Terahertz Pioneer: Paul F. Goldsmith

"New Eyes for THz Astronomers"

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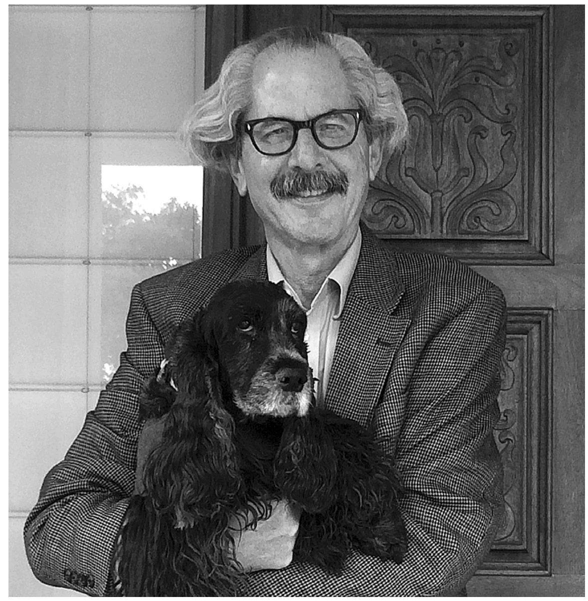

PAUL F. GOLDSMITH AND CHLOE

THE THIRD CHILD of two Ph.D. economists, Paul Felix Goldsmith[1] spent his teenage years in Washington, DC, while his father, Raymond W. Goldsmith, commuted back and forth to New Haven, CT, USA as a distinguished faculty member at Yale University. Raymond Goldschmidt, the son of a German banking family, was born in Belgium and educated in Berlin. He immigrated to the United States in 1934, and ended up teaching at Carleton College in Minnesota. Within a few years, he had made his way to Washington, DC, where he worked for various government agencies, including the Securities and Exchange Commission and the National Bureau of Economic Research. He also joined the faculty at New York University. Raymond Goldsmith was a well-recognized specialist in historical income and wealth accumulation, the author of 15 books [1], and is purported to have "demanded much of himself" and had little regard for puffed up self-esteem [2]. He was also praised for his "scientific approach" to economics [3], perhaps instilling this trait in his three children. Paul's mother, Selma Fine, was a Ph.D. of considerable repute herself, and worked for the U.S. Bureau of the Census as an economic statistician. Sadly, she passed away in 1962, when Paul was only 13.

As Vice-president of the Development Center of the International Organization for Economic Cooperation and Development (OECD),[2] Raymond Goldsmith spent significant time abroad, and Paul spent the last two years of high school living in Paris, France. There, Paul attended the American School of Paris in the suburb of Louveciennes. It was both a memorable cultural experience and an important exploratory period for Paul, who admits to having had time to build radio controlled boats, which he eagerly deployed in ponds in the Bois de Boulogne, as well as motorized model airplanes—which were somewhat less successful. He also tinkered with electronics and was good friends with several HAM radio enthusiasts. In his graduating class of only 29 students, Paul was ranked 3rd, which nonsensically, was considered to be below the top 10% admittance tier steadfastly maintained by many of the universities he was hoping to attend on his return to the United States. Fortuitously, his older brother Donald,[3] who had recently graduated with a degree in astronomy from Harvard, and who was then attending the University of California Berkeley as a graduate student in Astronomy, had sent Paul an application for undergraduate admissions. Paul completed the application for the Berkeley College of Engineering, which had no problem accepting this *expatriate* student. In 1965, Paul returned from Paris and joined his brother in northern California.

When Paul saw how little leeway there was in the engineering curriculum at Berkeley, and realized that his interests were leaning more toward bridging our understanding of the universe than toward spanning rivers, he decided to switch into the College of Letters and Science, and major in physics. He

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[1]Due to very busy schedules, but close proximity residences, Paul Goldsmith and I met on two occasions during the week of May 4th (2015) to complete the background for this THz Pioneer article. On both visits to Paul's house in Pasadena, CA, USA, we were joined by his friendly and affectionate English Cocker Spaniel, Chloe, who made sure any lapses in conversation were filled in by pets and caresses. Paul's amazingly broadband career in astronomy—from MHz to THz; from ground systems to space instruments—parallels the broad swings of his life–from academia to business, from engineering to science, from east coast to west coast, to east coast, and back.

[2]The OECD was a derivative of the Organization for European Economic Cooperation (OEEC), the agency established in 1948 to administer the Marshall Plan for the reconstruction of Europe after World War II. Raymond Goldsmith was an active participant in the development and formulation of the currency reforms put into place in Germany and other Axis countries following the war.

[3]Dr. Donald W. Goldsmith is an award winning science author and film maker specializing in astronomy and space science. His most recent text (with Neal de Grasse Tyson), "Origins: Fourteen Billion Years of Cosmic Evolution," was published in 2014. Paul has an older sister as well, Dr. Jane Goldsmith, who has a B.A. in Russian literature from Radcliffe College, and a Ph.D. in clinical psychology. Paul's only niece, Rachel, Donald's daughter, also has a doctorate in psychology, and his wife, Sheryl E. Reiss, has a Ph.D. in Art and Archaeology from Princeton, making this a family completely filled by Ph.D.s!

began with an interest in low temperature physics, working in Linn Mollenauer's[4] lab, but (now) lightheartedly claims he did not like working in the windowless basement (perhaps a prescient moment for an *astronomer*!). After receiving his undergraduate degree in 1969, Paul had a summer job at the Lawrence Radiation Lab in Berkeley and tried nuclear physics, working on beta decay, but he found the large (by the standards of the time) research team a bit impersonal.

Charles Townes arrived at Berkeley from MIT in 1967, and had then helped launch the field of molecular line astronomy with the discovery of ammonia [4], [5] and water [6] in interstellar space, using high-resolution microwave spectroscopy (20–25 GHz) with the Berkeley 20-ft radio telescope at the Hat Creek Radio Observatory, near Redding, CA. Townes was convinced that there was a strong future for millimeter-wave and far-infrared observations, but no high-resolution instruments were yet in hand. Goldsmith liked the approach the Townes' group was taking—building an instrument, and then using it for the collection of science data—and he joined the group in 1971. Although he did not state it at our meetings, the fact that his brother Donald had just completed a doctorate in theoretical astrophysics at Berkeley may have had some positive influence in on Paul's choice of research area.

Townes set Goldsmith on a path to construct a heterodyne receiver that could be used for astronomical spectral line measurements beyond 100 GHz. It was a particularly relevant experiment for astronomers because recent rocket and balloon measurements of the cosmic background emission at submillimeter wavelengths [7] showed anomalous excess radiation above the 3 K blackbody curve, and some at UC Berkeley were thinking this could be due to a strong unresolved spectral line [8]. At Townes' suggestion, Berkeley's John Clauser[5] had tried building a 220 GHz heterodyne instrument (working within an atmospheric window) for the purpose of detecting these possible narrow band signals, but the controversy was settled before Clauser got very far [9]. By the time Goldsmith became involved there was a box of components, including a harmonic mixer block built by Emory Horvath at Custom Microwave,[6] but not much in the way of a suitable receiver.

Townes was convinced that there was still significant merit in constructing and using a heterodyne instrument in the submillimeter, and Goldsmith decided to focus on observing the radiation from the $J = 2 - 1$ rotational transition of carbon monoxide at 230 GHz, which was yet to be observed in space. The lowest ($J = 1 - 0$) transition of this molecule had been observed with great fanfare in 1971 by Bob Wilson, Keith Jefferts and Arno Penzias with the 36-foot antenna of Kitt Peak National Radio Astronomy Observatory [10]. The modeling that Goldsmith carried out confirmed the viability and utility of observing the higher transition [11], and he started trying to assemble a working receiver from the parts Clauser had collected. Paul constructed his own 3rd harmonic mixer using the Horvath cross-waveguide structure and a hand-contacted crystal extracted from a 1N53 whiskered diode. The local oscillator source was a 77 GHz klystron and the intermediate frequency amplifier was an old radar paramp that Paul relayed was the size of a desktop computer. The system temperature was significantly higher than 100 000 degrees!

Fortuitously, and before any serious attempts at telescope observations were to take place, noted millimeter-wave radio astronomer Patrick Thaddeus (a former student of Townes, and at the time, with Columbia University and the NASA Goddard Institute for Space Studies in NYC, now Professor Emeritus at Harvard), visited the lab and suggested that Paul might have an easier time if he moved the local oscillator frequency up to 115 GHz and constructed a second, rather than third harmonic mixer. Berkeley's William (Jack) Welch, who was then in charge of the Radio Astronomy laboratory, which operated Hat Creek Observatory, was working at 3 mm wavelength and happened to have 115 GHz klystrons (quite expensive items at the time $>$ \$5000 $hboxeach$) that he consented to lend to Goldsmith. At the same time, Gerry Wrixon[7] (who had graduated from Berkeley in 1969 under Welch, and was working with the radio astronomy group at Bell Labs) came through with some new very low capacitance photolithographed Schottky diodes that were being fabricated by Martin Schneider and his team at the Bell facilities in Holmdel, NJ [12], [13]. After getting Horvath to modify one of the cross-guide mixers for use at a higher intermediate frequency (they were originally constructed for MHz output), and incorporating a *Schneider* diode, the receiver noise fell to 37 000 K—low enough to do some serious observations [14].

The immediate problem was that there were few radio telescopes that had surface accuracies suitable for working above 200 GHz. After some calculations on the impedance of metal films with thicknesses well below a skin depth, Paul convinced himself that the thin aluminum coating on an optical telescope mirror would serve at these long wavelengths. He managed to get a reasonably large amount of observing time (since optical astronomers work exclusively at night while radio astronomers can observe 24/7!) at the University of California's Lick Observatory, using their 120 inch optical telescope.

Goldsmith went out to the telescope in 1973 and did some initial observations at 230 and 345 GHz with Berkeley colleagues, Dick Plambeck and Ray Chiao [14]. Accurate pointing of the telescope towards small area radio sources during daylight hours turned out to be quite difficult, but eventually (in 1974) they got everything working and made extensive measurements

[4]Mollenauer worked at Berkeley from 1965 to 1972, after which he moved to Bell Laboratories, Holmdel, NJ. He is best known for his work (and textbook) on optical solitons, and is the recipient of several major awards including the R.W. Wood Prize, the Franklin Institute's Ballantine Medal and the Charles Hard Townes Award of the Optical Society of America.

[5]John Clauser came to Berkeley in 1969 and is best known for his contributions in quantum mechanics, especially quantum entanglement, which led to the Wolf Prize in Physics in 2010.

[6]Custom Microwave in Longmont, CO, USA, founded in 1965, was one of the first companies to supply submillimeter-wave components to science laboratories around the world. A key building block, constructed by founder, Emory Horvath, was the cross-guide multiplier/mixer. This precision component consisted of a point contact diode rectifier that generated harmonic power using an interconnected hole through a pair of waveguides arranged at right angles to one another, and sized according to the passbands of the fundamental and desired output harmonic signals. The device was extremely popular in the early days of THz spectroscopy and could be used either as a harmonic multiplier or harmonic mixer. Variations were also sold as broadband detectors and could be found in many THz spectroscopy labs—including several in which the author worked!

[7]Gerald Wrixon went on to become President of University College Cork, Ireland and the founder of Farran Technology in 1977, one of the first submillimeter-wave component companies in Europe.

of ^{12}CO and ^{13}CO in the Orion Nebula and other five other star forming regions [15]. By this time the system noise was down to 9000 K double sideband, and they had a 50-channel filter bank on loan from the National Radio Astronomy Observatory. Although this was not the first observation of the $J = 2 - 1$ transition of CO in interstellar space (Goldsmith was scooped by Tom Phillips, who was working with Keith Jefferts and Peter Wannier at Kitt Peak using an InSb mixer [16], [17], to make the first CO $J = 2 - 1$ measurements in July 1973), it led to a popular thesis. Before finishing up at UC Berkeley, Goldsmith and Plambeck got the receiver noise down to a record 6000 K double sideband (approaching the best fundamental mixer performance of the day) [18]. Paul's only regret from his Berkeley days was that he did not spend more time on observations with the new instrument [19], [20].

Both the successful measurements of CO, and the close contact with the Bell Laboratories team, led to a job offer from (soon-to-be) Nobel Laureate, Arno Penzias. Bell laboratories was just starting the development of their 7-m dish millimeter-wave telescope, and so different was the job market in science at the time, that Paul managed to turn Penzias' post-doc offer into a permanent staff appointment. He arrived in Holmdel, NJ, USA, in 1975, and began working with the radio astronomy team on receiver systems. This was an amazing period at Bell Laboratories, with almost every staff position occupied by a science notable. Paul was very interested in optical systems, and it was no coincidence that Jacques Arnaud as well as Herwig Kogelnik and Tingye Li [21] were working close by. Building upon his instrument work at Berkeley, Paul designed a novel single-sideband filter and local oscillator injection scheme based around a Fabry–Pérot. The design was complicated by the very large beam diameter required to keep diffraction and walkoff loss to a minimum [22]. He also participated in observations with the Bell team [23] and worked with many individuals who would become close long-term collaborators [23], [24].

In the fall of 1976, Paul was invited for a visit to Amherst, MA by well-regarded radio astronomer, Richard Huguenin.[8] Huguenin was assembling a notable team that included Nick Scoville (currently at Caltech), Joe Taylor (who won the Nobel Prize in 1993 for his discovery of Pulsars), cosmologist Ted Harrison (who passed away in 2007), Sigfrid Yngvesson (a former postdoc of Charles Townes), Peter Wannier (recently arrived from Princeton and from working with Arno Penzias' group at Bell, and later at Caltech and JPL), and others. Construction of a new 14 m radio telescope exclusively for millimeter-wave observations was underway. Huguenin was extremely persuasive, and he convinced Goldsmith to join the group and to come to the University of Massachusetts (UMass), Amherst, in June 1977.

[8]George Richard Huguenin, a graduate of MIT and Harvard, was founder and director of the Five College Radio Astronomy Observatory and professor of physics and astronomy at the University of Massachusetts. In 1982, he founded Millitech Corporation, South Deerfield, MA, the first US commercial company to focus exclusively on millimeter and submillimeter-wave components and systems. He later left academia and founded Millivision, to develop passive millimeter-wave imaging for commercial applications, including car radar and security screening systems. Both companies changed hands several times, but Millitech, LLC, Northampton, MA, USA, continues today as a successful piece of Smiths Microwave, supplying millimeter-wave components and systems, and Millivision can still be found in South Deerfield developing passive millimeter-wave imaging instruments. Huguenin passed away in 2012.

Paul recalls (perhaps with just a little bit of lament in the telling) giving up a \$21 000/year salary at Bell, for a \$15 000 nine-month stipend at UMass. On the plus side, he also remembers being able to trade a small house in Holmdel, for a more substantial one in Amherst at 3/5 the cost. Goldsmith also recalls the shock of leaving an institution where there were no proposals to write and with unlimited equipment (and people) resources, and arriving at a place where equipment was acquired by scanning government surplus lists and taking donations from anywhere and from anyone willing to part with something useful. However, Goldsmith had always been interested in teaching, and UMass provided this opportunity in spades!

The 14-m radio telescope was completed in 1976, and installed inside a radome (later upgraded to a novel Gore-Tex Teflon design) on the Prescott Peninsula in New Salem, MA. It was part of the Five College Radio Astronomy Observatory, a collaboration of UMass, Amherst, Hampshire, Mount Holyoke and Smith Colleges. Richard Huguenin was the director, and Paul became an associate director in 1980. The group included several other notable young astronomers, physicists, and engineers, including William (Bill) Langer (from Bell and Princeton), Neal Erickson (a former Berkeley Ph.D. student), Read Predmore (who came from the National Radio Astronomy Observatory), John Kwan (out of Caltech) and visiting scientist Antti Raisanen, from University of Helsinki, Finland (now Aalto University).

Between teaching assignments and proposal writing, *Professor* Goldsmith began working on receiver development and optical systems for the new telescope [25]–[27] as well as keeping up with radio science through observing runs [28]–[35]. A chance encounter with a nearby spectroscopy and radar group at MIT Lincoln Labs, and particularly with Harold Fetterman (currently at UCLA), resulted in a close collaboration on the first submillimeter-wave radio astronomy receivers based on whisker-contacted Schottky diode corner cube mixers. Paul contributed the idea of coupling the local oscillator into the mixer via a dual beam quasi-optical diplexer. These receivers required large and complex gas laser sources for pumping the heterodyne mixers, and were quite noisy (cryogenic cooling was later used to lower the thermal noise of the diode detector [36]), but were successfully deployed for astronomical observations above 600 GHz. Working with a NASA Goddard Space Flight Center, Greenbelt, MD, group led by Dave Buhl, the team made the first detection of the $J = 6$ to $J = 5$ transition of carbon monoxide in the Orion nebula at the NASA Infrared telescope facility (IRTF) on Mauna Kea in Hawaii in 1981 [37]–[39].

Using new diodes from Bell Laboratories (Martin Schneider's team) and from the University of Virginia (Bob Mattauch's group [40]), the W-band cooled Schottky mixer receivers for the 14 m FCRAO telescope broke all performance records in the 1980's, achieving noise temperatures well below 100 K [41]–[44].

During 1981/1982, Huguenin and Goldsmith ended up spending a lot of social time together. They started talking about the component development that had successfully been initiated for the FCRAO telescope, and wondered if there might be a commercial market for all this new millimeter-wave technology. FCRAO had just completed work on a Department of Defense contract for a continuous comparison radiometer instrument at 94 GHz [45], [46], which had brought in significant funding, and as a spin-off, support for the telescope. The two believed this type of contract might be a way to finance a start-up business. Huguenin took a sabbatical and began to develop a business plan and solicit investors. He decided to bring together a group of part-time technical people and to make a go of it. Goldsmith, Erickson, and Harold Fetterman were members of the founding technical group. The company became the Millitech Corporation in June 1982, and was to be one of the very first private companies to develop and market exclusively, millimeter and submillimeter-wave components and subsystems. Orders began coming in for a wide variety of custom millimeter-wave products, many of which required Goldsmith's unique optical design skills. He recalls spending a good fraction of his time on Millitech-related tasks in the early 1980's but, as a consequence, he acquired many new skills, which he would later put to good use. Paul stayed involved with Millitech through 1992, at which point there were more than 120 employees and the company was supplying hardware to nearly every science group worldwide that was working on millimeter or submillimeter-wave applications!

Goldsmith's interests in long wavelength optical elements and analysis techniques continued to grow. Mixed in with his more than 135 observational astronomy and astrophysics papers between 1982 and 1992 (including a compendium on radio astronomy instruments and techniques [47]), are the seeds [48]–[63] for what would later turn into an extremely popular text on quasioptics [64]. An excellent summary of this work is contained in a review article [65] in what the author considers to be the best compilation of Terahertz technology review papers ever published, the November 1992 issue of the PROCEEDINGS OF THE IEEE [66].

The Submillimeter-Wave Astronomy Satellite (SWAS) began as a proposal from Cornell University's Martin Harwit, with Goldsmith and others, to NASA in the mid 1980's [67]. Harwit was interested in water vapor, and Paul was interested in interstellar molecular oxygen [68], [69] and both molecules' role in cloud cooling and star formation. Although the proposal was not funded, it led to a much larger effort led by the Harvard Smithsonian Astrophysical Observatory's Gary Melnick in 1988. Melnick brought in a number of scientists, including Goldsmith (a co-investigator), but also placed most of the critical receiver development in the hands of Millitech, and specifically Neal Erickson (also a SWAS co-investigator). SWAS was to measure a wide variety of interstellar gases, explicitly targeting water, molecular oxygen, atomic carbon and carbon monoxide, with an ambitious complement of two passively cooled Schottky diode heterodyne receivers at 492 and 557 GHz. Although not completed and launched until 1998, SWAS proved to be an exceptional pioneering mission—the first submillimeter-wave heterodyne instrument to fly in space [70]. Goldsmith and his UMass and Millitech colleagues deserve a large measure of credit for both its technical and scientific successes.[9] A few of the many references to the SWAS instrument and the observational accomplishments that Goldsmith contributed to, are contained in [71]–[78], especially those involving interstellar water and oxygen.

In 1992, in part inspired by his wife Sheryl's research on Italian Renaissance art, Goldsmith took a sabbatical from UMass to work with the late Professor G. Tofani at the Arcetri Observatory in Florence, Italy, where he also began writing his textbook on quasioptics [64]. The FCRAO telescope had just completed and installed a breakthrough 15-element state-of-the-art heterodyne array receiver at the focal plane [79], and Paul was ready for a change. Cornell University was then searching for someone to take over the directorship of the National Astronomy and Ionosphere Center (NAIC) that had stewardship of the world's largest single dish radio telescope—the Arecibo Observatory in Puerto Rico. The move from Amherst to Ithaca, NY, in 1993, only exacerbated the misery of long, cold winters in the US northeast, but the frequent trips to Puerto Rico did offer brief interludes during the bleaker times of the year!

The 1000-ft diameter Arecibo telescope was conceived and constructed in the early 1960s by Cornell's William Gordon. Unique, in having a spheroidal surface that produced a line (rather than point) focus, the telescope was originally intended for active observations of the Earth's ionosphere (using radar reflection in the MHz bands). The telescope had undergone a major upgrade in 1974, when solid panels replaced its original wire mesh surface, and a 500 kW CW 2380 MHz transmitter was installed to be used for radar studies of the solar system [80].

When Goldsmith arrived at NAIC, the National Science Foundation had just approved a new dual-mirror Gregorian reflector feed system for construction. The new optical configuration, completed in 1997 [81], would overcome the limitations of the line feeds used until then to correct the spherical aberration of the primary reflector. The Gregorian correcting mirrors, which produced a point focus with low spherical aberration, had to be numerically designed and optimized, since the surfaces are both aspherics (typical Gregorian telescopes use an ellipsoidal correcting mirror with a parabolic main dish). The new optics, along with an individually hand-tweaked set of 40,000 aluminum surface panels for the main reflector (ultimately achieving a surface RMS of 1–2 mm), allowed the telescope to operate at significantly wider bandwidths (1–2 GHz instead of 20 MHz), much higher frequencies (up to and beyond 10 GHz), and with greatly enhanced sensitivity (4× higher), and more than two times higher transmit power [80]. During the time Goldsmith directed the NAIC, and while colleague Dr. Daniel Altschuler directed the observatory itself, Arecibo played a prominent part in two Hollywood films—*Goldeneye* in 1995, and closer to home—*Contact* (based on Cornell astronomer Carl Sagan's popular novel of the same title). For an interesting cocktail hour discussion be sure to ask Paul about Pierce Brosnan and Jodie Foster!

In 2003, Goldsmith left his position at NAIC, and returned full time to Cornell's astronomy department to continue teaching and research. During the years he had directed NAIC he had kept up his astronomical observations and his astrophysics studies [82]–[98], as well as his work on instrumentation [99]–[103].

[9]https://www.cfa.harvard.edu/swas/people.html

After yet another rough winter in Ithaca in 2005, Goldsmith's long-time colleague and friend (going back to their days at Bell Laboratories), Bill Langer approached Paul with an offer to join him (Langer) at the NASA Jet Propulsion Laboratory (JPL) in Pasadena, CA, where submillimeter-wave astronomy was in its *Renaissance* moment. The *Herschel Space Observatory* [104] was in the instrument build phase, and there were many more anticipated submillimeter-wave instrument programs in the European and US space mission queues. The Atacama Large Millimeter Array (ALMA) [105] was also in the last stages of planning before beginning telescope construction, and there were other major ground-based millimeter and submillimeter wave observatory proposals getting visibility. There was also a significant millimeter-wave astronomy community at nearby California Institute of Technology, where submillimeter astronomers Tom Phillips [104], Anneila Sargent, Nick Scoville, John Carpenter, and Dariusz Lis, among others, were working.

Paul opted for the warmer weather and the shift back to higher frequencies, and arrived in Pasadena, CA, in August 2005. He started work on various projects [106]–[109], but soon became involved in *Herschel*, taking the role as NASA Project Scientist, while he worked with a group at JPL focusing on galactic evolution. His experience with both instrumentation and pure science was a perfect fit for Goldsmith's roles at JPL, where he was able to relate to, and often mediate between, the sometimes-conflicting needs of technologists and scientists, as they worked toward the same goals.

The Herschel Space Telescope launched in May 2009 and, despite some early problems in the THz heterodyne instrument (HIFI), traced to a power supply in the spectrometer module that shut down abruptly, and in so doing took out several rectifying diodes (fortunately the instrument carried a complete spare that did turn on and worked perfectly), it has enjoyed spectacular success. Goldsmith led the Herschel Oxygen Project (HOP), a search for interstellar O_2, predicted to be the third most abundant molecule in interstellar clouds. It was finally detected in Orion [110] and rho Ophiuchi [111]. The explanation for its rarity in the gas is a result of oxygen atoms sticking on the dust grains, being converted to ice, and thus being unavailable for forming O_2 until a shock wave cleans off the grain mantles and restarts the “standard” gas phase chemistry.

Goldsmith also participated in more than 50 major papers (and counting) from the Herschel Space Observatory mission. In 2013, we were fortunate to get an early summary of a few of the important Herschel HIFI science results from Paul and colleague Dariusz Lis, as part of a review article for this journal series [112].

From 2009 to 2015, Goldsmith served as Chief Technologist for Astronomy and Physics at JPL, where he worked to coordinate technology development for future space missions. He is currently collaborating closely with Chris Walker (one of our original Topic Editors for these transactions) on an ambitious balloon-borne Stratospheric Terahertz Observatory (STO) program that carries heterodyne array receivers operating from 1.4 to 4.7 THz (targeting spectral lines of [CII], [NII], and [OI]) and launches into the Antarctic vortex for extended observation runs.

Since coming to JPL, Goldsmith has continued to collaborate and publish with astrophysicists around the world (more than 100 papers since 2005), and he is extremely excited by the new technologies that are rapidly coming on line through advances in CMOS circuits. He is confident that these will soon enable extremely wideband, low power spectrometers that will revolutionize future heterodyne array receiver capabilities.

Paul's eyes still light up when he is asked about the grand challenges facing astronomers today and the implications of potential observations from THz telescopes in the near future. What controls the rate of star formation? How does interstellar gas evolve from its initial atomic state into the rich molecular structures we measure throughout the galaxy? What role can polarization play in unraveling the origins and structure of the universe as we see it? We could go on for hours, but I think it is time to let Paul get back to work. *“There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.”*[10] THz science hopes to bring some of them to light.

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Paul Goldsmith (M'75–SM'85–F'91) completed the undergraduate and graduate degrees from the University of California, Berkeley, receiving the B.A. degree in 1969, and the Ph.D. degree in 1975 in physics, while working in the area of radio astronomy.

Following two years as Member of Technical Staff at AT&T Bell Laboratories, he was a faculty member in the Department of Physics and Physics and Astronomy at the University of Massachusetts, Amherst, MA, USA, from 1977 to 1992. Goldsmith's technical work centered on the development of low noise millimeter wavelength receivers for the FCRAO 14 m telescope and submillimeter systems for a variety of facilities. Continuing work started at Bell Laboratories, he focused on development of quasi-optical propagation and components for diplexers, filters, and other functions at millimeter and submillimeter wavelengths. Goldsmith's research in astronomy focused on determining the structure and physical conditions of dense interstellar clouds, out of which new stars form. The importance of observing key molecular species and understanding their role in molecular cloud structure and evolution motivated his work on the Submillimeter Wave Astronomy Satellite (SWAS), launched in 1998, on which he was a co-Investigator. In 1982 Goldsmith was one of the founders of the Millitech Corporation, and served for 10 years as Vice President for Research and Development. This activity involved exploiting quasi-optical techniques for a variety of remote sensing and materials measurement applications. In 1993, he moved to Cornell University, Ithaca NY, USA, as a Professor in the Department of Astronomy, and until 2002 served as Director of the National Astronomy and Ionosphere Center, which operated the Arecibo radio telescope in Puerto Rico. He was involved in major projects determining the atomic hydrogen content of molecular clouds and surveying the Milky Way for methanol masers as signposts of very recent star formation. Goldsmith moved to JPL in 2005, where he has been working on a number of projects in millimeter and submillimeter astronomy. He is NASA Project Scientist for the Herschel Space Observatory, and is PI on the "Herschel Oxygen Project", which recently made the first multi-transition detection of the O_2 molecule in the interstellar medium. From 2009 to 2015, he served as Chief Technologist for the Astronomy Physics and Space Technology Directorate at JPL, Pasadena, CA, USA, working to coordinate JPL and NASA technology development efforts for future space missions. He is Professor Emeritus of Astronomy at Cornell University, Adjunct Professor of Astronomy at the University of Arizona, and Senior Research Scientist at JPL.

Prof. Goldsmith is a Fellow of the Institute of Electrical and Electronics Engineering. Goldsmith is married to Sheryl Reiss, an historian of Renaissance art. They live with their English Cocker Spaniel, Chloe, in Pasadena, CA.