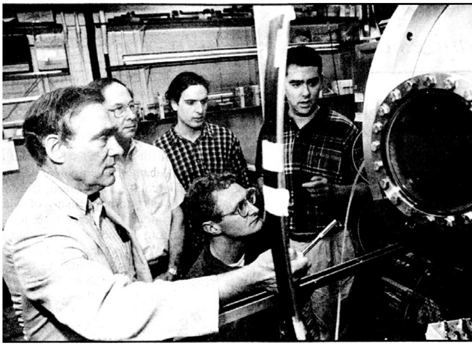


1.2-meter mini telescope atop Pupin Hall, Columbia University, New York City, circa 1980. (Photo by Sam Palmer.)

Mini-South at Inter-American Observatory, Cerro Tololo, Chile. Elevation 2200 m. 500 km North of Santiago, near La Serena. Circa 1982. (Photo by Leonardo Bronfman.)

was constructed and sent to the Inter-American Observatory on Cerro Tololo in Chile to map the southern sky. Richard Cohen led the construction of the facility, which was directed over the ensuing decades by Leonardo Bronfman, another of Pat's students. Ultimately the two telescopes provided the data for 24 of Pat's Ph.D. students and produced what is still the only complete map of the distribution of molecular clouds in the Milky Way. It was published in 2001. The original mini continues its survey work to this day in Cambridge, Massachusetts, more than 40 years after its commissioning. The second mini was moved to a site close to Santiago, Chile, and remains a teaching and instrument-development facility for the University of Chile.

At the same time the molecular cloud work was beginning, Pat realized that his spectroscopy lab would enable him to search for many more exotic molecules in space by first precisely measuring the frequencies of their spectral lines in the lab. To date, more than 200 molecules have been identified in the ISM, a substantial fraction of them discovered by Pat's group, his students, and his collaborators.[10] The molecules range from simple organics to large carbon rings and chains, the largest having twice the molecular weight of the simplest amino acid, glycine. Hearing Pat give a lecture about tracking down the identity of a set of spectral lines was like listening to a Sherlock Holmes mystery, where every logical step in tracking the culprit was logically laid out. He would often proclaim proudly that his "ironclad" identifications of molecules in space far exceeded the specificity of a human fingerprint. An excellent example of his sleuthing skills led to the identification of the first interstellar organic ring molecule, C_3H_2.



(l–r) Pat, Carl Gottlieb, Attila Kovacs, Michael Travers, and Michael McCarthy in front of their Fourier transform microwave spectrometer in Pierce Hall, Harvard University. *Harvard Gazette*, July 11, 1996. (Photo by John Chase.)

In 1996, Pat and his group built a very sensitive Fourier transform microwave spectrometer, based on a confocal Fabry-Perot resonator.[11] Through careful attention to design and the use of detection techniques from radio astronomy, they were able to improve on existing instruments by an order of magnitude or more. Gas samples were prepared in a supersonic beam with a temperature of only a few Kelvins. This setup made it possible to measure transitions of molecules that are normally unstable in the terrestrial environment, such as closed-shell cyanopolyynes (e.g., HC_nN) and cumulene carbenes (H_2CCCC). This instrument was steadily improved over the next decade, and cyanopolyynes as long as $HC_{15}N$ have been measured. The longest cyanopolyyne discovered in the ISM is HC_9N in the J=18–17 and 25–24 rotational levels. (It is interesting to visualize this very-long-chain molecule modeled as a thin elastic rod capable of rotating and bending in a cold, diffuse, molecular cloud).

Much of Pat's focus from 2006 to 2011 was on anions. The anion H^- had been shown to be a major source of the optical opacity of the Sun, and the anion CH^- had been known to exist in the ISM since 1941. In spite of the fact that Herbst[12] had predicted that many anions should be detectable in the ISM, none was found for decades. This changed in 2006 when Pat and his colleagues measured the frequency of the transition of $HC6^-$ in the laboratory and then detected it in the ISM. They had been motivated by the discovery a decade earlier of an unidentified harmonic series of lines known only as B1377 ("1377" denoting the inferred rotational constant in MHz), which they proved to be $HC6^-$. Combining laboratory and astrophysical observations, Pat and his colleagues quickly identified $HC8^-$, $HC4^-$, $HC3^-$, and $HC2^-$, as well as CN^-, the smallest anion detected so far in the radio spectrum. This discovery spawned a wide range of investigations that have continued to the present day. For example, models suggest anions can be the dominant negative-charge carrier (as opposed to electrons) in some sources, and they may play a key role in the synthesis of very large hydrocarbons such as polycyclic aromatic hydrocarbons.[13]

Move to the Center for Astrophysics

The move from GISS/Columbia University to SAO/Harvard University in 1986 was a major event in Pat's life. In addition, Jan left her teaching post at Barnard College and became a lecturer in history and literature at Harvard. Eight of the 25 people in his group at GISS moved to Cambridge: Sam Palmer, his chief engineer; Tom Dame, Carl Gottlieb, and Jan Vrtilek, research scientists; Hans Ungerechts and Lars Nyman, postdoctoral fellows; Erik de Vries, a graduate student; and Ellin Sarot, administrator and editor. The equipment relocation required seven 40-ton tractor trailers. The laboratory equipment went to Pierce Hall, in an area near the Department of Physics on the Harvard campus, about a mile from the CfA. The mini telescope and its Ash-Dome were installed on the roof of Building D at the CfA, and a penthouse was built as the control room and storage area. New arrivals who helped with the installation included Harvard physics graduate student Seth Digel and postdoctoral fellow Greg Stacy. A special elevator was installed to hoist liquid helium to the roof. By December 1987, everything was working, including the state-of-the-art quantum-junction receiver designed and built by Tony Kerr at GISS.

National Priorities

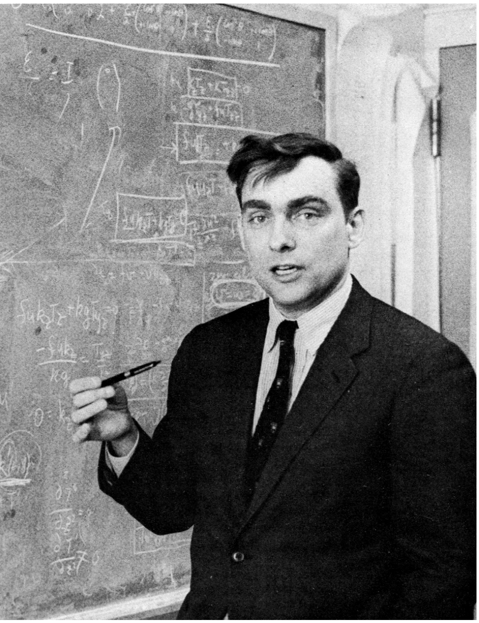
With the success of the mini telescope, Pat became an exemplary champion of "small-scale" science. However, he also played an important role in the development of some of the major radio astronomy instrumentation. He was appointed chair of the radio astronomy panel of the National Academy of Sciences' (NAS) 1980 Decadal Survey of Astronomy and Astrophysics, charged with setting priorities for projects in the decade following 1980. The panel's report gave highest priority to the Very Long Baseline Array (VLBA), and it was adopted as the top ground-based telescope project by the main committee, chaired by George Field.[14] After this decision, Pat convened a group of leaders from the very-long-baseline interferometry community at his summer home in the Taconic Mountains in the town of Hillsdale, New York, to thrash out the key details of the preliminary design specifications for the VLBA.[15] The other radio projects ranked in the Decadal Survey were a 10-m submillimeter-wavelength telescope, a fully steerable 100-m centimeter-wavelength telescope, and an upgrade proposal for the VLA and Arecibo Observatory. The proposal for a 25-m millimeter-wavelength telescope had been endorsed by the previous decadal committee, and because of that it was not ranked in 1980. Ultimately, the VLBA, along with the Robert C. Byrd 100-m telescope in Green Bank, West Virginia, and upgrades for both Arecibo and the VLA were completed. The 25-m millimeter-wavelength telescope was never built for complex reasons, a deep disappointment for the millimeter radio community, of which Pat was a member.

Pat was chair of the NAS committee for the mid-decadal (1996) review for space astronomy and astrophysics. The highest of four priorities was "the determination of the geometry and content of the Universe by measurement of the fine-scale anisotropy of the cosmic microwave background radiation." The committee's report moved NASA to approve the Wilkinson Microwave Anisotropy Probe mission, which provided the first detailed map of the CMB anisotropy.[16]

Pat's Character

Pat was a major presence in the radio astronomy community for over half a century. He had a *joie de vivre* that was infectious. He taught himself Italian and read an Italian newspaper every day. He had broad intellectual interests and was a raconteur par excellence. He held dinner audiences in rapt attention discussing topics as varied as the aerodynamics of the wandering albatross, the Greco-Persian Wars, and the foundational issues of quantum mechanics. I met him for the first time at a party at the home of Bernie Burke in 1965. I was searching for CH with the 140-foot telescope in Green Bank. A lively discussion ensued about the proper chemical name for CH. There was an abundant display of instant male knowledge (IMK), but Pat had the right answer, methylidyne.

Stories abound of Pat's mischievousness. Sitting among a group of British astronomers, he coaxed a colleague to bring up the recently reported story that the Duke of Clarence might have been Jack the Ripper. Pat chimed in with, "Amazing! Jack the Ripper was a member of the royal family." The Brits were outraged, he was amused. One day he organized a run around Mt. Locke in Texas between observations. He noticed vultures soaring overhead and wondered if he could pass as bait. He pretended to collapse, lying on his back and staring up wide-eyed. The vultures flew over, checked him out, but were not fooled. He once held an impromptu contest to prove who could hold a plug of chewing tobacco in their mouth the longest. He won.[17]



Pat at the blackboard. From *University News*, University of Delaware, spring 1966.

Pat didn't think highly of scientific work that required extensive computation or data analysis. He was fond of repeating the quotation attributed to physicist Ernest Rutherford: "Don't do better statistics, do a better experiment." Nonetheless, I was surprised to find him one day reading a book by the Bayesian analyst E. T. Jaynes entitled *Probability Theory: The Logic of Science*. Jaynes invented the method of maximum entropy, which combines elements of statistical mechanics and information theory and has been widely applied in image processing. It was typical of Pat to be curious about was going on in areas he did not approve of. In a similar way, he was an atheist, but he greatly enjoyed engaging his religious friends in theological discussions.

Pat prided himself on the vigor and clarity of his writing and insisted on meticulously copyediting any manuscript of which he was a coauthor. Nothing escaped his ruthless red pen. One story of legend is of Pat and Richard Cohen arguing whether to say, "We observed in the cold months of the year" or in "the colder months." In the days before digital files, he would have two people compare the journal proof with the submitted manuscript of a paper by reading the whole proof backwards.

Softball brought out Pat's competitiveness. He was also a serious gymnast[18] and an enthusiastic, if not highly skilled, tennis player. He often complained that one of his frequent partners, Alex Dalgarno, could beat him only with crafty trick shots.

Research Group and Collaborators

Pat assembled a remarkable group of scientists around him, and he led it with great effectiveness and enthusiasm. He advised 34 Ph.D. students and dozens of postdoctoral fellows. Perhaps most importunately, he inspired a core group to work with him for a very long time. Sam Palmer was his chief engineer starting in 1975. He designed the mini telescope and kept it going. Tom Dame started as a graduate student in 1977. He has managed the CO mapping program with the mini telescope up to the present day and published 30 papers with Pat. Carl Gottlieb, who has a Ph.D. in chemistry, joined Pat's group in 1974 as an astronomer and laboratory spectroscopist and published 104 papers with Pat. Michael McCarthy joined Pat's group in in 1994 and took over the leadership of the lab when Pat retired. He built the Fourier transform microwave spectrometer in 1996 and coauthored 128 papers with Pat.

Pat with students and group members, 65th birthday conference. (l-r)(first row) Hong-Ih Cong, Linda Gaines, Pat, S.-K. Pan, Victor Bortolot, (second row) Richard Cohen, Leonardo Bronfman, Tom Dame, David Leisawitz, (third row) Sam Palmer, Gordon Chin, John Clauser, David Grabelsky, Yi-Long Huang, and Ron Maddelena. 1997. Photo by Tamarliegh Lippegrenfell.

Pat's main external collaborators were Michel Guélin (16 papers), Bob Wilson (11 papers), and Nimesh Patel (6 papers). His closest colleagues on the astronomy faculty were Alex Dalgarno, George Field, and Josh Grindlay.

Pat had contentious relationships with some of his graduate students. One example is John Clauser, his third student, who graduated in 1969. While working on his thesis project related to the CMB, Clauser read an article by John Bell[19] confronting the Einstein-Podolsky-Rosen paradox that suggested that hidden variables were needed in the theory of quantum mechanics in order to avoid the issue of "spooky" action at a distance. At the time, quantum mechanics was enjoying a golden era with success after success, including the invention of the transistor, the rise of solid-state physics, the invention of the maser and laser, and the production of ever more complex spectroscopic results showing essentially perfect agreement between theory and observation. The prevailing attitude was to accept quantum mechanics and reap the rewards it offered. When Clauser told Pat of his interest in the problem of hidden variables and entanglement, Pat was concerned about it being a distraction from his thesis. He called the work a "waste of time" and "junk science."[20] Nevertheless, Clauser proceeded to write a paper about various laboratory experiments that could test the property of entanglement. That paper,[21] published in 1969, had little impact at the time but has gradually become recognized as a cornerstone document that started laboratory interest in the subject. As a postdoc at Berkeley, with the encouragement of Charles Townes, he and graduate student Stuart Freedman conducted the first critical experiment concerning entanglement. Pat wrote in a recommendation letter for Clauser, "There is the odd chance that he will accomplish something of unusual significance in an area of physical research where most workers of conventional good judgment would lack the temerity to tread."[22] This prediction was borne out when Clauser was awarded the Wolf Prize in 2010 for his work on entanglement.[23]

Awards and Service

At Harvard, Pat was the Robert Wheeler Willson Professor of Applied Astronomy, one of the oldest chairs in the department. He was elected to the NAS in 1987 and to the American Academy of Arts and Sciences in 1989. He received the Herschel Medal of the Royal Astronomical Society in 2001 and an honorary degree from the University of Chicago in 2003. He was awarded medals for exceptional scientific achievement from NASA in 1970 and 1985. He served on the visiting committees for the National Radio Astronomy Observatory, the Association of Universities for Research in Astronomy, Haystack Observatory, Hat Creek Observatory, and the Department of Astronomy at the University of Chicago. In addition to being a member of the 1980 NAS Decadal Survey of Astronomy and Astrophysics and chair of its radio astronomy panel, he was a member of three separate panels of the 1990 Decadal Survey (radio astronomy, infrared astronomy, and theory and laboratory astrophysics).

The Final Chapter

Pat's research interests live on at the CfA. On the faculty, the leadership in astrochemistry has been filled by Karen Öberg. She oversees a laboratory program to characterize the properties of interstellar ice and an observation program mainly carried out at the Atacama Large Millimeter/Submillimeter Array in Chile. As of 2021, Tom Dame continues to run the mini telescope, with the help of Sam Palmer and a host of undergraduate telescope operators. Michael McCarthy heads the laboratory spectroscopy facility, which has finally been relocated on the grounds of the CfA. Carl Gottlieb continues the research he began with Pat with the Submillimeter Array.

Pat's wife, Jan, died in 2001 at the age of 68. She was a scholar, poet, and editor as well as lecturer and head tutor in history and literature at Harvard. She authored the biography *Frances Burney: A Literary Life*, which renewed interest in Burney, who had been admired by her contemporaries. Jan edited a feminist anthology with John Kouwenhoven in 1963 entitled *When Women Look at Men*. When an interviewer asked her why women do not achieve as much as men in the professions, she answered with the quip, "They have no wives." Pat and Jan were married for 38 years and had two children, Eva, a public school teacher and charter school founder, and Michael, a professor of mathematics at Columbia University. Eva lives in the Hudson River Valley with her two children, Benjamin and Anna Bogenschutz. In 2003, Pat married Valerie McCollom, a division administrator at the CfA, who survives him.

The years took their toll on Pat physically, but they never diminished his zest for life. Just a few days before he died, bedridden in his Cambridge home, Valerie raised his curtains to a sunny morning. Pat's face brightened as he exclaimed, "Ah, spring!" He died peacefully at home after a short illness on April 28, 2017, of pneumonia. He was a month shy of his 85th birthday.

ACKNOWLEDGMENTS

I thank John Clauser, Tom Dame, Carl Gottlieb, Ken Kellermann, Sam Palmer, Eva Thaddeus, Michael Thaddeus, Valerie Thaddeus, Paul Vanden Bout, and Jan Vrtilek for providing valuable material and advice. This memoir was developed from the "Memorial Minute" presented to the Faculty of Arts and Sciences, Harvard University, and published in the *Harvard Gazette*, on May 9, 2019.

NOTES

1. Michael Thaddeus, private communication. Also retold in the obituary written by T. Dame in *Nat. Astron.*, June 19, 2017.

2. The title of Pat's Ph.D. dissertation was: Hyperfine structure in the microwave spectrum of hydrogen-deuterium oxide, hydrogen-deuterium sulfide, formaldehyde and formaldehyde-d beam maser spectroscopy on asymmetric top molecules. The instrument he built is described in: Thaddeus, P., and L. C. Krisher. 1961. A beam maser spectrometer. *Rev. Sci. Instrum.* 32:1083–1089.

3. John Farrar also founded in 1946 the renowned publishing company Farrar, Strauss, and Giroux (FSG), which exists today as a subsidiary of MacMillan Publishers.

4. McKellar, A. 1941. Molecular lines from the lowest states of diatomic molecules composed of atoms probably present in interstellar space. *Publications of the Dominion Astrophysical Observatory* 17:251–272. At the end of G. H. Herzberg's classic book, *Molecular Spectra and Molecular Structure: The Spectra of Diatomic Molecules* (New York: D. Van Nostrand Company, 1950), on p. 496 is the statement, "From the intensity ratio of the lines [of CN] the [excitation] temperature of 2.3 K follows, which has of course a very restricted meaning."

5. Peebles, P. J. E., L. A. Page Jr., and R. B. Partridge. 2009. *Finding the Big Bang*. Cambridge, U.K.: Cambridge University Press. The quotation on p. 84 ends, "…a shock of recognition perhaps comparable to that felt by Rutherford when he saw the back-scattered alphas and realized that our entire picture of the structure of matter was wrong."

6. According to Michael Hauser (in Peebles, Page, and Partridge, p. 418), this meeting was convened on September 27, 1974, in response to a NASA announcement about an opportunity to submit proposals for Explorer Class missions. In addition to Pat and John Mather, the other attendees were Joe Binsack, Michael Hauser, Dirk Muehlner, Rainer Weiss, and David Wilkinson.

7. Townes, C. H. Microwave and radio-frequency resonance lines of interest in radio astronomy. In: *Radio Astronomy, Proceedings of the 4th IAU Symposium of the International Astronomical Union*, ed. Hendrik Christoffel Van de Hulst, pp. 92–103. Cambridge, U.K.: Cambridge University Press.

8. Vanden Bout, P. A., J. H. Harris, and R. B. Loren. 2012. The University of Texas millimeter wave observatory. *JAHH* 15:232–245.

9. Bouton, K. Talk of the town: The view from Broadway. *The New Yorker,* February 1, 1982, p. 31.

10. McGuire, B. A. 2018. Census on interstellar, circumstellar, extragalactic, protoplanetary disk, and exoplanetary molecules. *Ap. J. Supp.* 239:17 (48pp.).

11. The Fourier transform microwave spectrometer in Pat's lab is described in: Thaddeus, P., and M. C. McCarthy. 2001. Carbon chains and rings in the laboratory and in space. Spectrochim. *Acta A* 57:757–774. Later improvements are described in: Grabow, J.-U., E. S. Palmer, M. C. McCarthy, and P. Thaddeus. 2005. Supersonic-jet cryogenic-resonator coaxially oriented beam-resonator arrangement Fourier transform microwave spectrometer. *Rev. Sci. Instrum.* 76:093106(11pp.).

12. Herbst, E. 1981. Can negative molecular ions be detected in dense interstellar clouds? *Nature* 289:656–657.

13. Millar, T. J., C. Walsh, and T. A. Field. 2017. Negative ions in space. *Chem. Rev.* 117:1765–1795; also Herbst, E. 1981. Can negative molecular ions be detected in dense interstellar clouds? *Nature* 289:656–657.

14. Thaddeus, P. 1983. Radio astronomy. In: *Astronomy and Astrophysics for the 1980s*. Vol. 2. Washington, D.C.: National Academy Press, pp. 211–258. See also: Thaddeus, P. 1982. Facilities for US radioastronomy. *Phys. Today* 35:36–42.

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17. Stories told by Paul Vanden Bout at the memorial service for Pat on June 17, 2017, at the chapel of the Mt. Auburn Cemetery in Cambridge, Massachusetts.

18. NASA produced a video documentary, *The Universe on a Scratchpad* (https://vimeo.com/48171442), about theoretical astrophysics at the GISS circa 1964. In it, Pat is shown describing the interplay between theory and experiments and observations while working out on the parallel bars and rings.

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22. From a copy of a letter from J. F. Clauser, dated March 3, 1971, sent to the author on December 2, 2020.

23. The Wolf Prize in Physics of Israel's Wolf Foundation was given in 2010 to John F. Clauser (United States), Alain Aspect (France), and Anton Zeilinger (Austria) "for their fundamental conceptual and experimental contributions to the foundations of quantum physics, specifically an increasingly sophisticated series of tests of Bell's inequalities, or extensions thereof, using entangled quantum states."

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