JILA

The First 50 Years

1962 to 2012

University of Colorado Boulder

NIST

JILA: The First 5O Years

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Acknowledgements

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Cover photo: The JILA X-Wing, completed in 2012. Credit: Brad Baxley

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Introduction

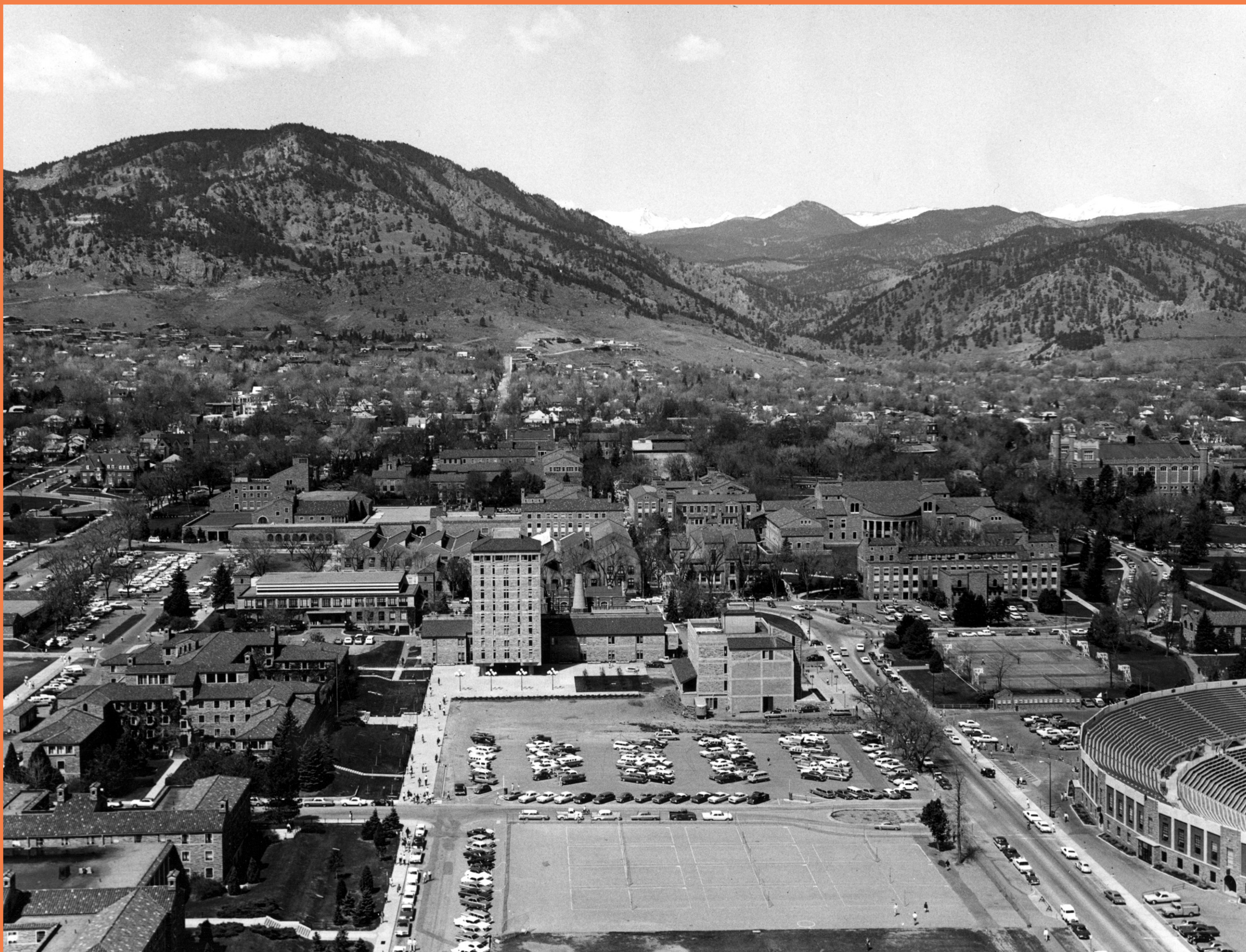
The 50-year history of the Joint Institute for Laboratory Astrophysics, now known simply as JILA, comprises the stories of thousands of dedicated people. These scientists and staff members include the JILA founders, the JILA faculty in Boulder, adjoint JILA faculty at other institutions, University of Colorado (CU) graduate students, postdoctoral research associates, and visiting scientists from all over the world as well as technical and administrative staff members. Although the contributions of all these people figured in the evolution of the Institute, only relatively few of them are identified by name in this account.

JILA scientists began their scientific journey together with a common goal of creating and strengthening the field of laboratory astrophysics. As time went on, the research interests of the JILA faculty diverged to the point where research in laboratory astrophysics became rare and, at times, nonexistent. Whether their work focused on laboratory astrophysics; theoretical astrophysics; atomic, molecular, and optical physics; biophysics; chemical physics; or nanoscience; generations of JILA scientists have helped the Institute grow into the powerhouse it is today. Precision measurement science has been the central theme connecting all these activities.

Over the years, JILA has profited from the work of an exceptionally good group of graduate students and postdoctoral research associates. The contributions of these young scientists are simply too numerous to recount here. They are, nevertheless, greatly valued and are central to the story of what has made JILA an exceptional Institute. Many of those trained at JILA are participating in the 50th anniversary celebration. They are faculty at JILA and other universities all over the world, staff members of national laboratories in the United States and abroad, and founders and valued technical staff of local, national, and international businesses. The JILA web site lists many of these career destinations at http://jila.colorado.edu/content/where-are-scientists-trained-jila.

For its entire history, JILA has also been blessed with a dedicated staff. Individual staff members have gone out of their way countless times to make the Institute "work." They've spent innumerable weekends helping JILA scientists assemble critical experimental apparatus and have freely shared their expertise in instrumentation, electronics, computing, and scientific writing with young scientists in training.

During the past 50 years, the people of JILA have created and fostered a culture of



Aerial view of the University of Colorado at Boulder campus showing JILA's new tower and laboratory building in August of 1967. *Credit: University of Colorado*

collaboration that was ingrained on the new Institute by its founders in the 1960s. This culture has placed a high value on collaborative research not only between JILA theorists and experimentalists, but among theorists and experimentalists as well. Collaboration is one of JILA's great strengths. The ability to work together on challenging scientific problems distinguishes JILA from many other academic departments and scientific organizations. It is JILA's shared legacy, a legacy that has spanned five decades. This legacy is a part of those who are in Boulder celebrating JILA's 50th anniversary this summer, of former JILAns who were unable to come to Boulder for various reasons, and of our colleagues whose time on Earth has passed. This short history is dedicated to all of you.

Reflections on the First 50 Years of JILA

Dr. Lewis M. Branscomb, Founding Fellow

JILA was conceived in Moscow, approved in Washington, and born in Boulder 50 years ago. Now, as we look into the past of this highly successful and widely admired scientific institution, we can appreciate how many people played key roles in this history. It is very unlikely that today's federal, state, and academic institutions could repeat such an achievement.

Dick Thomas, a key co-founder of JILA, was a Harvard-trained theoretical astrophysicist. He appreciated that quantitative knowledge of the optical and atomic collision processes of stellar atmospheres was necessary to understand the behavior of hot gases not in thermodynamic equilibrium. I am an atomic physicist, and my dissertation at Harvard explored non-equilibrium processes in the Earth's upper atmosphere. At the National Bureau of Standards (NBS), Steve Smith and I were exploiting new spectroscopy tools to study negative hydrogen ions that controls the temperature of the solar photosphere. Thomas and I were attending the Moscow meeting of the International Astronomical Union where our convergent interests led to the idea of a "Laboratory Astrophysics" institute, now known only as JILA.

Not only were our Ph.D.s both from Harvard, but we were both working at NBS. Dick was at the High Altitude Observatory in Boulder; I worked at NBS in Washington D.C. where a team of extraordinary talent, among them Steve Smith, Pete Bender, Jan Hall, Earl Beaty, and Syd Geltman had been assembled. How would we bring off the creation of a new JILA institution? We were naïve and idealistic, but Dick Thomas was especially determined never to let anyone say "it can't be done."

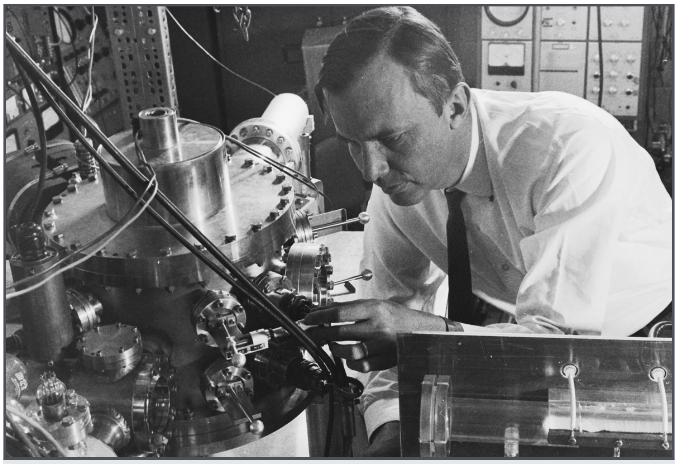
> When I told [NBS Director] Dr. Astin that the atomic physicists group and NBS astrophysicists in Boulder (Dick Thomas and John Jefferies) proposed to leave the "Bureau," to start a Joint Institute for Laboratory Astrophysics at a university, Astin's response was, "Great idea, but you don't have to leave the Bureau. I will move your team, budget, and apparatus to the university you choose."
>
> —Lewis M. Branscomb

Indeed, had it not been for the vision and willingness of the NBS Director, Allen Astin, to take risks, our vision would surely not have been realized. When I told Dr. Astin that the atomic physicists group and NBS astrophysicists in Boulder (Thomas and John Jefferies) proposed to leave the "Bureau," to start a Joint Institute for Laboratory Astrophysics at a university, Astin's response was, "Great idea, but you don't have to leave the Bureau. I will move your team, budget, and apparatus to the university you choose." We then shared with Astin Thomas' dream of an international Visiting Fellows Program, bringing the best physicists, chemists, and astrophysicists for a year of research at JILA, all at NBS expense. Astin raised the funds for that, too.

A number of universities liked our vision but, in Boulder, we encountered another remarkable parent-to-be of our JILA vision: University of Colorado Boulder President Quigg Newton. The childhood of JILA was then nurtured by the collaboration of NBS Director Astin and CU President Newton. Another indispensible founder was Wesley Brittin, Chairman of the CU Physics Department, who would bring NBS scientists into his faculty as adjoint professors and have his department renamed Physics and Astrophysics.

JILA's next problem: How to fund a new building on the campus? We sought financing from the Defense Department's Advanced Research Projects Agency (ARPA). ARPA's director, Robert Sproull, proved to be another visionary. He could no longer fund new buildings, but to our surprise and delight, he offered instead a continuing annual grant of $500,000 for research, to be renewed each year for three more years.

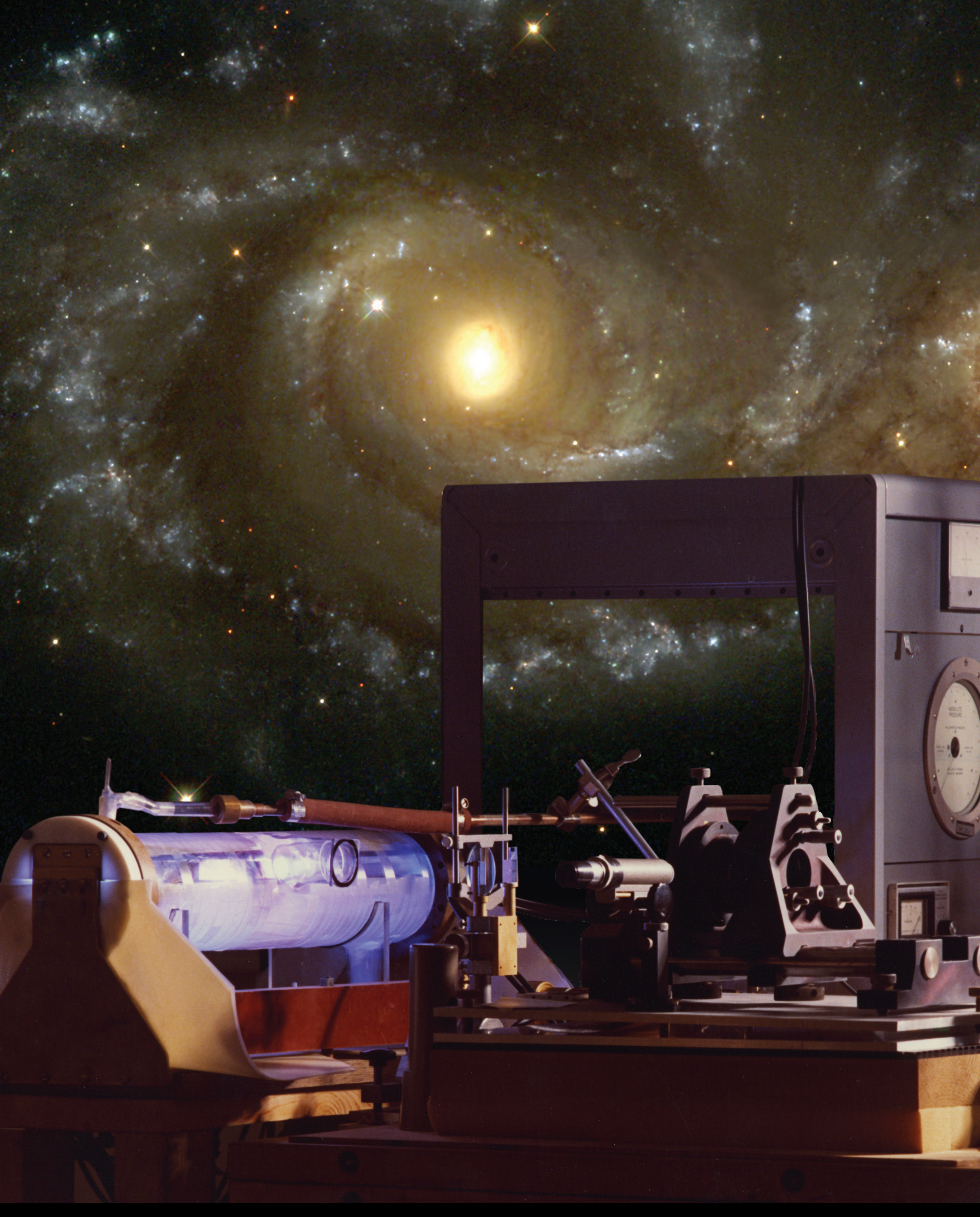
JILA's new building was made possible by the imagination of CU's chief financial officer, Leo Hill. With Allen Astin's reassurance that NBS would continue to rent its share of the new building, Hill had the collateral for a loan from the State of Colorado to match a grant to CU from the National Science Foundation (NSF) plus overhead on the ARPA grant. Another special thanks is due Steve Smith, who brought in Carl Pelander, JILA's instrument maker, arranged the move from Washington, and performed countless other tasks.


Fellow Lewis Branscomb working in his laboratory at JILA (circa 1966). *Credit: JILA*

The founding scientists at CU and NBS, together with Astin, Newton, and Hill, were responsible for the magic of JILA's extraordinary success. Not only did JILA offer a remarkable scientific environment, but also its collaborative organizational structure provided a minimum of unnecessary bureaucracy. From an administrative perspective, JILA really does not exist. The way it works rests on a set of simple principles:

- There is no Director of JILA, only a Chair of the Fellows, appointed from scientists of both partner institutions at JILA. JILA has no budget and makes no appointments. The partnership between two independent institutions, NBS and CU-Boulder, is governed through a simple Memorandum of Understanding (MOU).
- Each partner covers its own costs. Everyone in JILA is paid by one of these institutions, never by both.
- Each partner provides and supports those functions it does best; NBS provides highly professional instrument makers and shops; CU provides appointments to graduate students.
- Despite these clear distinctions in accountability between the partners, JILA's scientific program is guided by voluntary collaboration of its Fellows. The Fellows choose a Chair to preside over them.
- Should this voluntary collaboration with shared resources ever fail for lack of agreement among the Fellows, the problem is to be sent to the President of CU and the U.S. Secretary of Commerce to resolve. In 50 years this has never happened, since neither partner's interest in JILA can succeed without the other's success as well.

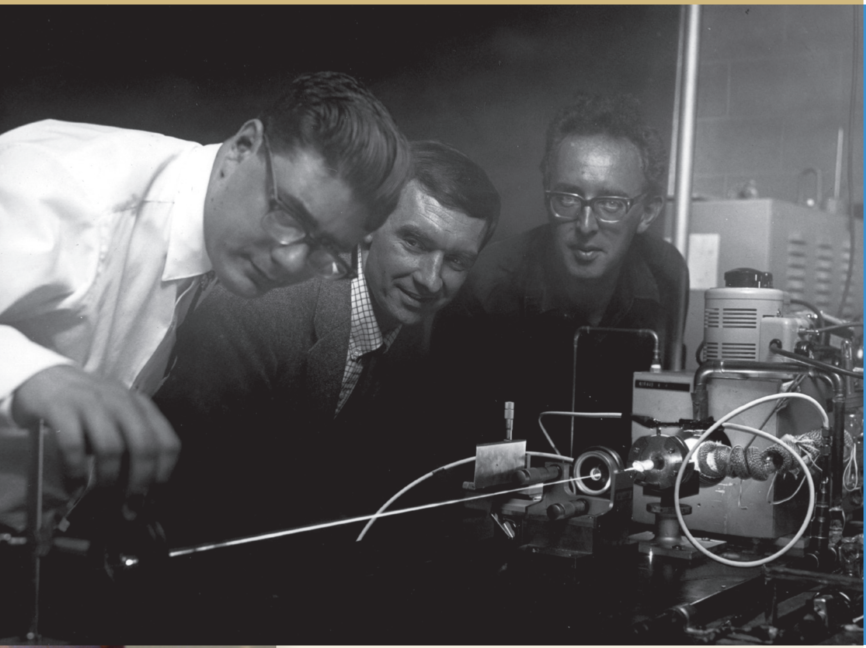
From a scientific perspective, JILA is unusual in another respect. It was created to pursue a broad vision to which it could contribute significantly, but never fully achieve. Within this vision, JILA has always been guided by maximizing scientific opportunities. JILA Fellows and staff would never have won three Nobel Prizes if each project had been subjected to the demands of conventional administrators: "How will JILA measure the extent to which each project fulfills the founding vision?" We didn't even try. "How much of its research will be 'basic,' how much 'applied?'" We never made these distinctions. JILA succeeds because of its core values, its freedom to take risks, its multidisciplinary community, and its links with scientists in other institutions in the United States and internationally. If JILA adheres to these traditions, it will continue to thrive for another half century.



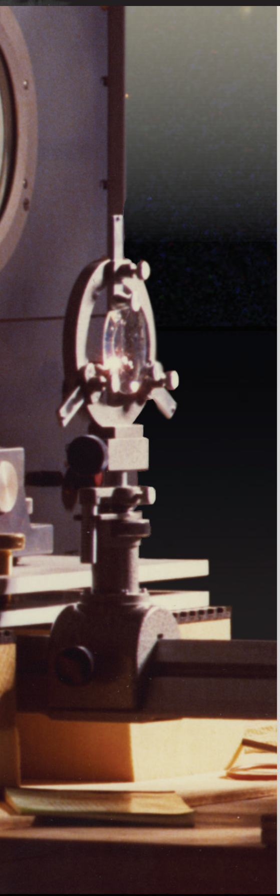
Genesis

Inspiration for an Institute

Dr. Stephen J. Smith, Founding Fellow



An early laser-based chemical physics experiment with (l-r) Fellow Dick Zare, postdoc William McClintock and Visiting Fellow Wolfgang Demtröder.



As the 50th anniversary of the founding of the Joint Institute for Laboratory Astrophysics (now simply named JILA) approached, JILA Chair Eric Cornell asked me to write a preface for a nontechnical history of JILA's founding, evolution, and scientific endeavors. The official date of this founding is April 13, 1962. An extensive documentation (more than 1000 pages) exists of the events surrounding that date and afterwards, thanks to the work of the late Professor Roy Garstang, who acted as the JILA historian for more than 40 years. An overview of what has transpired at JILA since mid-April of 1962 will be presented in the main part of this book.

However, the Joint Institute for Laboratory Astrophysics didn't suddenly appear out of nowhere in 1962. To understand its inception, I would like to include information here about the events and personalities of the previous decade that figured in JILA's founding.

For instance, there would have been no JILA without the leadership of Lewis Branscomb at NBS in Washington D.C. There also would have been no JILA without Richard Thomas at NBS Boulder and the atomic physicists who were recruited to NBS Washington by Lewis Branscomb during the 1950s.

Branscomb was a Harvard Junior Fellow while I was there as a graduate student. He had earned his Ph.D. from Harvard in 1949 and was continuing his laboratory research there. Branscomb's goal was to test an explanation of an important region of the Sun's visible light spectrum that was based on a calculation by Subrahmanyan Chandrasekhar.

The calculation modeled a simple atomic process known as negative-ion photodetachment. This process may take place at temperatures achieved in the upper levels of the Sun's atmosphere where hydrogen atoms are partially stripped of their outer electrons. The free electrons are available to attach to neutral hydrogen atoms, resulting in the emission of photons of light. Some of these photons escape and may fly into our eyes.

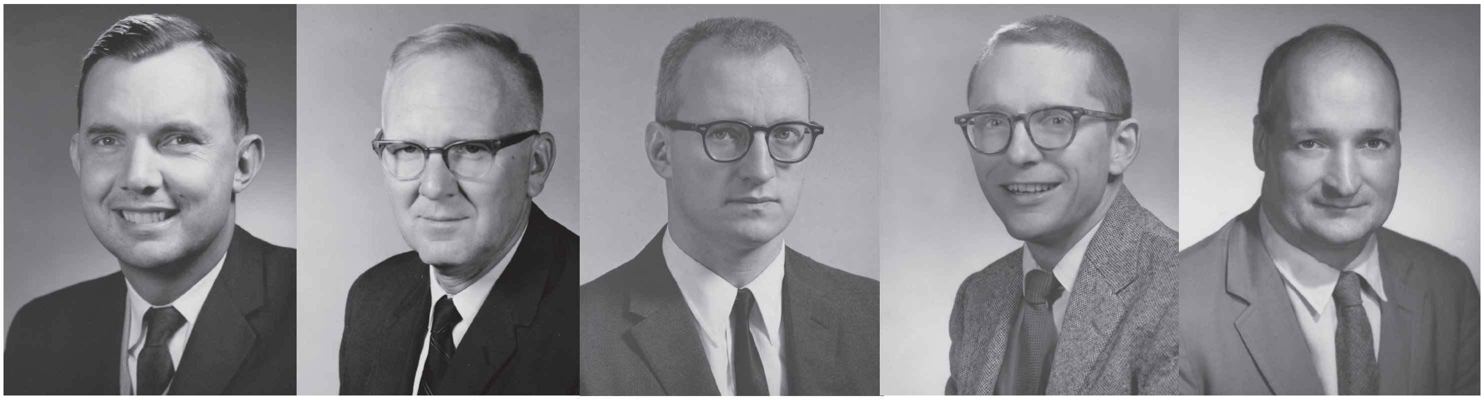
> "Thus, in my mind, was born the field of laboratory astrophysics."
>
> —Stephen J. Smith

This was a horrendously difficult laboratory project, particularly since Branscomb's approach was to undertake absolute measurements using a crossed-beam setup in an evacuated chamber. At the time, many physicists argued that the proposed measurement simply could not be done.

Not one to be deterred, Branscomb moved with his research apparatus in 1951 to NBS in Washington, D. C. Branscomb achieved a statistically significant result working with a visiting Harvard colleague, Wade Fite. Somewhat later, after I'd earned my own doctorate from Harvard, Branscomb brought me into NBS. We worked together to refine the apparatus and institute the use of radiometric standards. In the end, the accuracy of the data was improved to a level where it provided powerful support for the Chandrasekhar model of the solar visible spectrum.

Thus, in my mind, was born the field of laboratory astrophysics — laboratory work in atomic physics closely related to theoretical issues faced by astronomers. Though it didn't yet have a name, laboratory astrophysics was about to run headlong into the space race.

In 1958, Branscomb, by then head of the Atomic Physics Section at NBS Washington, spent a year working with British theoretician Mike Seaton at University College London. During this year, the two scientists attended the annual meeting of the International Astronomical Union in Moscow, where they met another Harvard Ph.D., Richard N. Thomas, a theoretical astrophysicist from Boulder,



Colorado. The three began to develop ideas for an institute that would bring together atomic physics, astrophysics, and a theory of energy transfer through the very hot gases in stars. Their efforts couldn't have come at a better time for getting people excited about linking atomic physics research with astrophysics.

At the time when Branscomb, Seaton, and Thomas came up with the idea of a joint institute for laboratory astrophysics, the space race was just a year old. The launch of Sputnik 1 in 1957 by the U.S.S.R. had turned the nation's attention toward the heavens. The idea for the new institute took root in this environment.

The dominant person in the whole process was Lewis Branscomb. He provided the necessary leadership at every step. One of the early steps was informing NBS Director Allen Astin of the idea to merge the Atomic Physics Section in NBS in Washington with the Astrophysics group in NBS in Boulder, Colorado — at a university. Astin's response was: Why leave NBS?

That question got us thinking about NBS partnering with a university to create a new kind of joint venture. It didn't take long for the idea to become the creation of a Joint Institute for Laboratory Astrophysics in which scientists, technicians, students, and administrative personnel of the sponsoring institutions — the NBS and the university — could pursue a common scientific goal. This goal would be to apply the techniques of atomic physics to answering interesting astrophysical questions. To make this happen, we had to find the right university partner.

We started looking for the right university as our discussions about founding an institute continued during 1960–1961. We considered nine institutions and visited four, including the University of Colorado at Boulder. Early in 1961, the CU Regents approved the title of Professor Adjoint for NBS faculty who offered courses at CU or supervised graduate students. After these positions were approved, six NBS scientists, including Dick Thomas and John Jefferies, a consultant in astrophysics working with the Director of the NBS Boulder laboratories, were appointed Professors Adjoint at CU. This decision laid the foundation for a closer relationship between CU and NBS.

By then, Branscomb had become the Chief of the NBS Atomic Physics Division in Washington, and I had taken over the leadership of the Atomic Physics Section. John Jefferies joined our discussions, as did Roy Garstang, who was a member of the astronomy faculty at University College London. Garstang spent April through December of 1961 as a guest worker in Branscomb's office.

JILA founding scientists:

- Lewis Branscomb
- Stephen Smith
- Pete Bender
- John (Jan) Hall
- Richard Thomas
- Earl Beaty
- Sydney Geltman
- John Jefferies
- Gordon Dunn

On January 2, 1962, Branscomb wrote a letter to CU President Quigg Newton acknowledging CU's interest in partnering with NBS to form a Joint Institute for Laboratory Astrophysics. He suggested that CU create a doctoral program in astrophysics by renaming its physics department the Department of Physics and Astrophysics. He encouraged CU to develop a new Department of Aerodynamics. He requested a single building on campus to be identified as the Joint Institute for Laboratory Astrophysics, or JILA for short. NBS would lease its share of the building and be self-supporting. However, Branscomb asked that CU seek support from the National Aeronautics and Space Administration (NASA), NSF, and other agencies. He also requested that the university appoint three faculty members by September to join the new institute.

President Newton replied to this letter on January 23, supporting all of Branscomb's proposals and promising to present the proposal to the Board of Regents on January 27. Newton's enthusiasm, which reflected the wholehearted support of Wesley Brittin, Chair of CU's Physics Department, resulted in CU's selection as a partner for NBS to found JILA. In my view, the unqualified support from Brittin was critical to JILA's evolution into one of the nation's outstanding scientific laboratories.

Meanwhile, back at NBS, the conversations turned to who would be willing to move to Boulder. Of course, nothing was going to keep Branscomb and me from coming out to Boulder to launch JILA. At Branscomb's invitation, Earl Beaty, Pete Bender, Gordon Dunn, Sydney Geltman and Jan Hall also signed up to move to Colorado.

Beaty and Bender were already working on laboratory experiments with rubidium that would one day contribute to the deployment of rubidium atomic clocks on satellites. Dunn moved to Boulder to continue his work on developing high-vacuum crossed-beam techniques. His objective was to study basic atomic and molecular collision processes that are important for understanding the behavior of extremely hot gases such as those found in stars. Geltman planned to continue his support of Branscomb's experiments with work on the theory of electron photodetachment. Jan Hall thought he might explore a recently invented new device — the laser.

Hall had arrived at the NBS Atomic Physics Section in Washington D. C. at the onset of the laser age (in 1960) and decided to move to Boulder two years later to help establish JILA. In the five decades since the move, he has maintained an international presence in the fast-moving field of laser technology. From the beginning, he was generous with his ideas and his techniques. As a result, he has had a huge effect on experimental research projects throughout JILA. He has also been an outstanding teacher, producing his own army of students, many of whom work at the more recent (1988) reincarnation of NBS as the National Institute of Standards and Technology (NIST).

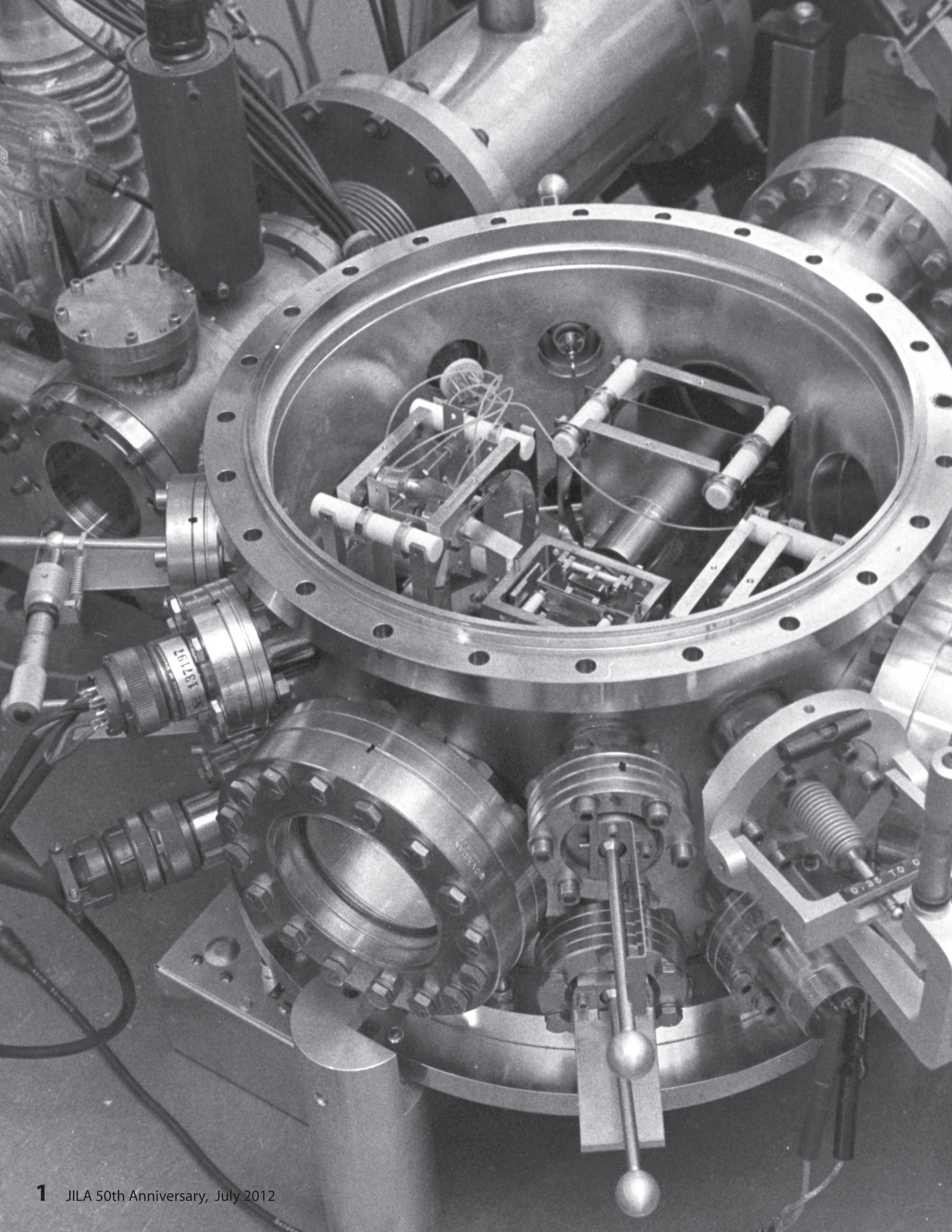
The seven scientists who brought experimental atomic and optical physics research programs from Washington, D. C. to Boulder helped shape the initial profile of the JILA laboratory program as well as its subsequent evolution. Forty-three years later in 2005, Jan Hall would win the 2005 Nobel Prize in Physics, the third one garnered by JILA scientists. Fifty years later, Hall and Bender still participate in research and help make decisions regarding JILA operations.

Goodbye to D.C.

On Our Way to Boulder

The farewell picnic & softball game for staff who left NBS to start JILA
July 1962

Credits: National Bureau of Standards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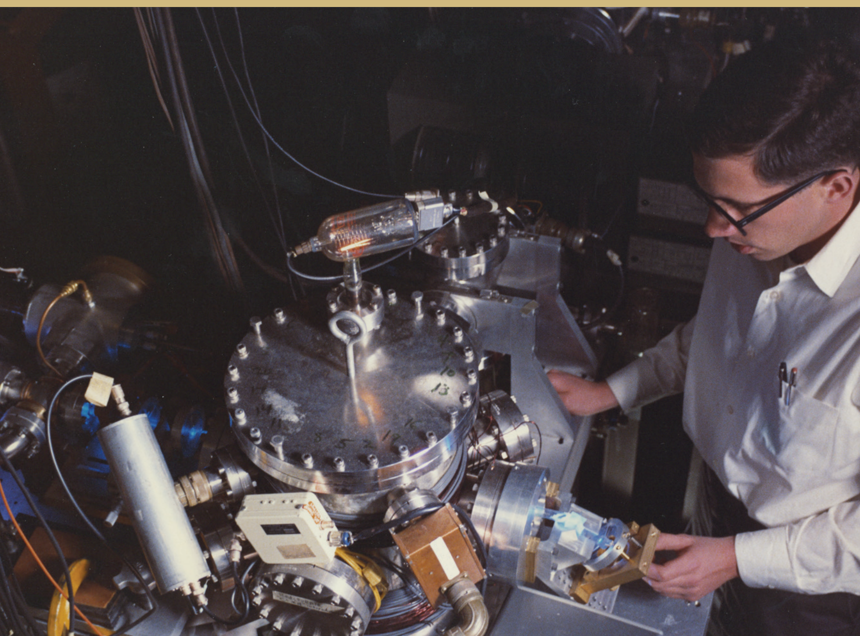
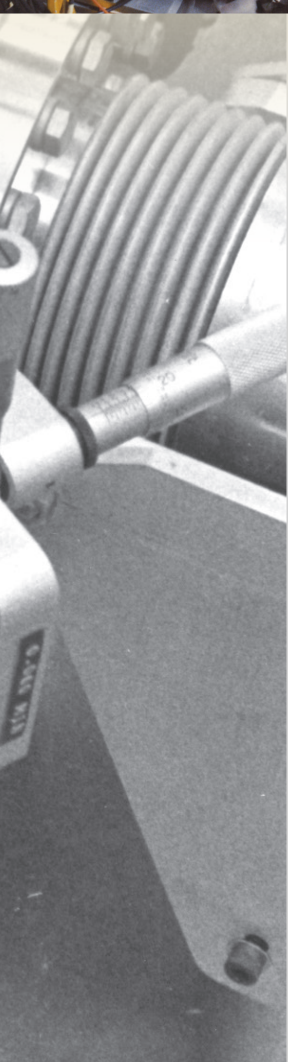
Chapter 1
1962 to 1969



Fellow Judah Levine as a postdoc investigating the electron affinity of O_2^- in Fellow Jan Hall's laboratory, circa 1968.



The Joint Institute for Laboratory Astrophysics was officially launched on April 13, 1962. The public announcement of the new Institute was the culmination of nearly five years of work on the part of Drs. Lewis Branscomb, Dick Thomas, Stephen Smith, and others. Many of the efforts in laying the groundwork for JILA are highlighted in Dr. Lewis Branscomb's "Reflections on JILA at 50" and in Dr. Stephen Smith's "Genesis: Inspiration for an Institute" in this book.

The new Institute's focus on laboratory astrophysics occurred in the context of the "space race" occurring between the U.S.S.R and the United States at the time. The 1957 launch of the Soviet Union's Sputnik satellite had ignited the rivalry, which was a central feature of American culture during the planning and implementation of the Joint Institute for Laboratory Astrophysics. Because of the national commitment to space exploration, it was relatively straightforward to obtain funding from NBS for JILA. At the same time, NBS Director Astin was willing to help launch an institute that was relatively free to make its own way scientifically.

Why Create a Joint Institute for Laboratory Astrophysics?

The JILA founders had six goals in creating a Joint Institute for Laboratory Astrophysics. First, they wanted an organizational structure that would maximize the quality and originality of scientific work. In particular, they wanted to combine insights from the theory of energy transfer through hot gases (such as those found in stellar atmospheres) with a better understanding of the optical properties and collision behavior of atoms and molecules found in those environments. In the process, they hoped to foster the field of laboratory astrophysics by combining investigations in atomic physics with relevant astrophysics research. Second, they favored a structure that would minimize the number of Civil Service jobs needed to achieve their scientific objectives. Third, they wanted ready access to international experts. Fourth, they desired to integrate their government research with related disciplines in science and technology. Fifth, they were looking for a mechanism that would allow the scientists from NBS to train young researchers in their specialized fields. Finally, they sought an organizational structure that would lead to the widest diffusion of their work, thus maximizing its impact.

To accomplish these goals, the founders planned for the scientists participating in the new joint institute to either be employed by NBS or the university partner. This structure ensured that all Federal employees would be supervised by another Federal employee and paid by the government (rather than the university partner).

That said, Civil Service employees at NBS would have to meet university appointment standards to work for the new Institute. The Institute had to be located on a university campus, but would not be a corporate entity. Rather it would be based on an intellectual unity of purpose. Institute activities had to conform to the academic culture and ethics, and technical activities had to be compatible with student needs and goals. The university would be responsible for academic affairs, and university scientists would have to raise their own research funds.

The JILA founders believed that good science would ensure the success of JILA. They also concluded that happy acquiescence, and perhaps forbearance, on the part of the sponsoring institutions would be necessary ingredients for the Institute's successful launching and ongoing operation.

Countdown to Launch

In January of 1962, Lewis Branscomb, Chief of the Atomic Physics Division of NBS, contacted CU President Quigg Newton as part of his search for a university partner for the proposed joint institute. Branscomb outlined what JILA would need for NBS to partner with CU. The requirements included establishing a Ph.D. program in astrophysics, renaming the Physics Department as the Department of Physics and Astrophysics, and developing a Department of Aerodynamics. Branscomb stated that three university faculty appointments would be needed by September of that year. He also requested that a single building on campus be identified as the Joint Institute for Laboratory Astrophysics. NBS would lease its share of the building and be self-supporting. However, CU would seek support from NASA, NSF, and other agencies.

On January 23, President Newton let Branscomb know that he supported the NBS proposals and would bring them to the CU regents on January 27. This unqualified support from President Newton and Wesley Brittin, Chair of CU's Physics Department, resulted in CU being effectively chosen from a group of nine universities that had been under consideration for the partnership. On February 2, Stephen Smith wrote to Brittin to inform him that five senior NBS scientists would be interested in appointments as Professors Adjoint at the university. Brittin agreed and changed the name of his department to the Department of Physics and Astrophysics.

On February 13, an MOU written by Branscomb was sent to CU President Newton and Oswald Tippo, the CU Provost. The MOU was subsequently approved by President Newton and NBS Director Allen Astin. The following day, Astin wrote to Under Secretary of Commerce Edward Gudeman explaining that NBS was planning to strengthen its interdisciplinary laboratory astrophysics program by establishing a Joint Institute for Laboratory Astrophysics in cooperation with CU at the university's Boulder campus. The plan was for 15 NBS staff members to relocate to the joint institute. Astin outlined specific plans for the joint institute and advantages that he foresaw for NBS.

On February 21, Branscomb presented his vision for the administrative structure of JILA, which he recapped in his "Reflections on JILA at 50." The new Institute would have no director, no budget, and no assets. Like the CU Physics and Astrophysics Department, the NBS Laboratory Astrophysics Group in JILA would have a chair, but no formal substructure. An Executive Office would include clerical, administrative, and technical staff. The group would operate its own machine shop, electronics shop, and small library. The goal of this structure was to create a setting "in which scientists, technicians, students, and administrative personnel of the sponsoring institutions — NBS and the University of Colorado — pursue a common scientific goal." [1]

Initially this goal was to contribute to the field of laboratory astrophysics.

Branscomb also laid out organizational principles[2] that have remained in place for 50 years and nurtured the pursuit of world-class physics research in JILA:

- JILA is a partnership with shared values and goals. Science opportunities rather than administrative priorities drive JILA's program. Each partner contributes to the joint institute what it does best, and both partners work to reduce constraints imposed by large-organization bureaucracies.
- The Institute is managed by the Fellows, who elect a new Chair from their ranks every two years. (This oligarchical structure was designed to prevent the personality of any long-term director from diverting JILA from its goal of collaborative research. Fifty years later, it remains in place.)
- There is unambiguous accountability on each side, with budgeting completely separate on the books. While all the activities in JILA are to be accountable to either the NBS or the university, JILA as an entity is, through the Fellows, independent.
- Each partner takes credit for the output of both. (Over 50 years, this principle has benefited both of JILA's parent organizations, each of which takes credit for all three Nobel Prizes and the two MacArthur Fellowships (genius grants) that have been awarded to JILA Fellows.)

On February 26, 1962, NBS Director Allen Astin requested legal approval to set up JILA from the General Counsel of the Department of Commerce (DOC). While

1. Stephen Smith, 1971.
2. NBS Goes West: JILA and the Boulder Labs, Lewis Branscomb, University of California, San Diego (2007).

Close up of entrance to the old State Armory Building, JILA's first home on the University of Colorado campus. *Credit: JILA*

Woodbury Hall on the University of Colorado at Boulder campus. In September 1963, JILA expanded into two and a half floors of this building. *Credit: University of Colorado* the General Counsel was considering this request, Dick Thomas, the man who'd developed the original idea for JILA with Lewis Branscomb in 1958, visited Roy Garstang in London to discuss plans for JILA with him and others at the Royal Astronomical Society meeting on March 9. Garstang would relocate to Boulder and become a Fellow of JILA in 1964.

During March, CU offered 20,000 ft^2 of space to JILA in the old State Armory Building just north of Macky Auditorium on University Avenue in Boulder. This offer was helpful in solidifying the commitment of both parties to the new joint institute. The plan was for NBS to pay rent for two floors of the Armory plus services and utilities. From CU's perspective, there were no remaining barriers to the formation of the Joint Institute for Laboratory Astrophysics.

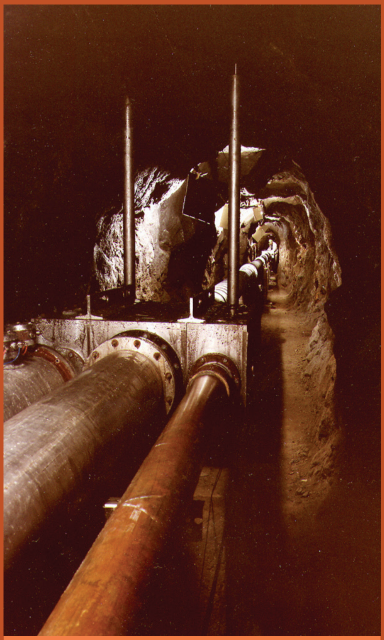
After the university opened up the Armory building, NBS provided money to equip the Armory basement for the laboratory-astrophysics experimental-research program. In Washington, Stephen Smith worked on the selection and purchase of equipment for the new JILA machine shop. He also traveled to Boulder with an NBS facilities engineer, who designed the utilities required to support the experimental program.

On April 9, the last hurdle at NBS was crossed. The DOC General Counsel advised Astin that it was legal for NBS to participate in JILA. This finding was communicated to President Newton, who obtained an official CU endorsement of the plan on April 13 from the Board of Regents, who signed the MOU[3] that created the legal basis for JILA the same day. The MOU specified the voluntary cooperation between NBS and CU. Each scientist and staff member would have reporting channels and salary from NBS or CU, but not both. JILA would become a successful example of interaction between the government and academia. Its MOU would later be used by several other joint ventures, including the Joint Quantum Institute in Maryland, as a model of such collaboration.[4]

3. Lewis Branscomb and Stephen Smith from NBS and CU Physics and Astrophysics Department Chair Wesley Brittin wrote most of the MOU.
4. A Unique Institution, The National Bureau of Standards, 1950–1969, p. 329.

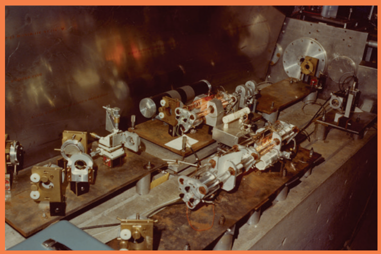
Underground SCIENCE

During his postdoc (1961–1962) with Pete Bender at NBS Washington, John L. (Jan) Hall became fixated on more precisely measuring the speed of light. He knew his quest would involve painstakingly setting up a precision measurement of the wavelength and the frequency of a particular color of light. As originally envisioned, the wavelength measurement required a long interferometer.


The 30-m interferometer inside the Poorman mine. *Credit: JILA*

Before the project got very far along, Bender and Hall moved to Boulder in 1962 to work at JILA. The two scientists started looking around for an abandoned mine to house a giant interferometer. They struck pay dirt with the discovery of the Poorman Relief Gold Mine just off Poorman Road, a few miles west of Boulder. Hall, Bender, Jim Faller, and John Ward spent 1966–1967 building a 30-m interferometer inside the mine.

"That instrument was so sensitive, it could detect an underground nuclear test," Hall recalls. He announced one such detection at a 1968 conference held in Warsaw, creating quite a stir. Though not widely appreciated at the time, the ability of the mine's interferometer to detect nuclear explosions and distinguish them from earthquakes played a role in generating U. S. support for the 1968 Nuclear Non-proliferation Treaty.



Early experiments conducted inside the Poorman Relief Gold Mine. ***Left:*** John Ward listens for signals inside the mine. ***Right:*** Methane-stabilized He-Ne laser at one end of the mine's 30-m long interferometer. The extreme sensitivity of this setup allowed scientists to detect tremendously small earth tides with an accuracy of better than one part in a thousand. *Credit: Jan Hall, NBS*

By the late 1960s, Hall and his NBS colleague Dick Barger realized they had to make their wavelength measurement with a stable laser and a krypton standard — a setup that proved easier to build and operate in JILA than in the Poorman mine. Hall and Barger successfully made the wavelength measurement in JILA in 1970.

Meanwhile, the interferometer in the mine was passed on to Judah Levine, who had been Hall's post doc from 1967 to 1969 before being hired by NBS. As a result of getting the interferometer, Levine decided to "go into the geophysics business." He found he could also get good measurements of some exotic components of the Earth's tides, in addition to identifying nuclear explosions. He briefly considered using the mine for gravitational wave detection, but preliminary calculations suggested that any signal would be lost in the noise.

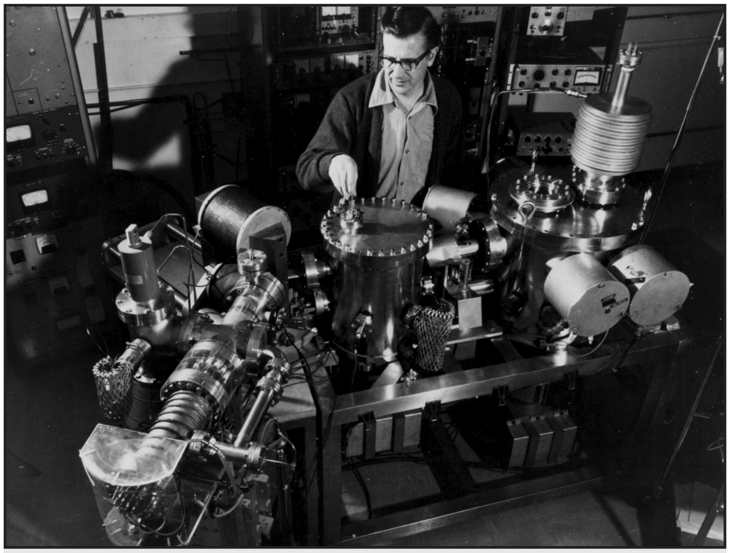
Within a couple of years, Levine realized he wouldn't be able to do much more interesting geophysics in the mine. The mine's unknown geology was limiting his ability to interpret the measurements. Levine's last paper on measurements of Earth tides in the Poorman mine was published in 1976.

After Levine's measurements were completed, the Poorman Relief Gold Mine was abandoned once again. Not long ago, however, Jan Hall visited the mine one more time. In the summer of 2010, he discovered a rockslide had mostly blocked the old entrance to the mine, making it impossible to check if the old interferometer was still in one piece.

Fellow Jan Hall standing at the entrance of the Poorman mine in late 1960s. *Credit: Jan Hall*

FORMATION OF THE JOINT INSTITUTE FOR LABORATORY ASTROPHYSICS

In the press release accompanying the official formation of JILA, Wesley Brittin said that JILA hoped "to create an atmosphere much like that of the Institute for Advanced Studies in Princeton, New Jersey, in the operation of the visitor's program. People of excellence will be brought here from all over the world to work on projects of their own choosing," he added. "They will have complete freedom for their research."



Fellow Gordon Dunn in his laboratory working with the crossed-beam apparatus (circa 1966) used for the study of collisions between electrons and hydrogen atoms. *Credit: JILA*

Dr. Walter Orr Roberts, Director of the National Center for Atmospheric Research said, "As director of NCAR, I hail the creation of the Joint Institute for Laboratory Astrophysics. This unites an outstanding research group from the National Bureau of Standards with the powerful and growing research programs of the Department of Physics of the University of Colorado."

As stipulated in the MOU, the Institute was officially named "The Joint Institute for Laboratory Astrophysics of the University of Colorado and the National Bureau of Standards." Although NBS Director Astin signed the MOU on April 18 and CU President Quigg Newton signed it on April 25, April 13 has always been considered the official birthday of JILA.

The first Fellows meeting occurred on April 12, the night before the public announcement of the formation of JILA. NBS Washington staff members Lewis Branscomb, Pete Bender, Syd Geltman and Stephen Smith, as well as Boulder staff members John Jefferies and Dick Thomas, joined CU Physics Department Chair Wesley Brittin for dinner at the Lamp Post restaurant in Boulder. During the dinner, Branscomb was elected Chair of JILA. NBS Washington staff members who missed the first Fellows meeting included Lee Kieffer, Gordon Dunn, Earl Beaty, George Chamberlain and John Hall.

In the late spring as equipment began to arrive at the Armory, Carl Pelander, a longtime employee of NBS Boulder, transferred to the JILA project. As an instrument maker, Pelander was already famous for inventing the water-driven high-speed dentist's drill (the original one of which is on display at the Smithsonian Institution). Pelander's initial job at JILA was to set up a specialized research-oriented shop in the basement of the Armory. He also oversaw the recruitment of instrument makers for the new Institute. Five years later, he organized a much larger and better-equipped Instrument Shop in the new JILA building. He stayed as the head of the Instrument Shop until his retirement in 1976.

As the summer of 1962 approached, Stephen Smith contracted with a moving company to move experimental apparatus to Boulder. The company managed to load about 3,000 pounds of laboratory equipment into a single van.

At the end of June, the NBS Laboratory Astrophysics Group (now also Fellows of JILA) began moving into the Armory, a space they shared with CU's Fine Arts Department, which occupied the top floor. The department's life drawing classes were magnets for at least one physicist busy setting up his office on the first floor.

At the time, the JILA Fellows were expected to include CU Physics faculty specializing in astrophysics and space physics as well as some members of the aerodynamics faculty. However, even though they were part of the original vision for JILA, CU aerodynamics faculty members were not successfully integrated into the new Institute.

Another important component of JILA was Dick Thomas' idea of bringing 10 "Visiting Fellows" to Boulder with their families for a year. These scientists would come from other institutions in the United States and abroad and spend a year at JILA without formal obligations. The program was originally funded by a $75,000 grant from NSF secured by NBS Director Astin. Subsequently, the Visiting Fellows program was financed by NBS funds transferred to CU, which managed the program.

> "As director of NCAR, I hail the creation of the Joint Institute for Laboratory Astrophysics. This unites an outstanding research group from the National Bureau of Standards with the powerful and growing research programs of the Department of Physics of the University of Colorado."
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> —Dr. Walter Orr Roberts, Director of the National Center for Atmospheric Research, Boulder, Colorado, 1962.

The Visiting Fellows program was a key feature of JILA's academic program. Students were expected to gain a large part of their advanced training from seminars and personal contact with distinguished visitors. The Fellows hoped that the visitors' presence would broaden the experience and vision of their students and help entice postdocs to come to JILA for training in laboratory astrophysics.

The program fostered collaboration with other top-notch scientists and institutions, effectively diffused JILA research, and helped create an international awareness of the best work in laboratory astrophysics. The fierce defense of the Visiting Fellows program when it was threatened with termination during JILA's early years was among the legacies left to JILA by co-founder Dick Thomas.

JILA'S SCIENTIFIC MISSION

The JILA founders envisioned a center for advanced research that would bring together scientists from many fields of physics and astronomy to exchange ideas and information. They also wanted to foster a significant increase in the number of young scientists in the field of laboratory astrophysics. Consequently, they were committed to training graduate students and postdocs in atomic physics and astrophysics. Although academic training of students would primarily be the purview of the CU faculty in the Department of Physics and Astrophysics, the adjoint faculty positions of senior NBS scientists allowed them to teach university classes and supervise graduate students.

From the beginning, JILA was fertile ground for innovative research. In a broad sense, the Institute's technical program has been driven by the desires of its parents, but only weakly and long term. Its initial scientific objectives adhered closely to the idea of laboratory astrophysics.

Laboratory astrophysics comprised three main areas: (1) research in basic atomic physics, with an emphasis on the atoms and molecules found in hot gases; (2) research in fluid physics, including energy transfer through hot gases and plasma physics; and (3) theoretical research in areas that applied the insights of atomic physics and energy transfer to stellar astrophysics. In other words, the plan was to investigate atomic, molecular, and ionic collisions under extreme conditions mimicking those on the surface of stars. However, then as now, scientific opportunities and the capabilities of JILA scientists guided the choice of specific research projects.

Lunar Laser *ranging*

Fellow James E. Faller came up with the original idea for a lunar laser-ranging experiment when he was a graduate student at Princeton under R. H. Dicke. Faller brought the idea along with him when he came to JILA as a postdoc with Fellow Pete Bender in December of 1962. Within two years (which saw the development of more powerful lasers), other scientists got excited about the idea as well. The first article proposing a lunar laser-ranging experiment (authored by Faller, Bender, Dicke, and four others) appeared in the Journal of Geophysical Research in 1965. The publication of this article soon led to the formation of the lunar laser-ranging experiment (LURE) group, whose goal was to convince NASA to support its proposed experiment.

When NASA moved the lunar laser-ranging experiment to high-priority status four years later, Faller and the LURE team oversaw the construction of a retroreflector package consisting of 100 fused-silica "corner cubes" arranged in an 18-inch square array. Each corner cube was essentially a considerably larger and precisely machined version of the reflectors used on bicycles, according to Faller, who came up with the preliminary design. The 100 cubes in the array were designed to reflect a beam of light coming from the Earth back to its source.

On July 21, 1969, astronauts Neil Armstrong and Edwin "Buzz" Aldrin placed the aluminum retroreflector array on the Moon.

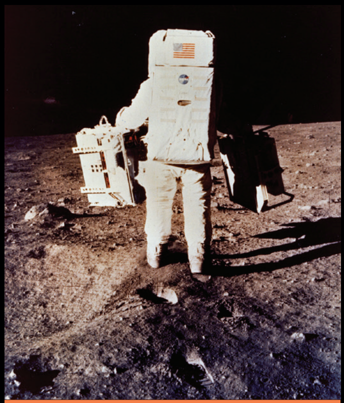
On July 21, 1969, astronauts Neil Armstrong and Edwin "Buzz" Aldrin placed the aluminum retroreflector array on the Moon. After setting the panel down, the astronauts removed the nylon cover, roughly leveled the panel, and oriented the array to point toward the Earth. Back on Earth, the LURE team held its collective breath as the lunar lander blasted off an hour later to return to the command module. Since the retroreflectors were left uncovered, there was a chance they might end up covered with moon dust — and unusable.

Within hours, a race was on to see whether Faller (by then at Wesleyan University), Joe Wampler of the University of California's Lick Observatory and their crew or J. E. Floyd's team at the University of Texas' McDonald Observatory would be the first get a return signal from ruby laser beams bounced off the lunar reflectors. Faller and Wampler used the precise guiding capability of the Lick 120-in telescope to transmit the laser beam, increasing their chances of hitting the retroreflectors. On August 1, 1969, the Lick Observatory team observed strong return signals. Soon afterwards, the McDonald Observatory team also obtained return signals. During the following four years, obser-

Studio photograph of the aluminum retrorelector array that was positioned on the Moon's surface on July 21, 1969 by astronauts Neil Armstrong and Edwin "Buzz" Aldrin. Forty-three years later, the longest-lasting experiment in JILA's history is still working. *Credit: NASA* vatories in Arizona, France, the U.S.S.R., and Japan also made successful ranging measurements.

Forty-three years later, the longest-lasting experiment in JILA's history is still working, although Fellows Faller and Bender are no longer involved. In 2012, lunar laser ranging relies on the panel left by the Apollo 11 crew, two more panels left on the Moon by the Apollo 14 and 15 missions, and two panels built by the French and left by the unmanned Soviet Lunokho 1 and 2 land rovers. The retroreflectors return pulses of laser light fired from the Earth back to telescopes in France and the United States, including the very accurate Apache Point Observatory Lunar Laser-Ranging Operation (APOLLO) in New Mexico that came online in 2006.

Fellow James Faller. *Credit: JILA*



Astronaut "Buzz" Aldrin placing the retroreflector on the Moon. *Credit: NASA*

Data gathered through the years via lunar laser ranging has been used for precisely measuring the distance from the Earth to the Moon, testing gravitational theory, verifying that the Moon has a fluid core, and determining that the moon is moving away from the Earth at a rate of about 3.8 cm per year.

These days, the APOLLO project can measure changes in the distance between the Earth and the Moon to an accuracy of 1 mm — a level of accuracy that is allowing scientists to further explore the question of whether Einstein's Theory of General Relativity correctly predicts the motions of the Moon.

Initially, the JILA Fellows elected to emphasize theoretical astrophysics rather than observational astronomy. They chose to study those areas of theoretical astrophysics that were most closely related to low-energy physics. As a result, they emphasized broad studies of stellar atmospheres, gaseous nebulae, and the interstellar medium. With respect to stellar atmospheres, they recognized that initial studies of the Sun would have the benefit of high-quality observations of the solar spectrum in all wavelengths. However, they also intended to investigate the physics of stellar atmospheres and, to a lesser extent, planetary atmospheres, including the high atmosphere of the Earth.

The Fellows selected topics in atomic physics, such as the study of radiation and its interaction with matter, relevant to astrophysics. They investigated collisions of atoms, electrons, and negative ions; high-power lasers (which had just been invented); ultraviolet and visible atomic spectroscopy; and the chemical reaction rates of negative ions. Their overarching goal was to learn more about the fundamental physics of these areas and develop basic concepts and techniques in atomic physics. In the atomic physics experiments, there would be an emphasis on absolute and precise measurements. In the related field of fluid physics, JILA started out with studies of the transfer of energy through hot gases and violent and dynamic systems such as stellar atmospheres, which are often far out of local thermodynamic equilibrium. JILA co-founder Thomas, for example, became well known for his theory of how spectral lines form in environments like this.

Regardless of the specific research topic pursued by an individual Fellow, JILA's scientific mission evidenced a commitment to four key tenets of the scientific culture of NBS. First, accuracy and precision were valuable and necessary components of measurements. Second, JILA's research was to be grounded in fundamental science. Third, JILA would make no distinction between basic and applied science, i.e., fundamental research versus science that is immediately useful. Finally, JILA would emphasize absolute measurements of atomic and molecular data.

GOVERNANCE POLICIES

Many policies that govern JILA today were developed early on. For example, JILA Fellows must either be tenured or tenure-track CU faculty or permanent staff members of NBS. NBS Fellows were encouraged to teach at CU on occasion, but were not required to do so. In contrast, CU Fellows were expected to carry a normal teaching load, help with comprehensive exams, attend department colloquia, and assist with department work. Five CU Fellows (Jinx Cooper, Peter Conti, W. Carl Lineberger, Ellen Zweibel, and Mitchell Begelman) would serve as chairs of their departments.

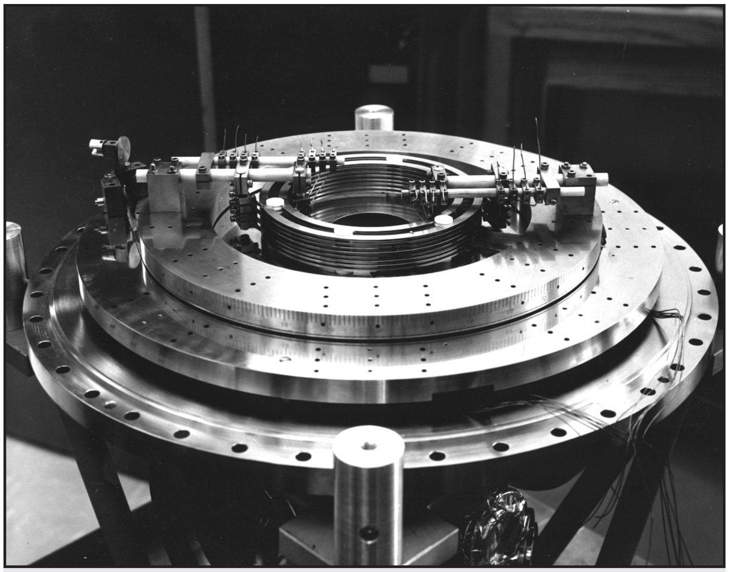
From the early days, Fellows meetings have been held on alternate weeks during the academic year. From 1968 to 1973, Fellows meetings were held in the Faculty Club. Since 1973, they have been held on the 10th floor of the JILA tower.

The JILA Chair serves a two-year term, commencing January 1 of the first year and ending December 31 of the second year. The Chair is responsible for implementing the scientific and academic policies recommended by the Fellows. The Chair also presides over meetings of the Fellows and the Executive Committee, which consists of the Chair, the Chief of the NBS Laboratory Astrophysics Group (now NIST's Quantum Physics Division), and three other Fellows. The NIST Executive Officer and the JILA Chief of Operations (a position created in 2008) also attend. The Executive Committee approves research proposals as well as postdoc appointments and reappointments.

The Chair serves as the liaison with the university and the division chief. No Chair may succeed him or herself. In 2007, the Fellows created an elected position of Associate Chair, who normally becomes the next Chair.

JILA SHOPS

In planning for the Joint Institute for Laboratory Astrophysics, the founders made the decision to include

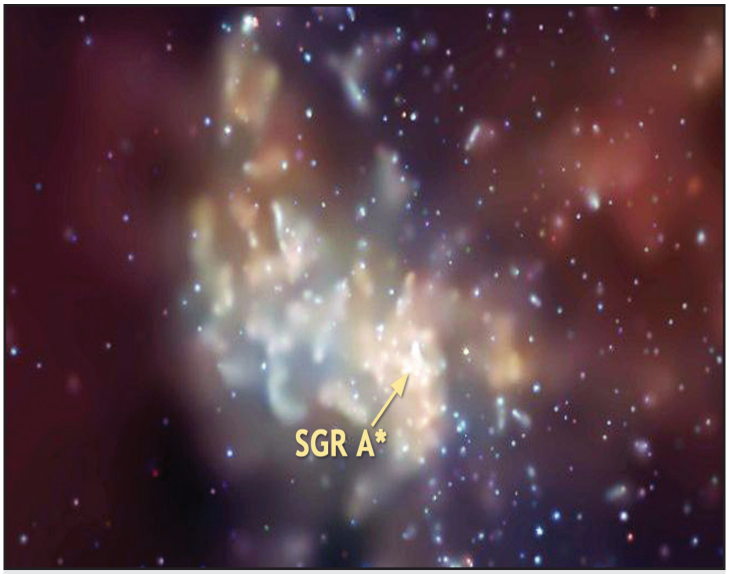


Carl Pelander, an instrument maker at the NBS Boulder Laboratories, was appointed head of the first JILA Instrument Shop. Above, a portion of the Smith-Kleinpopper instrument fabricated in the shop in 1968. *Credit: JILA*

high-quality shops and outstanding personnel to staff them. For instance, chemist Richard Weppner came to JILA from NBS in Washington to organize and direct the Special Techniques Laboratory (later called the Specialty Shop). This shop performed such services as glass blowing, etching, and the fashioning of specialty parts for laboratory experiments. Today the Specialty Shop is integrated with the Instrument Shop.

JILA also added an Electronics Shop in 1962. During the 1990s, this shop was combined with Computing to form the Computing and Electronics group to support building custom-made computers and experiment controllers for the JILA laboratories and groups. Computing and Electronics were split apart into separate shops in 2008.

In 1963, the Fellows created the Scientific Reports Office (SRO) and hired their first editor. For many years afterwards, SRO staff members typed, edited, and proofread handwritten scientific manuscripts for the Fellows. They also managed reprint requests, which rose to 12,000–14,000 per year during the 1980s and 1990s. Lorraine Volsky managed the SRO from 1968 to 1995 and continued to volunteer there once a week for the next 17 years.



X-ray photograph of the center of the Milky Way Galaxy showing the location of a black hole. *Credit: NASA/CXC/MIT/ Frederick K. Baganoff et al.*

After 2004, SRO gradually assumed responsibility for JILA communications as the demand for typing and reprint services dwindled. Communications/SRO is now responsible for the content, look, and function of the main JILA website; the development of websites for the Fellows; the production of high-quality scientific illustrations for journal articles and covers; the writing and designing of a quarterly publication; the creation of research highlights that describe JILA research in terms understandable by the public; the editing of scientific papers; and a scientific writing class offered to graduate students and postdocs.

Advantages of the JILA Organization

It did not take long for the JILA Fellows to recognize the advantages of their unique organization. The joint institute arrangement greatly reduced administration. The rotating Chair helped to weld together the two groups from NBS and CU whose objectives have not always been the same. And, there was nothing in the structure of JILA that curtailed scientific independence, which has been appreciated by scores of JILA scientists.

The JILA Fellows have even turned "disadvantages" of the organizational structure to their benefit. For example, because no one entity has ever been responsible for the financial support of JILA, it has been relatively easy for the Fellows to develop a collaborative culture as they invented new experiments and measurement techniques. From day one, JILA research fields were essentially interdisciplinary in terms of the physics and chemistry training of the times. Institute scientists supported one another and freely shared ideas and instrumentation. Their wives also contributed during JILA's early years by organizing social events and parties, helping to create lasting friendships among JILA scientists, visitors, and staff members.

JILA's innovative organization and culture have made JILA work for 50 years. Both were made possible by NBS Director Astin's vision and his confidence in the founding Fellows. JILA's organization was a departure from the conventional public-private partnership. The joint institute was an experiment by NBS to see whether JILA could achieve its specific objectives more effectively than either of its partners. Instead of creating a not-for-profit corporation to govern JILA or arranging for the university to act as an NBS contractor to establish an on-campus institute, NBS and CU entered into a full partnership. Each supplied part of the permanent staff and each contributed to the cost of the venture. As a result, JILA was operated with a relatively small administrative staff. At the same time, it provided a relatively large infusion of scientists into the new academic field of laboratory astrophysics.

The First Decade (1962–1969)

1962

As early as November of 1962, the space needs for JILA and the CU Physics Department had become pressing. The Fellows began looking for money for a new building and research support. Discussions around space needs led to a vision for a large physics complex. The new JILA building would be designed to fit in with the new complex, which would be named as the Duane Physical Laboratories in 1970. After seeing preliminary plans for a new JILA building, the Fellows applied to ARPA for $1 million to fund the construction of a new building.

1963

In March of 1963, the Fellows learned that instead of funding a new building for JILA, ARPA would provide the Institute with three years of research support at $500,000 per year. ARPA quickly became the biggest early funder of postdoc salaries, which were set at $9500 per year. From the beginning, JILA's training of postdocs brought big benefits not only to JILA, but also to NBS and later NIST. In 2012, for example, approximately one-fourth of the JILA faculty had first come to the Institute as postdocs or graduate students. Many scientists hired at NBS (and NIST) in Boulder and Gaithersburg since the mid-1960s have also received their scientific training at JILA.

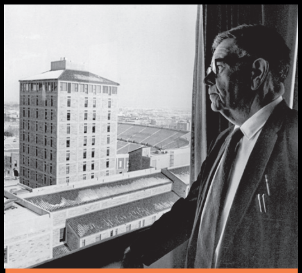
In 1963, former NBS Director Edward U. Condon came to JILA as a Visiting Fellow. He was convinced to stay in Boulder by founders Dick Thomas and Lewis Branscomb. Condon became a JILA Fellow and a non-tenured CU Professor of Physics, positions he held until his retirement in 1970. He was well known for his contributions to the theory of atomic spectra, and in 1949, he had played an important role in the selection of Boulder as the site for a new NBS laboratory complex (now NIST Boulder). Condon was the first JILA Fellow who was also a member of the National Academy of Sciences.

Condon was famous during his time at JILA for his role in conducting the *Scientific Study of Unidentified Flying Objects*, commissioned by the U.S. Air Force. This work was performed in CU's Department of Physics rather than at JILA, however.

Two other 1963 Visiting Fellows, David Hummer and John Cox, also went on to become Fellows of JILA. Hummer, who became a Fellow in 1966, was encouraged to come to Boulder by Dick Thomas. Hummer's research emphasized the formation of spectral lines in stars and the transfer of radiation through gases and stellar atmospheres. Cox, who joined the CU faculty as an associate professor in 1963, was a theoretical astrophysicist who studied the interiors of stars.

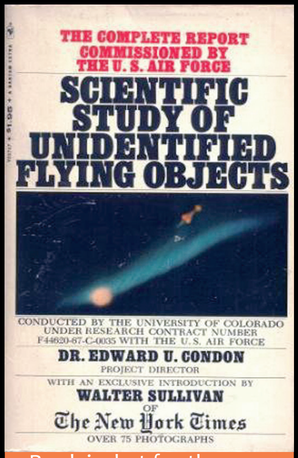
The

Physicist Edward U. Condon (1902–1974) wrapped up an illustrious career by joining the CU faculty in 1963 and becoming JILA's most distinguished Fellow. During his time at JILA, Condon chaired the Condon Committee, which was tasked by the U. S. Air Force Office of Scientific Research with investigating unidentified flying objects, or UFOs. The committee was housed in the University of Colorado's physics department because the other JILA Fellows considered the project likely to be misinterpreted, if not outrageously silly.



Fellow Edward Condon looks out of the window of his 10th Floor office in the JILA tower. The window was made of photochromic glass, which Condon invented while he was Director of Research at Corning Glass Works. *Credit: JILA/NIST*

Condon accepted the controversial job because he was curious. "It was the sort of hot potato other people had turned down, but it intrigued me," Condon explained at the time.



Book jacket for the *Scientific Study of Unidentified Flying Objects*, published by E. P. Dutton/University of Colorado in 1969. *Credit: E.P. Dutton*

The committee's report was published in January 1969 as a 965-page book entitled *Scientific Study of Unidentified Flying Objects*. It sold almost 200,000 copies — to skeptics and believers alike. Although the committee looked for evidence of UFOs in every way they could think of, it was unable to uncover anything definitive. However, the committee acknowledged that 30 of the 91 case histories it examined remained without a scientific explanation. According to Condon, the UFO study did not prove that extraterrestrial beings

Scientific Study of UFOs

were not visiting Earth, but it did not discover any positive evidence that they were. Following the publication of the study, widespread interest in UFOs waned, and the Air Force discontinued its own UFO studies.

Though well known by the public for the UFO study, Edward Condon had a noteworthy career as a journalist, physicist, and administrator before coming to JILA. He started his career as a reporter for the Oakland Tribune, where he met his wife Emilie Honzik. The "newspapering" job helped finance his education at the University of California at Berkeley, where he earned a doctorate in physics in 1926 just five years after entering as an undergraduate. During this time, he went to Goettingen, Germany, where he learned about the new field of quantum mechanics. This new knowledge not only allowed him to complete his dissertation in record time, it also positioned him as the first scientist to bring the exciting new ideas of quantum mechanics to the attention of the American physics community.

After obtaining his Ph. D., Condon worked briefly as a public relations specialist for the Bell Telephone Laboratories before launching his academic career at Princeton University in 1928. Between 1937 and 1954, he was associate director of research at Westinghouse Corporation (1937–1943), Chair of the Theoretical Physics Division of the Radiation Laboratory at the University of California at Berkeley, where he worked on the production of ^{235}U for the atomic bomb (1943–1945), Director of NBS (1945–1951), and Director of Research and Development at Corning Glass Works (1951–1954). For the last six years of this period, he was subject to innuendo and accusations by the Un-American Activities Committee in the U. S. House of Representatives. Though cleared four times, this experience pushed him out of industry and back into academia. In 1956, he became chair of the physics department at Washington University in St. Louis. Then, in 1963, at the urging of JILA founders Richard N. Thomas and Lewis Branscomb, who were inspired by Condon's leadership and courage during his tenure at NBS, the CU Regents offered Condon a non-tenured appointment to the CU physics faculty.

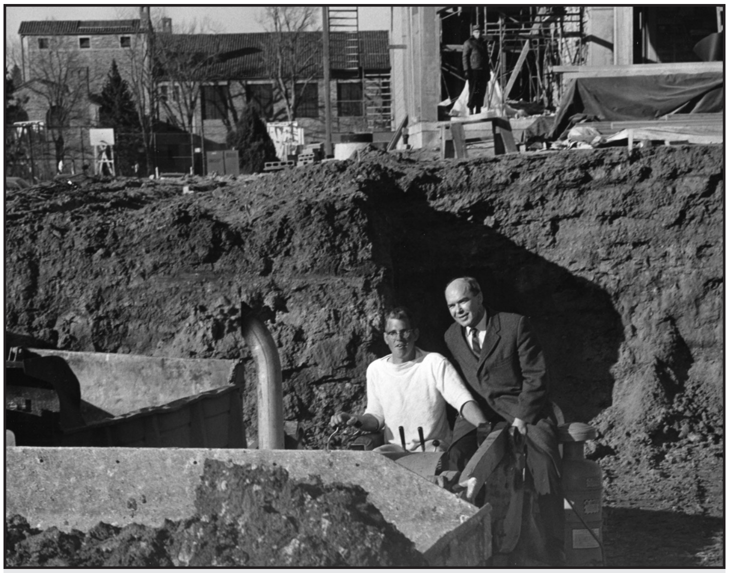
"This is one of the great things that CU did," says Distinguished Professor W. Carl Lineberger. "CU offered Condon a position when he'd been hounded out of multiple positions in industry and academia. This was a proud moment for CU." Lineberger added that Condon has had an enduring impact on JILA in the field of chemistry and inspired several young JILA faculty to public service.

> [Ed was] "a moral, impassioned man, with a depth of concern for mankind [...]; a man fiercely principled and anti-diplomatic; a man who believes and feels in sharp contrasts, who will let the world know his position without ambiguity. Fuzzy mindedness is anathema to him and he insists on saying so at every opportunity. But this rasping trait is wedded to an extreme generosity and kindness."
>
> —Grace Marmor Spruch, *Saturday Review*

At JILA, Condon served as thesis advisor and mentor in atomic physics to the late Halis Odabasi, who went on to teach physics at Bogazici University (Turkey), Central Missouri State University, East Carolina University, and the University of Mississippi, Oxford. Condon also directed the Scientific Study of Unidentified Flying Objects — almost certainly because, as Grace Marmor Spruch wrote in a 1969 *Saturday Review* article, he was "a moral, impassioned man, with a depth of concern for mankind not common in scientists; a man fiercely principled and anti-diplomatic; a man who believes and feels in sharp contrasts, who will let the world know his position without ambiguity. Fuzzy mindedness is anathema to him and he insists on saying so at every opportunity. But this rasping trait is wedded to an extreme generosity and kindness."

Forty-three years after the scientific UFO study was published, JILAns still remember it and other, more traditional books he wrote or edited, including *Quantum Mechanics*, with Philip M. Morse (1929), *Theory of Atomic Spectra*, with G. H. Shortley (1935), and the *Handbook of Physics*, with Hugh Odishaw (1967). Edward Condon died in Boulder in 1974.

Groundbreaking ceremony for the new JILA laboratory wing and the 10-story office tower, February 25, 1965 (l-r) Lewis Branscomb, Chair of JILA; Donald Hornig, Science Advisor to President Lyndon Johnson; Joseph Smiley, CU President, and Robert Huntoon, Director of the Institute for Basic Standards at NBS. *Credit: University of Colorado Publications Service*



Presidential Science Advisor Dr. Donald F. Hornig (right) on a bulldozer with driver. Although Dr. Hornig could not drive the machine as he had always wanted to do, he appeared to be having fun. *Credit: JILA*

During the early 1960s, JILA atomic physicists studied collisions of photons with electrons, negative ions, and atoms — gathering data to use in interpreting astronomical spectra. For example, in one of JILA's first experiments, Stephen Smith, Visiting Fellow Douglas Heddle, and George Chamberlain measured collisions of electrons with hydrogen atoms. These collisions excited the atoms and resulted in the emission of Lyman-alpha radiation when the atoms returned to their ground state. Since Lyman-alpha radiation is also produced in space, the scientists hoped to compare the processes in the laboratory with those occurring in space. Similarly, laboratory atomic physics data were also being collected for use in investigating nonequilibrium processes in stellar atmospheres.

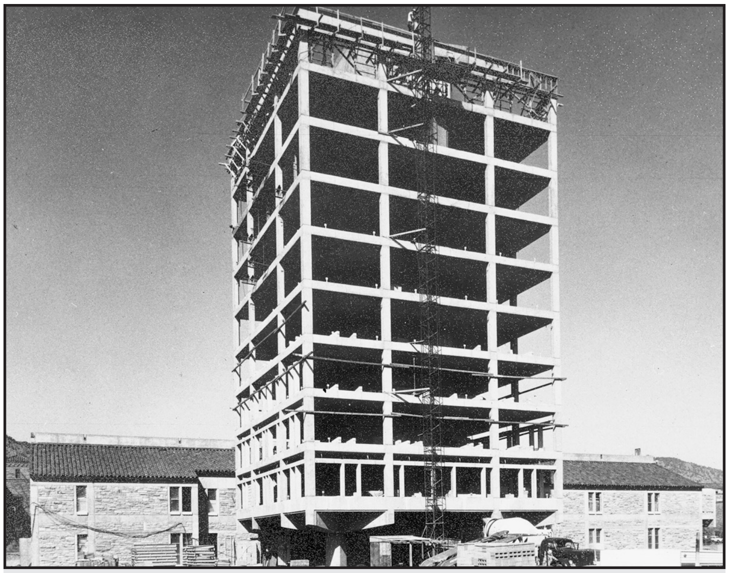
Research in precision measurement at JILA also started right away. Jan Hall and Pete Bender began a project to more precisely measure the wavelength of light, initially by building a 30-meter-long interferometer inside the Poorman Relief Gold Mine west of Boulder. Hall also built a ruby laser and used it to excite molecules of anthracene to fluoresce in JILA's first laser experiment.

Postdoc (and future Fellow) James Faller arrived at JILA in late 1962 with a proposal for a lunar laser-ranging experiment that would make it possible to precisely measure the distance from the Earth to the Moon and learn more about the interior of the Moon and the Earth's rotation.

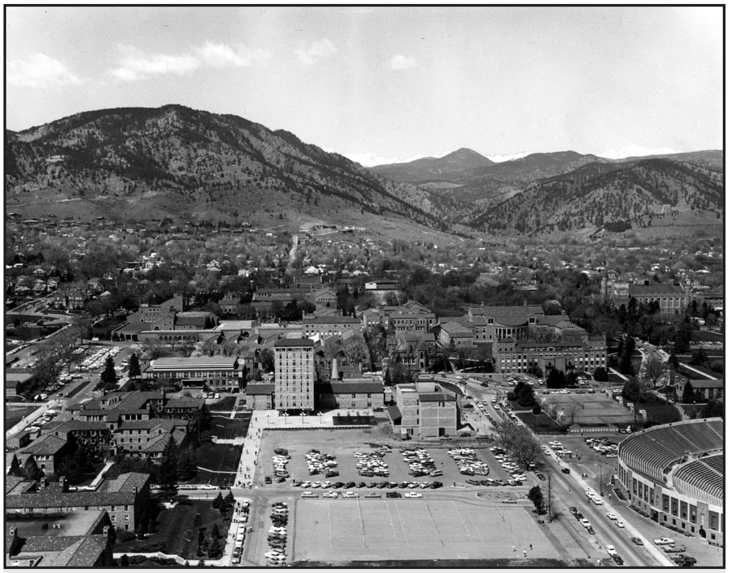
By the middle of 1963, new JILA labs were up and running, giving the Fellows time to consider some important housekeeping items. First, the Fellows remembered that By-laws governing the operation of the Institute needed to be written. Earl Beaty, Pete Bender, John Jefferies, and John Cox volunteered to serve on the By-laws committee. Second, the Fellows decided to have JILA seminars (now called JILA colloquia) on Tuesdays at 4:00 p.m. Finally, the Fellows were able to convince CU to provide them with more space. In September of 1963, JILA was given use of two and a half floors for offices in Woodbury Hall, located on the main campus about two blocks from the Armory building.

1964

During the first five months of 1964, the JILA By-laws were drawn up, discussed and adopted. On May 11, 1964, the original JILA By-laws were signed by Earl C.



JILA tower (circa 1966) under construction in front of the recently completed laboratory wing, now known as the B-wing of the Duane Physical Laboratories complex. *Credit: JILA*



Aerial view of the newly completed JILA tower situated on the University of Colorado at Boulder campus, 1967. *Credit: University of Colorado Publications Service*

Beaty, Peter L. Bender, Lewis M. Branscomb, Wesley E. Brittin, Edward U. Condon, John P. Cox, Sydney Geltman, John T. Jefferies, William A. Rense,[5] Stephen J. Smith, Richard N. Thomas, and Mahinder S. Uberoi. The By-laws were then ratified by CU President Joseph R. Smiley and NBS Director Allen Astin.

The key provisions of the By-laws were:

- The responsibility for JILA rests with the Fellows.
- New JILA Fellows must work in the field of laboratory astrophysics.
- Election to Fellow requires a three-fourths majority.
- The title "Visiting Fellow" identifies participants in the Visiting Scientists program.
- The term of the JILA Chair is two years, and the Chair may not succeed himself.
- An Executive Committee of five members assists the Chair. This committee serves one year.
- The Executive Officer is a permanent NBS position to ensure continuity of administrative functions.
- Fellows meetings must occur at least once every two months. The Executive Committee meets at least twice a month.
- The JILA By-laws can be amended by a two-thirds majority vote.

On June 8, Lewis Branscomb was elected Chair of JILA for two more years. Because of the newly adopted By-laws, Branscomb would be the only JILA Chair ever elected to serve two consecutive terms (although David Hummer served two nonconsecutive terms as Chair during the 1970s). Four months later in October of 1964, the first Executive Committee was formed. The organizational structure of JILA was now in place.

1965

The construction of the JILA wing of CU's physics complex began on February 1, 1965. The project consisted of erecting two new buildings, a new laboratory wing (now called the B-Wing) and a connecting 10-story office tower. The NSF provided a $900,000 grant for the $2.1 million building project. The remaining money came from a loan from the State of Colorado. The loan was secured by anticipated NBS rental payments and overhead from the ARPA grant. The university donated the land for the buildings.

5. Rense went on to become one of the founders of CU's Laboratory of Atmospheric and Space Physics (LASP).

CU was in charge of the construction, with NBS participating in the building design process. The architect was Harry Weese of Chicago. The official groundbreaking ceremony for the new buildings occurred on February 25, 1965. Dr. Donald F. Hornig, Science Advisor to President Lyndon Johnson, participated in the ceremony. Since excavation of the site had already begun, Dr. Hornig rode on a bulldozer. It had been Hornig's lifelong ambition to drive a bulldozer, according to Lewis Branscomb.

In November, the JILA Fellows allocated space for a new JILA Atomic Collisions Cross Sections Data Center in the tower under construction. Fellow Lee Kieffer was the driving force behind the new center and served as its director from 1968 to 1974. He was followed as director by Fellow Earl Beaty (1974–1981) and Jean Gallagher (1982–1989). The center was tasked with compiling, critically evaluating, and reviewing data from the literature on cross sections and rates for low-energy collisions of electrons, photons, and heavy particles with atoms, ions, and simple molecules. JILA data center reports provided recommended data and key citations for specific topics in atomic physics. The reports also highlighted missing data and pointed out inconsistencies in existing data.

The center's goal was to organize and summarize the output of research in atomic, molecular, and chemical physics for the use of scientists who produced the data and those who applied it to such fields as energy research, astrophysics, aeronomy, and gaseous discharges. Consequently, the center played a critical role in the early history of JILA by creating a bridge between astrophysics and atomic, molecular, and chemical physics. The theoretical calculations of Fellows David Hummer, David Norcross, and John Castor reinforced and expanded the bridge built by the data center between astrophysics and atomic physics.

The data center later became part of the National Standard Reference Data System operated by NBS. In August 1994, the NIST Data Center manager in Washington terminated funding for the JILA center, and its database was transferred to Oak Ridge National Laboratory.

1966–1967

From 1965 to 1967, JILA acquired four new Fellows: John (Jinx) Cooper, Richard Zare, Alan Gallagher, and David Hummer. Cooper, an experimental physicist specializing in atomic physics and plasma spectroscopy, left Imperial College London to become an assistant professor of physics at CU. Richard Zare, who was appointed assistant professor of chemistry, specialized in chemical physics. Gallagher specialized in atomic, molecular, and chemical physics. Hummer was a theorist specializing in atomic collisions in the upper atmosphere and astrophysics.

In October of 1966, JILA's new three-story laboratory wing (B-Wing) was completed. It included a new auditorium. The Fellows relocated their laboratories from the Armory building to the new B-Wing. The 10-story office and conference tower was not completed until April of 1967.

The JILA tower on the Boulder campus was dedicated on April 7, 1967. Guests at the dedication included Colorado Governor John Love, NBS Director Astin, and CU President Joseph Smiley.

In 1967, Alan Gallagher joined the JILA faculty. Judah Levine, who would become a JILA Fellow in 1969, arrived as a postdoc with Jan Hall. At the time, JILA had 24 permanent scientific staff and 40 graduate students. During 1966–1967, the Institute hosted 20 short-term and 10 long-term Visiting Fellows. In its four and a half years of existence, JILA had already produced 220 scientific papers.

By the time the move to the new buildings was complete, JILA was running smoothly. It was clear that its broad goal of physics research related to astrophysics had opened the door to most fields in atomic, molecular, and optical physics. The scientific emphasis was on the transfer of energy through hot gases and such aerodynamic phenomena as shock waves and turbulence, but new research ideas were also taking shape.

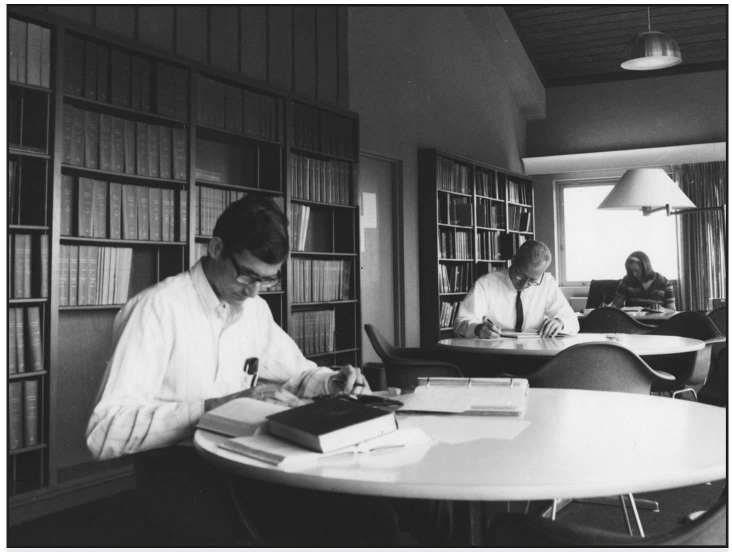
1968–1969

In 1968, postdocs Carl Hansen, John Castor, Jeffrey Linsky, and Carl Lineberger arrived at JILA, as did Fellow Ludwig Oster. All four new postdocs would become JILA Fellows: Linsky in 1969, Hansen and Lineberger in 1970, and Castor in 1979.

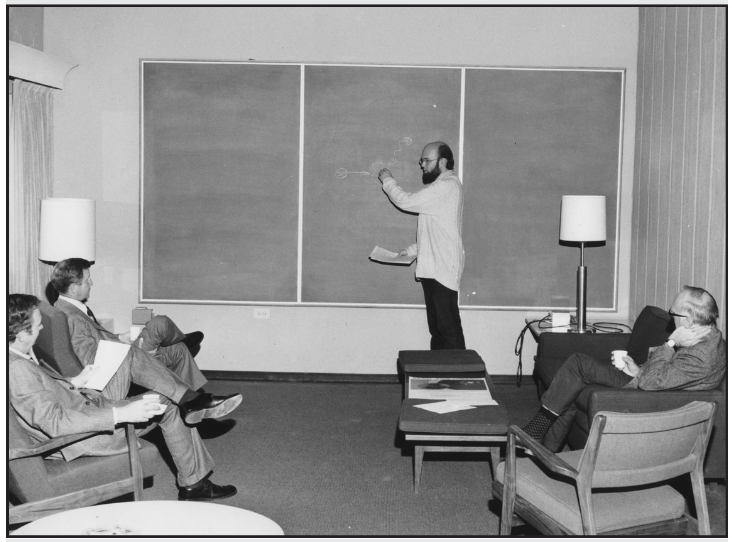
Katharine Gebbie was also appointed to the JILA scientific staff in 1968. Gebbie was devoted to investigating the physics of solar and stellar atmospheres, a very hot topic at JILA. She would become the Institute's first woman Fellow in 1974.

As the decade of the 1960s drew to a close, JILA's astrophysical research increased substantially. Solar physics, stellar atmospheres, stellar interiors and evolution, planetary nebulae, high-energy astrophysics, and interstellar matter were all important research topics for the astrophysics faculty. Related work in atomic physics included the excitation of atoms and molecules by collisions with light, electronic transitions in atoms, and spectral line broadening. The latter focused on both bright and dark spectral lines to better understand the fluctuations in the number of photons that sometimes occur over very narrow ranges of frequency.

As the research output of JILA began to skyrocket, the typists in the SRO were thrilled to obtain type balls containing mathematical symbols for their typewriters. Until 1968, SRO staff typed up handwritten scientific manuscripts, but JILA scientists still had to add in their equations by hand. With the new type balls, manuscript preparation went more smoothly. In addition to typing, editing, and proofreading the manuscripts, SRO staff also prepared figures and cover letters to accompany the manuscripts mailed off to scientific journals. It was a job the SRO staff took very seriously. After a lengthy discussion of a particular point of grammar with Fellow Dick Zare and his postdoc, for instance, the postdoc was moved to remind SRO Director Volsky that he and the other scientists were "after the Nobel Prize, not the Pulitzer Prize."

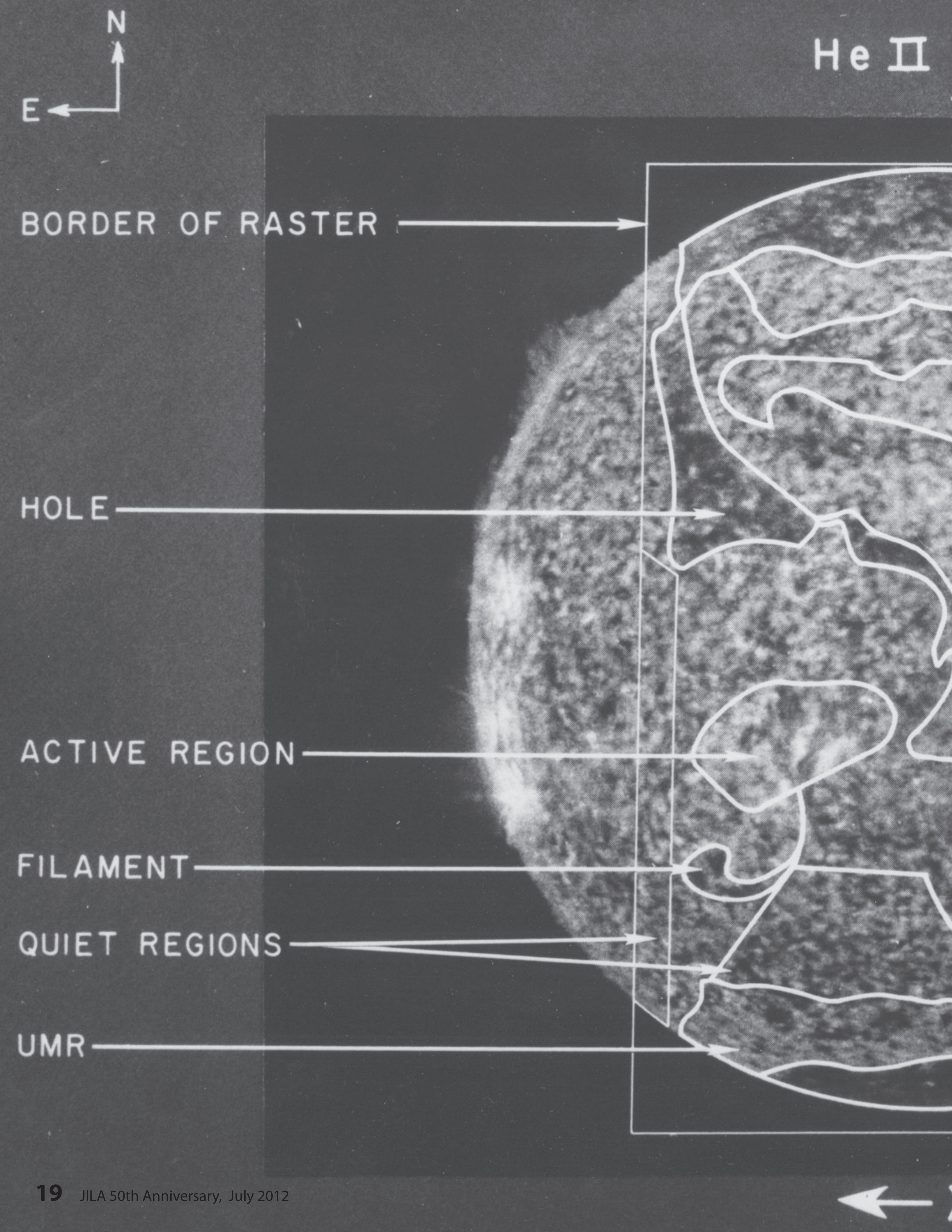


JILA scientists studying in the library on the 10th floor of the JILA tower. *Credit: JILA*



Fellow David Hummer at the chalkboard in an informal scientific discussion with colleagues. *Credit: JILA*

Visiting Fellow Jim Faller shows off a retroreflector array like the one placed on the Moon in 1969. *Credit: JILA*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Chapter 2
1970 to 1979

Fellow Jan Hall working on one of his early stable lasers.

During the 1970s, JILA was in full swing. Laboratory astrophysics was still the primary focus of Institute scientists, but changes were already afoot. Early in the decade, chemical physics was added as a new research area, and by 1970, Carl Lineberger had not only been appointed a Fellow of JILA, but also was making electron affinity measurements in atoms and simple molecules. This work would provide most of the measurements for an entirely new section of the *Handbook of Chemistry and Physics*.

Throughout the decade, Fellows and Visiting Fellows continued to explore the precision measurement potential of the laser for research in atomic and chemical physics. In one such effort in 1972, Jan Hall and Dick Barger made a hundredfold more accurate measurement of the wavelength of light.

More significant for the Institute was the decision in 1976 to allow the purpose and role of JILA to evolve and expand beyond what had been spelled out in the original MOU, setting the stage for the evolution of physics research in future years. And, despite gloomy early predictions that JILA would be lucky to last for five years, the Institute celebrated two anniversaries during the 1970s: its 10th anniversary in 1972 and 15th anniversary in 1977.

During the 1970s, JILA was a fun, fast, and free-spirited place. People thought nothing of scheduling a ski trip, renting a bus, and spending a day during the week on the slopes of Winter Park. There were softball games, staff hikes, raft trips, and parties, including extreme Halloween parties featuring wild and creative costumes.

THE SECOND DECADE (1970–1979)

1970–1971

The Visiting Fellows program continued to be an integral part of JILA throughout the decade of the 1970s. During 1970–1971, eleven visitors, including the world-renowned molecular spectroscopist Herbert Broida, came to the Institute for up to a year of study. In May (as every year), a special dinner was held for the visitors.

In 1970, Carl Hansen, David Norcross, Art Phelps, and Carl Lineberger were appointed Fellows. Lineberger was also hired as an assistant professor of chemistry at CU. A year later astrophysicist Richard McCray arrived at CU and JILA to study interstellar physics at an Institute whose primary specialty was the study of stars. A major thrust was the study of stellar spectra as a means of learning about stellar composition. With this information, Fellows David Hummer and John Castor, together with Fellow Adjoint Mike Seaton, made models of stellar atmospheres. John Cox and Carl Hansen worked on the interior structure of stars. Others, including John Castor, used the new discoveries about stars to pioneer and develop a theory of stellar winds. With this kind of work going on around him, McCray opted to begin his research at JILA with a study of the impact of stellar winds on the interstellar medium. He soon added studies of compact objects, x-ray sources, and the application of atomic theory to understanding x-ray sources.

In 1976, the Fellows decided that the purpose and role of the Joint Institute for Laboratory Astrophysics should continue to evolve and expand beyond the areas of science outlined in the original MOU.

Astrophysicist Juri Toomre also joined the CU faculty and JILA in 1971. He began exploring convection and fluid motions.

1972–1973

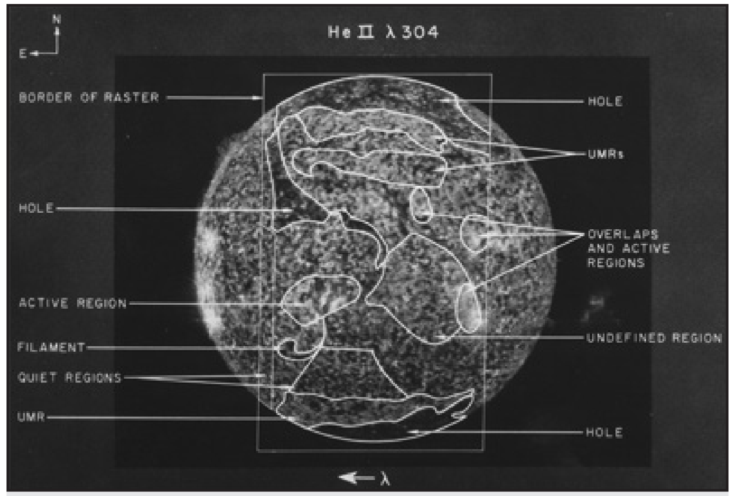
In 1972, the Joint Institute for Laboratory Astrophysics celebrated its 10th anniversary on April 13. The Fellows had an anniversary dinner at the Red Lion Inn. A separate reception was held for JILA staff and guests. NBS Director and JILA co-founder Lewis Branscomb attended both functions.

Scientific highlights included Dick Barger and Jan Hall's collaboration with Ken Evenson and others at NBS Boulder in a measurement of the speed of light from direct frequency and wavelength measurements with methane-stabilized lasers. Judah Levine was busy building and deploying instruments to measure earth movements in eastern Colorado, the seismically active zones of southern California, and tectonically active areas near and inside Yellowstone National Park. His goal was to learn about earthquake prediction.

In 1972, JILA welcomed former postdoc Jim Faller back as a faculty member. Faller was hired as a NIST Fellow specializing in precision measurement research, including fundamental constants.

In 1973, JILA experienced a serious, but fortunately temporary, funding crisis with the phase-out of funding from ARPA. After discussion among the Fellows, Carl Lineberger and JILA Chair David Hummer applied for a core block grant from NSF. They proposed collaborative investigations of electron impacts on atoms and ions; atomic transitions; atmospheric models; solar physics; and stellar evolution as well as the strengthening of research in molecular and chemical physics. They hoped to use 75% of the block grant to fund research in atomic and molecular physics, 15% for astrophysics, and 10% for aeronomy. Although NSF awarded JILA a block grant of $500,000 per year for three years to support atomic and molecular physics, the agency declined to fund the proposed research in either astrophysics or aeronomy. This decision led to a phase-out of aeronomy research at JILA. It also impacted the collaborative work between the two disciplines (astrophysics and AMO physics) at the heart of the JILA founders' original vision.

Since 1973, a substantial part of JILA has been funded by a series of multiyear NSF block grants in support of AMO physics research. Other funding sources for astrophysics research had to be developed. The funding changes along with the 1973 departure of JILA cofounder Dick Thomas to l'Institute d'Astrophysique (Paris) played a role in JILA's expansion into other research fields during the remainder of the 1970s. The same year Thomas left, Peter Conti, an observational astronomer, joined the Department of Physics and Astrophysics and was appointed a Fellow of JILA.



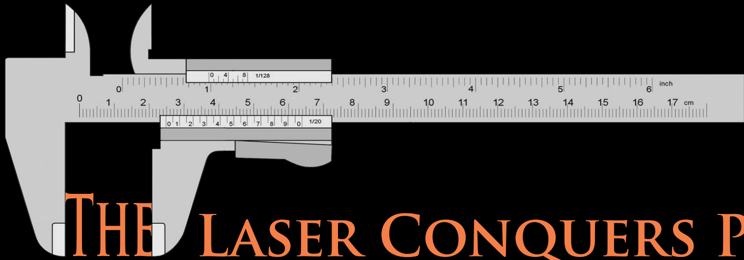
A monochromatic picture of the sun in the 304 Å line of a singly ionized helium atom obtained by the Naval Research Laboratory experiment on Skylab and analyzed by JILA astrophysicists. *Credit: Naval Research Laboratory*

1974–1975

Most of the JILA news in 1974 and 1975 was scientific. In June of 1974, JILA Chair David Hummer was recognized by NBS for his research in developing practical methods for predicting and describing the behavior produced by the passage of intense radiant energy through gases. He was also credited with helping JILA to become an international leader in interdisciplinary research on the properties of highly excited gases. JILA's role in producing high-quality research in the field of laboratory astrophysics was rapidly gaining recognition beyond the walls of the Institute.

In laboratory astrophysics, hot research topics included solar and chromospheric physics, stellar astronomy, stellar atmospheres, stellar interiors, the interstellar medium, high-energy astrophysics, as well as atomic and spectroscopic data. Highlights of these efforts included John Castor's and his colleagues' new theoretical model of the stellar wind that the researchers used to model the envelopes of O stars; new models of substructures in the Sun's chromosphere by Jeffrey Linsky and his colleagues; progress by John Cox and his colleagues on developing a theory of the pulsational stability of stars in thermal imbalance; the modeling of convection in stars by Juri Toomre and his colleagues at Columbia and Nice; and studies by Dick McCray and his colleagues on ionization of the interstellar medium and gas flows near compact x-ray sources.

Electron impact ionization apparatus. A gas jet directed downward from the dome in the center crosses an electron beam from the electron gun at the left. Scattered incident electrons and electrons knocked-out of the target atoms are detected by the electron analyzer at the right and by the moveable analyzer that is positioned below the scattering center. *Credit: JILA*



The Laser Conquers Precision Measurement

When Jan Hall was a postdoc with Pete Bender at NBS Washington in 1961–1962, he developed a fixation with measuring the speed of light. Initially, he played with some solid-state devices and a cathode ray tube. Hall even built a couple of lasers, a brand new technology that had been invented in 1960.

> At JILA, Jan Hall and Dick Barger "got our act together and got the wavelength measured."
>
> —Jan Hall, JILA

Once he arrived in JILA, Hall and Dick Barger "got our act together and got the wavelength measured," Hall said. The two researchers set up a krypton (Kr) standard lamp and a pair of methane-stabilized helium-neon (He-Ne) lasers. The goal was to see if they could measure the wavelength of the 3.39-µm methane line with greater precision than the Kr standard adopted in 1960. Hall and Barger developed a new interferometry technique employing the lasers that made it possible to "see" an asymmetry inherent in the Kr line as well as identify and remove most of the "noise" from their measurements. In 1972, they measured a wavelength of 3.392 231 376 (12) µm for the 3.39-µm methane line (as measured to its center of gravity).

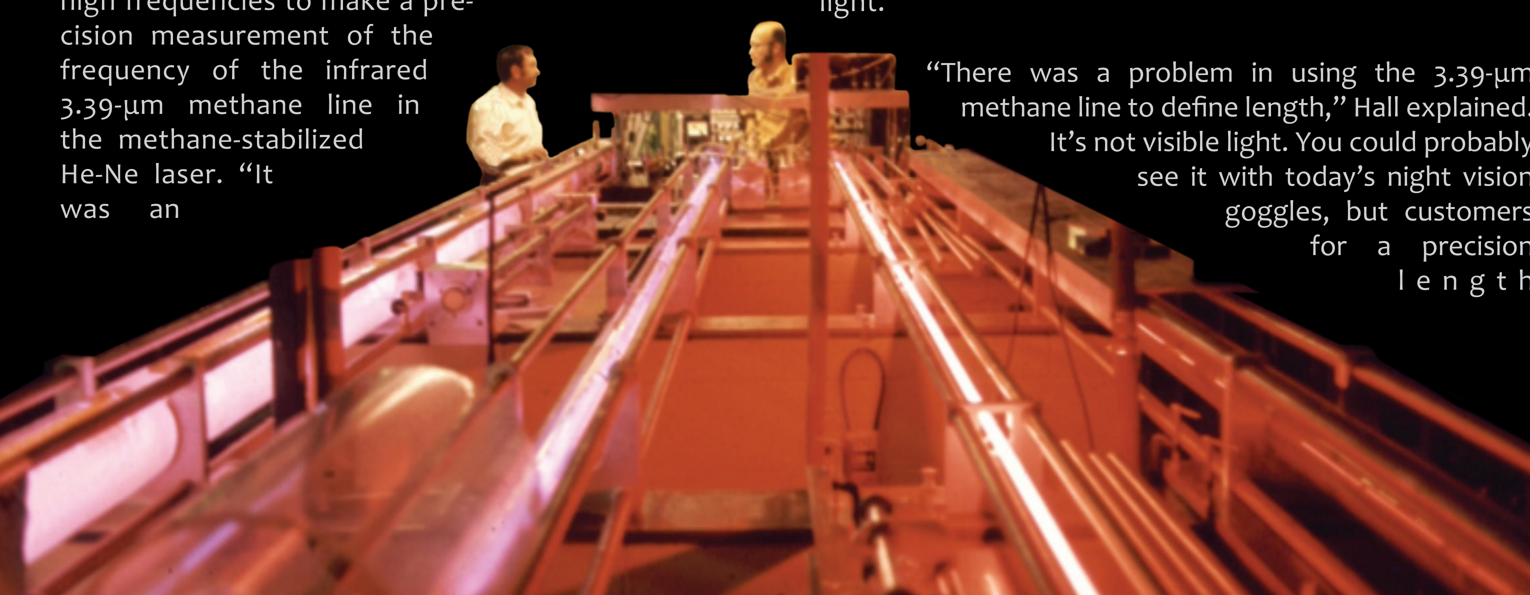
While the wavelength measurements were underway at JILA, an NBS team led by Ken Evenson was creating a long chain of molecule-based lasers of increasingly high frequencies to make a precision measurement of the frequency of the infrared 3.39-µm methane line in the methane-stabilized He-Ne laser. "It was an amazing sight," Hall recalled. "Measuring the frequency took 12 scientists two years building 13 lasers on top of massive tables. The longest lasers in the room were eight meters long. It was visually rich!"

To make frequency measurements with all these lasers at once was a challenge, Hall says. At least six or eight times, twelve scientists, including Hall, stayed all night trying to get everything working. Those nights Hall's wife Lindy and other wives would bring the kids and sandwiches so the families could have dinner on the grass at NBS.

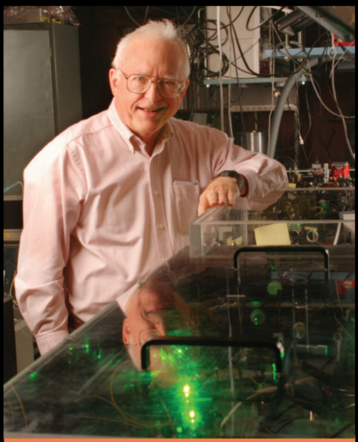
The persistence of the NBS scientists finally paid off in 1972. Evenson and his team measured the frequency of the 3.39-µm methane line as 88.376 181 627 (50) THz. Multiplying this frequency with Hall and Barger's new value for the wavelength of light resulted in a speed of light of 299 792 456.2 (1.1) m/s. This value not only agreed with a previous measurement of the speed of light, but also was a hundred times more precise. The joint JILA/NBS accomplishment was announced to the world in *Physical Review Letters* in November of 1972.

Two years later in 1974, the U. S. Department of Commerce awarded a Gold Medal to the team responsible "for the last measurement of the speed of light." The awardees included Hall, Barger, Evenson, Bruce Danielson, Russ Petersen, Gordon Day, and Joseph Wells. By then, Hall was already thinking about the next challenge: redefining the meter in terms of the speed of light.

"There was a problem in using the 3.39-µm methane line to define length," Hall explained. It's not visible light. You could probably see it with today's night vision goggles, but customers for a precision length



standard need to be able to see it. It's hard to work efficiently with something you can't see."



Fellow Jan Hall in his laboratory. *Credit: Greg Kuebler, JILA*

It took 11 more years of research on laser-based frequency and wavelength measurements at NBS and other national laboratories around the world to bring laser technology to the level where people grew confident enough to consider a redefinition of the meter. The key step was measuring the frequency of a red He-Ne iodine-stabilized laser, commonly used by metrologists. In 1983, the speed of light was defined as exactly 299,792,458 m/s. Thus the meter could be officially defined as the length traveled by light in a vacuum in exactly 1/299,792,458 s (about 3 nanoseconds).

"The redefinition of the meter was a huge amount of work," Hall said. "To measure frequencies, we still had to make these long frequency chains, and that was serious work. It took a team to do it." Hall added that the new standards for the speed of light and the length of the meter occurred well before the invention of the optical frequency comb, which after 1999 would make frequency measurements relatively easy.

Top: NBS awarded a gold medal in 1974 to the "Speed-of-Light" team from JILA and NBS (l–r) Richard L. Barger, Kenneth M. Evenson, John L. Hall, Bruce L. Danielson, F. Russell Peterson, Gordon W. Day, and Joseph S. Wells. *Credit: NBS*

Left: The new measurement of the frequency of light took 12 scientists two years, during which the scientists built 13 lasers on top of massive tables. *Credit: NBS*

jilanews

March 4, 1974
JILA Tower Will Fall

The Joint Institute for Laboratory Astrophysics (JILA) will soon fall over according to information received by University Police last week. According to the report, a man told police he had noticed a crack at the base of the JILA tower. He said he had been measuring the crack for some time and it is getting wider. He also said he has made careful calculations on a computer and has determined the tower will fall at 3 a.m. on the morning of Jan. 23, 1979. Police have taken no action at this time.

Editor's note: The tower was still standing in 2012.

In 1974, Senior Research Associate Katharine Gebbie was elected a Fellow of JILA. Gebbie had begun her career at JILA as a postdoc for JILA co-founder Dick Thomas in 1968 and most recently had worked with Juri Toomre. The following year Judah Levine, Juri Toomre, and William Reinhardt were also appointed Fellows of JILA.

A significant new development in JILA astrophysics research occurred in 1975 with the founding of the field of helioseismology by new JILA Fellow Juri Toomre, Fellow Adjoint Douglas Gough, and other solar astronomers. Toomre and Gough, who was on the faculty of the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge, figured out that solar physicists could make use of sounds (oscillations) within the Sun to deduce its internal structure and motions.

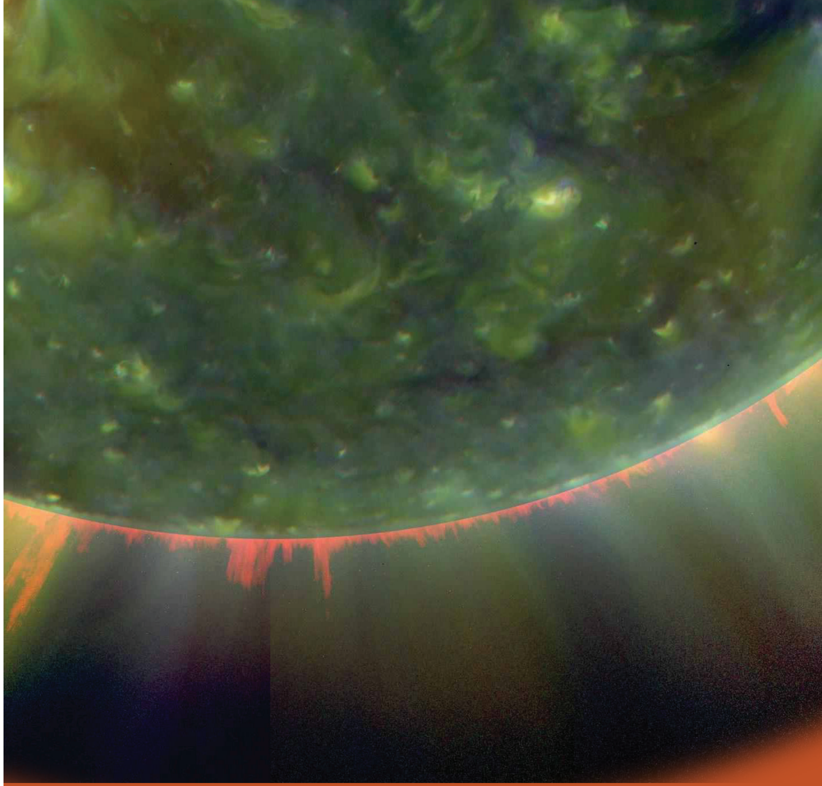
JILA researchers continued with vibrant research programs in chemical physics, laser (optical) physics, and precision measurement. In the area of laser physics, an important development was taking place that would help shape the nature of JILA research in upcoming decades. As researchers in atomic, molecular, and chemical physics began increasingly to plan experiments using lasers, Jan Hall volunteered his time in JILA labs to help build and stabilize the new lasers. Over time, Hall's behind-the-scenes efforts helped develop a broad expertise in laser physics in JILA. This expertise would one day contribute to the exciting new field of chemical physics, the creation of the world's first Bose-Einstein condensate, the world's first fermionic condensate, the world's first optical frequency comb, the world's first ultracold molecules, and countless other research advances.

In 1975, Jim Faller was nearing completion of work on a special purpose telescope called the LURE-Scope to receive lunar laser-ranging signals reflected off the Moon. The new 90-inch telescope was computer controlled. During the same period, Pete Bender and J. P. Hauser continued to work with the Jet Propulsion Laboratory and the University of Texas at Austin on understanding the lunar range data.

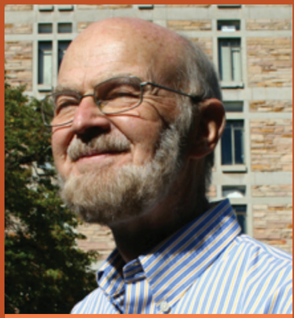
1976–1977

On January 26, 1976, JILA Chair Jinx Cooper and the Fellows drank a champagne toast to the future of JILA on the occasion of the 200th Fellows Meeting. Around this time, the Fellows recognized that JILA's research program had evolved to the point where an addendum to the original MOU was needed. JILA's scientific mission had expanded to include research in laser physics, precision measurement, geophysics, atmospheric chemistry, and the collection and evaluation of scientific data. The mission clearly also included the education of young scientists.

The Fellows decided that in view of these more recent contributions, the purpose and role of JILA should continue to evolve and expand beyond the areas of science outlined in the original MOU. An addendum dated March 1976 was prepared for the 1962 MOU. In March, both NBS and CU reaffirmed their support of JILA by signing this addendum. The addendum expanded the scope of JILA activities and reinforced the mandate of the Institute for research and advanced training in areas within the mission of both partners.



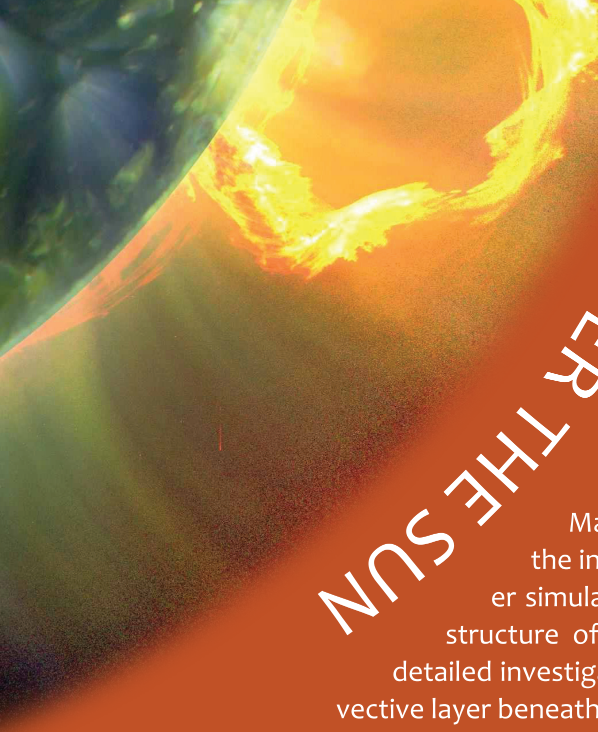
In 1972, Douglas Gough came to JILA from the Institute of Theoretical Astronomy in Cambridge (UK) to work with Juri Toomre. Toomre had joined the University of Colorado's Department of Astro-Geophysics and become a member of JILA in 1971. The two collaborated on a simulation of how ocean (i.e., salt water) convection involves the transport of both heat and salt. Gough soon began exploring whether what they'd learned could be applied to studying convection in stars, which are made of mostly hydrogen and helium. In the process, he began wondering if the frequency of the Sun's oscillations could provide clues to its internal structure and motions.



Fellow Juri Toomre. *Credit:JILA*

Gough and Toomre consulted seismologists who were using sound waves to figure out the internal structure and motions of the Earth. By 1975, Gough and other scientists realized that it should be possible to deduce the internal structure of the Sun by studying its oscillations. The new field of helioseismology was born.

By 1984, helioseismology was exploding as observations of the Sun confirmed the basic tenets of the new theory. At that time, Gough was focusing on the internal structure and basic physics of the Sun, and Toomre was exploring the motions inside the Sun and a fundamental theory of



SOMETHING NEW UNDER THE SUN

convection. Two years later, JILA formally recognized the long-term relationship between Gough and Toomre by making Gough an Adjoint Fellow of JILA. About the same time, Gough also began thinking about applying helioseismology to other stars. He has dabbled in asteroseismology ever since.

Many years later, Toomre would follow suit, but first he wanted to understand the internal workings of the Sun. His group combined helioseismology with computer simulations to probe the internal structure of the Sun. They conducted detailed investigations of the turbulent convective layer beneath the Sun's surface.

> Gough and Toomre consulted seismologists who were using sound waves to figure out the internal structure and motions of the Earth. By 1975 [they] realized that it should be possible to deduce the internal structure of the Sun by studying its oscillations. The new field of helioseismology was born.

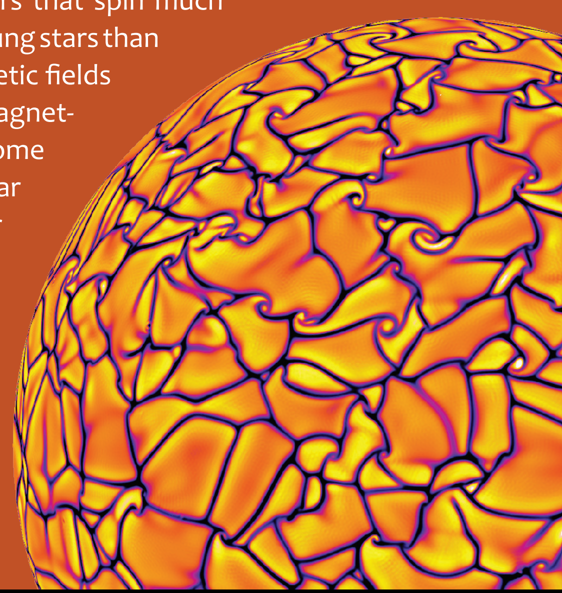
The group showed that the convective layer, which comprises the outer 30% of the Sun, exhibits weather patterns such as strong winds, jets, and tornadoes. This layer interacts with an area of rapid change (called the tachocline) between it and the (relatively) quieter radiative interior of the Sun. This interaction causes the formation of magnetic structures that influence sunspot behavior and other surface phenomena.

Fellow Adjoint Douglas Gough. *Credit: Institute of Theoretical Astronomy in Cambridge (UK)*

Eventually, Toomre and his colleagues were able to explain the Sun's nonuniform rotation, which extends through the convection zone but does not occur in the radiative interior, which rotates uniformly. The researchers added a small difference in temperature of ~10 K in the tachocline between the cooler equator and the slightly warmer poles to their simulation. With this change, the simulation mirrored the observed solar rotation pattern in which the Sun's equatorial regions rotate with a period of about 27 days and the poles rotate with a period of about 35 days.

By 2008, the Toomre group was using their simulations to compare the internal structure of the Sun with that of young Sun-like stars that spin much faster. The researchers found different global-scale circulation patterns in the young stars than in the Sun. These circulations act as a conveyor belt that helps transport magnetic fields through the convection zone to the tachocline. In the young stars, large-scale magnetic fields were created throughout the convection zone. These fields likely become starspots at the surface of a young star. However, the Sun not only has similar magnetic fields throughout the convection zone, but also a global-scale solar dynamo capable of generating sunspots that is rooted in the tachocline.

The detailed understanding of these circulations has led to a goal of predicting space weather events. Key steps in developing a solar weather-prediction system include mapping out the Sun's internal winds and developing an even more detailed understanding of the solar dynamo.



A Laser into the of Matter

CU Professor Edward Condon (1963–1974) and Dick Zare, a member of the CU chemistry (and physics) faculties (1966–1969) initially articulated the vision for chemical physics at JILA. They imagined a new interdisciplinary program that would cut across physics and chemistry and focus on molecular science.

An innovative electron photo-detachment experiment played a key role in launching the new field. The photo-detachment experiment had been pioneered by physicists Lewis Branscomb, one of the JILA founders, and Stephen Smith in a series of heroic experiments that began in 1954 at NBS in Washington, D. C. In 1962, Branscomb and Smith brought the photo-detachment apparatus from Washington to JILA.

Six years later in August of 1968, Branscomb welcomed a new postdoc to his research group: W. Carl Lineberger. Three months later, Branscomb announced he was leaving JILA to become the director of NBS Washington, leaving Lineberger as the senior person in charge of a small group of two. Lineberger took advantage of the change in plans to switch his project to work on the lab's electron photo-detachment experiment — but with a major modification. Lineberger decided to build a brand new tunable dye laser for the experiment.

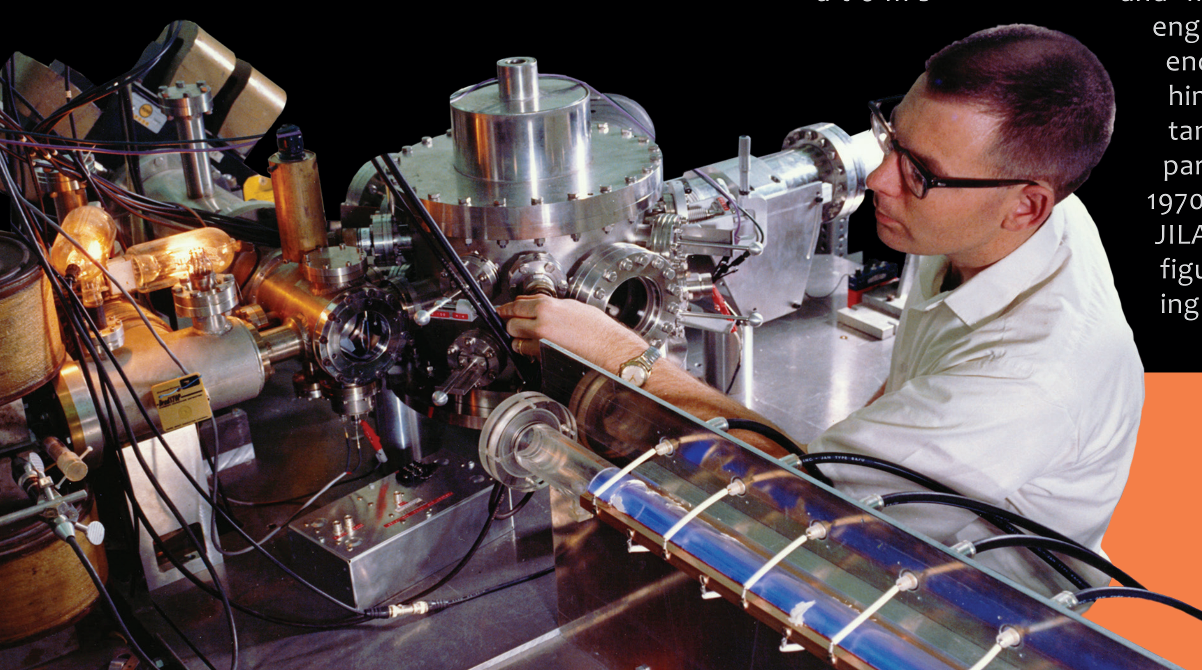
He enlisted the help of some hot-shot laser scientists in the area: Don Jennings and Ken Evenson at NBS, Art Schmeltekopf at NOAA, and Jan Hall at JILA. This collection of technology wizards had already taken the idea of the laser and run with it. Within a couple of weeks, the laser experts had helped Lineberger put together the first high-resolution tunable-laser photo-detachment apparatus. "This story exemplifies what is so special about JILA," Lineberger says. "Once the experts at NBS, NOAA, and JILA built the laser, the shops people started work on a Thursday afternoon and worked day and night through the weekend to get everything set up in the lab so it would be ready for an experiment on Monday."

"This story exemplifies what is so special about JILA," Lineberger says. "Once the experts at NBS, NOAA, and JILA built the laser, the shops people started work on a Thursday afternoon and worked day and night through the weekend to get everything set up in the lab so it would be ready for an experiment on Monday."

— W. Carl Lineberger, JILA

Lineberger's first experiment looked at the threshold for electron photo-detachment in sulfur ions (S-). It immediately began producing results that were a thousand times better than ever before, thanks to the new laser.

Lineberger was hooked — not so much on building the laser, but on what it would allow him to learn about atoms and molecules. Trained as an engineer, he quickly learned enough chemistry to land himself a job as an assistant professor in CU's Department of Chemistry in 1970, when he also joined the JILA faculty. By then, he had figured out that by determining the longest wavelength



The negative photo ion detachment apparatus first pioneered by physicists and JILA founders Lewis Branscomb and Steve Smith. Later W. Carl Lineberger modified the apparatus for his own experiments using a tunable dye laser. *Credit: JILA* (i.e., lowest energy) of light needed to detach an electron from an atom or molecule, he could determine the detachment threshold, or electron affinity, of that substance. During his first year on the faculty, he not only determined the electron affinities of multiple atomic ions, but also his first molecule, the diatomic carbon ion, or C_2^-.

Fellow Carl Lineberger. *Credit: JILA*

In fact, Lineberger was able to see the entire spectrum of energy levels of C_2^-. The spectrum, which had been hard to see with other methods, confirmed a prediction of Gerhard Herzberg, who had just been awarded the 1971 Nobel Prize in Chemistry for his work in molecular spectroscopy. The Lineberger group sent Herzberg a copy of their as-yet-unpublished paper when they heard the news of his Nobel. At Herzberg's request, Lineberger let him use three JILA figures for his Nobel address in December.

Three years later in 1974, Lineberger was appointed Professor of Chemistry at CU. For the rest of his distinguished career, he has continued to use lasers to explore the structures and dynamics of increasingly complex atomic and molecular systems. Over time, the Lineberger group has determined most of the values for the electron affinities of atoms and molecules in the Handbook of Chemistry and Physics. In the process, Lineberger took the fledgling field of chemical physics at JILA and built it into the powerhouse it is today.

In 1985, Lineberger was appointed as the E. U. Condon Distinguished Professor of Chemistry. The appointment was not only a tribute to Lineberger's accomplishments in nurturing chemical physics research at CU and JILA, but also a tribute to one of the original visionaries in the field.

These days, the Lineberger group still relies on lasers in its chemistry research. Current topics include the structure and stability of ions and free radicals, the structure and behavior of anions, and the photophysics and behavior of cluster ions. The group uses lasers to not only peer into the heart of atoms and molecules, but also to study chemical reactions as they happen.

In 1976, JILA appointed Steve Leone as a Fellow of JILA. Leone's hire enhanced chemical physics research at the Institute.

The next year was a banner year for JILA. The Institute's scientific cornerstones still included atomic and molecular physics as well as astrophysics. In addition, however, there were ongoing projects in lunar laser ranging, precision laser-based geophysical measurements, the application of stabilized lasers to precision measurement and tests of relativity theory, and an enhanced chemical physics research effort. The latter brought JILA closer ties to CU's Department of Chemistry.

Astrophysics was also evolving. There was growth in observational work at both Earth- and space-based observatories. Research areas included cool stars, astrophysical gas dynamics, stellar winds of hot stars, the atmosphere of the Sun and other stars, binary x-ray sources, and pulsar modeling.

Catharine (Katy) Garmany came to JILA in 1977 as a postdoc from the University of Virginia to work with Fellow Peter Conti on problems in stellar astronomy. She held this position until 1983 when she became a Senior Research Associate in Conti's group.

In 1977, NBS changed the name of its JILA division from the Laboratory Astrophysics Division to the Quantum Physics Division (QPD), reflecting the ongoing diversification of research programs at JILA. Soon afterward, the Institute celebrated its 15th anniversary over a period of two months, with a chairman's party on the 10th floor of the JILA Tower on April 14, talks about JILA science in everyday language for the staff by Fellows Gordon Dunn, Carl Hansen, Bill Reinhardt, Dick McCray, Jim Faller, Alan Gallagher, and Art Phelps on May 17 and 19, and a pot-luck picnic lunch and softball game on May 21.

In the middle of this long anniversary celebration, Chair David Hummer launched the ***jilanews*** on May 13 to disseminate information, help rekindle a sense of community, stimulate conversation, and provide an opportunity for occasional satire. In the latter vein, Hummer wrote that, "When JILA first started, the Division was called the Laboratory Astrophysics Group, the acronym being LAG. Some felt LAG denoted slowness. It then became LAD (when the group became a division), which had a connotation of youthful immaturity and a growing process. Currently the QPD is a tough one to figure out and the nearest thing I can come up with is a connotation of speed 'Quick Pretty Damn,' which perhaps is our ultimate answer to being called LAGs in the first place." On a more serious note, Hummer raised the issue that astrophysics appeared to be increasingly decoupled from the rest of the Institute, which was focused more on research in atomic, molecular, and optical physics as well as chemical physics.

Chair Hummer also wrote a more serious anniversary letter on April 13. SRO Director Lorraine Volsky and NBS Executive Officer Pat McInerny helped Hummer with the letter, which was sent to all current and former JILAns. A copy of the letter was placed in a time capsule buried under the sidewalk in front of the Boulder County Courthouse as part of the downtown Pearl Street Mall dedication ceremonies in 1977. The time capsule will be opened in 2077.

A copy of the 15th Anniversary Letter preserved by JILA Historian Roy Garstang is shown on the right.

1978–1979

By 1978–1979, JILA was receiving hundreds of applications for the 10 positions available for Visiting Fellows. The broad scientific topics under investigation by the visiting and resident JILA Fellows included stellar astronomy, stellar atmospheres and radiative transfer, stellar interiors, solar system physics, the interstellar medium, high-energy astrophysics, extragalactic astronomy, atomic and molecular collisions, spectroscopy, laser physics, and precision measurement. By the end of 1979, JILA scientists had published more than 2000 papers on these topics.

Text of the 15th Anniversary Letter preserved by JILA Historian Roy Garstang, dated 13 April 1977:

Dear Colleagues,

Fifteen years ago today Carl Pelander began to set up the first JILA shop and laboratories in the old Armory Building on the university campus. I would like to take the occasion of our fifteenth anniversary to write to everyone who has been involved with JILA in order to bring you news of our personnel and research activities. As each of you has in some way participated in the development and productivity of the Institute, I would like to thank you for your contribution and to invite you to regard JILA's success as your own.

In recent years, we have experienced a considerable diversification of programs. In the first place we have increased emphasis on research directed toward definite areas of application, particularly those relevant to energy and precision measurements. On the other hand, because of a large and crucially important block grant to JILA from the Physics Division of the National Science Foundation, and a variety of smaller grants, we are also able to follow a program of vigorous research in basic science. I personally feel quite pleased with the balance between these categories, particularly as activities in both so frequently turn out to be complementary.

Although atomic and molecular physics, on the one hand, and astrophysics, on the other, remain the two cornerstones of JILA, they have stimulated a host of related activities that now have a clear identity of their own. Lunar ranging and, more recently, a very active program in precision geophysical measurements, with earthquake prediction as an important stimulus, have arisen from early work on laser development. A vigorous and extremely productive program in chemical physics has evolved from our work in atomic physics and has been strengthened by two excellent appointments in recent years; this area was selected for emphasis because of the vastly increased importance of molecular processes in both technology and astronomy. As a result, our links with the CU Department of Chemistry have become stronger. Stabilized lasers are being applied to a number of experiments in precision measurement and to experimental tests of relativity theory.

On the astrophysical side of JILA, the past few years have seen a spectacular growth in observational work. A number of JILA Fellows and their postdocs and students have made heavy use of instruments at Kitt Peak, Cerro Tololo in Chile, Sac Peak, and at other observatories, as well as of the OSO and Copernicus satellites. A number of observers have been appointed recently as Visiting Fellows; we were very proud when one of them played a major role in the discovery and identification of the SiO maser associated with cool stars; astrophysical gas dynamics and turbulence have become major areas of research in JILA with applications to stellar winds of hot stars and the atmospheres of the Sun and related stars. A strong program on binary x-ray sources is making important contributions, as is a new program on pulsar modeling; of course, many of the more familiar JILA programs are still flourishing and productive. The negative ion work goes from strength to strengthen. Atomic theory continues to focus on atomic and molecular structure and collision problems, as well as on line-broadening work, and a new effort on the interaction of intense radiation with atoms is making progress. The ion trap experiment, which was featured on the cover of an issue of Physics Today, is producing data of a kind previously unobtainable. A very energetic program is devoted to the study of properties of excimer laser systems. A new generation of measurements of fundamental constants is under way. A study of multiphoton processes in sodium has been producing its share of interesting surprises, and the work on triply differential ionization cross sections has moved to obtain data on secondaries lying out of the scattering plane. The Atomic Collision Cross Section Information Center, headed by Earl Beaty since Lee Kieffer's move to NBS Gaithersburg, continues to provide a worldwide service with its bibliographies and reviews.

The work on the evolution and stability of stars that has played such an important part in JILA's astrophysics program continues to be highly productive. Theoretical programs on atmospheres of both hot stars and solar-type stars remain active, and now benefit greatly from our in-house observational program. Recent work on the spectra of white dwarfs with very high magnetic fields has been quite timely. I am pleased by both the diversity and integration of our astrophysical program.

The past several years have been a period of slow but steady growth toward our current population of more than 150 persons in JILA. As a result of our increased emphasis on postdoctoral training, the number of postdocs has shown the largest growth and is now at nearly 50. The Visiting Fellows program continues to make its unique and vital contribution to JILA but despite a substantial increase a few years ago in the NBS grant for this program, inflation has once again reduced the program level to about six person-years.

Because of the election of a substantial number of new, younger Fellows to replace those who have retired or resigned, the mean age of the Fellows has increased by only approximately four years since the founding of JILA. In the past two years, we have elected new Fellows: Steve Leone, Judah Levine, David Norcross, Bill Reinhardt, and Juri Toomre. Our local expertise is currently reinforced by our Fellows-Adjoint: Dick Deslattes, NBS Gaithersburg; Mike Seaton, University College London; and Dick Zare, who will shortly be moving to Stanford. In recent years Jinx Cooper, Steve Smith, and I have served as Chairman

Although Carl Pelander retired last fall from the NBS after heading the shops since the first day of JILA, he has returned to work as a CU employee; Carl was honored by a banquet on his retirement. Bill Lees is now head of the shops, his counterparts in the special techniques and electronic shops are Dick Weppner and Saul Lissauer. Pat McInerny continues as JILA's Executive Officer and Lorraine Volsky as head of publications. Margaret Massey has just taken over the Visiting Scientists Office. As many of you know, Ursula Palmer died tragically early this year following a car accident. A large pin oak will be planted in her memory later this year at the site of the derelict fountain east of the laboratory wing. Joining Chela Kunasz in the programming group as replacements for Ursula are Steve ONeil and Susan Ross.

A number of JILA personnel have received distinguished awards this year. Steve Leone has received a Sloan Fellowship, and Jinx Cooper and Bill Reinhardt have been awarded Guggenheim Fellowships; Bill has also received the Fresenius Award of the American Chemical Society, and along with Carl Lineberger has been designated as a Camille and Henry Dreyfus Teacher-Scholar. Katy Garmany has received the Annie J. Cannon Award of the American Astronomical Society. In recent years Dick McCray has received a Guggenheim Fellowship, and Jim Faller, Carl Lineberger, and Bill Reinhardt have held Sloan Fellowships. A number of NBS staff members have received Department of Commerce Gold Medals and other government awards. All of us are very proud that so many of our colleagues have received high honors.

You might be interested in a few statistics from JILA's first 15 years. Since 1962, 68 Ph.D. theses have been written and accepted and 1446 papers and books have been published. Although our records are not complete for every year, we estimate that more than 170,000 requests for reprints have been filled. The mailing list for this letter includes approximately 350 names of people who have been associated with JILA at some time during the past 15 years.

I remain optimistic about JILA's future. Although problems exist and new ones are sure to arise, our success in dealing with some very tough problems in recent years gives me confidence in our ability to cope with any future difficulties.

When you are next in this part of the country, please stop and renew your acquaintance with us here at JILA.

With best regards,

David G. Hummer, Chairman

JILA Chair David Hummer (l) and Fellow Carl Lineberger (r) celebrate the award of JILA's first NSF block grant in support of atomic and molecular physics research. *Credit: JILA*

During the 1970s, JILA staff and scientists were fond of wild and creative Halloween costumes. *Credit: JILA*

The year 1978 brought the first written record of student workers at JILA, whose role was highlighted in the October 27, 1978 issue of the ***jilanews***.

jilanews

October 27, 1978
JILA's Student Workers

Those folks you often see in the reception area are the people who do the foot work for many of the administrative and scientific staff. Computer runs, airport runs, runs to virtually all buildings on campus help us to make JILA run. Coffee, cookies, and donuts appear through the likes of Doug Johnson, a graduate student in business.

What the news story doesn't say is that Johnson's student worker status lasted until 1982, when he joined JILA's administrative staff, where he has continued to make significant contributions to JILA, including serving as JILA's liaison to the architects and builders of the new X-Wing, completed in 2012.

On July 1, 1979, the University of Colorado Boulder completed a departmental change that affected JILA. Before this change, the university had astrophysicists in two departments, Physics and Astrophysics as well as Astro-Geophysics. The two departments lacked both a cohesive graduate program and a coherent plan for going forward. To help solve these problems, JILA's astrophysicists, who were rostered in the Physics and Astrophysics Department, left that department to join the Astro-Geophysics department. Carl Hansen, John Castor, Dick McCray, Peter Conti, Ludwig Oster, newly appointed Fellow John Cox, and Roy Garstang all made the transition. Only Garstang retained a joint appointment with the newly renamed Physics Department. The move to the Astro-Geophysics department[1] paved the way for developing a more robust graduate program at CU in astrophysics.

The first issue of the ***jilanews***, an internal newsletter for JILAns, 13 May 1977, with an introductory note from then-JILA Chair, David Hummer. The newsletter was hand-typed, copied, and paper copies were distributed to each mailbox!

1. The Astro-Geophysics Department was renamed the Department of Astrophysics, Planetary, and Atmospheric Sciences in 1979, and once again as the Department of Astrophysical and Planetary Sciences in 2001.

jilanews

13 May 1977 Number 1

From the Chairman. I hope you will find JILANEWS informative and useful. Although it is scheduled to appear weekly, it cannot do so unless each person in JILA contributes items of general interest. Karen Dirks is responsible for editing and producing the newsletter, but not for gathering news. Please give her your contributions in writing by noon on Thursday. We are starting with a relatively free format, and only vague ideas of coverage, and are looking for suggestions as to content and style. Nancy Morrison, Pat McInerny and I are assisting Karen for the first few issues, but would like some help from someone in the lab wing. We would be happy to discuss any aspects of the newsletter.

Organizational Name Change

In case you haven't yet heard, the NBS contingent of JILA has recently undergone an organizational name change. The "Laboratory Astrophysics Division" has been renamed the Quantum Physics Division. A note of interest is that this is the third time the Divisional name has changed. When JILA first started, the Division was called the Laboratory Astrophysics Group, the acronym being LAG. Some felt LAG denoted slowness. It then became LAD which had a connotation of youthful immaturity and a growing process. Currently, the QPD is a tough one to figure out and the nearest thing I can come up with is a connotation of speed "Quick Pretty Damn" which perhaps is our ultimate answer to being called LAGs in the first place.

* *

REMEMBER THE JILA 15th ANNIVERSARY PICNIC AND SOFTBALL GAME SATURDAY, MAY 21, 12:30!

* *

Softball Practice for Postdocs and Graduate Students

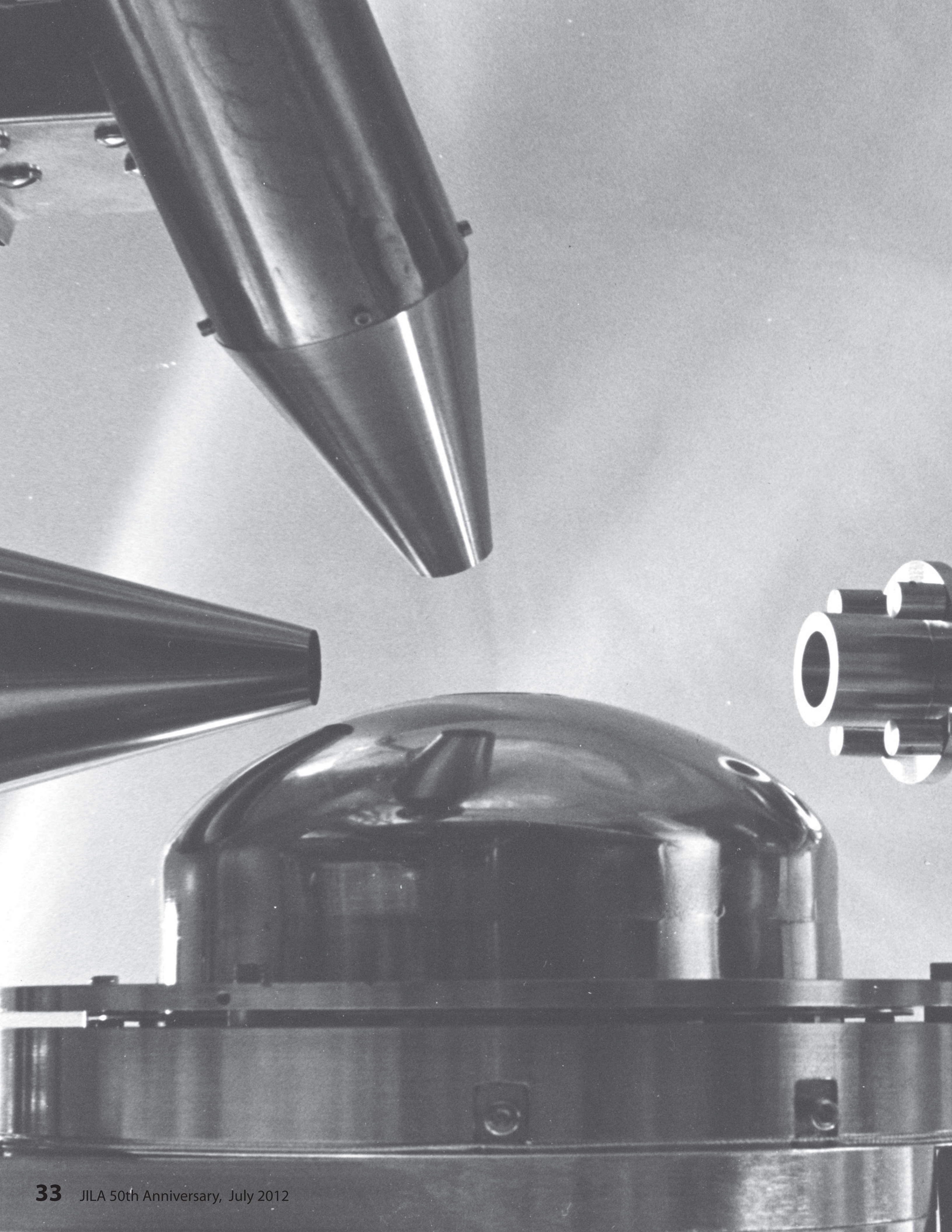
In anticipation of the Great JILA Challenge Softball Match, we (postdocs and graduate students) will hold a practice on this Saturday, May 14, at 2:00 p.m. at the Paddock School Field. It is located just south of the Table Mesa King Soopers. Go west off Broadway on Table Mesa Drive. Turn left (south) onto Gillaspie. Paddock School is about a quarter mile on the right. Ability is not necessary.

Atomic and Radiation Theory Seminar

Tuesday, May 17, 10:00 a.m. JILA Auditorium--R. Van Brunt: Present shape of the He ^{2}S resonance - analysis of high resolution electron scattering.

Talks About JILA's Scientific Work

Tuesday, May 17, 3:00 p.m. JILA Auditorium, G. Dunn, B. Reinhardt. R. McCray, J. Linsky.
Thursday, May 19, 3:00 p.m. JILA Auditorium, A. Phelps, C. Lineberger, C. Hansen, J. Faller.



Chapter 3
1980 to 1989

Fellow Carl Wieman teaching a physics class to CU undergraduates.

During the 1980s, JILA scientists worked in astrophysics, atomic and molecular physics, chemical physics, geophysics, laser physics, and precision measurement. They continued to explore exciting frontiers in their respective disciplines. Astrophysical research was largely in the areas of theoretical astrophysics; observations and theory of stellar atmospheres, winds, and interiors; optical, ultraviolet, and x-ray astronomical spectroscopy; and laboratory astrophysics.

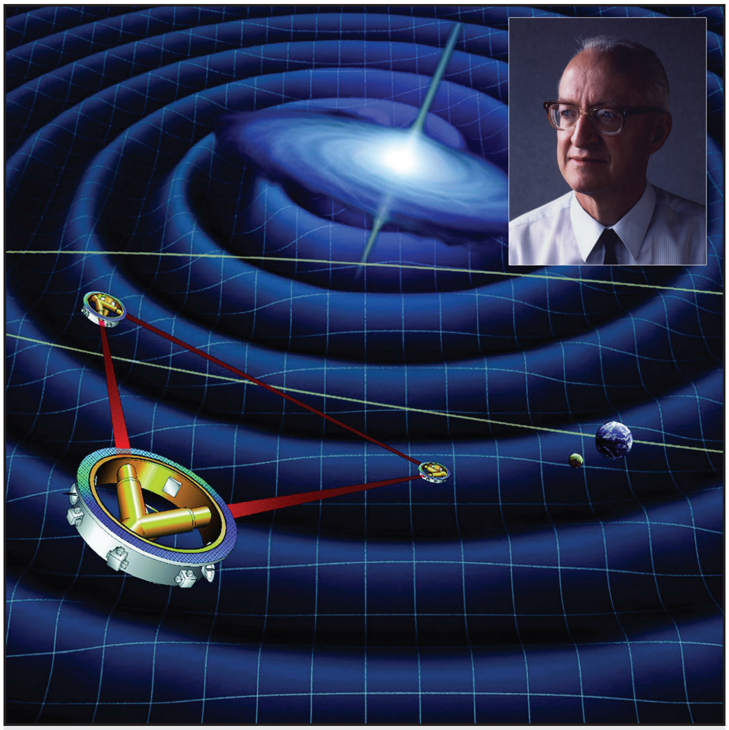
Major research programs were under way in the areas of atomic and molecular interactions, spectral line studies, molecular radiation, development and application of stabilized lasers, radiative transfer, solid-earth geophysics, and the determination of fundamental physical constants.

In 1980, the Fellows included Earl Beaty, Pete Bender, John Castor, Peter Conti, Jinx Cooper, John Cox, Gordon Dunn, James Faller, Alan Gallagher, Roy Garstang, Katharine Gebbie, Sydney Geltman, Jan Hall, Carl Hansen, David Hummer, Steve Leone, Judah Levine, Carl Lineberger, Jeffrey Linsky, Richard McCray, David Norcross, Ludwig Oster, Art Phelps, Bill Reinhardt, Stephen Smith, and Juri Toomre. Michael Seaton (University College London, U.K.) and Richard Zare (Stanford University) were Fellows Adjoint.

At the beginning of the decade of the 1980s, the University of Colorado began the process of changing the name of the Department of Astro-Geophysics to the Department of Astrophysical, Planetary, and Atmospheric Sciences (APAS). The change was completed in 1982. APAS was housed in the Duane Physics complex along with JILA, CU's Physics Department, and the Laboratory for Atmospheric and Space Physics. JILA's astrophysicists held either regular or adjoint faculty appointments in APAS. For their research, they used national facilities, including optical telescopes at Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory, a radio telescope at Socorro, New Mexico, and spacecraft such as the International Ultraviolet Explorer, the Solar Maximum Mission, and the Einstein X-Ray Observatory.

In the mid-1980s, JILA not only installed its first shared computer, a VAX 8600, but also a hardwired local-area network (LAN) in 1985. The Institute began participating in a primitive "e-mail" system known as BITNET a year later. By 1988, Judah Levine and colleagues from NBS had completed an important first step in modernizing time transfer by bringing the Automated Computer Time Service online. The time service allowed users to access atomic clock time via dial-up modems.

The decade of the 1980s also witnessed two JILA anniversaries, including a three-day celebration of its 20th anniversary in 1982. JILA's 25th anniversary was held a year late in 1988 in conjunction with the dedication of a brand new laboratory wing, the S-Wing. The new building was designed to support JILA's enhanced research efforts in AMO physics, chemical physics, and precision measurement.



An artist's conception of the Laser Interferometer Space Antenna (LISA), worked on by Fellows Pete Bender (inset) and Jim Faller. LISA will detect gravitational waves from black hole binaries. *Credit: European Space Agency*

THE THIRD DECADE (1980–1989)

1980–1981

During 1980 and 1981, things were running smoothly in JILA. Winter ski trips and noon bridge games offered diversions for scientists and staff alike. In the food department, the price of doughnuts in the reception area increased by a whopping 33.33% to $0.20 each, with no noticeable decline in popularity.

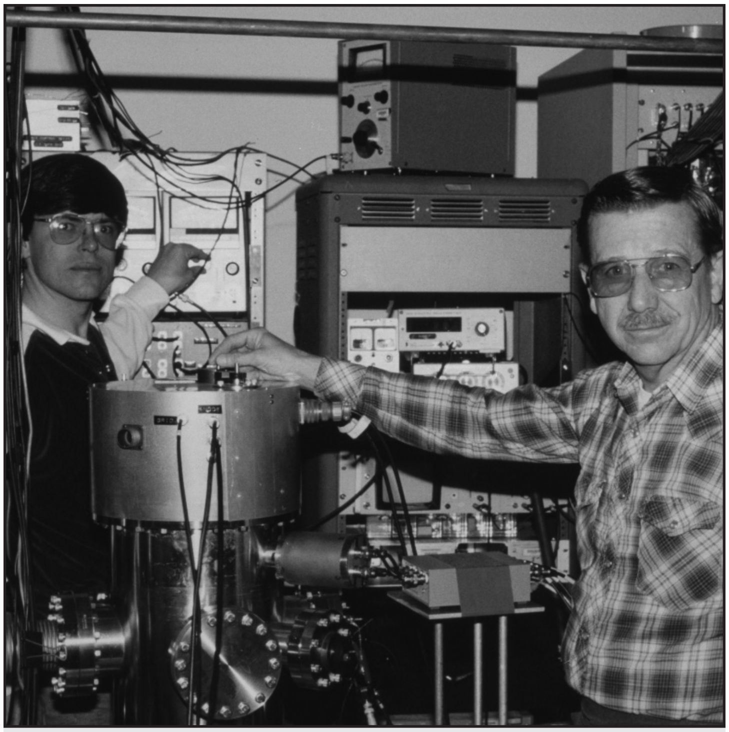
The Visiting Fellows program continued to be a vital part of JILA, but experienced one short-lived change. From 1980 to 1986, one of the visitor fellowships was offered to a teacher under a program called Research Fellowships for Teachers.

JILA's expertise in laser physics led to discussions by Fellows Pete Bender and Jim Faller of possible gravitational-wave measurements in space. The basic idea for what came to be called the Laser Interferometer Space Antenna (LISA) was developed in 1980. The ambitious goal for LISA was to use lasers aboard three spacecraft in a triangular configuration to detect and measure gravitational waves produced by massive black hole binaries and other sources. Bender and Faller believed that such studies could lead to an understanding of how massive black holes formed and grew in the early Universe.

From the beginning, it was clear that a major effort would be needed to design a mission like LISA. The first funding for the project came from the NBS director's reserve, with later support coming from NASA in 1986–1987. In 1989, NASA considered LISA for a future astronomy program known as Astrotect-21, which was scheduled to begin after the launch of the great space observatories.

1982–1983

In 1982, JILA marked its 20th anniversary with a three-day celebration May 6–8. On May 6, Harvard University's Alexander Dalgarno (the father of molecular astrophysics) gave an invited lecture. The following day, a ceremony in the JILA auditorium featured speeches by NBS Director Ernest Ambler and CU Chancellor Harrison Shull. JILA held an open house of the labs for



Fellow Gordon Dunn (r) and a young researcher in his laboratory, 1982. *Credit: JILA*

the public following the ceremony. There was also a reception on the 10th floor, followed by a banquet for the Fellows and Visiting Fellows at the Broker Inn. On May 8, there was a softball game at the Baseline Junior High School field, followed by a potluck dinner for all JILA staff at JILA Chairman Dick McCray's home. That party is fondly remembered as a "rip-roaring party for present and former JILA people."

Postdoc David Nesbitt said goodbye to JILA to go to the University of California at Berkeley, but his departure didn't stick. He returned two years later (in 1984) as a JILA Fellow and member of the NBS Quantum Physics Division.

In the fall of 1982, JILA's annual picnic for the Fellows and staff was held at the Mountain Research Station west of Boulder. It was an all-day affair. The following year featured a three-day ski trip to Winter Park in March and a two-day JILA raft trip on the Delores River in June.

One particularly noteworthy event occurred in 1983 after Jan Hall and his NBS colleagues made a collaborative precision measurement of the frequency and wavelength of an iodine-stabilized He-Ne laser in 1982. The 1982 measurement paved the way for the official adoption in 1983 of a revised definition of the International System of Units (SI) standard meter. Since 1983, the meter has been defined as the length of the path travelled by light in a vacuum during a time interval of 1/299,792,458 of a second (~3 ns).

In 1983, Judah Levine and his colleagues at NBS began tackling the challenge of modernizing time transfer. This effort would lead to the development of the NBS/NIST time services that are now critical to controlling the U. S. electric grid; time-stamping financial transactions, such as stock market trades; synchronizing telecommunications; and managing Earth- and space-based observatories.

In 1983, Mitch Begleman joined CU's APAS department as an assistant professor and became a member of JILA's theoretical astrophysics, high-energy astrophysics, and fluid dynamics groups. The same year, Ed Holliness joined the Supply Office, where he worked for more than 20 years until his retirement in 2005.

1984–1985

By the mid-1980s, JILA had become internationally renowned. As the JILA Self-Study Report to the University of Colorado (dated December 1984) stated,

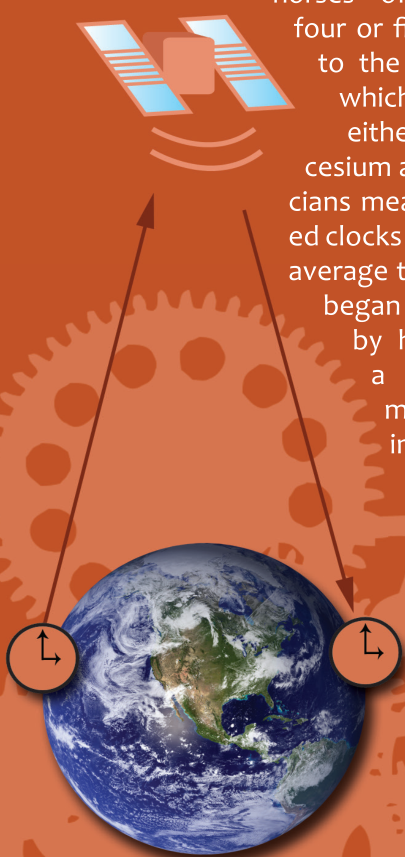
> *This collaboration has been extremely effective and scientifically productive over the years. When JILA was formed 25 years ago, "laboratory astrophysics" focused special attention on aspects of astronomy and atomic physics that were relevant to the well-defined national interest in space that prevailed at the time. However, since its inception, JILA has responded to the changing national needs and to the requirements of its parent organizations. Experimental and theoretical contributions have been made not only to atomic physics and astrophysics, but also to molecular, chemical, and laser*

The Transformation of GLOBAL Timekeeping

Judah Levine has been a key participant in the transformation of global timekeeping since 1978. Since then, time communication has increasingly relied on telephone networks, the Internet, and satellite networks, which together were responding to about 11 billion requests per day for the exact time in April of 2012. There has been a revolution both in determining the exact time and in communicating it to personal computers, interactive tablets, telecommunications networks, electric power grids, financial markets, scientific institutions, and navigation systems on Earth and in Space. Judah Levine has been in the middle of all of this.

Judah Levine has been a key participant in the transformation of global timekeeping since 1978.

In 1978, Levine began working with NBS colleague Dave Allan to create a modern Time Scale featuring a computer-controlled time measurement system. The first "workhorses" of modern timekeeping were four or five cesium clocks calibrated to the nation's primary standard, which from 1972 to 1993 was either the NBS-5 or the NBS-6 cesium atomic clock. At first, technicians measured time on the calibrated clocks by hand and calculated their average time. In the early 1970s, NBS began "automating" this process by having each clock produce a paper tape containing a month's worth of time readings. Computers used the tapes to calculate the average time of the clock ensemble for the month. These monthly time averages were sent via telex to the Bureau International de l'Heure at the Paris observatory.



Modernizing this system initially required an automated measurement system. Levine focused on writing the first of what would become 200 analysis programs (software) for the new measurement system, which included two brand new computers. His colleague Dave Allan developed the system's statistical underpinnings. Aided by other NBS professionals, Levine and Allan had the nation's first automated Time Scale up and running by 1980.

Levine received a U. S. Department of Commerce Gold Medal in 1983 for his role in developing the automated Time Scale. The measurement system, which is now 32 years old, remains the official system today.

Although the measurement system has stayed the same for more than three decades, the clocks in the Time Scale have undergone continual improvement. The Time Scale currently has four cesium atomic clocks, which provide long-term stability, and six hydrogen masers, which are extremely stable in the short term. One of these is the original maser purchased for the Time Scale, and the rest have been added over three-to-four year intervals. Since 1999, the Time Scale has been calibrated by the NIST-F1 cesium fountain atomic clock.

Once the new automated Time Scale was up and running in 1983, Levine and his NBS colleagues began modernizing time transfer. At the time, the only time-transfer services were two short-wave radio stations (WWV and WWWB) that broadcast time signals to wall clocks and other devices.

Levine and colleagues Mark Weiss, Dickie Davis, Dave Allan, and Don Sullivan decided to build a telephone-based time-transfer system. Levine's job was designing

Fellow Judah Levine with the NIST Time Scale. *Credit: Jim Burrus, NIST*

the user interface for the system. The Automated Computer Time Service (ACTS) came online in 1988. The service grew rapidly as personal computer users took advantage of their dial-up modems to access atomic clock time. Today, ACTS runs on six-to-eight servers at NIST. It has 30 phone lines in the continental United States, and another four in Hawaii.

As early as 1990, ACTS could not handle the burgeoning number of time requests. Levine came up with a novel idea for solving this problem: He proposed syncing a computer with ACTS so the computer could disseminate time information over the Internet. Initially considered a minor addition to the existing time service, this idea quickly became the foundation for NIST's Internet Time Service (ITS).

With one exception, Levine wrote all the software for the new time service, whose popularity grew exponentially after it was introduced in 1993. Since then, Levine has overseen software improvements and several hardware upgrades for the ITS, which was handling the majority of the requests for atomic clock time. In 2007, he was awarded a second Gold Medal from the Department of Commerce for his many accomplishments related to the NIST Time Scale and time services.

In 2007, Levine installed a back-up Time Scale near Fort Collins, Colorado. The back-up Time Scale became fully operational when telephone lines and high-speed Internet connections were installed at the remote site.

Levine's role in transforming global timekeeping continues to be acknowledged. In 2011, President Obama selected him for a Presidential Rank Award. The award recognized him for his precision time and frequency measurements based on systems of atomic clocks, including the use of satellites for time and frequency distribution.

physics; precision measurements; geophysics; data measurements necessary for new energy sources; and the collection and evaluation of scientific data. The need for JILA to be dynamic in its focus and programs was explicitly stated in the Amendment to the MOU signed in 1976 by NBS and CU.

In 1984 and 1985, three new Fellows, David Nesbitt, Dana Anderson, and Carl Wieman, arrived at JILA. Chemical physicist Nesbitt arrived in 1984, while CU Fellows Anderson and Wieman came in January of 1985. Anderson planned to undertake research in nonlinear optics and precision measurement. Wieman arrived from the University of Michigan with a postdoc and two students in tow. He intended to continue studies of laser spectroscopy and parity violations in atoms.

The new Fellows found their new home to be anything but "all work and no play." Snowy 1984 featured two JILA ski trips, one in late February to Winter Park and another to Copper Mountain in late March. The annual JILA picnic was held in early October on Flagstaff Mountain.

The big news of 1985 was (1) the startup of the new JILA computer system and (2) the approval by the CU regents of JILA's plan for a new building addition. In late June, Chairman Carl Lineberger and David Norcross of JILA's Computing Committee invited the Fellows and staff to witness the launch of JILA's new VAX/8600, which was up and running under a VMS 4.1A operating system in August. The VAX/8600 had two floppy disk drives and three 9600-baud dial-up lines. Its software included multiple VMS features, an IMSL mathematical library, a DISSPLA graphics package, and an excellent magnetic tape exchange utility. Soon after JILA installed its new computer, the Computing Group also set up a hardwired communications network throughout the lab wing and tower.

A second exciting event also took place on August 8th when the CU Board of Regents approved a program plan for a new JILA building addition, to be called the S-Wing. The next step would be approval from the Colorado Council on Higher Education.

1986–1987

Technology improvements continued during 1986. A new phone system was installed. And, CU became a BITNET node on a primitive university email network invented at the City University of New York and Yale University in 1981. BITNET links ran at 9600 baud and were widely implemented under VAX/VMS systems like the one at JILA. By May, JILA was working to install a BITNET node of its own for the transfer of email and files between educational and research institutions.

The year 1986 also saw the start of construction for JILA's new S-Wing. Site preparation began in August, but was halted temporarily to obtain a sewer easement and approval of the design by the City of Boulder. With these approvals in hand, the utility phase of the construction resumed on September 26 and was completed in two weeks. The same week the utility work resumed, CU issued a contract to the low bidder for the construction of the building.

The official ground-breaking ceremony for the S-Wing took place on the south side of the tower at 11:30 a.m. on October 20. CU-Boulder Chancellor James Corbridge, CU President Gordon Gee, and JILA Chair Carl Lineberger gave short speeches.

New faces in 1986 included Fellows Andrew Hamilton and Robert Parson, as well as John Andru, the new Instrument Shop supervisor. Theorist Parson specialized in chemical physics. Hamilton, a theoretical astrophysicist, arrived from the University of Virginia. His main interests were supernova remnants, the interstellar medium, and cosmology. With tongue in cheek, Hamilton noted that 50% of his time would be available for "playing squash, enjoying nature, chopping wood, and solving the problems of the Universe, especially on Wednesday evenings."

There were other activities available in 1986 for JILAns to enjoy: the summer Coors Classic bicycle race, the annual (October) JILA picnic at Jinx Cooper's home, and JILA's new intramural basketball team, which defeated the law school 25–22 in its first-ever preseason game.

Fellow Dick McCray, 2011.
Photo: JILA

When Dick McCray came to JILA in 1971, astrophysics research was dominated by the study of stars, including investigations of energy transfer through the atmospheres and interiors of stars; solar physics; hot stars; and cool stars. But, McCray's specialty was the physics and chemistry of interstellar matter. However, since he wanted to expand his research horizons, he decided to look into x-ray astronomy, in particular binary-star x-ray sources and x-ray emissions through interstellar gases. Within two decades, McCray's eclectic set of research interests would dovetail into a multifaceted, 25-year study of the brightest supernova visible on Earth since 1604.

> "Webster Cash (of Astrophysical and Planetary Sciences) had a rocket that could detect x-rays, and he asked me if there would be any x-rays to see."
>
> — Dick McCray, JILA

On February 23, 1987, Supernova 1987A appeared in the southern sky. This dramatic celestial event was due to the explosion of a blue supergiant star in the Large Magellanic Cloud, a nearby galaxy located 163,000 light years from Earth. The day after the supernova was discovered, JILA member Mike Shull organized a special seminar to present the exciting results.

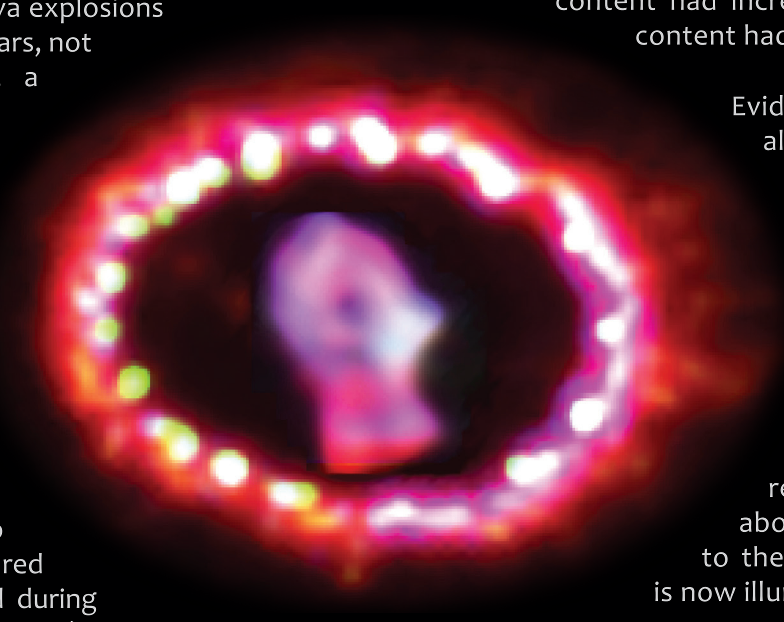
"Webster Cash (of APS) had a rocket that could detect x-rays, and he asked me if there would be any x-rays to see," McCray recalls. "So one day after the supernova, I started working on a new theory on the emergence of x-rays after a supernova. I predicted that x-rays would start leaking out six months to a year after the event."

After publishing his prediction, McCray headed off to China in August of 1987 on sabbatical. In October, McCray was in his apartment, practicing dialog in Mandarin with his teacher from Peking University. He got a phone call from Japan's Institute of Space Astronomy informing him that the x-rays he'd predicted had been found. "I was whooping and hollering I was so excited," he says. "But I couldn't do much else because my teacher said I had to explain what had happened in Mandarin. It took me more than an hour because I had to figure out how to say words like 'x-rays' in Chinese!"

Supernova 1987A

McCray was hooked. He realized he had the tools in hand not only to study the supernova, but also to make predictions about its behavior. In the ensuing 25 years, he and his colleagues have studied this remarkable event in the visible, ultraviolet, and x-ray wavelengths. They have figured out the reasons for the star's spectacular demise and important aspects of the original star's structure and chemistry before it exploded.

McCray and his collaborators found four pieces of circumstantial evidence that the blue supergiant was undergoing a core merger of two stars when it exploded. First, the cylindrical debris cloud in the center of the illuminated ring suggests the presence of two stellar cores. Second, there are two faint outer rings beyond the brightly illuminated ring that resemble the planetary nebulae surrounding binary star systems. Third, since there is no second star to be found, the two original stars must have merged. Finally, the progenitors of supernova explosions are typically red giant stars, not blue giants. However, a progenitor star formed by a merger of two stellar cores might be blue instead of red.



The two-star merger theory also explains a key step in the evolution of the star that exploded. About 20,000 years prior to the supernova, a huge red supergiant star (formed during the early steps of the merger) shed a dense outer layer to become a smaller blue supergiant star. This outer layer now makes up the illuminated ring (about one light year across) that encircles the debris cloud. The glistening diamond-like structures are hot spots that McCray and his students predicted would develop when the supernova shockwave encountered dense fingers of gas in the layer originally shed by the larger star.

More recently, McCray and his colleagues have been able to study ultraviolet light signals from carbon, nitrogen, and helium ions emitted by the debris and the illuminated ring. When they compared the ratio of nitrogen to carbon in the ring and in the debris, they found 10 times more nitrogen and 10 times less carbon in the debris cloud than in the ring. They already knew that the ring itself had 10 times more nitrogen than the interstellar space around it.

The scientists determined that the nuclear furnace inside the original red supergiant star had already been converting carbon and oxygen to nitrogen when it shed its dense outer layer. This process accounted for the tenfold enrichment of nitrogen in the circumstellar ring. However, during the 20,000 years before the supernova, the blue supergiant star's nuclear furnace continued to forge new nitrogen from carbon and oxygen. By the time the star exploded, its nitrogen content had increased tenfold and its carbon content had dropped tenfold.

Evidence of stellar chemistry has also been recently detected in x-ray wavelengths. After 25 years, the stellar explosion has overtaken the circumstellar ring, creating a reverse shock wave that is now illuminating the supernova debris with both x-rays and visible light. The x-rays, in particular, are expected to reveal even more information about the stars whose merger led to the cataclysm. Supernova 1987A is now illuminating its own past.

McCray, too, is revisiting his past research on the chemistry of interstellar matter. Though mostly retired, he is now working to better understand the chemistry at play in the past, present, and future of an ill-fated pair of stars in a neighboring galaxy.

Background Photo: Supernova 1987A taken by the Hubble Space Telescope in 2011. *Credit: Pete Challis/NASA/ESA/CfA*

The following year (1987), construction began on the S-Wing. The new building faced south onto a pleasant tree-bordered brick plaza. It was scheduled for completion in 1988 — a good thing because the Institute was already bursting at its seams. There were now more than 200 people at JILA: 23 Fellows, 12 Visiting Fellows, 10 short-term senior scientists, 71 graduate students, 53 postdocs and senior research associates, and 50 technical and administrative staff members. Five senior scientists had been hired within the previous five years, and two more appointments were anticipated within two to three years. In addition, more space was required for offices, service facilities, and labs. Fortunately, the new S-Wing under construction represented a 40% increase in physical space for JILA. The prospect of having more space was so exciting that the Fellows decided to postpone celebrating JILA's 25th anniversary until April of 1988 to coincide with the dedication of the new building.

While eagerly anticipating the new building, the JILA staff decided to launch a new tradition in 1987: The annual staff power hike and breakfast meeting, which was held in early June. The hike began at NCAR and ended at Chautauqua. Breakfast was on the porch of the Chautauqua Dining Hall and included staff members who chose not to get up at 6:30 a.m. to hike the Mesa Trail. The JILA staff has subsequently carried on this tradition for 25 years, although the word "power" has mysteriously disappeared from the hike's description.

Scientifically, the year 1987 was a watershed year for Fellow Dick McCray. In August of that year, a Japanese satellite detected x-rays being emitted by a brand new supernova, denoted SN 1987A. "I was so excited," McCray remembers. " I knew I had the tools in hand to study this supernova." He has continued to study SN1987A for more than 25 years. And, he has seen prediction after prediction verified as he and his collaborators investigated the supernova's x-ray emissions.

In September, JILA continued with its tradition of holding an orientation in the JILA Auditorium. Staff members from SRO and the Electronics Shops were especially creative in the slides they produced to introduce their capabilities to new JILA staff.

During the 1987 staff orientation, the Electronics Shop highlighted their sponsorship of "lunchtime games" of ping pong, darts, basketball, and Frisbee. Most days, shop staff wheeled the ping pong table out into the hallway near the freight elevator where anyone could join in the fun. The creative shop staff shown here are (l–r) Alan Dunwell, Ralph Mitchell, Jon Feeney, and Dan Marvin. *Credit: JILA*

In December of 1987, JILA held its first holiday charity bake sale, starting a tradition that has continued for 25 years. Instead of selling doughnuts or bagels in the reception area, JILA scientists, students, and staff sign up to provide homemade goodies to sell. Proceeds of the sale are donated to a local charity.

1988–1989

In 1988, Congress passed the 467-page Omnibus Trade and Competitiveness Act of 1988 (PL 100-418) that, among many other things, changed the name of NBS to NIST. The new name came with an expanded mission emphasizing international competitiveness, support to American industry, and the development of new American technology. In its new incarnation, NIST was to function like a civilian version of the Defense Advanced Research Projects Agency.

NIST's new mission had little immediate impact on JILA's basic and applied research in atomic, molecular, and optical physics or precision measurement. However, it did not bode so well for NIST-supported astrophysics research, which would soon be discontinued.

In another staff orientation slide, SRO director Lorraine Volsky demonstrates how she keeps staffers Leslie Haas and Gwendy Romey in line. *Credit: JILA*

On a happier note, in 1988 the JILA Fellows and Staff welcomed the completion of the new S-Wing and the combined celebration of JILA's 25th anniversary and S-Wing dedication. The S-Wing featured 16,000 square feet of office and laboratory space. It included a suite of basement labs designed for vibration and sound isolation as well as temperature control for precision laser experiments. The upper floors were designed to be converted from offices to lab space, should the need arise. The design also allowed for an additional four stories in the future, although this idea has never materialized.

Construction costs for the S-Wing came in at $122/ft^2, or $3,605,000. This figure included the building, furnishings, and research equipment, including lasers and computers. The building was paid for with grants from NSF ($0.5 million) and the Department of Education ($0.5 million) and bonds issued by CU. An additional $200,000 was spent on renovating the existing JILA building.

The building dedication and 25th anniversary took place on April 7–9. The combined ceremony featured a wine and cheese reception held on April 7 from 7:30–9:30 p.m. on the 10th Floor. A baroque wind quintet provided live music for the reception, which was attended by visitors and all JILA personnel. Rumors persist that chief organizer David Nesbitt did not wear blue jeans to the reception.

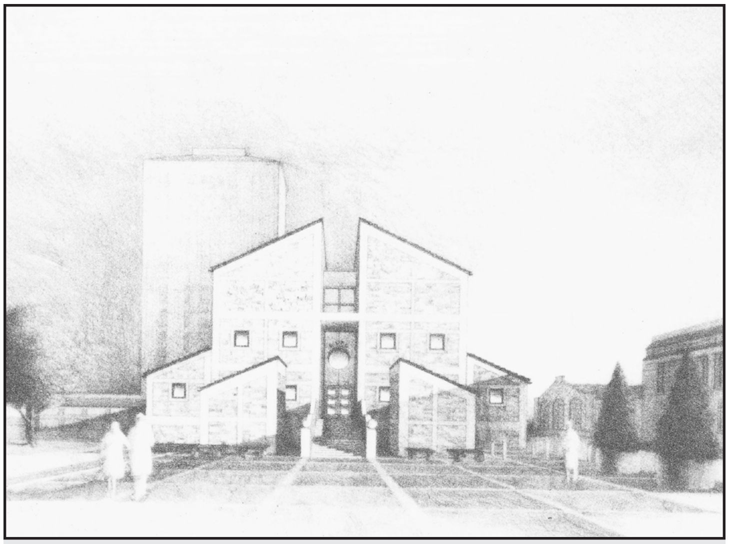
jilanews

October 25, 1988

Neatness in the Laboratory Award

Judah Levine was recently awarded the Jan Hall prize for "Neatness in the Laboratory Environment." Judah's entry consisted of three surplus vans that have seen use as an electromagnetic distance-measuring system. (The fourth vehicle, a Chevrolet Blazer, was disqualified.) In presenting the award, the Chief of NBS security called the entry an "eyesore" and hoped that it could be converted to a traveling exhibit. In accepting the award, Judah praised the diligence of the selection committee and its perseverance in sticking with the selection process in the face of many other pressing duties. He further expressed hope, which he was confident was shared by all his colleagues in the Flat Earth Society, that additional awards would be considered inasmuch as the award is "such a fine example of the principles that have brought us here and made us what we are today." He did not venture an opinion on the suitability of presenting future awards on the northeast corner of Baseline and Broadway. The award consists of a deliquescent medal with the inscription "Novus Ordo Seculorum" on the obverse and "In Hoc Signo Vinces" on the reverse.

The next day, the dedication of the S-Wing was held in the sunny courtyard south of the new addition. Colorado Governor Roy Romer and JILA founder Lewis Branscomb spoke at the dedication, which was followed by a reception hosted by CU-Boulder Chancellor James Corbridge. A scientific symposium was held in the afternoon in the JILA auditorium. Dick Zare (Stanford University), J. C. Wheeler (University of Texas, Austin) and Norman Ramsay (Harvard University) were featured speakers.



Construction on JILA's new S-Wing began in 1986. *Credit: JILA*

The day concluded with the annual JILA Visiting Fellows dinner at the Broker Inn. Ankle-deep snow greeted the Fellows and their guests after dinner, reminding everyone of the fickle nature of Colorado weather.

On April 9, John Taylor of CU's Department of Physics presented one of his famous Wizard shows. Afterwards, an open house was held in the JILA laboratories. The Institute showcased its research in astrophysics, atomic and molecular physics, laser physics, quantum optics, chemical physics, and geophysical measurements.

As the excitement of the dedication and anniversary receded, JILA returned to its primary tasks of research and training young scientists. Carl Wieman and David Bartlett of CU's Physics Department (with support from the NSF) started a new program called Research Experiences for Undergraduates (REU). The program allowed 16 undergraduates from colleges and universities across the nation to come to Boulder during the summer and work in labs in the physics department or JILA. The new program emphasized the active participation of students in research. The program was so successful that it has continued ever since. In 2012, Fellow Deborah Jin and Dan Dessau of the CU Physics Department directed the program.

People news in 1988 included the appointment of Katharine Gebbie as Chief of NIST's Quantum Physics Division at JILA. Gebbie would serve in this position for three years.

In 1988, JILA formed an unofficial softball team and continued its tradition of a fall JILA picnic, which was held in Farrand Field in late September. In December, CU Professor and Fellow Chris Greene arrived at JILA. Greene is a theoretical physicist specializing in AMO physics.

In 1989, the Fellows decided to turn the SRO into a full-function desktop publishing house with the capability of creating graphics and camera-ready layouts. SRO hosted an open house to show off their new office space and desktop-publishing equipment.

JILA sports men and women were unusually active in 1989. First, the JILA volleyball team won first place in the Boulder Parks and Recreation Department's volleyball tournament. Second, JILA competed in the 10th annual Kinetics Race with the "JILA Mud Monster," also known as the "Astrophysical Monstrosity." Finally, there were occasional Sunday afternoon softball games, Wednesday afternoon volleyball games, JILA/CASA pickup softball games as well as kayaking and rafting trips.

As exciting as the sports events were during the 1980s, they didn't hold a candle to the rapidly evolving impact of scientific computing at JILA. Discussions were taking place regarding an upgrade or replacement of the VAX/8600 computer in the aftermath of a serious flood in the computer room. Although computers had played a role in JILA's scientific research since 1962, advances in computer technology during the 1980s began a process that would move scientific computing to center stage in JILA's research efforts.

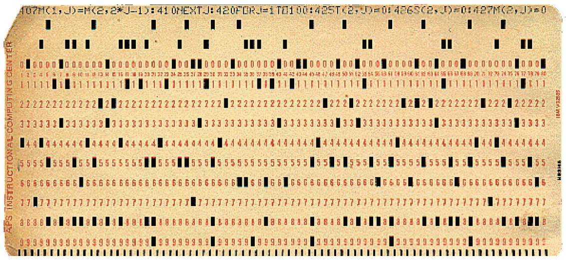
The Quantum JILA Fellow

…or, the four positions of Carl Lineberger

JILA in 1980 as seen through the eyes of Visiting Fellow and artist Zdenek Herman (1979–1980). Fellow Carl Lineberger simultaneously appears in four locations — a classic "superposition." *Artwork: Zdenek Herman*

COMPUTING AT JILA

A 50-Year Odyssey from Punch Cards to Cluster Computers



Phase I

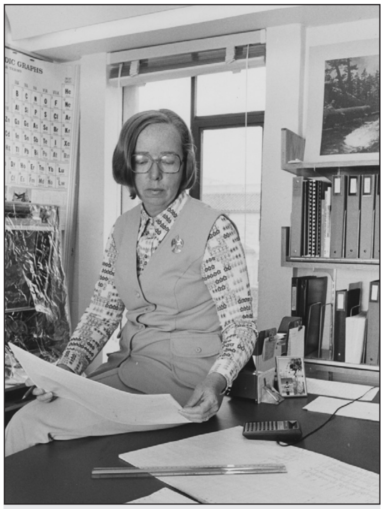
JILA scientists initially had to rely on a CDC 3600 computer at NBS Boulder for scientific computing. Shortly after JILA was established in 1962, the Fellows set up a truck delivery service between the Armory and NBS. This service continued to carry programmed punch cards, printouts, and punched paper tape until after the move to the new building in 1967.

Upon his arrival at JILA in 1966, David Hummer was put in charge of scientific computing. He spent many hours working on upgrading JILA's computing facilities. He was also responsible for assembling a staff that could develop computer algorithms applicable to JILA research areas.

During 1966–1967, "mini" computers became available for laboratory use. At first, the input-output (I-O) device was a teletype machine. About the same time, NBS Boulder installed a computer that could accept input from telephone lines. Users could dial up and use teletypes as I-O devices. Alternatively, they could use terminals, which could also be used as an I-O device. The minicomputer could not only do data processing, but also submit files to the much larger CDC machine at NBS. JILAns could use this machine to edit a FORTRAN file and then submit the file to the larger CDC computer. The output still came back to JILA on a truck.

When Judah Levine arrived at JILA as a postdoc in 1967, CU didn't have a central computing facility. So he had to rely on the NBS Boulder CDC 3800 just down the road. This machine used a card reader to input programs, 10 peripheral processors, and 10 tape drives for memory storage. It also had a paper tape reader.

Using this computer for scientific computation required a trip to NBS with a box of cards created with one of three key-punch machines at JILA. At the time, Levine, who'd learned computing as a graduate student on a room-sized CDC 1604, thought it was a pretty good setup.

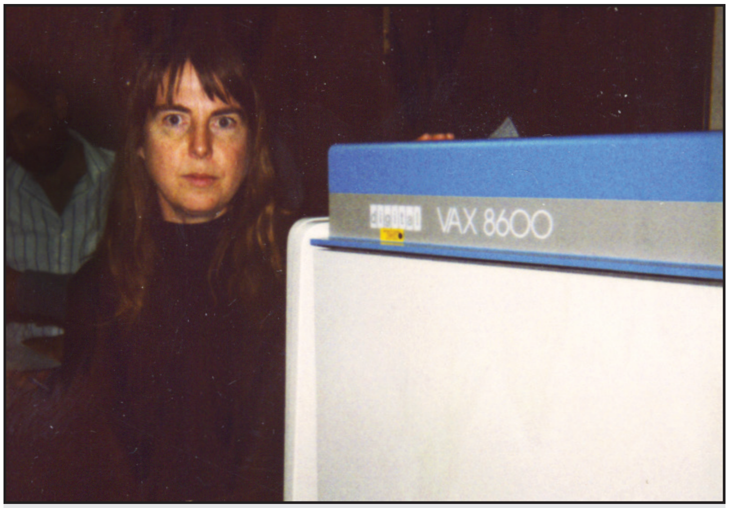


Pat Ruttenberg, JILA Atomic Collisions Data Center. Ruttenberg authored a number of papers on scientific data techniques. *Credit: JILA*

By the mid-1970s, Levine had purchased an LSI-2 computer and helped Mike Fellinger (head of the Computing and Electronics Shop) write the JILA BASIC programming language and create other needed hardware and software. By the mid 1970s, CU had created a central computing facility with a single CDC 6400 computer. The National Oceanic and Atmospheric Administration also had a new computer that it was willing to share with JILA.

The increased computing capacity was badly needed at JILA for atomic structure calculations, astrophysics calculations, and the operation of JILA's Atomic Collisions Data Center. The center's Pat Ruttenberg wrote an Xcel-like database for use with the computer at NBS to keep track of the lists of data under evaluation at the center. Patti Krog, who currently is part of JILA's computing team, originally worked with Ruttenberg in the data center.

By the mid-1970s, JILA had full-time Computing Group staff members Ursula Palmer, Carol Hildalgo, and Chela Kunasz, who came to JILA with a Master's in mathematics from Berkeley. When Kunasz arrived at JILA, the scientists either did their computing at the CU computer center or at NBS on a CDC 6600. Occasionally, JILA scientists also used NCAR's CDC 7600 computer. In 1977, NCAR acquired its first Cray supercomputer, which JILA scientists were allowed (to pay) to use.



Chela Kunasz, member of JILA's Computing Group with the new VAX 8600 computer. The growth and importance of scientific computing brought new tools and talents to JILA. *Credit: JILA*

Chela Kunasz laying cables in 1988 for the VAX8600 computer under the subfloor of JILA's new computer room in the basement of the new S-wing laboratory building. *Credit: JILA*

Despite the advancements incorporated into these new computers, they were all relatively small for meeting the needs of an entire university, national laboratory, or research institution. And, using any of these machines required the scientists to carry individual programs over to the computers in about four boxes, each containing approximately 3000 IBM punch cards.

There were many problems with this system. Key-punch machines and card readers occasionally jammed, requiring technicians to use pick tools to remove the pieces. It was an even bigger disaster if a box of punched cards was dropped. And, these early computers could only handle the simplest graphs. More complex illustrations were still drawn by hand.

To address problems like these as well as poor documentation, Kunasz wrote subroutines to solve matrix equations, do integration, and solve differential equations. Sometimes she acquired good routines from others, some of whom later went on to create Matlab and other math software still in use today. Kunasz also wrote Easy-Plot, which allowed scientists to more easily graph their results. She also helped the SRO more efficiently enter and store data on journal articles and manage reprint requests.

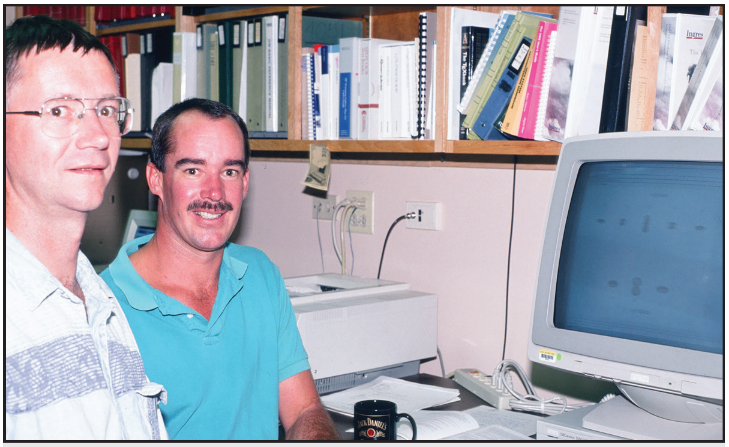
Near the end of the 1970s, Levine acquired a washing-machine-sized stand-alone disk drive that used 8-inch floppy disks. This computer did not require a box of cards to program and was used well into the 1980s. However, even this machine would soon become obsolete as JILA moved into the next phase of scientific computing around the mid-1980s.

Phase II

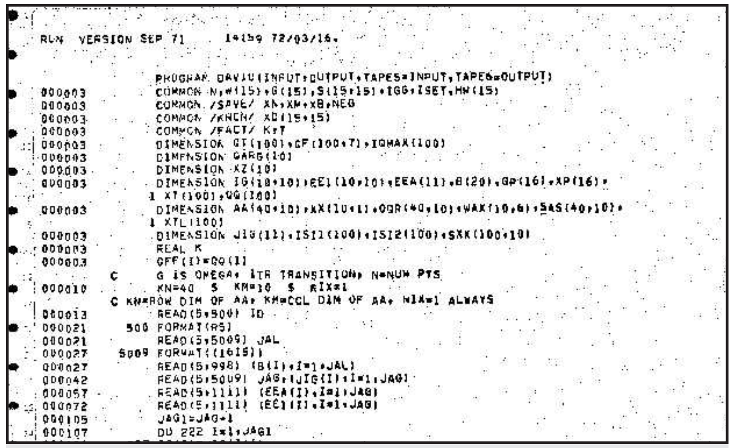
Two important changes occurred in scientific computing at JILA during the 1980s. The first change began in 1983–1984 when JILA Chair David Norcross and Levine received an NSF grant to purchase new computer hardware for JILA. This grant would lead to a change in the style of computing at JILA. After much discussion, JILA purchased and installed a new VAX 8600 computer in a basement room in the new JILA S-Wing in 1988. Now JILA owned its own "free" machinery instead of having to pay thousands of dollars to buy time on computers at NBS, CU, or NCAR.

The new VAX meant hours of laying cables in the new computer room in the basement of the S-Wing in the summer and fall of 1988. Having a VAX also meant that the computing staff had to rewrite all of JILA's software for the new machine.

The VAX 8600 could read a hundred punch cards a minute. At the same time, a new network upgrade offered a much faster link to the computers at both CU



John Brood and Steve Krog of the JILA Atomic Collisions Data Center. *Credit: JILA*



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RUN  VERSION SEP 71     14159 72/03/16.

                PROGRAM DAVIU(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
 000003         COMMON N,W(15),G(15),S(15,15),IGG,ISET,HW(15)
 000003         COMMON /SAVE/ XN,XM,XB,NEG
 000003         COMMON /KNCN/ XC(15,15)
 000003         COMMON /FACT/ K,T
 000003         DIMENSION GT(100),GF(100,7),IQMAX(100)
 000003         DIMENSION GARG(10)
 000003         DIMENSION KZ(10)
 000003         DIMENSION IG(10,10),EE1(10,10),EEA(11),B(20),GP(16),XP(16),
               1 XT(100),QQ(100)
 000003         DIMENSION AA(40,10),XX(10,1),OQR(40,10),WAK(10,6),SAS(40,10),
               1 XTL(100)
 000003         DIMENSION JIG(11),ISI1(100),ISI2(100),SXK(100,10)
 000003         REAL K
 000003         OFF(I)=QQ(1)
          C     G IS OMEGA, ITR TRANSITION, N=NUM PTS
 000010         KN=40   $  KM=10   $  RIX=1
          C KN=ROW DIM OF AA, KM=COL DIM OF AA, NIX=1 ALWAYS
 000013         READ(5,500) ID
 000021     500 FORMAT(R5)
 000021         READ(5,5009) JAL
 000027    5009 FORMAT((16I5))
 000027         READ(5,998) (B(I),I=1,JAL)
 000042         READ(5,5009) JAG,(JIG(I),I=1,JAG)
 000057         READ(5,1111) (EEA(I),I=1,JAG)
 000072         READ(5,1111) (EE1(I),I=1,JAG)
 000105         JAG1=JAG+1
 000107         DO 222 I=1,JAG1
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JILA Fortran code, circa 1971. *Credit: JILA*

and NBS. The link to the CU computing center was via an infrared transmitter held with a bracket affixed to the roof of the JILA tower. It allowed JILA scientists to input or output large programs in about an hour, a huge decrease in turnaround time. The VAX 8600 machine also provided basic email to local users at JILA.

Soon after the VAX machine was installed in the basement computer room, the JILA Computing Group routed cables into every room in the JILA tower. The new cable network opened the door to the use of remote Unix-based workstations, which soon replaced the VAX. By 1989, Unix-based workstations were handling much of JILA's scientific computing.

In the meantime, the early Internet had been undergoing development since the early 1980s. CU's first connection to an external system was a point-to-point network called BITNET, which was a primitive email system. It allowed users to create a text message and mail it to another user — provided they knew the route so they could specify the path for the message.

By the early 1990s, the personal-computer (PC) revolution arrived at JILA. PCs sprang up in offices and laboratories. Suddenly, the Fellows could purchase powerful new computers instead of having them custom built by the JILA Electronics and Computing Shop. Dial-up modems also made it possible for these early PCs to begin to communicate via the now rapidly evolving Internet. At the same time, powerful supercomputers, such as the Cray, were getting faster and faster as parallel processing came online. JILA's astrophysicists gravitated to these new systems.

In the early 1990s, the demand for computing was also changing at JILA. NIST eliminated its astrophysics research program and moved the JILA Atomic Collisions Data Center to Gaithersburg. Radiative transfer calculations dwindled as atomic and chemical physics calculations grew more common. As these efforts intensified throughout the 1990s, the stage was being set for the next phase of JILA scientific computing.

Phase III

In 2002, JILA received a grant from the Keck Foundation that included some funding for resources to support the Institute's theorists. Fellow John Bohn suggested that JILA look into getting its own supercomputer. He thought that the existing workstations were too slow to use, particularly since what was needed was more processing capacity. Bohn's idea quickly caught on — with both theorists and experimentalists. For instance, one experimental group wanted a supercomputer to run simulations of cold-atom and cold-molecule experiments to determine in advance the best experimental parameters to study.

Conversations with the Computing Group (in particular, Peter Ruprecht) resulted in the purchase of JILA's first cluster computer, the Keck Cluster, which contained 38 nodes (individual servers networked together). This powerful new JILA computer used lots of power and produced a lot of heat; it required power and cooling upgrades to the S-Wing 4th floor computer room. Once online, the Keck cluster was instantly in high demand. The hardest part of running it was managing the demand.

Jean Gallagher, Pat Ruttenberg, and Patti Krog of the JILA Atomic Collisions Data Center. *Credit: JILA*

Demand management is now accomplished via automated queuing that fairly distributes the computing resources among the various jobs competing for them.

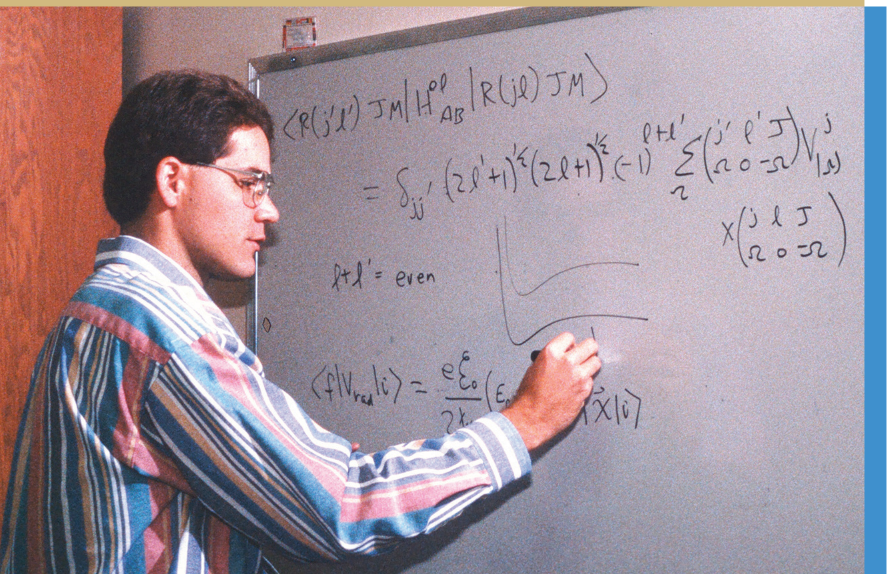
Designing cluster-computing system hardware was also a challenge. The challenge was figuring out how to optimize new hardware for a wide range of applications with different needs. For instance, quantitative chemistry calculations required fast memory and a fast disk, cold molecule simulations needed a fast CPU, and astrophysics calculations required a high-speed network to connect the nodes. With all these hardware configurations in demand, the Computing Group decided to build a second cluster computer named Yotta.

Yotta came online in 2007. Components for Yotta came from collaborative efforts of the Kapteyn/Murnane, Nesbitt, and Rey groups as well as the Physics Frontier Center. Yotta consisted of a 16-CPU head node and 21 compute nodes. It soon became clear that even this new cluster computer wasn't powerful enough to meet JILA's rapidly expanding needs for local supercomputing.

JILIAC, the most recent cluster computer, was built and tested in 2011 after being purchased by the Physics Frontier Center. The powerful JILIAC cluster is available for use by any of the research groups. It contains 18 nodes of 8 processors each and several souped-up video cards that each contain the equivalent of hundreds to thousands of low-power CPUs. JILIAC entered full production mode when construction was completed on the JILA X-Wing in 2012.

JILA's cluster computer Yotta, which came online in 2007. In 2011 a new, more powerful cluster computer called JILIAC was built. JILIAC is about 1/4 the size of Yotta. *Credit: Brad Baxley, JILA*

Chapter 4
1990 to 1999



Fellow John Bohn investigates molecular collisions as a postdoc for Paul Julienne of NIST Gaithersburg.

By 1990, Lewis Branscomb's original scientific vision for JILA had mostly faded away, but his organizational genius was continuing to pay big dividends. The original collaboration between astrophysics and atomic physics had become outdated and was no longer cutting edge. At the same time, national priorities for scientific research had transitioned away from a "space race" to explorations of precision measurement, laser science, quantum physics, nanoscience, quantum information processing, and other aspects of atomic, molecular, and optical physics. In addition, the NIST side of the JILA collaboration had gained a new mission to support the development of standards for high-tech industries. Despite these many changes, however, the key JILA concept of collaboration among research groups continued unabated. Creative collaborations continued to result in sometimes unconventional, and often dramatic, advances of the Institute's science and technology.

In the 1990s, JILA expanded its mission to reflect NIST's mandate to develop new measurement methods and standards, improve industrial competitiveness, and educate graduate students in new technologies. In 1990, NIST made the decision to eliminate its astrophysics research program, a decision that put the nail in the coffin of the idea of the laboratory astrophysics collaboration between NIST and CU. By the end of 1991, NIST astrophysicists either found their own funding, secured appointments at CU, or left JILA. At the same time these changes were occurring, astrophysics research at CU was moving away from stellar atmospheres and interiors (laboratory astrophysics) in response to the evolving interests of JILA's CU faculty.

These changes led to a name change for the Institute. In November of 1994, the JILA Fellows voted to keep the name "JILA," but discontinue the use of "Joint Institute for Laboratory Astrophysics." The Fellows believed that the latter no longer adequately described the scope of science being conducted at JILA. The name change went into effect in 1995 and subsequently led to confusion among journalists covering stories about JILA. Journalists don't like to use acronyms without giving the title behind them, so the outdated title has occasionally appeared in news stories since the name change.

The organizational changes early in the decade soon gave way to cutting-edge scientific breakthroughs. The first major discovery was the 1995 observation of the world's first Bose-Einstein condensate (BEC) by Carl Wieman, Eric Cornell, and their collaborators. The BEC appeared when a cloud of rubidium atoms was cooled to a few hundred billionths of a degree above absolute zero, causing the atoms to fall into the same low-energy state and form a "superatom." The superatom was large enough to allow the JILA scientists to study the tiny, strange quantum world as if they were looking through a giant magnifying glass.

The decade's second major discovery was the creation of the world's first optical frequency comb laser in 1999 by the Jan Hall, Jun Ye, and Steve Cundiff groups. The comb laser produced very short, equally spaced pulses of light that created a "comb" of millions of individual colors (frequencies). The comb lines were like tics on the world's tiniest ruler. They allowed researchers to precisely measure smaller increments of distance or frequency than had ever before been possible. Since its discovery, the optical frequency comb has ushered in major advances in precision measurement and in optical physics.

THE FOURTH DECADE (1990–1999)

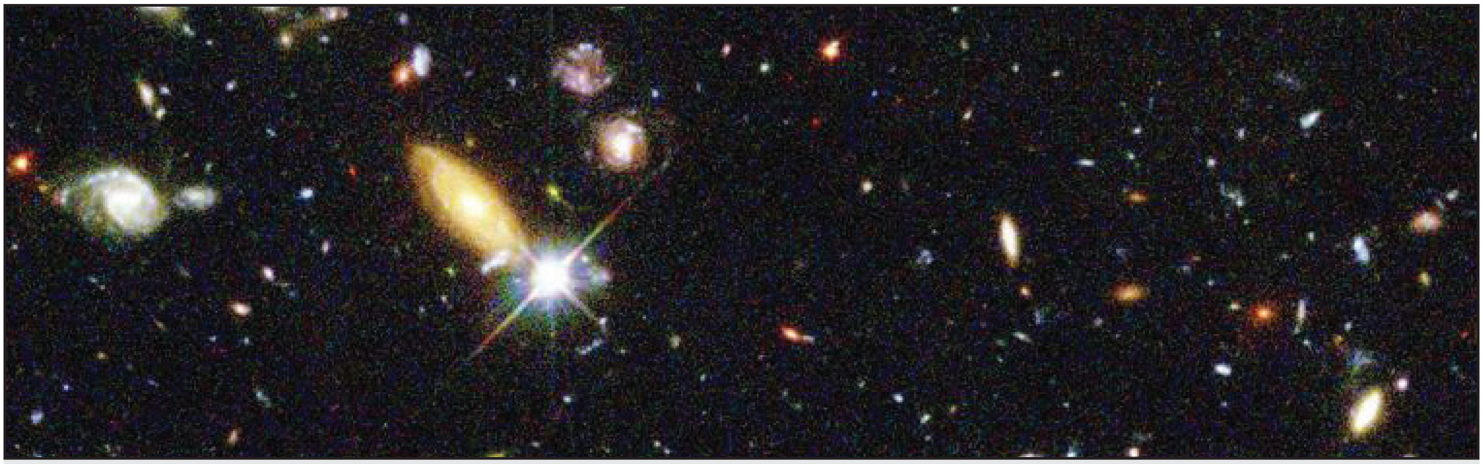
1990–1991

In 1990, JILA astrophysicists and AMO physicists expanded their research horizons. In AMO physics, JILA scientists investigated the interaction of laser light with matter via atom cooling and trapping, high-resolution laser spectroscopy, precision measurement, the interaction of laser light with atoms, and electronic energy transfer. Theorists studied the quantum behavior of light and a new theory of alkaline earth atoms. Chemical physicists explored polyatomic systems and clusters, the photo-dissociation of ions, simple molecular systems, the interaction of laser light with molecular and cluster ions, photoelectron spectroscopy, and solvent dynamics. At the same time, JILA astrophysicists were investigating high-energy astrophysics, x-ray astronomy, and the hydrodynamic motions of magnetic fluids.

A 1992–1993 NSF Progress Report identified new JILA research areas in AMO physics as squeezed states that occur in quantum light; Monte Carlo (probabilistic) theoretical methods; the photo-dissociation, recombination, and relaxation dynamics of atomic anions in molecular clusters; and the combination of high-resolution infrared laser absorption with slit-jet supersonic expansion to make cold clusters.

Two new astrophysics Fellows were appointed in 1990: Ellen Zweibel and Katy Garmany. Garmany had been at JILA since 1977, serving as a research associate and senior research associate with Peter Conti. Zweibel, who specialized in the theory of hydrodynamic motions of magnetic fluids, had been a CU astrophysics professor for 10 years before being appointed a Fellow.

JILA continued its tradition of working hard and playing hard in 1990. The Institute hosted a February ski trip to Copper Mountain and entered a JILA team called "Dan Quayle's Manned Mission to Mars" in the May Kinetics Classic race. The Institute also became non-smoking



In 1991, JILA astrophysicists gained observing time of 100 early hours on the new Hubble Space Telescope. *Credit: Hubble Space Telescope*, *NASA*

in response to growing concerns about the deleterious effects of secondary smoke on those who do not smoke.

The following year, theoretical physicist Peter Zoller, who specialized in AMO physics, was appointed a Fellow of JILA. The arrival of Zoller at CU and JILA coincided with JILA's becoming recognized as having one of the nation's most active theory groups in AMO physics.

In other news, Art Phelps, Syd Geltman, and Stephen Smith officially retired from JILA. Smith went to Washington D. C. to do a rotation as a program manager for NSF. Phelps left with enough data to write one paper a year for at least the next 17 years.

In 1991, JILA astrophysicists gained observing time of 100 early hours on the new Hubble Space Telescope. The lucky Fellows included Katy Garmany, Peter Conti, David Hummer, Andrew Hamilton, and Dick McCray.

A major organizational change also occurred in JILA and NIST. Katharine Gebbie, who had been serving as the Chief of NIST's Quantum Physics Division, left JILA to go to NIST Gaithersburg to design and manage NIST's new Physics Laboratory. David Norcross became the Quantum Physics Division Chief.

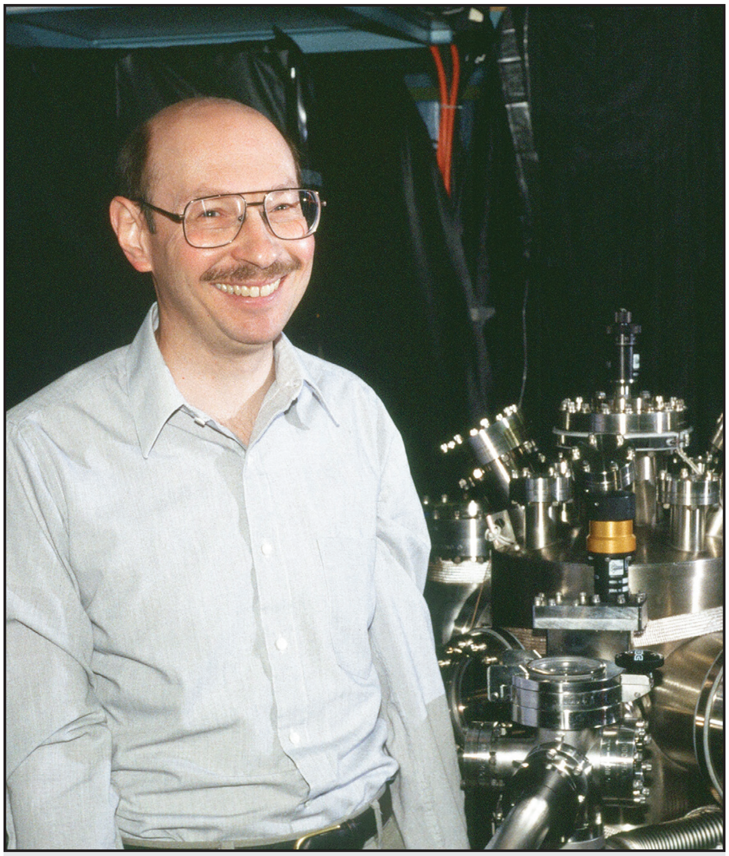
JILAns managed to thoroughly enjoy themselves in 1991 as well. On February 1, the Fellows prepared and served a pancake breakfast to the staff. The following summer, JILA started its first coed softball team to play in the City of Boulder league, a tradition that has continued into the present. In September, the annual JILA picnic was combined with an orientation and show.

1992–1993

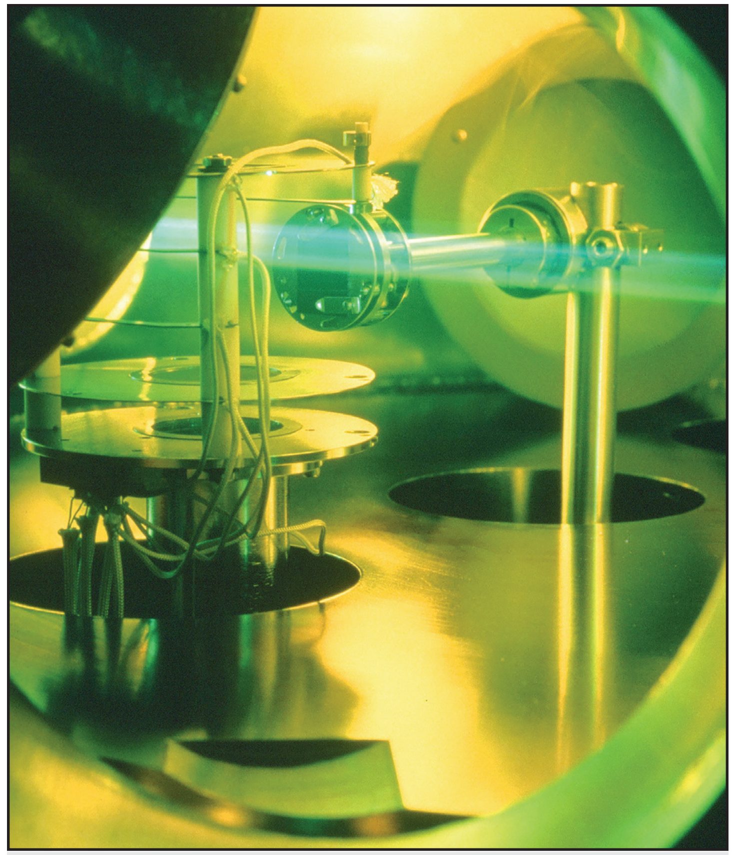
A 1991–1992 self-study as part of an NSF program review raised the issue of JILA giving priority to hiring women and minority faculty members. The self-study would lead to long-term impacts, described in the final section of this chapter, on the diversity of JILA scientists.

Eric Cornell, who had arrived at JILA in 1990 as a postdoc for Carl Wieman, joined JILA as a NIST scientist and assistant professor adjoint of physics at CU in 1992. Cornell launched a research program in atomic physics and the interactions of atoms with light. He also planned to continue to work with Wieman on the BEC experiments he had started as a postdoc.

Another JILAn-to-be, Peter Ruprecht, did some important early theoretical work on BEC from 1993 to 1995 at Oxford University as part of his D. Phil work in physics. Three years after completing his doctorate, Ruprecht arrived at JILA — to join JILA's Computing Group.



Fellow Steve Leone in his chemical physics lab. *Credit: JILA*



Laser focusing apparatus in Steve Leone's chemical physics lab. *Credit: JILA*

A 1992–1993 NSF Progress Report identified new JILA research areas in AMO physics as squeezed states that occur in quantum light; Monte Carlo (probabilistic) theoretical methods; the photo-dissociation, recombination, and relaxation dynamics of atomic anions in molecular clusters; and the combination of high-resolution infrared laser absorption with slit-jet supersonic expansion to make cold clusters.

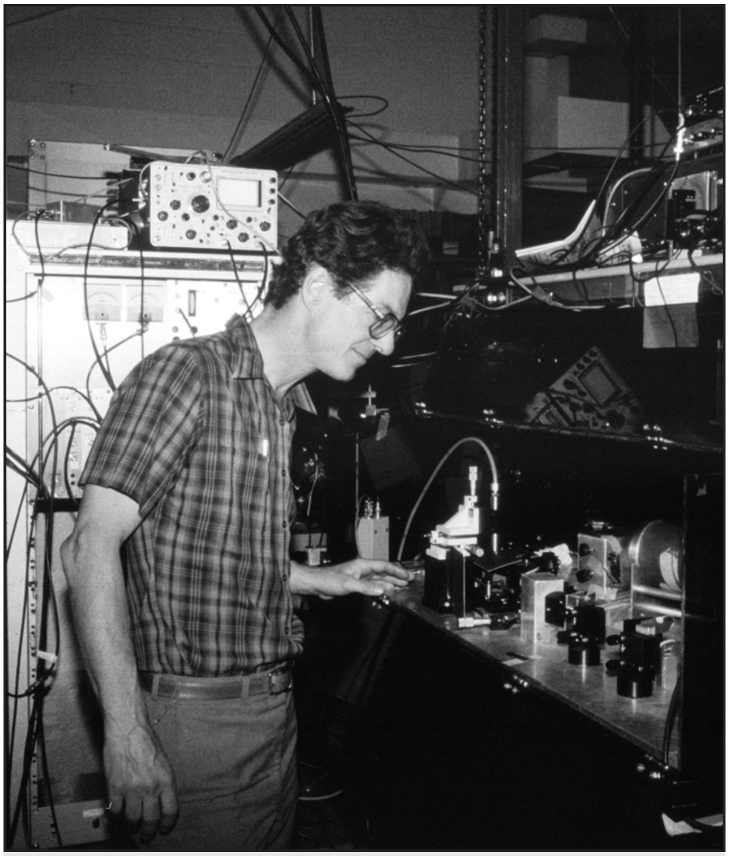
The 1993–1994 NSF Progress Report noted that JILA had developed improved evaporative cooling techniques for magnetically trapped atoms. These new techniques would pay off handsomely in 1995.

In 1993, the European Space Agency (ESA) began studying the LISA gravitational wave mission. By 1997, LISA was under consideration for a joint ESA-NASA mission.

1994–1995

In 1994, JILA continued to evolve in response to NIST's new mission. In February, the Institute established an Industry Outreach Program to increase contacts with U. S. industry and strengthen existing contacts. A key part of the new program was the Industry at JILA Visitor Series, sponsored by the Visiting Fellows program. Implementation of the series began with a visit from JILA founder Lewis Branscomb, who was then serving as Director of the Science, Technology, and Public Policy Program in the John F. Kennedy School of Government at Harvard University.

A few months later in June, JILA ran two diode laser workshops to transfer its expertise in this technology to the private sector. Information about JILA and its research was also published in databases available to industry.



Fellow Alan Gallagher in his laboratory. *Credit: JILA*

NIST Executive Officer Pat McInerny demonstrates how he balances the JILA budget. *Credit: JILA*

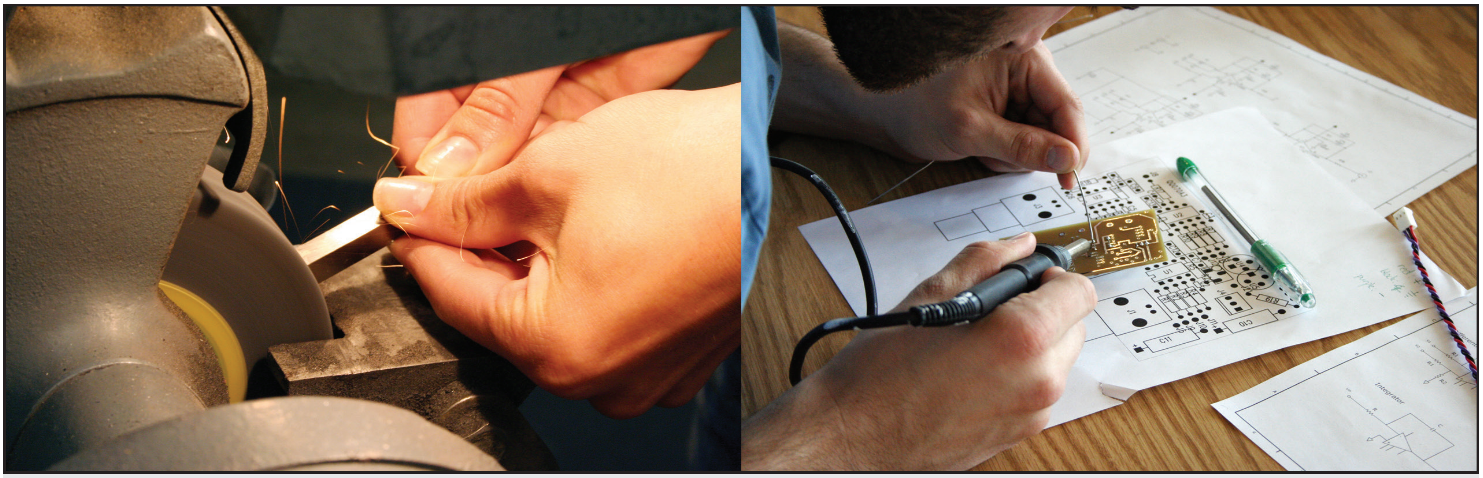
The Institute's major research areas were atomic physics, chemical kinetics, a search for a new state of matter, laser photo-detachment of molecular ions, the ongoing use of retroreflectors on the moon for measuring continental drift, cool stars, the influence of black holes on galaxy formation, the formation of planets around stars, and cosmology.

JILA was well known in the fields of astrophysics, optics, AMO physics, and chemical physics. However, the Institute was little known outside these fields. This circumstance was about to change, however.

On June 5, 1995, Carl Wieman, Eric Cornell, and their collaborators observed the world's first BEC, a new form of matter made in a JILA laboratory. Until that day, the observation of a BEC had been the "holy grail" of late 20th century atomic physics. Predicted in 1924 by Satyendra Nath Bose and Albert Einstein, a BEC occurs when the wave functions of individual atoms overlap and behave as a single superatom. Making this happen requires the cooling of a cloud of identical bosons, which are atoms with zero spin, to a few billionths of a degree above absolute zero (-459.67 ˚F).

To create the BEC, Cornell and Wieman used laser and magnetic traps to cool a tiny ball of rubidium atoms to the point where they were as immobile as they could be and still obey the laws of quantum mechanics. The BEC formed inside a carrot-sized glass cell and was large enough to be photographed with a video camera. It looked like the pit in a cherry, except it was only 20 μm in diameter, or about one-fifth the thickness of a sheet of paper.

Wieman described the BEC as a new state of matter with properties different from any other kind of matter. He said it could not have existed naturally anywhere



JILA experiments often require custom-built apparatus and electronics. The expertise of the staff in JILA's Instrument and Electronics shops is critical to scientific success. *Credit: Greg Kuebler, JILA*

else in the Universe. To give people an idea just how different it was, Cornell pointed out that BEC atoms travel at speeds of roughly three feet per hour. In contrast, normal atoms race around at room temperature at speeds of roughly 1000 miles per hour!

Cornell and Wieman were assisted in their discovery by postdoc M. H. Anderson and graduate students J. R. Ensher and M. R. Matthews. In their preliminary work between 1990 and 1995, Cornell and Wieman worked with eight graduate students and three undergraduate students.

The creation of the BEC was the beginning of a series of theory investigations and experiments with ultracold atoms and molecules that have continued into the present. For instance, the successful creation of the BEC inspired longtime experimentalist John (Jinx) Cooper to become JILA's first theorist to investigate Bose-Einstein condensation. And, experimentalist Deborah Jin, who arrived at JILA in 1995 as a postdoc for Cornell, soon began to tackle the challenging problem of making a fermionic condensate from atoms or molecules that can't normally be in the same quantum state and form a superatom.

Other JILA scientists continued to investigate laser science, atomic physics, chemical physics, semiconductors, astrophysics, gravitation, and optical physics. At the same time, they undertook a new mission of supporting standards for high-tech industries.

Optical physicist Tracy Clement joined JILA's NIST faculty in September of 1995.

1996–1997

In 1996, the Institute hired a new associate Fellow, AMO theorist Murray Holland. Holland specialized in many of the theoretical aspects of Bose-Einstein condensation and quantum optics.

JILA Chair Jim Faller instituted shorter terms of four months for Visiting Fellows. Until 1996, Visiting Fellows couldn't be appointed for less than six months. Appointments could still be for up to twelve months. JILA continued to provide a stipend for salary, travel, laboratory, and computer expenses. The same support was offered to visitors from industry. The Visiting Fellows program continued to bring distinguished scientists to JILA from all over the world. These visitors made important contributions to the atmosphere of scientific excellence.

JILA's culture of collaboration also extended to scientists at NIST (in both Boulder and Gaithersburg), CU's Center for Astrophysics and Space Astronomy, the

National Oceanic and Atmospheric Administration, the Cooperative Institute for Research in Environmental Sciences, Optoelectronic Computing Systems, the High Altitude Observatory, the Laboratory for Atmospheric and Space Physics, as well as local and national high-tech companies. The collaborations included both experimentalists and theorists.

JILA scientists were also actively engaged in educating young scientists. NIST and CU Fellows advised graduate students and postdocs and taught courses in the Departments of Physics, Astrophysical and Planetary Sciences, as well as Chemistry and Biochemistry. The Fellows also taught undergraduate courses and participated in community outreach programs such as the CU Wizards Program directed by Fellow David Nesbitt.

Major funding for the Institute came from NIST, CU, NASA, the U. S. Department of Energy, the U. S. Department of Defense, and a large group grant from NSF.

On April 2, 1996, the Fellows celebrated their 500th Fellows meeting with a small party.

In 1997, JILA began describing its research in terms of seven broad research areas: atomic physics, chemical physics, materials physics and chemistry, optical physics, precision measurement, and astrophysics. JILA scientists pursued many different research topics within these broad areas.

In atomic physics, research included the manipulation of ultracold atoms with lasers; a theory of ultracold collisions; ultralow temperature physics in trapped gases, including superfluid flow, persistent currents, and the optimization of condensate formation; a search for the fermionic equivalent of BEC to gain insight into Fermi seas in neutron stars; an investigation of how BEC atoms are analogous to the coherent field of photons inside a laser; preliminary considerations of an "atom" laser; and experiments with ultraslow collisions at nano-Kelvin temperatures.

jilanews

October 25, 1991

A Legend is Born

Jim Faller, having rushed back from Washington, D.C. to play his recorder for the Senior Citizens, found himself trapped in lot 360 by a gate that would not open. The persuasive physicist talked a passing student into holding up the PVC arm so he could get out in time to perform. Upon his return to lot 360, he inserted his gate-key in the slot and watched the arm rise. He then pressed forward in his white Legend coupe. Ka-bong! The gate arm landed heavily on the roof of his car – and then bounced around a number of times, leaving numerous, painful bruises in the pristine white paint. Sir James, in true Knight of the Royal Garter chivalrous style, grabbed the offending arm (after moving his car out of the way), applied superhuman force (having carefully calculated angle and stress, or whatever), and bent the arm so it wouldn't ever be able to harm another car.

He then stormed to his office, reported the problem to the authorities, did a bit of work and returned to the parking lot to await the arrival of the police. To his surprise, the gate arm he had bent so effectively had already been replaced! And, presumably, repaired.

Faced with a perfectly good gate arm, it was easy to imagine how the police would feel about his story of being attacked by it.

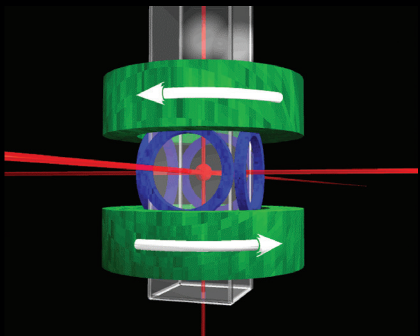
Smooth-talking Jim was trying to figure a way out when he saw the police car turn towards the lot and head for the gate. The policeman, in slow motion, rolled down his window and inserted his key into the slot. The gate arm rose and the police car proceeded through the gate.

Ka-bong! Right before Jim's eyes, the arm crashed down on top of the police car, inflicting multiple bruises and scratches in the paint.

The damage to Jim's Legend is about $220, but it's almost worth it when Jim remembers how the policeman shouted, "It happened to you, too! Right?"

And that's how legends are born.

The World’s First Bose-Einstein Condensate



JILA BEC trapping and cooling apparatus. *Credit: The Wieman group*

In 1990, Carl Wieman and his new postdoc Eric Cornell decided to attempt to make a BEC from a cloud of atoms cooled to near absolute zero. They wanted to create a system where exotic quantum behavior would be observable with ordinary laboratory equipment. If they succeeded, they reasoned that a BEC might somehow be related to superconductivity, superfluidity, or laser light — three other phenomena that exhibit evidence of quantum behavior. From the beginning of their quest, the two researchers recognized that success would represent a major contribution to physics.

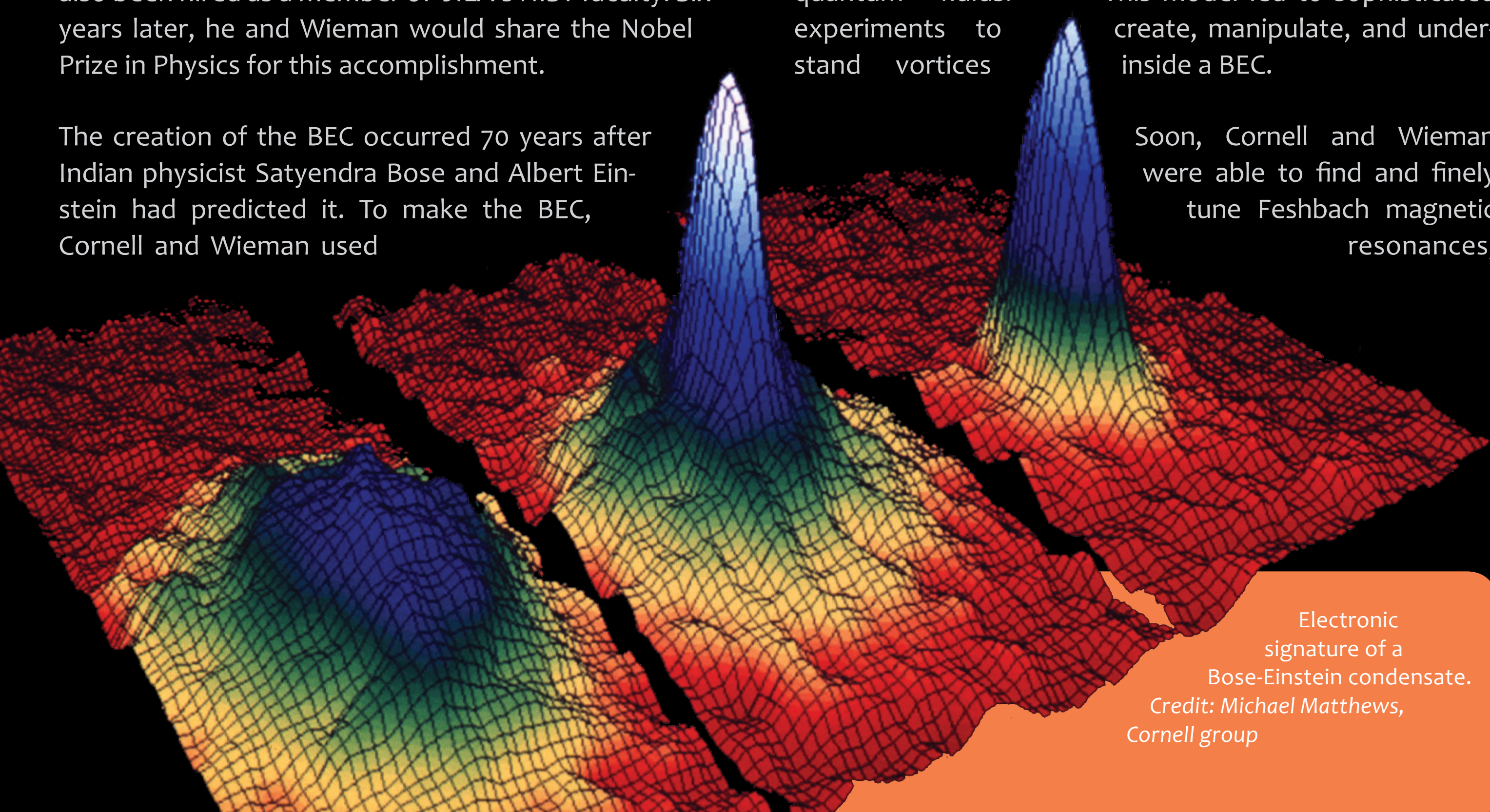
What they didn’t yet realize was that they would have to encounter (and overcome) considerable experimental difficulties in cooling a gas to a few billionths of a degree above absolute zero. Five years went by before they succeeded in creating the world’s first BEC in June of 1995. By then, Cornell had not only completed his postdoc, but also been hired as a member of JILA’s NIST faculty. Six years later, he and Wieman would share the Nobel Prize in Physics for this accomplishment.

The creation of the BEC occurred 70 years after Indian physicist Satyendra Bose and Albert Einstein had predicted it. To make the BEC, Cornell and Wieman used laser-based and magnetic cooling techniques to lower the temperature of a cloud of rubidium atoms (87Rb) to 170 nK. Suddenly, a large fraction of the gas simultaneously entered its lowest possible energy state and formed a “superatom,” or BEC. The superatom contained thousands of individual atoms that formed it. However, all these atoms danced in unison and behaved as a single entity. The BEC was an entirely new state of matter, one that didn’t even exist in the coldest reaches of outer space.

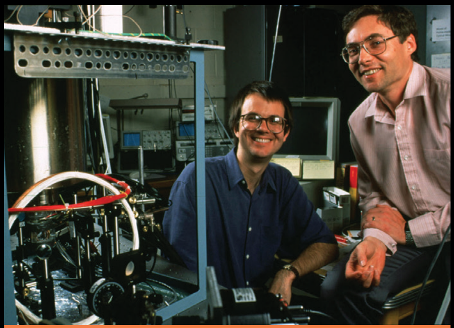
> The creation of the world’s first BEC opened up a rich new field of physics research.

Cornell and Wieman performed many experiments to help them understand the new state of matter. They discovered that the behavior of a BEC was sensitive to even slight variations in temperature. They found that if the atoms in a cooled gas cloud had been in two different spin states, then two condensates would form. They performed many experiments to characterize systems with two condensates and found they could use atoms in one spin state as a cooling fluid to chill atoms in a second spin state. Eventually, Cornell and Wieman were able to model the behavior of a two-BEC system as if it consisted of two distinct quantum fluids. This model led to sophisticated experiments to create, manipulate, and understand vortices inside a BEC.

Soon, Cornell and Wieman were able to find and finely tune Feshbach magnetic resonances,



Electronic signature of a Bose-Einstein condensate. *Credit: Michael Matthews, Cornell group* which had been predicted by theorist Boudwijn Verhaar. Feshbach resonance physics had begun to play a major role in JILA's ultracold research by 1999. Cornell and Wieman were able to use Feshbach resonance physics to study the instability of condensates when atomic interactions were attractive and explore the impact on a BEC's quantum wave function when atom interactions were large and repulsive. They began to probe BECs made of molecules, investigate the quantum behavior of liquids, and think about creating condensates that oscillated back and forth between condensates of atoms and molecules. This curious system was a quantum superposition of two chemically distinct species, the original atoms and molecules made of two of these atoms.



Fellows Eric Cornell and Carl Wieman in the lab with their BEC apparatus. *Credit: University of Colorado Boulder, Office of News Services*

This discovery spurred a whole series of experiments, including those that led to condensates of fermionic atoms, which on the face of it shouldn't form a superatom. In 2003–2004, the Deborah Jin group was able to Bose condense both diatomic molecules made of two fermionic atoms and pairs of ultracold fermionic atoms that were dancing in sync like Cooper's pairs of electrons. These achievements opened the doors to research on superconductivity and superfluidity under extreme ultracold conditions.

JILA scientists have continued to perform groundbreaking research on ultracold atoms and molecules. By 2010, a collaboration led by Jin and Jun Ye began to redefine chemistry at JILA with studies of ultracold chemistry. Within two years, theorists John Bohn, Chris Greene, and Ana Maria Rey were also actively participating in the cold molecule collaboration. In a separate effort, Dana Anderson has developed and continues to refine a microchip-based system that not only rapidly produces BECs, but also is compact and transportable.

In chemical physics, investigations included a quantum mechanical study of molecular collision dynamics and chemical reactions; the use of lasers to probe time-resolved concentrations of reactive chemicals and radicals; studies of crossed-molecular beam reactions; wave-packet manipulations; and the coherent control of chemical reactions. JILA's chemical physicists were also exploring the use of femtosecond lasers in pump-probe experiments as well as the dynamics of electron transfer in clusters, photodissociation, and ion solvation, fragmentation, and relaxation.

In materials physics and chemistry, the focus was on understanding surface processes at the quantum level, surface science, semiconductors, nanotechnology, and advanced laser technology. This broad area would undergo a profound transformation over the next decade as the retirement of long-term faculty led to sweeping changes.

In optical physics, researchers explored the control of matter with light and the control of light with matter in both fundamental and applied investigations. These investigations included atom optics, the amplitude and phase of ultrashort pulses, the evolution of pulses from a femtosecond laser, carrier dynamics in semiconductors, holography, and the relationship of BEC and quantum physics to optical sensors and ultrashort-pulsed laser techniques.

With respect to precision measurement, nearly all laboratory investigations relied on some form of precision measurement. This work included studies of parity violation, precision control of lasers, length measurements with optical interferometry, detection of gravitational radiation, the development of LISA (a space-based gravity-wave observatory), measurement of the gravitational constant G, development of better frequency standards, and digital time stamping and synchronization of atomic clock time to personal

RULERS OF LIGHT

The fields of ultrafast laser development and laser stabilization rapidly converged during the late 1990s. This convergence led to the creation of the world's first optical frequency comb at JILA in late 1999. An optical frequency comb is a stabilized ultrafast laser whose spectrum consists of several million evenly spaced sharp colors (spectral lines). The line spacing in a comb spectrum is so exact that a comb laser can be used to precisely measure the frequency of millions of discrete colors of light. This new ruler of light is now providing measurement precision and research opportunities that were inconceivable until the dawn of the twenty-first century.

> Hall, Cundiff and Ye realized that the white light output of this "magic fiber" might be a spectral comb of coherent frequencies. They set out to test this idea at JILA in the fall of 1999.

Three JILA scientists, Steven Cundiff, John L. Hall and Jun Ye were instrumental in the development of the frequency comb. When Cundiff arrived at JILA in 1997, he brought with him an ultrafast mode-locked laser. He set it up in his new JILA lab across the hall from Hall's lab. That made it relatively easy for him to tap Hall's laser-stabilization expertise. Hall soon introduced the idea of combs being able to directly link optical frequencies to the microwave region. This direct link sparked Cundiff's interest in making an optical frequency comb.

In 1998, Ted Hänsch's group demonstrated the feasibility of making a femtosecond-laser frequency comb. Ye visited the lab and reported this demonstration to Hall. In response, the Hall and Cundiff groups decided to work together to build an optical frequency comb with a mode-locked laser. Post docs David Jones and Scott Diddams were key participants in the effort.

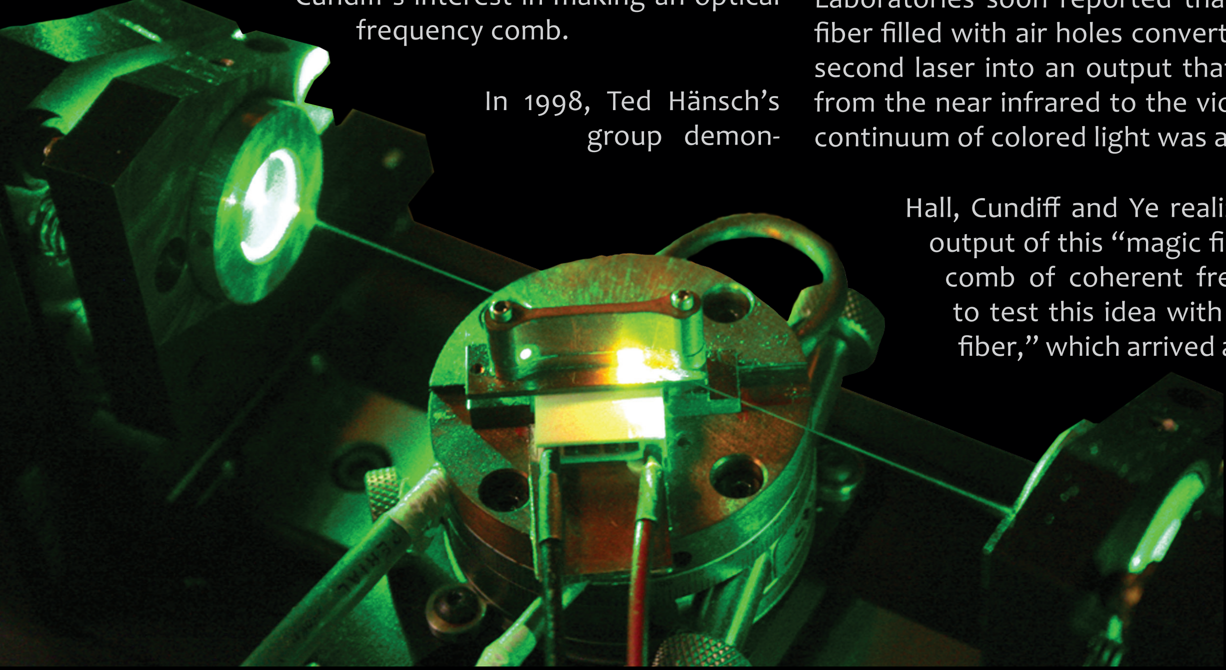
To make comb "teeth," oscillations of light over time had to be converted to frequency numbers. Because time and frequency are inversely related, faster oscillations of light waves (i.e., smaller units of time) correspond to higher frequencies. The lowest frequencies are those of the red colors of light, while the highest frequencies are violet colors of light. Each tooth would be a slightly different color, with red and violet on opposite ends of the comb. If Cundiff and Hall were correct, equally spaced lines of orange, yellow, green, blue, and indigo colors would sweep a rainbow of color across the middle of the comb.

Hall and Cundiff had a stabilized ultrafast laser by the spring of 1999. But they didn't know the frequencies of the comb teeth. To figure those out, they needed to measure the offset frequency, a small frequency shift in the comb due to small differences between the peak of the carrier wave and the laser pulse. And, to measure the offset frequency, they needed an octave-spanning spectrum provided by white light.

Fortuitously, Jinendra Ranka and his colleagues from Bell Laboratories soon reported that a silica microstructure fiber filled with air holes converted pulses from a femtosecond laser into an output that spanned the spectrum from the near infrared to the violet. An octave-spanning continuum of colored light was a reality.

Hall, Cundiff and Ye realized that the white light output of this "magic fiber" might be a spectral comb of coherent frequencies. They set out to test this idea with a sample of the "magic fiber," which arrived at JILA in the fall of 1999.

At this point, Ye was back in Boulder working with Hall and Cundiff. The Boulder team had a significant advan-



tage in efforts to produce an optical frequency comb. The first octave-spanning stabilized frequency comb was demonstrated in Cundiff's lab and soon replicated in Ye's and Hall's labs. The three groups figured out how to measure the repetition rate of their stabilized mode-locked lasers (frep) and the offset frequency (f0) of the light pulses. The measurement of these two parameters made it possible to completely characterize the frequency comb in terms of both time and frequency. Cundiff's group also built a cross-correlator to connect the time and frequency description of the output of mode-locked lasers.


Fellows Jun Ye, Jan Hall and Steven Cundiff at the 2005 Nobel reception. *Credit: H. Jeff Kimble, Caltech*

The researchers reported the creation of an optical frequency comb, the cross-correlation measurements, and optical frequency measurements that were directly referenced to a microwave clock in the April 28, 2000, issue of Science. A month later, reports of the generation of an octave-spanning frequency comb and frequency measurements in the microwave and optical regions using the comb finally appeared in the May 29, 2000, issue of Physical Review Letters.

Five years later in 2005, Jun Ye's group extended the optical frequency comb into the (invisible) ultraviolet region of the electromagnetic spectrum. In 2011, the group extended the frequency comb into the extreme ultraviolet (XUV) region. The new XUV frequency comb has opened the door to making precision measurements of the quantum states inside atoms and molecules.

Frequency combs have opened up new vistas of research at JILA, including the Ye group's development of a strontium-lattice optical atomic clock and molecular fingerprinting, which is a comb-based tool for identifying multiple different atoms and molecules in a single sample. It is expected to have applications in homeland security and in medicine for breath analysis. Eric Cornell is using a frequency comb in his search for the electric dipole moment of the electron. And, Steve Cundiff is using an optical frequency comb in efforts to create designer waves of laser light.

computers. In Jan Hall's group, for example, graduate student Jun Ye and visiting scientist Long-Sheng Ma developed the world's most sensitive laser spectroscopy for molecular absorption measurement.

In astrophysics, JILA scientists explored the Sun, stellar atmospheres and coronae, stellar winds, convection and magnetic flows inside stars, star formation, cool stars, supernovae, x-ray stars, active galaxies, the interstellar medium, extragalactic physics, and cosmology. Supernova 1987A remained an exciting topic at JILA throughout the 1990s and beyond.

In 1997, JILA hired two new NIST scientists, Fellows Deborah Jin, an AMO experimental physicist, and Steven Cundiff, a specialist in optical physics.

1998–1999

In 1998, the Fellows decided that new faculty would have the title of Associate Fellow. They also voted to contribute approximately 25% of the research start-up costs for new Associate Fellows.

In 1999, JILA hired a husband and wife team of experimental physicists with expertise in ultrafast laser development — Henry Kapteyn and Margaret Murname. JILA also hired experimental physicist Jun Ye, who had just completed his postdoctoral research with Jeff Kimble at CalTech after earning his Ph.D. from CU under Jan Hall in 1997. Hall continued to collaborate with Ye after Ye joined the JILA faculty. After he retired in 2004, Hall donated much of his laboratory space in the basement of the S-Wing to the Ye group.

JILA dedicated its new KECK Lab on June 28, 1999. The W. M. Keck Optical Measurement Laboratory provided a suite of optical measurement and characterization instruments, including a Fizeau interferometer and a Multimode Atomic Force microscope, to the researchers at JILA. The Keck Lab also included nanofabrication facilities and a clean room.

The Keck Lab in the S-Wing. The Keck Lab is an optical metrology laboratory with advanced capabilities for precision measurement; micro and nano fabrication in a Class 1000 clean room; atomic force, optical, and scanning electron microscopies; and optics education. *Photo: Greg Kuebler, JILA*

Guests attending the dedication included Katharine Gebbie, head of NIST's Physical Laboratory and members of the CU Foundation. Fellows and staff representatives also attended. After a tour of the new equipment, James Faller, Quantum Physics Division chief, and JILA Chair Carl Wieman spoke briefly.

During November and December of 1999, Fellows Jan Hall and Steve Cundiff reached the culmination of a two-year partnership to create an optical frequency comb from a femtosecond mode-locked laser. Once Hall, Ye, and Cundiff made combs in their laboratories, they figured out the frequencies of the comb teeth, made a cross-correlator to connect information in the comb about time and frequency, and made precision measurements of the frequencies of selected comb lines.

The development of the optical frequency comb would soon impact precision measurement, ultracold matter investigations, the development of optical atomic clocks, and the invention of quantum simulators, to name just a few research areas transformed by this new technology. The stunning developments inspired by the comb would be accompanied by another transformation in JILA set in motion during the 1990s: The welcoming of women and minorities into the JILA faculty.

The Colorado Daily, July 14, 1995 reported on JILA's six-year quest to create an entirely new form of matter, known as a Bose-Einstein condensate. *Image right: Courtesy of the* ***Colorado Daily****.*

Best in the hoop West
Raegan Scott, Erin Scholz playing in Olympic Festival 9

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Hootie and the Blowfish headline Winter Park concert 13

Weather
Showers
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Colorado Daily

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THE INDEPENDENT PRESS FOR CU AND BOULDER. JULY 14-16, 1995

JILA is a very cool place

CU lab's six-year scientific quest ends in victory

By CHRIS LOGAN
Colorado Daily Staff Writer

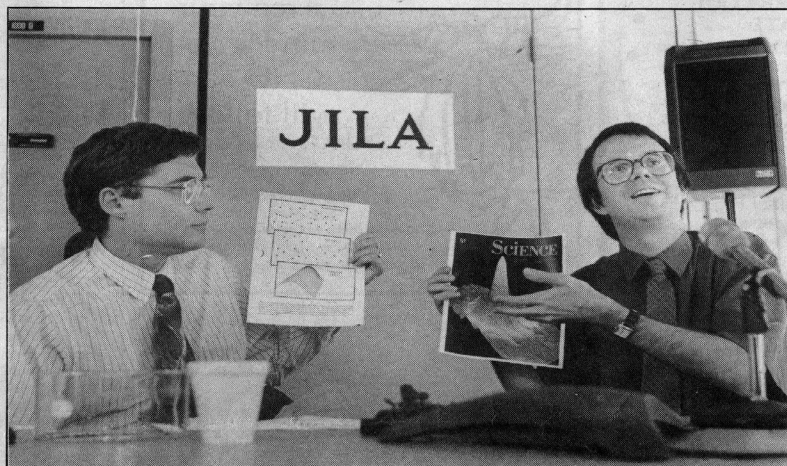
On the morning of June 5, a team of physicists at CU succeeded in creating an entirely new form of matter at the lowest temperature ever recorded anywhere in the universe.

Known as a Bose-Einstein Condensate, the matter was predicted by Albert Einstein in 1925.

The team, led by physics Professor Carl Wieman and researcher Eric Cornell, cooled 2,000 rubidium atoms to less than 170 billionths of a degree above Absolute Zero — a theoretical temperature at which a substance has no motion and no heat, causing the atoms to lose their individual identity and begin acting as one atom.

The atoms exist in a strange, smeared-out condition, the properties of which have yet to be investigated.

SEE VICTORY PAGE 3



Charlie Johnson/Colorado Daily

Physicists Carl Wieman, left, and Eric Cornell discuss their success in creating a form of matter first predicted by Albert Einstein 70 years ago. They spoke to the press about their findings on Thursday.

Find puts 'electricity' in the air

By CHRIS LOGAN
Colorado Daily Staff Writer

Eric Cornell knew his team of researchers at the Joint Institute of Laboratory Astrophysics at CU was on the verge of creating the elusive Bose-Einstein Condensate on the morning of June 5.

"I was coming into the lab about every hour or so," he said. "I knew we were close. I could sense it."

In the lab that morning were postdoctoral researcher Mike Anderson and CU graduate students Jason Ensher and Mike Matthews. The three were manipulating laser beams and magnetic

SEE LAB PAGE 3

...Scientists get rubidium close to absolute zero

VICTORY FROM PAGE 1

"It's a phase transition similar to going from solid to liquid to gas," Cornell said. The simplest comparison, he said, is to think of the Bose-Einstein Condensate in relation to normal atoms the way a laser beam relates to normal light.

"The atoms have been put into the same quantum mechanical state," Wieman said. "Technically, they still exist as a gas, but they are much more organized."

Einstein predicted the effect after reading the work of Indian physicist Satyendra N. Bose, who made similar predictions in an unrelated field.

"Einstein picked up on his idea and predicted this effect at these ridiculously low temperatures," Wieman said.

"That anyone could actually reach these temperatures and observe this was a flight of fancy even for Einstein," added Cornell. "Had it been anyone else, the idea probably wouldn't have been taken seriously."

But it was taken seriously, and about 15 years ago, the Bose-Einstein Condensate became the object of serious scientific pursuit. Its final achievement, Wieman said, is a triumph of human intellect.

Wieman began working on reaching the Bose-Einstein Condensate six years ago and was joined in his pursuit in 1990 by Cornell. Both work for the Joint Institute for Laboratory Astrophysics, a program funded by CU and the U.S. Department of Commerce's National Institute of Standards and Technology.

Using a technique called laser cooling in which an array of lasers are fired at atoms from six directions in order to slow them down, Wieman and Cornell soon reported reaching the coldest temperature ever recorded: 1 millionth of a degree above Absolute Zero.

But the laser-cooling technique only worked to a certain point, because it relied on manipulating the Doppler effect to "trick" the atom into absorbing the laser's light. Once the atoms were slowed down, the Doppler effect became smaller and smaller — to the point where it could no longer be used.

"So we had to find a new trick to make the atoms colder," Cornell said. And that trick relied on the same physical laws that cause a hot cup of coffee to cool down.

"When you have a cup of hot coffee, all the atoms in the liquid are excited and are rushing around in random directions," he said. "Every now and then, one of those hot atoms jumps out of the cup, taking with it some excess energy. That leaves less energy for the remaining atoms, and the coffee cools."

Cornell and Wieman have applied that process, known as evaporative cooling, to rubidium atoms in a gaseous state.

Their "cup" is a magnetic field created by coils of wire. At the bottom of this magnetic cup, atoms of rubidium roll around like marbles in the bottom of a bowl. The atoms are held in place in the cup by the force of the magnets on their individual magnetic charges.

But the team discovered a hole in the bottom of the cup in the form of an area with a zero magnetic field. The coldest atoms, clustered at the center, leaked out, leaving scientists without the necessary density of atoms to achieve the condensate.

Cornell put the missing piece of the puzzle in place about a year ago, Wieman said, by introducing an additional magnetic field that moved the "hole" around.

"It's like playing keep-away with the atoms, because the hole circulated faster than they could respond," Cornell said.

Then, at 10:54 in the morning, a predicted density peak appeared on the researchers' computer screens.

"Our first impression was this is exactly what we're looking for," Wieman said. "Once we checked to make sure it wasn't a mistake in our instruments, we knew we had it."

...Scientists felt 'electricity' in the air

LAB FROM PAGE 1

fields in an attempt to cool a collection of 2,000 rubidium atoms to the coldest temperatures ever recorded in the universe.

At 10:54, the temperature inside the small glass tube containing the rubidium dropped to 170 billionths of a degree above Absolute Zero, and the rubidium atoms suddenly stopped moving individually and blended into a new state of matter predicted by Albert Einstein some 70 years ago.

"There were dignitaries from NIST touring JILA that day, and we were so excited we could barely speak," Cornell said. "I think they sensed the electricity in the air and probably enjoyed that more than the regular dog-and-pony show."

Cornell, Anderson, Ensher and Matthews, however, were frantically checking instruments and readings to confirm that they were, in fact, the first of at least six teams working nationwide to create that which Einstein had only predicted. Within a few hours it was clear they had.

"I had to keep going out in the hall to get cups of water, because I was sure I wasn't seeing what I thought I was seeing," Anderson said.

Cornell said the discovery left him numb for the first couple of days.

"It didn't really sink in until the third day," he said. "That night, I didn't sleep at all."

The team's discovery can be used to improve precision standards in atomic clocks and may lead to the development of atom lasers, which use beams of particles rather than light.

"There are certainly implications for what we know about quantum mechanics, but we may also be able to use technology stemming from this discovery in making materials at the microscopic level," said CU physicist Carl Wieman, the other leader of the team, adding that it's too early to rank the importance of the team's discovery.

"You have to wait a while and see what kind of impact it has," he said. But Wieman conceded there are a number of physicists walking around who would like to be in his shoes.

But those physicists were among the first to congratulate the Boulder scientists.

"This was a race in which there was a winner but no real loser," said M.I.T. physicist Wolfgang Ketterle, who is attempting to create the effect using sodium atoms.

"Of course, we all go through life with our own ambitions," he said. "But this achievement, regardless of who did it first, opens up new spheres in atomic physics. Any advancement in fundamental science has many more applications in the future than we can possibly think of now."

THE WELCOME MAT

JILA's first female Fellow, Katharine Gebbie, is now Director of the Physical Measurement Laboratory at NIST. *Credit: NIST*

In the early 1990s, JILA began an effort to hire senior scientists and promising young faculty members from under-represented groups such as women and minorities. The Institute tried different strategies to make JILA a more welcoming place for a more diverse faculty, modifying approaches as JILA members learned what did and did not work well. These strategies included helping spouses find employment in the area and addressing the needs of families with young children. As a result, the composition of the JILA faculty has since evolved differently than it did during the first three decades. For example, in 2012, more than 20% of the JILA faculty was female, and 7% was minority. In contrast, when JILA was founded, there were no women or minorities on the faculty.

In the 1960s, it was difficult for women to find employment in the sciences and other fields outside of the traditional fields of nursing, teaching, or clerical work. Those women who managed to find employment outside these fields were often paid lower wages. With respect to the field of physics, many scientists felt there was no point in investing time and effort into hiring women who would soon leave the field to start families. Fortunately for JILA, the field of astronomy was more open to women, even in the 1960s.

JILA's first (and for many years only) female Fellow, Katharine Gebbie, arrived at JILA in 1968 as a research associate for JILA co-founder Dick Thomas. She later worked with JILA Fellow and CU astrophysicist Juri Toomre. Gebbie was a JILA Fellow from 1974 to 1986, when she left JILA to work for two years in the office of the Director of NBS. She returned to JILA in 1988 for another three years as chief of NIST's Quantum Physics Division [NBS had just changed its name to NIST]. Gebbie departed JILA again in 1991 to establish and manage the new Physics Laboratory at NIST headquarters in Gaithersburg, Maryland.

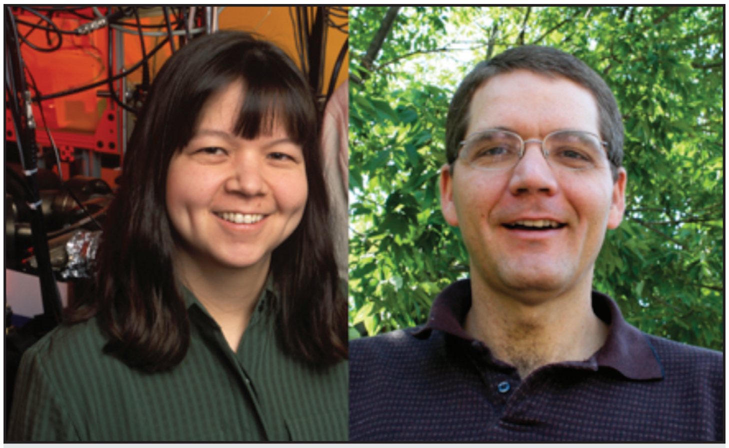
In 2010, Gebbie became Director of the new NIST Physical Measurement Laboratory, which included the previous Physics Laboratory plus several additional research and measurement programs at NIST. In Gebbie's various positions, she has had overall responsibility for the NIST side of JILA for more than 20 years.

Soon after Gebbie left JILA in 1991, the Fellows discussed the hiring of female and minority scientists during a self-study conducted for the 1991–1992 program review of the NSF group grant. They endorsed the following statement:[1]

JILA sees the need for, and wishes to give the highest priority to, attempting to hire a protected class (woman or minority) faculty member who would eventually become a Fellow of JILA. Such an appointment, or appointments, would add immensely to our ability to educate and provide role models for protected class students and postdoctorals in JILA. We view this added dimension as essential to the long-term health of JILA. To enhance our prospects of success in this endeavor, we will consider hiring a qualified candidate in any field appropriate to the research in the Institute. We would seek to hire the most highly qualified candidate consistent with the tenure standards of the University and JILA.

JILA soon discovered that retaining women faculty was more challenging than expected. For instance, two female astrophysicists were appointed Fellows in 1990 and a female optical physicist received the nod in 1995. Even though both astrophysicists served as the JILA Chair (Katy Garmany in 1997–1998 and Ellen Zweibel in 2001–2002), both left JILA by 2002. In addition, optical physicist Tracy Clement left after only three years at JILA to work for NIST. Garmany left in 2000 to take a position at the Biosphere 2 Center.

1. Roy Garstang, *JILA History*, 1965-2009.



Spouses Deborah Jin (l), an experimental physicist, and theorist John Bohn (r) are both JILA Fellows. *Credit: (l) JILA; (r) Brad Baxley, JILA*

Spouses Margaret Murnane (l) and Henry Kapteyn (r) are both JILA experimental physicists and Fellows. *Credit: Glenn Asakawa, University Communications*

And, Zweibel left in 2002 when she and her husband were both offered tenured positions at the University of Wisconsin.

By the time a new round of hiring began in 1999, JILA better understood that attracting and retaining women increasingly meant finding ways to solve the "two-body problem" of two spouses both having professional careers. In 1999, JILA recruited Margaret Murnane and her husband Henry Kapteyn as a team. Both had separate academic appointments in CU's physics department, but they jointly operated a large experimental research group at JILA. Over time, the large Kapteyn/Murnane group has proved to be just as productive as two separate groups.

A second two-body solution resulted in the successful recruitment of experimentalist Deborah Jin and theorist John Bohn in 1997. Jin joined the JILA faculty as a NIST Fellow and started an experimental group. Bohn spent three years as a senior research associate before joining the CU Physics Department's research faculty and becoming a JILA Fellow in 2000. Bohn's theory group often collaborates with different experimental and theory groups across JILA, including the Jin group.

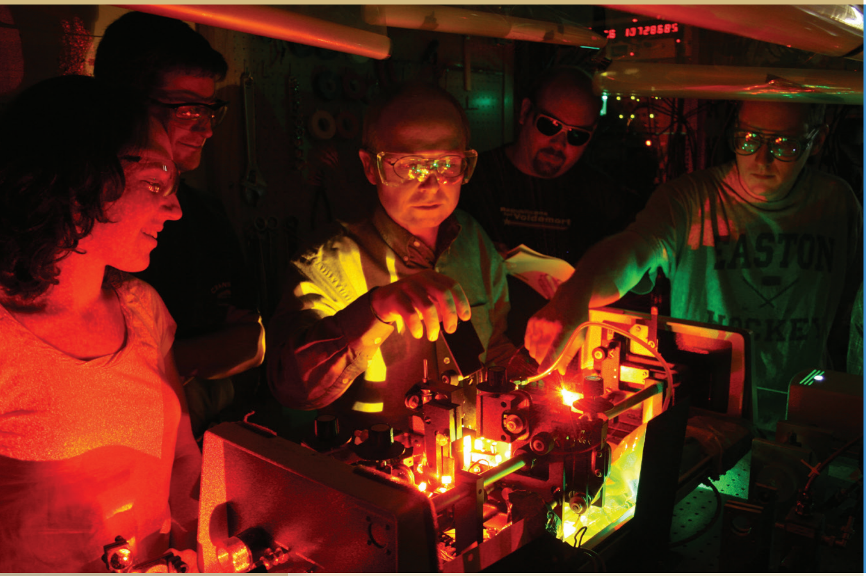
Yet another approach was used in 2008 when theorist Ana Maria Rey was appointed to JILA. As the result of a collaborative recruitment between JILA and the math department, Rey's husband, Juan Restrepo, became a faculty member in the CU Department of Applied Mathematics. Most recently, JILA and the nearby NIST Boulder Laboratories cooperated to bring experimental physicist Cindy Regal to JILA and her husband, Scott Papp (who is also an experimental physicist), to NIST.

At the same time it was developing solutions for the "two-body" problem, JILA quietly adjusted to the reality that young women faculty were choosing to have families. Many of the original JILA Fellows — all male — were parents of young children. But the majority had wives who focused on the family, permitting the Fellows to focus on their research careers. As the roles of mothers and fathers are evolving in American society, JILAns are also adapting and changing. Female Fellows Jin, Rey, and Regal as well as senior research associate Agnieszka Jaron-Becker are all parents of young children. These women are pioneering new roles for active JILA researchers and helping to change attitudes toward, and expectations of, women in JILA.

Such changes matter to the young women who are getting their advanced training in physics at JILA and being mentored by the Institute faculty. In 2012, 37% of undergraduate research assistants and 25% of JILA graduate students were female, as were 13% of research associates and 33% of senior research associates. The change in the complexion of the JILA faculty may have been a long time in coming, but it will likely color not only JILA, but also the field of physics for many years to come. Women scientists trained at JILA are bringing a new vision of what is possible professionally and personally in the field of physics, thanks, in part, to the role models they have encountered at JILA.

Photo Credit: Denver Museum of Nature & Science

Chapter 5
2000 to 2009



Graduate student Melanie Roberts works with Fellow David Nesbitt in his chemical physics lab.

The 2000s saw three JILA Fellows named as Nobel Laureates: Carl Wieman and Eric Cornell in 2001 and Jan Hall in 2005. Wieman and Cornell, along with Wolfgang Ketterle of MIT, were feted for the creation of the first Bose-Einstein condensates. Hall, who shared the prize with Theodor Hänsch of the Max Planck Institut für Quantenoptik and Roy Glauber of Harvard University, was honored for a long and successful career developing and refining laser technology, in particular the creation of the world's first optical frequency comb laser.

At the Nobel press conference held at CU on the morning of October 9, 2001, Eric Cornell explained what was special about JILA that had made it possible for Carl Wieman and him to accomplish something that would have been impossible if they had worked at just CU and NIST.

"First and foremost, (JILA) lets Carl and me work together in a very natural way. I'm a federal employee. He's a state employee. Here we are, sworn enemies, and yet we're in this neutral ground here called JILA. It is a wonderful place, because it really does allow the resources of a federal laboratory to meet with the excitement of the university environment where you have students and postdocs — the young people who make up the university. It's a wonderful combination in that respect. JILA, in particular, is a place that really fosters and encourages collaboration between senior people, which doesn't always work so well. Of course, it works everywhere in the University of Colorado, but in brand X universities, it can be a problem."

In one sense, the 2001 Nobel Prize could be thought of as a capstone of JILA's decades-long adventures at the forefront of atomic physics; in another sense, however, it also heralded a fruitful new era of discovery. This era would see the realization of a fermionic condensate, the synthesis of the world's first ultracold ground-state molecules, the introduction of the whole new field of ultracold chemistry, the implementation of an optical atomic clock, the design of a quantum simulator based on ultracold atoms, and a foray to the very frontiers of physics to answer the question of whether the electron has an electric dipole moment.

That JILA research was firmly rooted at the frontiers of physics was underscored when two Fellows, Margaret Murnane and Deborah Jin, were awarded prestigious John D. and Catherine T. MacArthur Fellowships, or "genius grants," in 2000 and 2003, respectively. Murnane's work in ultrafast laser development and Jin's growing expertise in ultracold-atom experiments had gained national prominence .

For its part, the 2005 Nobel Prize underscored the promise of the optical frequency comb, which had already facilitated the Ye group's development of an optical atomic clock based on neutral strontium atoms and the invention of a noninvasive medical breath analyzer. The comb was also on its way to enabling ultracold molecule research and innovative probes into the quantum nature of light and matter.

"I am so proud and happy that JILA has turned out so well."

—Dr. Quigg Newton, while attending the CU campus Nobel celebration for Eric Cornell and Carl Wieman on October 16, 2001. The 90-year-old Newton was president of the University of Colorado Boulder in 1962. He played a key role in bringing the Joint Institute for Laboratory Astrophysics to the CU-Boulder campus.

During the 2000s, JILA scientists Henry Kapteyn and Margaret Murnane developed a table-top x-ray laser. David Nesbitt investigated chemical reactions in outer space and made progress in learning how to control these reactions in the laboratory. Deborah Jin and Ana Maria Rey studied high-temperature superconductivity, and Tom Perkins and Ralph Jimenez investigated the physics of DNA and proteins. Konrad Lehnert made CT scans of the quantum states of microwave fields. JILA astrophysicist Phil Armitage modeled the formation and evolution of planetary systems around stars. Andrew Hamilton came up with a theory to explain the strange physics inside rotating black holes, while his colleague Mitch Begelman developed a novel explanation for the origin of the gargantuan black holes at the center of most galaxies. Rosalba Perna focused on the gamma-ray bursts emitted when black holes first form. Juri Toomre teased out a deeper understanding of the magnetic flows under the surface of Sun-like stars of different ages.

This rapid pace of discovery combined with the recognition that came with three Nobel prizes and two MacArthur Fellowships turned JILA into a magnet for young scientists. By the latter part of the decade, JILA was producing 5–10% of the nation's new Ph.D.s in AMO Physics.

For this reason, the Fellows were soon forced to address a growing scarcity of office and laboratory space to ensure that JILA would continue to be able to recruit and retain talented new faculty members. One of the biggest concerns was the loss of common space for spontaneous interactions, something that had a long history of generating powerful collaborations among JILA scientists.

The Fellows determined that a building expansion of just over 26,000 (useable) square feet for offices, labs, and conference rooms would not only alleviate crowding in busy laboratories, but also allow for a 50% increase in the number of AMO graduate students working with JILA faculty. NIST and CU agreed to jointly finance the new JILA expansion, dubbed the "X-Wing." The total cost of the X-Wing was approximately $33 million. NIST provided $22.5 million through a cooperative agreement with CU, and CU provided the remaining funding, plus significant infrastructure support through land, utility connections, and other services.

Scientifically, the new building was expected to assist JILA in maintaining its leadership in the physical sciences with new laboratory space dedicated to the development of optical atomic clocks and precision laser measurement tools as well as innovative methods to probe ultracold matter. The X-Wing was also expected to add to the nation's capacity to train top scientists for government, industry, and academia. And, the JILA Fellows expected that their new, modern facility would help them deliver advanced technological innovations. Future technologies developed at JILA would improve not only quality of life, but also competitiveness.

The Fellows decided to move ahead with the building expansion in late 2009. Groundbreaking for the new X-wing took place in May of 2010. The building was completed and ready for occupancy by March of 2012. A formal dedication of the X-wing took place on the CU campus on April 13, 2012.

THE FIFTH DECADE (2000–2009)

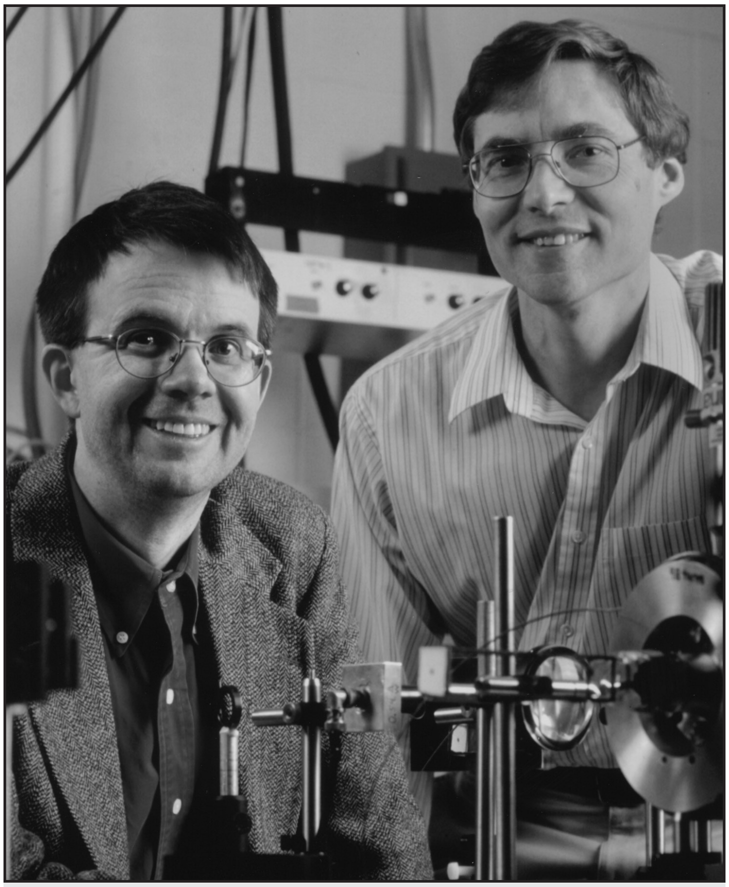
2000–2001

In 2000, the six new JILA faculty members hired during the late 1990s were settling into the Institute. Enthusiasm for new avenues of inquiry was pervasive. The excitement was palpable, particularly after Fellow Margaret Murnane was awarded a MacArthur fellowship in 2000.

Soon, well-known Visiting Fellows, talented postdocs and graduate students, as well as highly skilled staff members were competing for positions at JILA. The Institute was not only leading the world in the exploration of BEC and degenerate Fermi gases, but also rapidly advancing the development of optical frequency comb technology.

The year 2000 saw the development of the world's first octave-spanning optical frequency comb, new methods for extending the frequency comb over larger and larger intervals (including down to microwave frequencies), and new strategies for stabilizing an entire frequency comb. The new developments in comb technology ensured that precision measurement, the traditionally strongest link between research at NIST and CU in JILA, would remain robust well into the future.

JILA'S NOBEL LAUREATES



Fellows Eric Cornell and Carl Wieman shared the 2001 Nobel Prize in Physics for the creation of the world's first Bose-Einstein condensate. *Credit: University of Colorado*

Fellow Jan Hall performs an early stabilized-laser experiment. Hall shared the 2005 Nobel Prize in Physics for a lifetime of accomplishment in laser science, including the creation of an optical frequency comb. *Credit: JILA*

A TABLETOP X-Ray Laser

During 1997–1998, Kapteyn and Murnane explored ways to make the high-harmonic generation as efficient as possible, with the goal of making bright beams of laser-like x-rays at energies that would allow them to visualize fast motions in the nanoworld. To make the process efficient, they found ways to ensure that the laser and x-ray waves moved in sync throughout the gas, making it possible for the x-rays to add coherently to make a bright beam, which they observed for the first time in 1998.

In the early 1990s before they came to JILA, Henry Kapteyn and Margaret Murnane created what was then the fastest laser in the world. To make it, they used a short, highly doped titanium:sapphire (Ti:S) crystal and a pair of fused-silica prisms inside the laser. Since then, similar ultrafast Ti:S lasers have been used in research laboratories around the world.

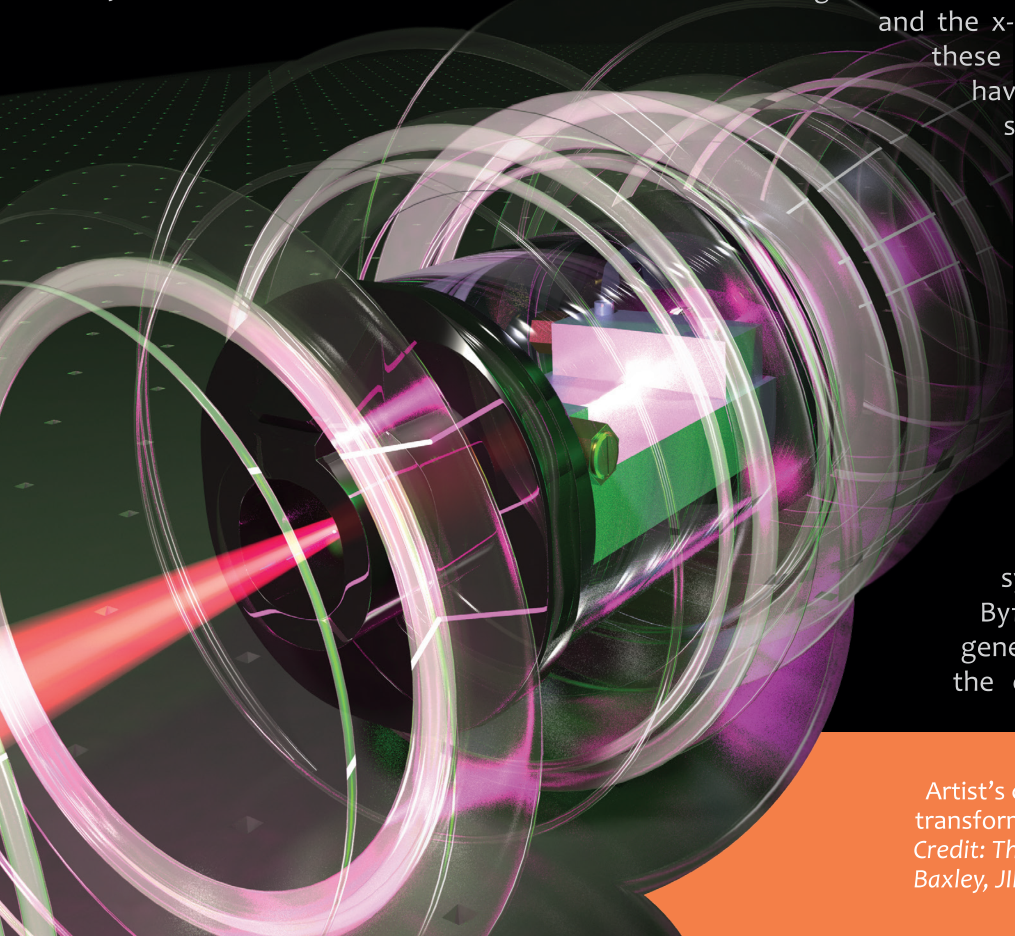
After this triumph, the researchers turned their attention to producing bursts of x-ray light using a technique called high-harmonic generation.

After this triumph, the researchers turned their attention to producing bursts of x-ray light using a technique called high-harmonic generation. In high-harmonic generation, a high-intensity laser pulse plucks electrons out of atoms such as argon. The electron then gains energy from the laser as it gains distance from its parent atom. When such high-speed electrons crash back into their parent atoms, the atoms emit short bursts of x-rays.

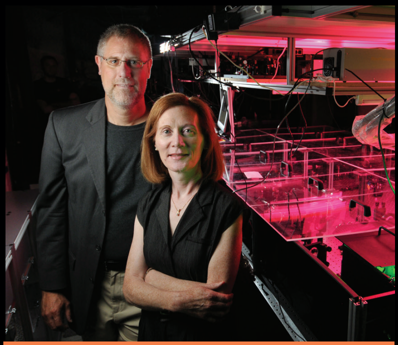
Over time, Kapteyn and Murnane, who joined the JILA faculty in 1999, have refined their technique to the point where they can generate laser-like beams of x-rays that span the range from the ultraviolet wavelengths (400–100 nm) to wavelengths shorter than 0.8 nm. To do this, their system combines more than 5000 infrared photons to produce each high-energy x-ray.

A key improvement was the propagation of a visible laser pulse through a hollow capillary tube called a waveguide filled with argon or another noble gas. The waveguide made it possible to control the phase velocity of the laser beam and eliminated beam divergence, making it easier to keep the phases of the emitted x-rays in sync. The waveguide also allowed the researchers to keep the laser light and the x-rays traveling at the same speed. Since these developments, Kapteyn and Murnane have explored many experiments in x-ray science. Their investigations have included studies of the internal structure of molecules, the interplay of electronic and atomic motions inside a molecule, the transport of heat through different materials, the magnetic behavior of atoms in response to laser light, and the process by which radiation interacts with, damages, or destroys specific chemicals.

In 2010–2011, the Kapteyn-Murnane group made important advances to their system, creating a true tabletop x-ray laser. By focusing a femtosecond laser into a gas, they generated many colors of x-rays at once, from the extreme ultraviolet into the soft x-ray

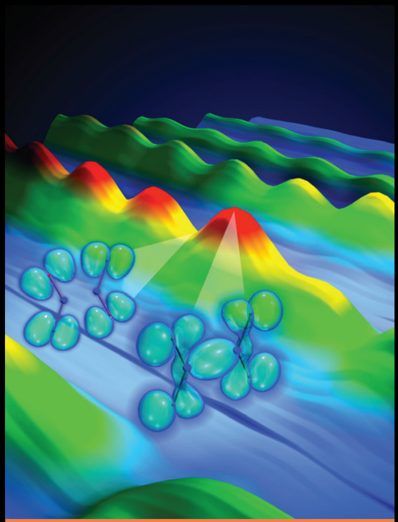


Artist's conception of the device used to transform infrared laser light into laser-like x-rays. *Credit: The Kapteyn/Murnane group and Brad Baxley, JILA* region of the electromagnetic spectrum. Added together, these colors formed the shortest strobe light in existence, with its light lasting for as short a time as 2.5 attoseconds. The highest energy colors of this light have energies of up to 1.6 kiloelectron volts.



Henry Kapteyn and Margaret Murnane in the laboratory. *Credit: Glenn Asakawa, University Communications*

The new ultrafast x-ray laser can probe the "water window" of the spectrum where biological molecules rich in carbon, hydrogen, and nitrogen can be clearly imaged. That means it can "look inside" the internal structures of cells or other living structures. This invention has also opened up other new fields of research, including the ability to image electron dynamics in molecules and materials, develop high-resolution nanoscale microscopes, understand how atoms of magnetic materials respond to laser light, follow energy and charge transport at the nanoscale, and characterize individual atoms inside a solid.



Study of the emission of bright bursts of x-rays from vibrating molecules. *Credit: The Kapteyn/Murnane group and Greg Kuebler, JILA*

The x-ray laser has made it possible to perform x-ray spectroscopy investigations in ordinary research laboratories. Scientists will soon be able to simultaneously probe the behavior of electrons, atoms, or molecules at multiple sites inside the same liquid or solid. And, because x-rays have much shorter wavelengths and much higher energies than visible light, it will be possible for researchers to image incredibly tiny structures at a much higher resolution than ever before.

In 2000–2001, JILA hired two new Fellows, AMO theorist John Bohn, a research professor at CU, and Thomas Perkins, a NIST Fellow and Adjoint Professor of Molecular, Cellular, and Developmental Biology. The hiring of Perkins signaled a move on JILA's part into precision-measurement research on biophysical systems. This new field merged optical-based measurement science with single-molecule studies of fundamental biological processes. Perkins' philosophy was that biomolecules should make great precision measurement tools. By 2008, his group would be developing DNA as a force standard for the nano world.

In 2001, JILA research emphasized advances in precision measurement, a deeper understanding of low-temperature states of ultracold gases, the characterization of chemical processes and materials, new laser-based measurement systems, optical physics, and astrophysics. That the JILA Fellows were working at the forefront of science was evidenced by the news that Carl Wieman and Eric Cornell, along with Wolfgang Ketterle of MIT, had won the 2001 Nobel Prize in Physics for making the first BECs. Wieman heard the news about 4:00 a.m. on October 9 from his younger brother, who had checked the Internet. Cornell heard the news from his former thesis advisor, David Pritchard of MIT.

An impromptu gathering was held in the JILA auditorium that afternoon. Wieman and Cornell received thunderous applause from a capacity audience and opened a bottle of champagne to loud cheers.

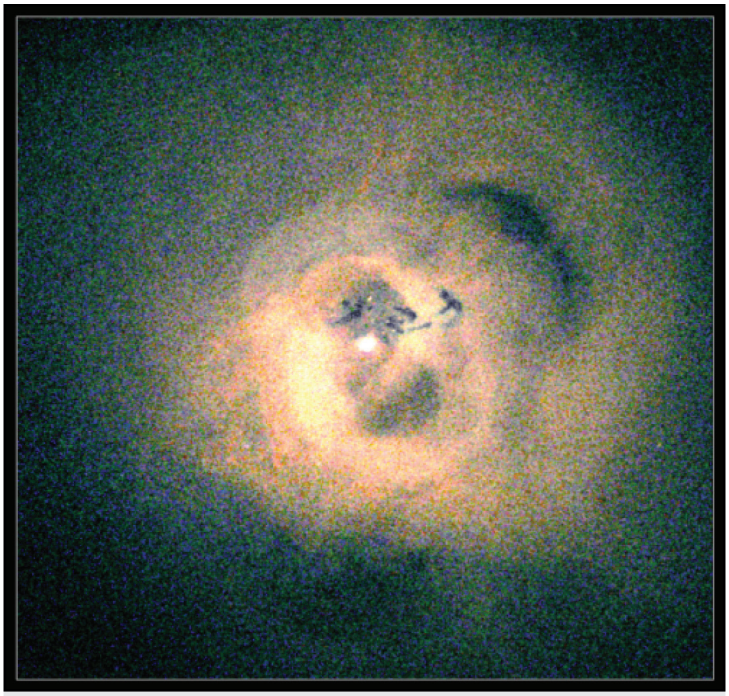
The CU campus Nobel celebration took place on October 16 at Norlin quadrangle. Among the attendees was 90-year-old Quigg Newton, who had been CU president when JILA was founded in 1962. Newton said he was so proud and happy that JILA had turned out so well. Katharine Gebbie noted that 2001 was also the 100th anniversary of the founding of NIST as well as the 100th anniversary of the Nobel Prize. She reminded the audience that JILA had been founded to provide young scientists with a fertile environment for their work. The 2001 Nobel Prizes were a testament to the vision of JILA's founders.

Other exciting events followed. NIST Boulder Laboratories held a Nobel celebration on November 1. On November 26, Wieman and Cornell attended a special event at the Swedish Embassy in Washington. The next day, the two met with President Bush and the other 2001 Nobel Laureates at the White House. Finally, on December 10, they were awarded their prizes at a ceremony in the Grand Auditorium of the Stockholm Concert Hall.

By the time Wieman and Cornell received their Nobel Prizes, it was clear to everyone at JILA that their work had not occurred in isolation. Their accomplishment was an important by-product of the cooperative and collaborative atmosphere at JILA. The Institute had a long history of bringing together capable, productive scientists and letting them pursue their ideas across institutional, laboratory, and disciplinary boundaries with little hindrance. JILA was the model of productive interdisciplinary research that served both teaching and research at CU and met the national priorities of NIST's research mission.

2002–2003

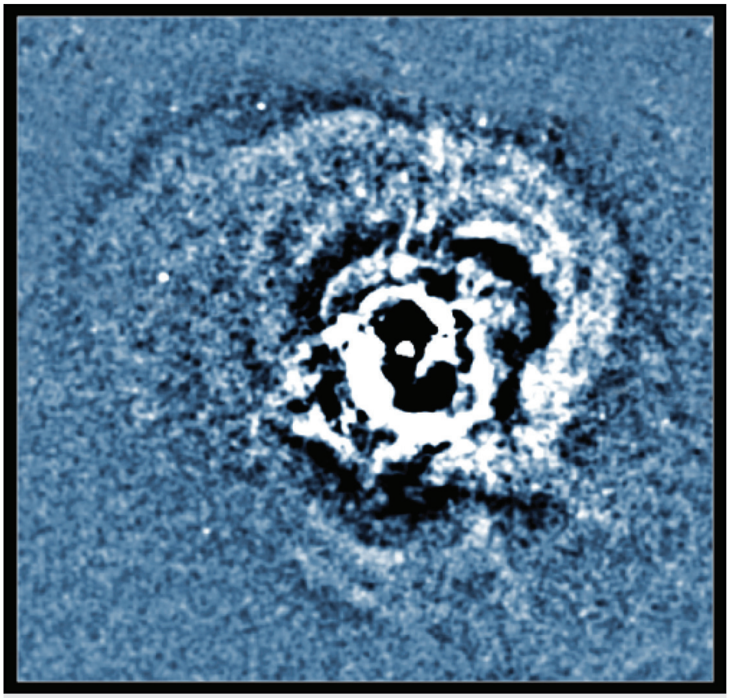
Local Nobel celebrations continued into 2002. On January 8, the City of Boulder feted the Nobel Laureates with a resolution designating the day as "Eric Cornell and Carl Wieman Day in the City of Boulder." On February 25, an all-JILA Nobel presentation and celebration was held in the auditorium. When Quantum Physics Division Chief Jim Faller introduced Wieman and Cornell, he announced that they had just been awarded Marsico Endowed Chairs of Excellence at CU. Not to be outdone, the Colorado Legislature and Governor Bill Owens recognized the two on March 6 with a joint resolution honoring their achievements and a proclamation making the day "Carl Wieman and Eric Cornell Day in the State of Colorado." Finally, on April 18, Wieman and Cornell gave a public lecture to a packed house at Macky Auditorium as part of the 40th anniversary celebration of JILA. JILA founder Lewis Branscomb also spoke about the government-industry partnership in the era of catastrophic terrorism.



Chandra X-ray Observatory image of the center of the Perseus galaxy cluster. The image appears to be bubbling with sound waves. The Begelman group simulated processes like this. *Credit: NASA/CXC/IoA/A.Fabian et al.*

In 2002, JILA had 29 Fellows, 10 in NIST's Quantum Physics Division, one in NIST's Time and Frequency Division, and 18 CU Fellows rostered in the Departments of Physics, Chemistry and Biochemistry, and Astrophysical and Planetary Sciences. The size of the faculty was already stressing the capacity of the original tower and laboratory wing as well as the 1988 S-Wing laboratory building. As a result, NIST recommended that JILA's parent organizations begin to look for ways to improve the quality and quantity of space at JILA.

In 2002, the Jun Ye group began what it imagined would be a relatively straightforward research project to develop an optical atomic clock based on neutral strontium atoms confined in an optical lattice. The new clock would incorporate an optical frequency comb. At the time, the group had no clue that it was embarking on a challenging journey into the heart of quantum physics that was destined to lead them to the design and operation of a new quantum simulator in less than a decade. The combination of precision metrology and quantum physics continues to open up new fields of scientific research.



The same picture as left after image processing to enhance concentric sound waves. *Credit: NASA/CXC/IoA/A.Fabian et al.*

In 2002–2003, JILA hired three new Fellows: Phil Armitage and Konrad Lehnert in 2002 and Ralph Jimenez in 2003. Armitage, a CU Professor of Astrophysical and Planetary Sciences, specializes in investigating the formation and evolution of planetary systems. Lehnert, a NIST Fellow, investigates the quantum behavior of small electrical or electromechanical circuits. Jimenez, a NIST Fellow, is a biophysicist interested in protein motions and structures.

The year 2003 was particularly exciting for Fellow Deborah Jin. That year she won a MacArthur Fellowship. She and her team also created the world's first fermionic condensate. Making the condensate required the creative use of Feshbach physics to create diatomic molecules of potassium (K_2) from an ultracold Fermi gas of ^{40}K atoms. The new molecules were bosons; unlike their constituent fermionic atoms, they could (and did) form a Bose-Einstein condensate. Jin's team included Cindy Regal, who went on to become a CU physics professor and JILA Fellow in 2010.

In 2003, the journal *Nature* published a news feature on JILA history, research, and the qualities that make JILA special. In a nutshell, it described the hot action in the early 1960s as studying the atmospheres of stars with detailed observations of atomic collisions under extreme conditions. These investigations gave rise to the marriage of atomic physics and astrophysics at JILA. Forty years later, JILA astrophysicists were exploring supernovae and black holes, while its atomic physicists were investigating atomic properties using laser spectroscopy and ultracold atoms.

According to *Nature*, the unbridled success of JILA's atomic physics program was due to 30 years of NSF group grants, which accounted for 12% of NSF's total spending on AMO physics. The collaborative research environment fostered by these grants was responsible for making JILA something of a physics paradise. Eric Cornell added another perspective on what made JILA special: "We have a very high quality of support staff," he said, noting that JILA budgets 10% of its income from grants to support the technical shops.

Whatever the reason, JILA did feel like a special place in the first decade of the 21^{st} century. And, that sense of being special was communicated to the six Fellows hired in the late 1990s, the five Fellows hired during the first half of the 2000s, and the six Fellows hired since then. At the same time, however, JILA allocated fewer resources for the Visiting Fellows program, which had figured prominently in JILA's development during its early history.

In 2003, JILA Chair Judah Levine changed the Visiting Fellows program to allow for shorter visits and fewer appointments. Visitors no longer had to be part of a group but were required to have an agreement from a Fellow to sponsor a visit. A flat stipend of $4000 per month was included, but there was no additional funding for spouses or families. The average length of stay was to be six weeks, but with an option to extend the visit. Even as they approved these changes, the Fellows insisted that collaboration with visiting scientists was still highly valued.

2004–2005

In the mid-2000s, JILA's main areas of research were astrophysics, atomic and molecular physics, biophysics, chemical physics, materials physics and chemistry, optical physics, and precision measurement. Astrophysicists looked for answers about our origins and place in the scheme of things. They studied the structure and evolution of stars, the interstellar medium, black holes and galaxies, planetary formation, and cosmology.

In atomic and molecular physics, JILA researchers made major contributions to research in ultracold matter, the control of atoms and molecules with ultrafast light, and dense atomic vapors.

Biophysicists applied the tools and concepts from physics and precision measurement to the understanding of living systems at the molecular level. They studied the structure, behavior, function, and interactions of important biomolecules such as proteins and nucleic acids.

JILA's chemical physicists used lasers and other tools to probe the structure and behavior of matter, investigate chemical reactions at the quantum level, study clusters and solvation, and explore the physics underlying tiny artificial atoms called quantum dots.

Materials scientists used lasers, including a tabletop x-ray laser under development in the Kapteyn/Murnane group, and other precision measurement tools to study semiconductors, optical fibers, chemical surfaces, polymers, and other nanoscale objects. In the process, they learned more about microscopies and laser science.

Optical physicists manipulated light to produce ultrashort laser pulses, and then studied the pulses to understand the fundamental properties of light. The investigation of light was intertwined with the development of advanced lasers and the control of ultrafast pulses. The goal was to create "designer" light pulses to control processes in chemistry, biology, nanotechnology, and other fields.

Fellows Ana Maria Rey and Jun Ye. *Credit: Greg Kuebler, JILA*

In 2002, the Jun Ye group began developing an optical atomic clock that keeps time with electronic transitions in strontium (Sr) atoms. The Sr atoms are located inside crystals of light formed by interacting laser beams. The light crystals do not perturb the critical electronic clock transitions inside the Sr atoms.

A diode laser probes the optical clock transition of the atoms and counts the ticks. An optical frequency comb serves as the clockwork gears and converts the rapid ticks (high frequencies) of the atomic transitions into much slower ones that can be read by standard electronic devices. Initially, Ye expected it would be straightforward to make a new optical atomic clock with greater precision than the nation's microwave-based time and frequency standard, the NIST-F1 cesium fountain atomic clock at NIST. (The precision of a clock represents how well repeated measurements of the clock's frequency match up over time.)

At the same time, Ye expected that determining the accuracy of the new optical clock would be more complicated. The accuracy would have to be determined by how well the measured clock frequency matched that of the atom's natural frequency.

However, what should have been a relatively straightforward research project has turned into an eventful and challenging journey. The first breakthrough occurred in 2005 when, working with the Greene theory group, the Ye group discovered a design that used two lasers (and three electronic levels) to create a unique, very narrow, and stable transition that would otherwise not occur in nature.

Then in 2006, the Ye group made the world's first accurate measurement of the Sr clock transition frequency. The researchers continued to work on refining their clock system to be more precise (which was relatively easy) and more accurate (which was more challenging). In 2008, they succeeded in measuring a clock uncertainty (a measure of accuracy) better than that of NIST's F1 cesium fountain atomic clock.

However, the group also discovered a much more serious, unanticipated problem with the clock: The researchers identified tiny shifts in their optical clock caused by colliding fermions. This was a problem they had to solve to make further progress on their clock. And, the solution led them straight into the heart of quantum mechanics.

The laws of quantum mechanics forbid collisions between identical fermions

Strontium atoms loaded inside crystals of light created with laser beams can be used to simulate the behavior of liquids and solids. *Credit: The Rey group and Brad Baxley, JILA*

The Incredible Journey

From Strontium Atomic Clocks to Quantum Simulators

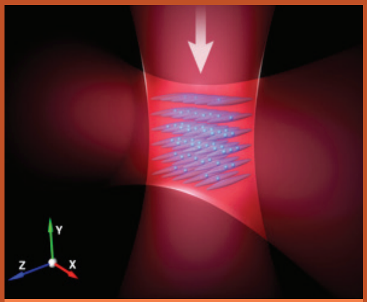
at very low temperatures! In fact, the Ye group had chosen to use an ensemble of identical ^{87}Sr atoms in their clock because the laws of quantum mechanics forbid them from occupying the same space. Atoms that can't occupy the same space shouldn't be able to collide!

The Ye group figured out that their clock laser was causing atoms in the light crystals to transition to their excited states at different rates. Since they were evolving differently, they were no longer identical and could collide!

The Ye group figured out that their clock laser was causing atoms in the light crystals to transition to their excited states at different rates. Since they were evolving differently, they were no longer identical and could collide! With this information, the Ye group was able to devise some strategies to reduce the frequency shifts due to collisions.

Fortunately, in 2009, theorist Ana Maria Rey helped the group solve the problem of colliding fermions. The solution was to use a new two-dimensional light crystal that made the Sr atoms inside interact much more strongly. Paradoxically, strong interactions actually suppressed Sr-atom collisions and increased the clock's accuracy by a factor of 50.

Their interest piqued by this unexpected turn of events, Rey and Ye realized that this collision-suppression method was the key to pursuing better clock precision and accuracy via engineering of atomic quantum states. Rey soon discovered that the unique atomic structure of Sr atoms was not only ideal for clocks, but also for constructing a new type of quantum simulator. In particular, the Sr atoms could be simultaneously studied in their ground and optically excited states. The idea of building a quantum simulator for complex quantum systems merged seamlessly with the Ye group's research work on precision measurement. The group soon began planning to use the simulator to investigate the quantum mechanics of electron orbitals, nuclear spin states, and electron charge.



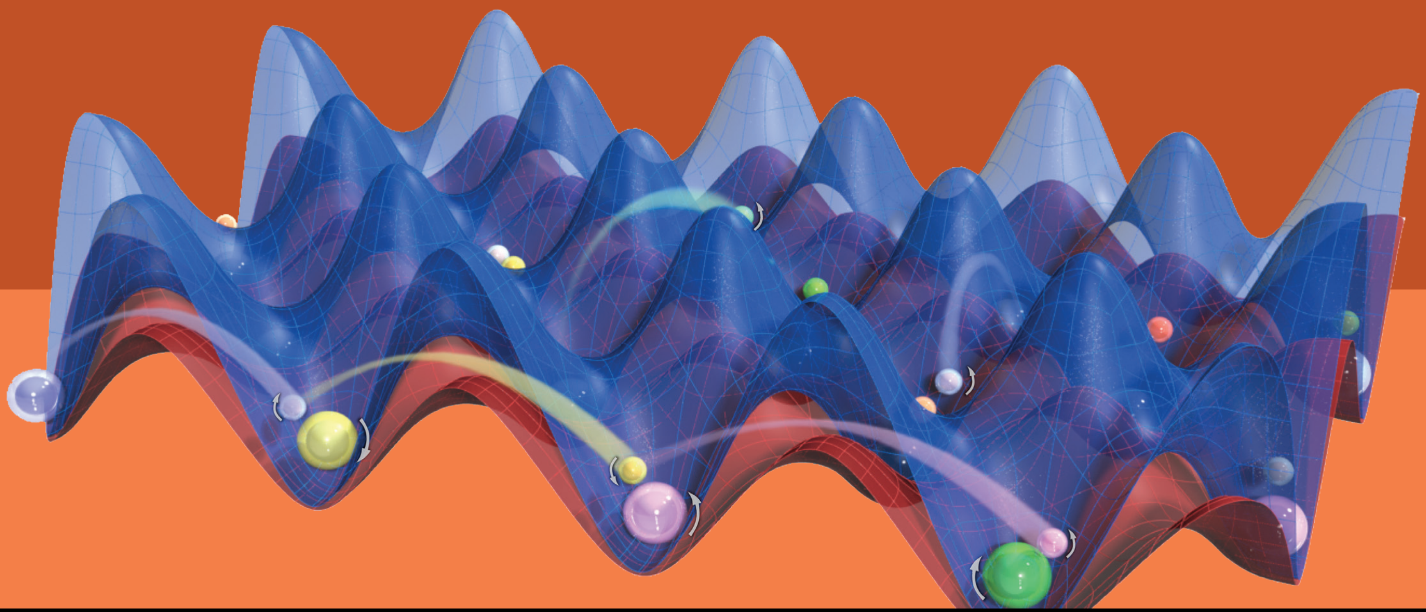
Artist's conception of a 2D clock lattice . *Credit: The Ye group and Greg Kuebler, JILA*

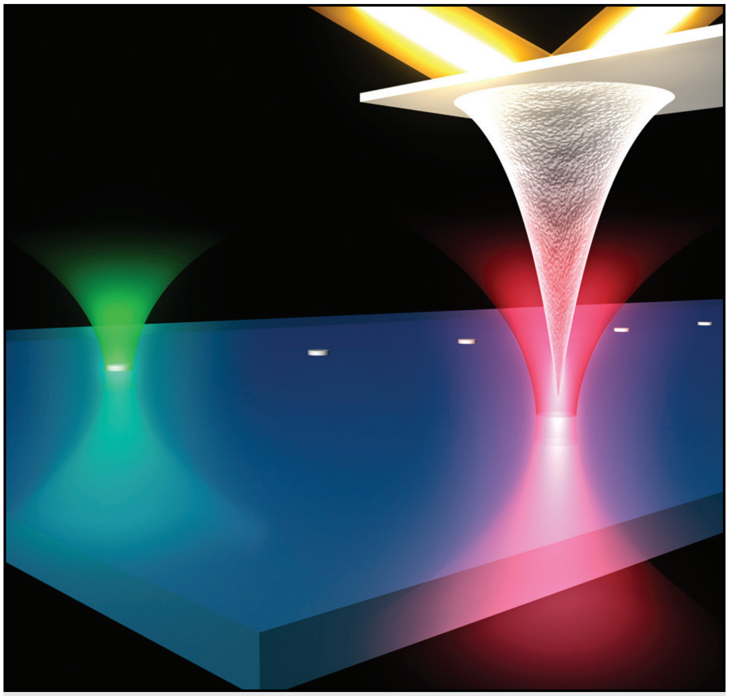
The simulator will allow the researchers to precisely manipulate and engineer the quantum states of atoms. Their hope is to use it to understand quantum magnetism and exotic materials such as high-temperature superconductors. So far, the temperatures that the researchers can reach in the lab are too high to explore exotic materials. However, they are looking for new ways to cool down the atoms and exert precision control over atomic interactions.

Even at current temperatures, the simulator is already helping the Ye and Rey groups to better understand the transition from the quantum world to the familiar classical world. This transition appears to flow naturally from the loss of quantum information that occurs as more and more atoms start to interact.

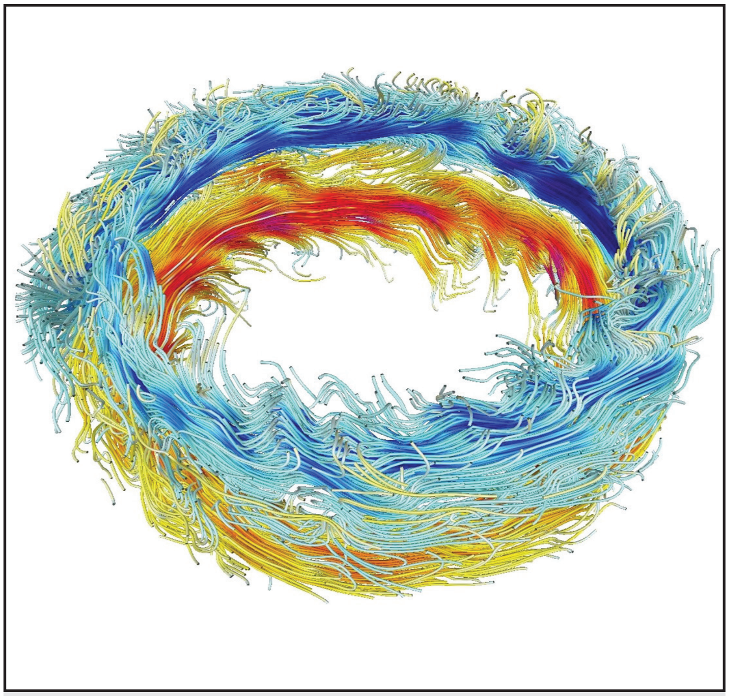
Of course, the devil is in the details of exactly how atomic interactions play out in a complex quantum system. Teasing out a myriad of details about the quantum world and its relationship to our more familiar world is a challenge Ye and Rey plan to meet together. They are now studying how atomic interactions determine the evolutionary behavior of a quantum system. And, they are investigating how various system properties, such as the collisional frequency shift for clocks, emerge from such interactions.

Together, Rey and Ye are making pioneering contributions to the emergent scientific field of quantum simulation. This field is destined to be very active in the foreseeable future.





Artist's conception of atomic force microscopy. *Credit: The Perkins group and Greg Kuebler, JILA*



Magnetic wreaths in a young star rotating three times faster than the Sun. *Credit: The Toomre group, JILA*

Working with researchers at NIST, JILA's precision measurement experts worked at the forefront of efforts to invent and refine precision measurement tools. These tools allowed scientists to probe tiny structures inside cells, study the properties of ultracold matter, monitor chemical reactions, measure the frequency of visible light, and investigate other aspects of our world that used to be too small or too fast to "see."

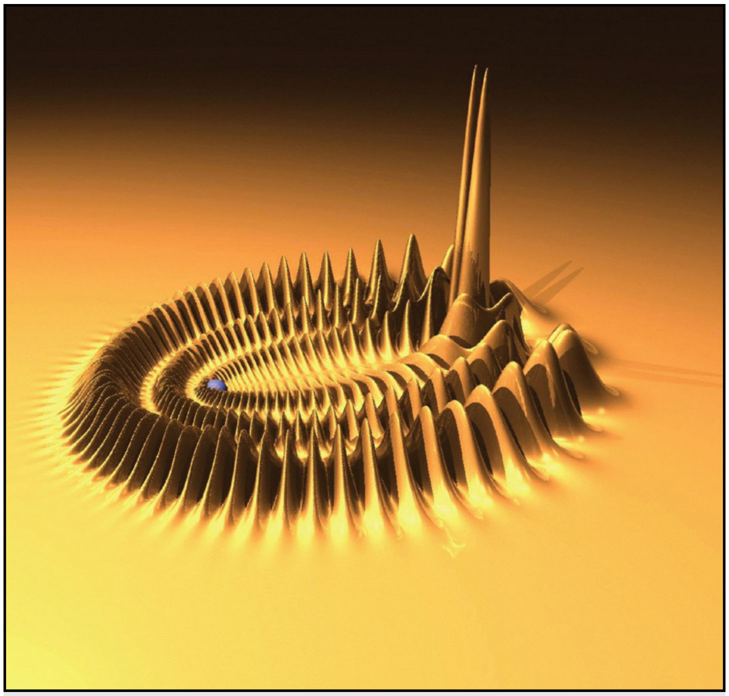
To extend its expertise in astrophysics and AMO physics, JILA hired two new Fellows, Rosalba Perna, CU assistant professor of astrophysical and planetary sciences in 2004 and Heather Lewandowski, CU assistant professor of physics, in 2005. Perna's research interests include high-energy gamma-ray bursts and neutron stars, Jupiter-like planets that orbit close to their stars, and selected topics in cosmology. Lewandowski's research emphasized cold collisions between atoms and molecules.

On the sports front, rafting trips and softball games took center stage. "Coach Lew," a.k.a. Heather Lewandowski, organized a JILA softball team in 2004. Three years later, the team joined the City of Boulder's Parks & Recreation league program. The team is named the JILA Monsters. Eric Cornell, Debbie Jin, and John Bohn have been "Monsters" ever since the launch of team play and helped the team win the championship in 2007.

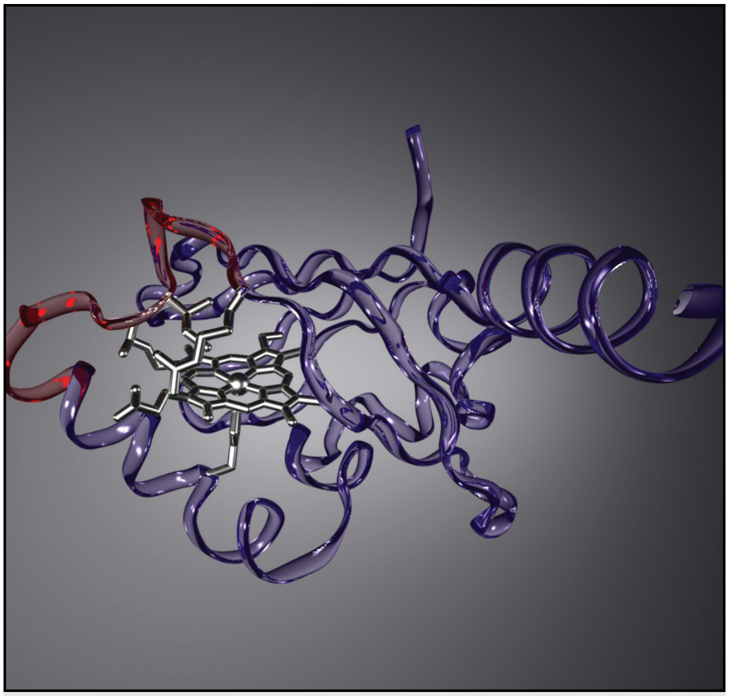
In the summer of 2005, and for several years afterward, graduate student Martha-Elizabeth Baylor and staff member Erica Mady organized some very exciting rafting trips for JILAns on the Arkansas River and through the Royal Gorge.

On October 4, 2005, longtime JILA Fellow Jan Hall learned he would share the 2005 Nobel Prize in Physics. Hall was cited for his contributions to the development of the laser from a laboratory curiosity to a fundamental tool of modern science and a ubiquitous component of modern communications systems. Hall was also cited for the creation of the world's first octave-spanning optical frequency comb in 1999.

The University of Colorado hosted a reception for its newest Nobel Laureate in March of 2006 in the UMC ballroom. Since then, Hall has regularly attended the



Electron density pattern of a giant weakly bound Rydberg molecule that resembles a trilobite. *Credit: Fellow Chris Greene, JILA*



Artistic rendition of FixL protein. *Credit: Fellow Ralph Jimenez, JILA*

Lindau Nobel Laureate meetings that bring together Nobel Laureates and enthusiastic young students and gotten involved with colleagues at Stanford to develop ideas for a STAR mission to send precision lasers into space to probe the fabric of the Universe.

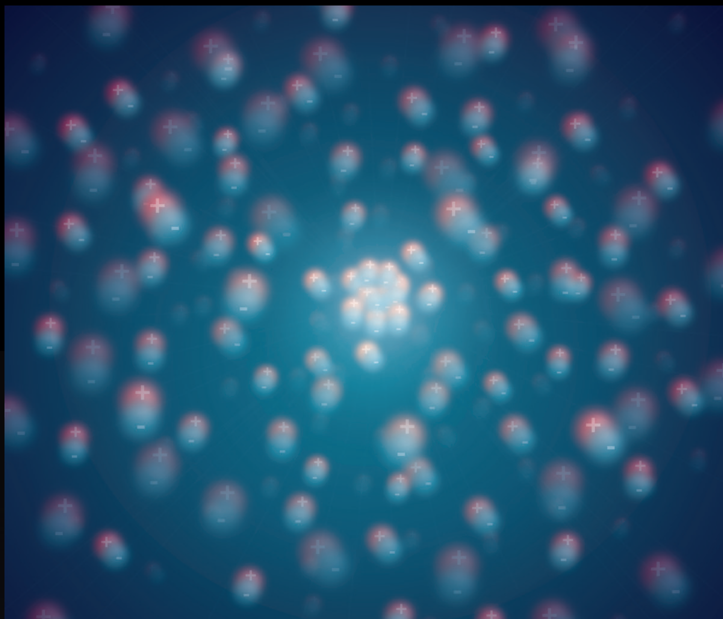
Hall has also started a project to inspire elementary school students to study science. He and his wife Lindy are using some of his Nobel Prize money to fund their work teaching science to students in kindergarten through sixth grade at Swanson Elementary School in the Jefferson County School District. Their goal is to build a platform of learning by supplying the students with a set of tools, such as tops and beads that glow in the dark, that allow the young students to explore the world around them in the same way scientists investigate things. After spending time in class encouraging the students to explore how interesting objects work, Hall and his wife provide each student with a package full of interesting tools to take home and "play" with.

Hall wants his legacy to be an improvement in science education. Whatever the future of this effort, however, Hall already has left a lasting imprint on JILA.

Hall came from NBS Washington when JILA was founded in 1962 and performed the first laser experiment at the Institute. Since then, he has devoted his entire scientific life to the development of stabilized lasers for precision spectroscopy and other applications. Jan's generosity with his understanding of lasers is often credited with helping to make JILA an AMO powerhouse. This expertise in AMO physics was reaffirmed in 2011 when JILA was selected as an NSF Physics Frontier Center and awarded another five-year grant to support collaborative, cutting-edge research.

To support JILA's ongoing research, the Fellows discussed JILA's lack of space during 2005. At the September 27 Fellows meeting, a vote was taken to begin planning for another JILA expansion to be located in the space occupied by the patio just south of the S-Wing.

ULTRACOLD CHEMISTRY



Artist's conception of a cloud of ultracold KRb molecules. *Credit: The Jin and Ye groups and Greg Kuebler, JILA*

During the first decade of the 21st century, experimental physicists Carl Wieman, Deborah Jin, and Jun Ye collaborated with theorists Murray Holland, Chris Greene, and John Bohn to create the brand new field of ultracold chemistry. Their story began in 2003 when the W. M. Keck Foundation donated $1.5 million for research at JILA on cold molecules. At the time, there were no ultracold (<1 K) molecules anywhere in the Universe. And, it took JILA scientists more than five years to create the molecules in their lowest quantum-mechanical state and another two years to learn how to observe, manipulate, and control them.

Before the first ground-state molecules were ever made, Wieman left JILA in 2006 to found a physics education research program at the University of British Columbia. His departure led to a high-powered experimental collaboration on cold molecules between Jin and Ye. Two years later (in 2008), Jin and Ye succeeded in crafting tens of thousands of ultracold polar potassium-rubidium (KRb) molecules in their lowest energy state, creating an entirely new form of quantum matter in the process.

To make the ultracold molecules, JILA researchers started with a cloud of ^{40}K and ^{87}Rb atoms cooled to less than a millionth of a degree above absolute zero. Then they adjusted a magnetic field to bring the atoms close enough together to form large, fluffy, and loosely bound "Feshbach" molecules of KRb. Next, they used a custom-made pulse of laser light to transfer the Feshbach molecules into an electronic level with the lowest-energy rotations and vibrations. But even this level wasn't the lowest-possible quantum mechanical state.

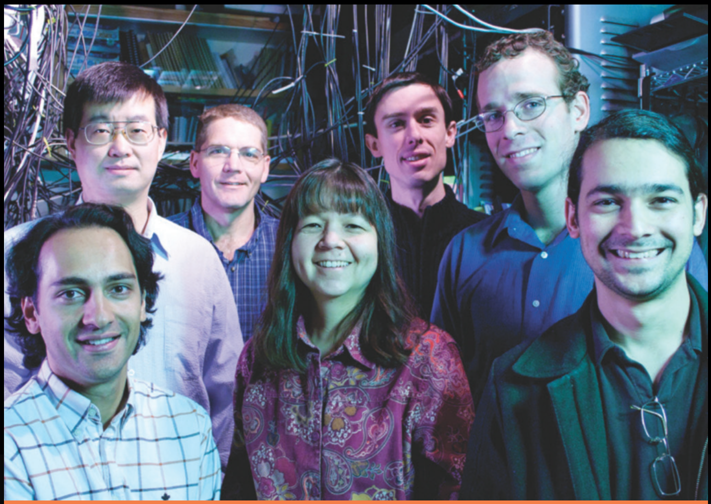
Getting to the lowest quantum mechanical state meant moving the ultracold molecules into the lowest of 36 possible nuclear spin states. It took the Cold Molecule team another year to overcome major technical challenges before it finally produced ultracold KRb molecules in their lowest quantum mechanical state. Now the door was open to explorations of ultracold chemistry!

Soon the Cold Molecule team observed the KRb molecules colliding as well as making and breaking chemical bonds. The researchers realized that at such low temperatures, the molecules were manifesting mostly as quantum mechanical waves, rather than particles. These waves extended long distances inside the gaseous cloud. And, chemical reactions were taking place in a strange world governed by the laws of quantum mechanics!

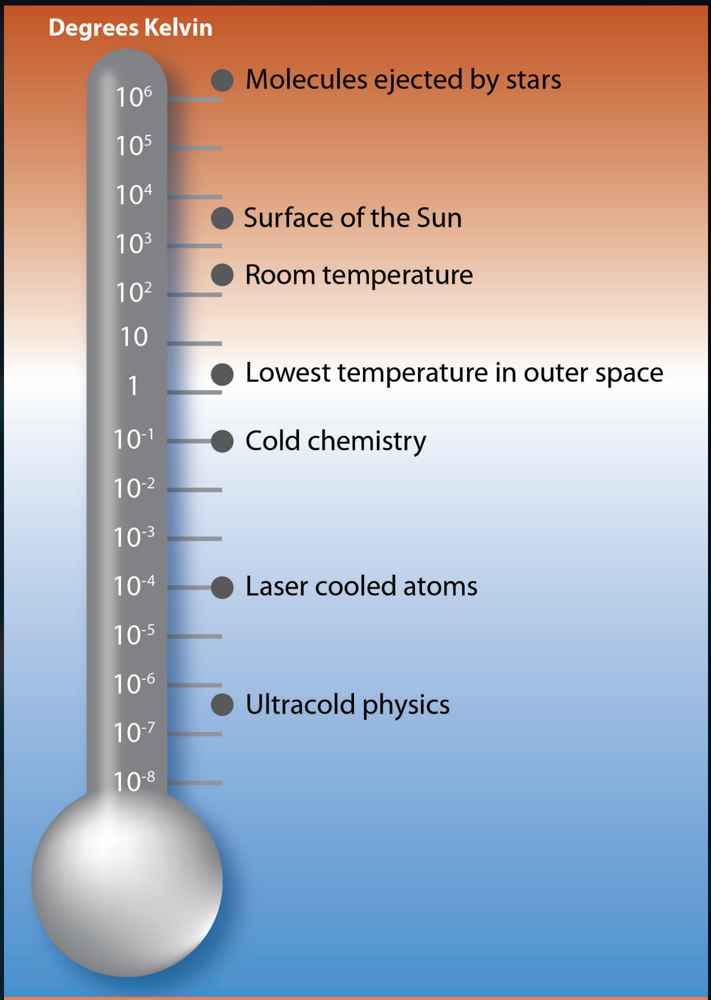
"When molecules are waves, their sphere of influence is much, much bigger than when they are particles," Ye said, adding that lowering the temperature even further should allow the team to see exotic quantum behaviors such as chemical reactions influenced by an entire gas in a collective fashion.

"When molecules are waves, their sphere of influence is much, much bigger than when they are particles," Ye said, adding that lowering the temperature even further should allow the team to see exotic quantum behaviors such as chemical reactions influenced by an entire gas in a collective fashion.

In 2011, the team gained even better control of the ultracold chemical-reaction rates by modifying the spatial dimensions confining the molecules. In 2012, the Jin and Ye groups were able to move their ultracold chemistry experiments to a much larger space in JILA's new X-Wing laboratory building, where they continue to conduct ground-breaking experiments in ultracold chemistry.



The JILA Cold Molecule Team in January of 2011 (l–r) Amodsen Chotia, Fellow Jun Ye, Fellow John Bohn, Fellow Deborah Jin, Goulven Quéméner, Brian Neyenhuis, and Marcio de Miranda (now at the Universidade de São Paulo). *Credit: The Jin and Ye groups and Brad Baxley, JILA*



Temperatures throughout the Universe. *Credit: Kristin Conrad, JILA*

2006–2007

During 2006, discussions about a possible building expansion intensified. The original lab wing built in 1966 was now 40 years old and had never had a major renovation.

A debate arose whether to expand the S-Wing up by two floors or expand south over the area of the patio. The advantage of the latter plan was the ability to add additional underground, lower-vibration laboratory space. Either way, there was a growing consensus that JILA needed to grow to maintain its vitality. The arguments were persuasive. The Fellows voted to look for funding sources to expand the building.

They also moved to hire two new young experimentalists: AMO physicist James Thompson and chemical physicist J. Mathias Weber. Thompson planned to attempt to break quantum limits with collective interactions between laser-cooled atoms and a single mode of an optical cavity. Weber planned to use such chemical physics techniques as mass spectrometry and laser spectroscopy to characterize ions and biomolecules.

On April 24, 2007, the Fellows created a position of Associate Chair to foster more continuity in JILA leadership. The associate chair was to be elected by the same procedure as the chair and would often succeed the chair.

In the fall, JILA co-founder Lewis Branscomb presented a history of JILA in the auditorium at NIST Boulder. He emphasized three aspects of JILA that he believed had remained true during nearly 50 years of operation:

1. No other scientific institution so successfully combines the best strengths of government and academia.
2. The Visiting Fellows program is a key feature of JILA effectiveness, yielding lab collaboration, international awareness of JILA research, and effective diffusion of JILA research.
3. From the beginning of JILA, there has been a lack of distinction between pure and applied science.

2008–2009

By 2008–2009, JILA's main research areas had changed slightly. Materials physics and chemistry was replaced by nanoscience. The broad research areas were now astrophysics, atomic and molecular physics, biophysics, chemical physics, nanoscience, optical physics, and precision measurement.

JILA astrophysicists investigated topics ranging from the interior dynamics of the Sun to the fundamental properties that gave rise to the Universe. Major avenues of inquiry included the evolution of stars and galaxies, the genesis of supermassive black holes at the centers of galaxies, the formation and migration of planets, the interiors of black holes, and the interplay of the dark and luminous Universe.

Atomic and molecular physicists studied ultracold atoms, cold and ultracold molecules, the control of atoms and molecules with light, crystals of atoms made with intersecting beams of laser light, as well as quantum simulation and quantum information processing. The Institute's research programs in optical physics and precision measurement increasingly supported its atomic and molecular physics research.

Biophysicists applied the tools and concepts from physics to the understanding of living systems at the molecular level. Research topics included protein motions, RNA folding, and single-molecule biophysics.

JILA's chemical physicists probed the structure and behavior of matter, the quantum features of chemical reactions, the process of solvation, and the nature of chemical surfaces and polymers. They used advanced laser-based techniques to better understand hydrogen bonding, hydration, electron transfer, the making and breaking of chemical bonds, and the fundamental interactions of light with matter.

Researchers in nanoscience explored the ultrasmall world of ultracold atoms, quantum dots, molecules, semiconductors, tiny electronic devices, and surface-based chemical reactions. Nanoscale objects had dimensions measured in nanometers, or billionths of a meter, perhaps as small as a few atoms. Understanding their behavior required insight into the laws of quantum mechanics.

Optical physicists were learning to manipulate light to produce ultrashort laser pulses for investigation into the fundamental properties of light and the creation of "designer" light pulses.

Experts in precision measurement at JILA and NIST worked together to invent and refine ever-more sophisticated measurement tools. The tools allowed scientists to probe tiny structures inside cells, study the properties of ultracold matter, monitor the dynamics of chemical reactions, measure the frequency of visible light, study electrons in semiconductors, and precisely transmit time and frequency information from atomic clocks. Their goal was to make it possible to investigate phenomena previously too small or too fast to "see," much less quantify.

The year 2008 was a banner year for the strontium atomic clock and the ultracold molecule collaboration of Jun Ye and Deborah Jin. During the summer, they were able to make ultracold KRb molecules in their ground state. The following year, the collaboration was able to also bring the molecules into their lowest nuclear-spin state, opening the door to an entire new field of ultracold chemistry.

JILA hired two new theoretical AMO physicists in 2008, ultrafast laser theorist Andreas Becker and Ana Maria Rey, who specializes in ultracold optical-lattice systems. Becker and his wife, senior research associate Agnieszka Jaron-Becker, have worked closely with the experimental group run by Henry Kapteyn and Margaret Murnane. Rey has worked closely with experimentalist Jun Ye and theorist colleagues around the world.

The world of science (...AND softball) can't escape the JILA monster

JILA MONSTERS vs. Tiny Killer Kittens

July 2010

Sports reporting by John Bohn

The JILA Monsters split an adorable double header this week against the Tiny Killer Kittens and the Thunder Bunnies. Let's get right to the highlights.

In the first game, the Tiny Killer Kittens toyed with the Monsters, handing them a 9–8 defeat. The damage was mostly done in the Kittens' first, when they used up six of their nine runs. After this, the Monsters tamed the Kitties, and the game settled into a hard-fought pitcher's duel. In the early innings, runs were hard to come by, one exception being a solo shot over the right-center-field fence by John "Bread" Bohn. "Well, I guess I got a rise out of that one," said Bohn. "It was the yeast I could do."

"It was a crummy result, though; we really kneaded the win."

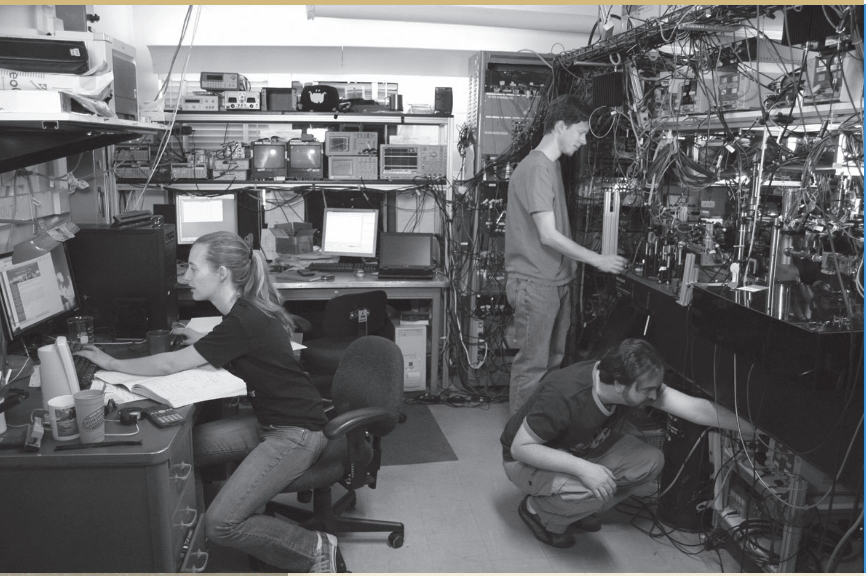
Down by five runs in the top of the seventh, the Monsters put on their rally caps and their offense took off accordingly. Extra base hits by Don Woodraska, Carrie Weidner, Chester Rubbo, and Heather "Lew" Lewandowski got the Monsters right back into the game. Later in the frame, trailing by a single run with two outs on the board, the team sent rookie Chloe "TwoFitch" Fitch to the plate with the tying run forty feet away at third. Fitch stared down the Kittens' southpaw with steely determination, then hammered a hard ground ball to third that sent the tying run toward home. Fitch knew this was to no avail, however, unless she could land safely at first, a feat she accomplished by fearlessly running right through the stunned first baseman, forcing the game to the bottom of the inning. However, the Kittens showed new life in the seventh, scoring the last run needed to bat the game, like a ball of yarn, just out of reach.

Eric Cornell at bat. *Credit: Greg Kuebler, JILA*

In game 2, the Monsters fricasseed the Thunder Bunnies by a score of 10–4. The top of the order came up big, with Don Woodraska and Chester Rubbo producing three doubles and three home runs between them. Knowing that a third dinger over the fence would count as an out in the E league, Rubbo slyly scored his second one as an inside-the-parker. Later in the fifth, Noah Fitch belted yet another ball over the fence, but this time the team suffered the out. The score would have been more lopsided, but plenty of hard hit liners by Heather Lewandowski, Karen Bryant, and others went straight into the Bunnies' waiting paws. On one play, Jim "Clincher" O'Dowd hustled to first to beat out a hard grounder, but the Bunnies threw him out by a whisker.

Pitcher Carrie Weidner (2–2, 7.5 ERA) showed mid-season form, striking out six Bunnies and walking none. She retired the side on three pitches in the third, making the final putout herself by snagging a line drive. The Bunnies nibbled away at the score, hoping something would turnip, but the Monsters didn't carrot all about their plight, and went on to beet the harried Hares. "They sure didn't lettuce get many runners on," lamented the Bunnies' captain. The Monsters' record climbs to 3–2.

Chapter 6
Looking to the Future



Graduate students Ruth Shewmon and Tyler Cumby and postdoc John Perreault investigate mixtures of bosons and fermions in Fellow Debbie Jin's laboratory.

As JILA celebrates its 50th anniversary, it's clear that the Institute was built on a solid foundation. The people who work at JILA make it an extraordinary organization. JILA's distinguished scientists form the core of the Institute. For 50 years, they have created a lasting tradition of collaboration and exceptional achievement. There is a high level of cooperation among JILA researchers and a unity of purpose to achieve the best possible science with the available resources. JILA scientists take pleasure in the triumphs of colleagues and consistently make decisions with an eye to the long-term good of the Institute as a whole.

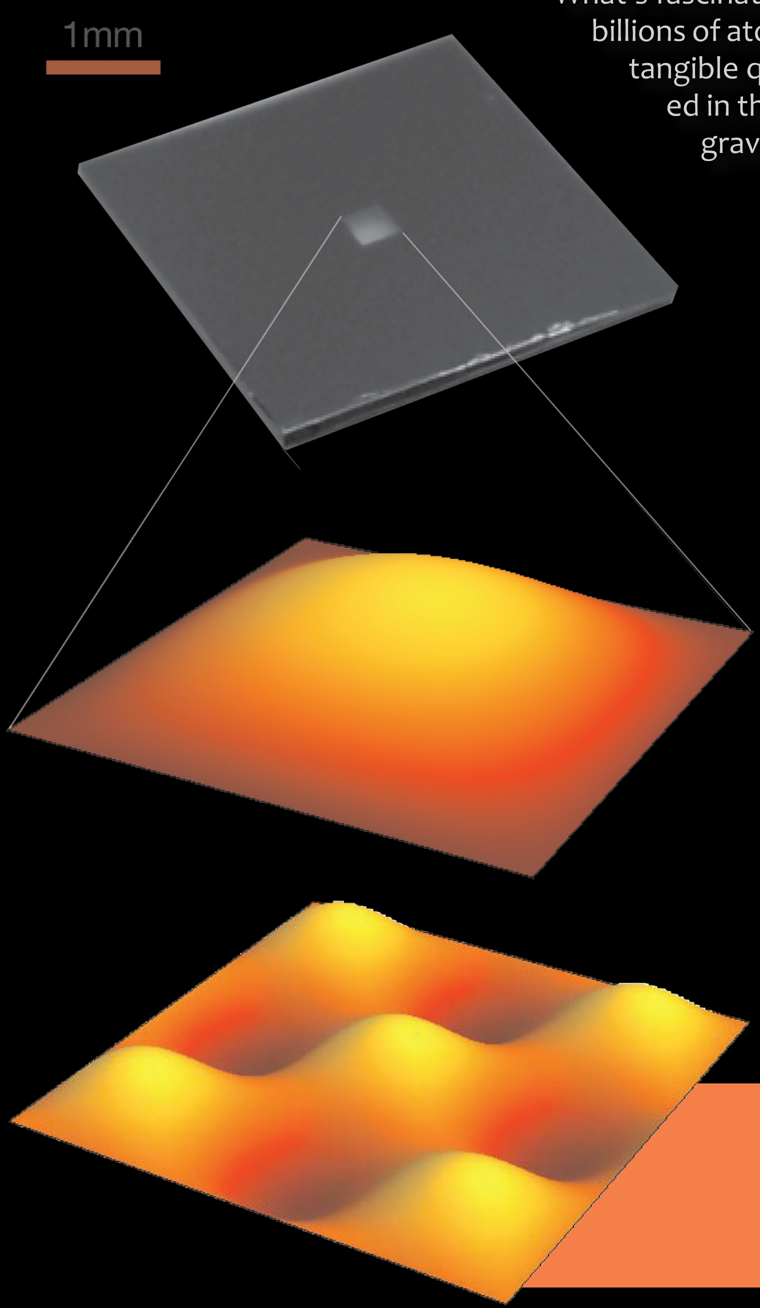
JILA has had an organization for 50 years in which the JILA Fellows, as a group, are responsible for running the Institute. The two-year position of rotating Chair ensures that the top executive remains accountable to the Fellows for management decisions. The Executive Committee ensures support and assistance for the Chair, who continues to lead his or her scientific group while discharging critical executive functions. Two staff executives, the NIST Executive Officer and the JILA Chief of Operations, are charged with ensuring the smooth operation of the Institute on a day-to-day basis. This organizational structure has worked well for half a century to successfully integrate scientists employed by a national laboratory with university professors in CU's departments of Physics, Chemistry and Biochemistry, and Molecular, Cellular, and Developmental Biology as well as the CU School of Engineering.

In addition, the physical layout of JILA's laboratories and offices creates common areas to facilitate connections and sharing of expertise. In the new X-Wing, for example, hallways on every floor contain alcoves furnished with comfortable chairs and white boards. The re-creation of such "conversation" areas was a top priority in the design of the new wing because these areas had previously been successful in facilitating collaborations that often yielded innovative approaches to research at the frontiers of physics.

Quantum Systems Engineering

As JILA heads into the future, researchers in the Lehnert and Regal groups are pursuing an innovative strategy for unlocking the secrets of the quantum world. They have launched a collaborative project to engineer and investigate tiny mechanical systems that exhibit quantum behavior that is visible to the naked eye. They plan to use one such tiny system to explore the quantum interface between light and micromechanical motion. Accomplishing this goal will require nanomechanical engineering combined with Lehnert's expertise in tiny electrical circuits and Regal's expertise in AMO physics.

Lehnert and Regal are planning to make tiny, cold "drums" of silicon nitride (Si_3N_4) that are thin enough to behave quantum mechanically when a tiny force causes them to vibrate. These tiny drums are essentially identical to such musical instruments as drumheads or violin strings, except for being 10,000 times smaller.



What's fascinating about these tiny drums is that when they resonate, billions of atoms inside them act as one. In other words, they exhibit tangible quantum behavior that can be observed and manipulated in the laboratory. And, a few physicists even speculate that gravity could impact the quantum state of the drums.

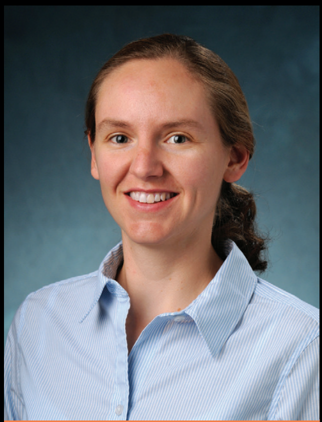
A very nice feature of the tiny drums is that one can apply tiny, localized forces to them. In other words, researchers can make the drums vibrate and explore what happens to their quantum states.

And, if they can apply a force to a drum in a way that keeps the billions of atoms inside acting in unison, they will open the door to an exchange of quantum information between different physical systems such as light and mechanical motion.

To create a quantum interface between light and mechanical motion, the researchers will have to learn to not only exquisitely control the tiny drum, but also control the drum's interactions with the surrounding environment. Thus Lehnert and Regal must learn how to prevent any erosion of the collective action of the atoms making up the drum.

The two researchers have already figured out a strategy for accomplishing this control: They plan to simultaneously couple the motion of a tiny square Si_3N_4 drum to both the microwave and optical cavities. One

A tiny drum is embedded in a silicon chip (top). When tiny forces cause it to vibrate, the drum vibrates in its resonant modes, two of which are shown here. These resonant wave patterns are the result of billions of atoms acting as one. *Credit: The Regal group*



Fellow Cindy Regal.
Credit: JILA

Fellow Konrad Lehnert.
Credit: JILA

half of the drum will be coated with aluminum, allowing it to couple with a tiny electrical circuit. Any motion of the drum will perturb the electrical circuit, and vice versa.

The other half of the drum will couple to an optical cavity that will surround the drum. Amazingly, the optical cavity is expected to act just like the electrical circuit, except the light will be at much smaller wavelengths than in the electrical circuit. Of course, Regal and Lehnert will have to prove things work this way when they test this neat idea in the lab.

A very nice feature of the tiny drums is that one can apply tiny, localized forces to them. In other words, researchers can make the drums vibrate and explore what happens to their quantum states.

Their whole setup will make it possible to map the quantum description of the electrical circuit onto the quantum description of a laser light field. The trick will be to do this without losing any information in a process planned to be completely reversible. This much-anticipated result will be a coherent and simultaneous coupling of microwave fields and optical light.

With futuristic projects like this getting underway at JILA, it's no wonder that JILA physicists are so excited about upcoming AMO research. The next 50 years promise to be every bit as exciting and productive as the first 50, possibly even more so.

JILA also has a high-quality support staff. Its technical shops include (1) a fully equipped Instrument Shop staffed by expert machinists and other specialists, (2) a Computing Group that not only makes sure JILA scientists have access to advanced cluster supercomputers, but also full support for personal computers and peripherals in offices and laboratories, (3) an Electronics Shop that offers custom electronic designs, tech support, and repair services, and (4) a Communications/SRO Group that produces state-of-the-art scientific illustrations and Drupal-based websites, a quarterly publication highlighting JILA research, scientific writing and editing services, and support of new media. All four technical shops offer classes for JILA's young scientists and new staff. The classes include the Instrument Shop class, Computing at JILA, the Electronics Survival class, and the Scientific Writing class.

JILA's administrative staff includes the NIST Executive Officer, Julia Bachinski, and the JILA Chief of Operations, Elizabeth Kroger. Bachinski and Kroger manage their respective staffs and are responsible for the accounting and financial affairs of JILA's NIST and CU portions, respectively. Other administrative staff manages human resources, database programming and repair, accounting, parking passes, travel arrangements, grants and contracts management, supervision of student workers, event planning, and executive assistance.

THE SIXTH DECADE AND BEYOND

2010–2011

During 2010–2011, JILAns watched the new X-Wing take shape just south of the S-Wing. Staff members with windows overlooking the site were treated to a bird's-eye view of the construction until the windows were removed. Others watched the building take shape via strategically situated webcams. In March of 2011, the Fellows were given a construction tour by Douglas Johnson, JILA's liaison to the project.

In the midst of the excitement of the building project, research was the main activity during 2010–2011. The main research fields continued to be astrophysics, atomic and molecular physics, biophysics, chemical physics, nanoscience, optical physics, and precision measurement.

The now three-decades-long history of JILA participation in studies of the LISA gravitational wave mission continued. LISA was one of the three highest priority recommendations for large space missions by NASA's new Decadal Survey in Astronomy and Astrophysics. However, although NASA has withdrawn from participation in such a mission, ESA's Cosmic Vision Program has the option to select LISA in the future.

In 2010, JILA welcomed its newest Fellow, Cindy Regal, who is also assistant professor of physics at CU. Regal began a research collaboration with Fellow Konrad Lehnert on a quantum systems engineering project. The goal of this project is to map the quantum states of light onto a microwave field using a thin drumhead and microelectronics inside an optical cavity.

In 2010–2011, three Fellows were selected by President Obama to fill key leadership positions in science and technology. Fellow Carl Wieman was nominated by President Barack Obama to be Associate Director for Science at the White House Office of Science and Technology Policy. Wieman was confirmed by the United States Senate in September of 2010.

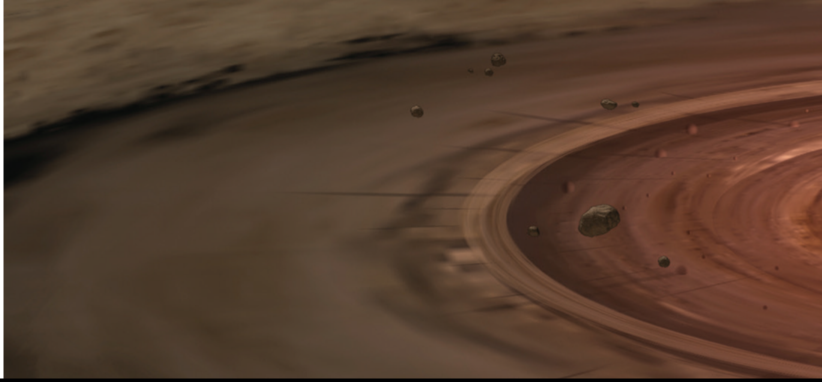
Wieman is part of a long tradition of public service by JILA Fellows in key leadership positions in government, industry, and academia. During 2010–2011, this tradition was also continued by Fellows Margaret Murnane and Carl Lineberger. In 2010, Murnane was appointed by President Obama as member of the President's Committee on the National Medal of Science. She was appointed Chair of the committee in 2012. The 12-member committee selects individuals for the National Medal of Science who have advanced human knowledge in the fields of behavioral and social sciences, biology, chemistry, engineering, mathematics, and physics.

Fellow Phil Armitage. *Credit: JILA*

Fellow Phil Armitage wants to understand in exquisite detail how planetary systems form around stars. He'd also like to figure out the relationship between the origins of the hundreds of "nearby" planetary systems detected so far in our Galaxy and the history of the Solar System. He figures he'll have the problem pretty much solved once he figures out how to correctly calculate the origin and evolution of a protoplanetary disk starting from the fundamental laws of nature, or "first principles," that govern our Universe.

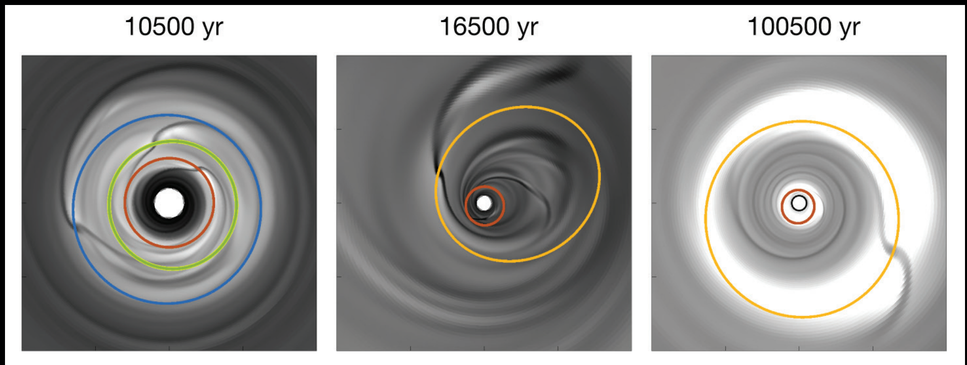
> "I want to answer the question of how giant planets grow up in a real environment."
>
> — Phil Armitage, JILA

This endeavor is a bit of a challenge. To model the formation of a planetary system, Armitage will need to input a lot of information about planet formation that he and his colleagues have been gathering for decades. The information will include a realistic estimate of the variation of the density (with distance from the star) of the disk of gas and dust; an estimate of the concentration of dust relative to the hydrogen gas that makes up most of the disk; an approximation of the variations in temperature with distance from the central star; and information about how temperature and density gradients affect the interaction of the disk with magnetic fields. He also has to account for the formation of planets inside the disk of gas and dust, their evolution inside a transitional disk where gas and dust are being blown away and gravity begins to affect the behavior of the new planets, and what happens to the planets



when they are solely under the influence of gravity after the disk has disappeared.

"I want to answer the question of how giant planets grow up in a real environment," Armitage says, noting that figuring out the concentration of dust will be challenging and critically important. "There is only a small amount of dust in a protoplanetary disk, but it is very important for planet formation."



Computer simulation of the evolution of a planetary system and its gas disk. *Credit: Nick Moekel, Institute of Astronomy, University of Cambridge, UK*

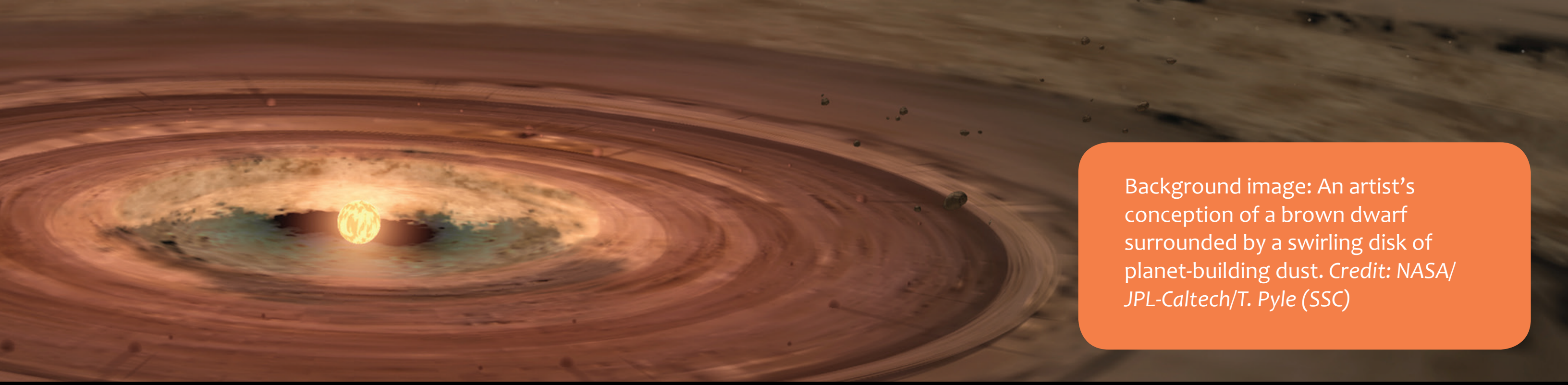
Armitage hopes his model will reveal why giant gas and ice planets do not typically form far away from the central star — even though protoplanetary disks have been seen to extend out to hundreds of AU (astronomical units) from their star. One AU is the distance from the Sun to the Earth, and the planet Neptune at 30 AU is the most distant large body in the Solar System. Around other stars, Jupiter-sized planets have proved to be uncommon at distances of 100 AU or more.

Ideally, the model will also shed additional light on the impact of collisions and violent interactions of giant gas and ice planets during and after their formation. Armitage's earlier work showed that giant-planet interactions can move planets in toward their star or eject them entirely from a star system. These interactions can also eject one or more terrestrial planets (like Earth) that typically form closer to their star than the giant planets.

In fact, the ultimate fate of entire planetary systems appears to depend on interactions of closely packed giant planets, whose gravitational influence dominates everything else, including the inner rocky planets like Earth, asteroid belts, and outer debris disks. In the Solar System, for example, we owe the survival of our four terrestrial planets (Mercury, Venus, Earth, and Mars) to the relatively stable orbits of Jupiter, Saturn, Uranus, and Neptune during the 100 million years it took to form the inner planets.

Armitage's experience modeling our Solar System and other star systems is preparing him for the task ahead of modeling the creation of a star system from scratch. He recently completed a model of the turbulent environment in which planetesimals form. Planetesimals are small celestial bodies that collide to form actual planets. He and his colleagues were able to simulate the early turbulence in a protoplanetary disck and make predictions for how Chile's new radio telescope, the Atacama Large Millimeter/submillimeter Array (ALMA), can identify calm and turbulent parts of a disk. With the new information, ALMA may be able to discern whether dust is settling near the middle of the disk or concentrating in eddies like those that form in the ocean. From the perspective of the powerful new telescope, it's like looking at the formation and breaking of waves on the ocean — from dozens of light years away.

This information will be critical for Armitage's model of planet formation and evolution. He plans to use it to refine his model to make it more closely mirror what actually happens during the formation of a new planetary system. "I expect we'll be about this for a good few years," he says with a twinkle in his eye.



Background image: An artist's conception of a brown dwarf surrounded by a swirling disk of planet-building dust. *Credit: NASA/JPL-Caltech/T. Pyle (SSC)*

JILAns donned hard hats in anticipation of a tour of the construction site of the new X-Wing in March of 2011. They are (l–r) Construction Liaison Doug Johnson, and Fellows James Thompson, Jun Ye, Henry Kapteyn, Cindy Regal, Konrad Lehnert, Heather Lewandowski, Andreas Becker, Eric Cornell, Debbie Jin, Tom Perkins, Murray Holland, Tom O'Brian, John Bohn, Carl Lineberger, and Steve Cundiff. *Photo: Brad Baxley, JILA*

In April of 2011, JILA Fellow Carl Lineberger was nominated by President Barack Obama to serve as a member of the National Science Board. He was confirmed by the United States Senate in August of 2011. As a board member, he is advising the NSF on budgetary matters and helping to establish policies governing the organization.

In June of 2011, the AMO collaboration at JILA won a competitive five-year NSF grant that will support collaborative research in advanced AMO systems in JILA's AMO Physics Center through 2016.

2012

JILA officially turned 50 on April 13, 2012. That day was selected for the dedication of the new JILA X-Wing, which was completed in March. Speakers at the dedication included JILA Chair Eric Cornell, CU-Boulder Chancellor Philip DiStefano, NIST Director Patrick Gallagher, Boulder Mayor Matt Applebaum, and JILA alum and local entrepreneur Chris Myatt. The 50th anniversary celebration was moved to July 12–13 to make it possible to host a two-day event honoring the people, research, and events that have made JILA one of the nation's most innovative and productive research institutions.

While JILA's reputation for research innovation and productivity rests solidly on the experimental and theoretical investigations performed by the Fellows and their groups, JILA also has a proud tradition of leadership and public service that spans five decades. This tradition has been carried on by some of the remarkable scientists who have called JILA home.

JILA SPIN-OFF COMPANIES

JILA has generated many spin-off companies, including 12 companies in the Colorado Front Range area. The Colorado companies have created more than 140 jobs and a variety of high-tech products used around the world. These contributions to U.S. industry have been made by current and former JILA scientists and staff.

Company	JILA Affillіation	Location	Products
BioOptix (formerly Alphasniffer) *founded 2003*	Hall group	Boulder, CO	Real-time, sensitive detection of such molecules as DNA, proteins, toxins, and contaminants
Black Hole Visualizations, LLC *founded 2010*	Hamilton group	Boulder, CO	Scientifically accurate general relativistic visualizations
ColdQuanta *founded 2007*	Dana Z. Anderson	Boulder, CO	Atom chips, ultrahigh vaccum systems
Hall Stable Lasers, LLC *founded 2004*	Jan Hall	Boulder, CO	Consulting on stable lasers, electro-optics, and electronics for lasers
High Precision Devices, Inc. *founded 1993*	Bill Hollander, Instrument Shop	Boulder, CO	Precision mechanical instrumentation integrated with optics, cryogenics, electronics, and vacuum & UHV
KM Labs *founded 1994*	Henry Kapteyn & Margaret Murnane	Boulder, CO	Ti:S lasers, amplifiers, CEP stabilizers
MBio Diagnostics *founded 2009*	Wieman group (Chris Myatt)	Boulder, CO	Diagnostic tests for healthcare
Micro-g LaCoste *founded 1993*	Faller group	Lafayette, CO	Gravimeters, seismometers, software
Precision Photonics *founded 2000*	Wieman group (Chris Myatt)	Boulder, CO	Mirrors, beamsplitters, polarizers, micro-optics, solid-state lasers, prisms
Stable Laser Systems *founded 2009*	Hall & Ye groups (Mark Notcutt)	Boulder, CO	Turnkey laser systems, measurement services, vacuum housings
Vescent Photonics *founded 2002*	Smith & Cornell groups (Mike Anderson)	Denver, CO	Electronics for lasers & electro-optics, ultrastable lasers, optical & electro-optic modules, diode lasers
Winters Electro Optics *founded 1993*	Hall group	Longmont, CO	He-Ne lasers, laser callibration

As of April 2012

A TRADITION OF LEADERSHIP AND PUBLIC SERVICE

Fellow Edward Condon (1963–1974). *Credit: NBS*

JILA's tradition of leadership and public service started soon after the Institute was created. The earliest role models were Fellow Edward Condon (1963–1974), JILA co-founder Lewis Branscomb (1962–1969), and Visiting Fellow Neal Lane (1965–1966; 1975–1976).

By the time Condon came to JILA and CU, he had served on the National Defense Research Council and been president of the American Physical Society, Director of NBS, Chief Scientist at Corning Glass Works, and head of the American Association for the Advancement of Science. During his tenure at JILA, he served as president of the American Institute of Physics and the American Association of Physics Teachers, the President of the Society for Social Responsibility in Science, and the co-chair of the National Committee for a Sane Nuclear Policy.

Fellow Lewis Branscomb (1962–1969). *Credit: JILA*

Condon brought not only a tradition of leadership, but also a vision of what was possible in the new field of chemical physics. He had a major influence on two young JILA postdocs — Dick Zare (with Gordon Dunn) and Carl Lineberger (with Lewis Branscomb)— in the exploration of atoms and molecules with a powerful new tool: the laser. Zare and Lineberger went on to have distinguished careers in chemical physics, Zare at Stanford University and Lineberger at the University of Colorado and JILA.

Zare and Lineberger have also distinguished themselves in leadership and public service, in part because of the example set by Branscomb and Condon. For Zare, the key person in launching his public service career was Branscomb, who served on President Johnson's Scientific Advisory Committee from 1964 to 1968 and chaired the National Science Board from 1980 to 1984. The National Science Board was responsible for NSF's budget and major scientific decisions. It functions much like a company board of directors, except that it does not hire the NSF director. National Science Board members are appointed by the President, and the Board elects its Chair.

Branscomb left JILA in 1969 to become the Director of NBS until 1972, Chief Scientist at IBM from 1972 to 1986, and Professor of Public Policy and Corporate Management in Harvard University's John F. Kennedy School of Government from 1986 to 1996. In the early 1970s, Branscomb invited Zare to serve on IBM's Scientific Advisory Board. Zare got hooked on public service and has subsequently served on dozens of committees, editorial boards, and scientific advisory boards, including the National Science Board from 1992–1998 where he was chair from 1995–1998. Zare has remained in close contact with his former colleagues at JILA, where he was made a Fellow Adjoint in 1990. Zare is the Marguerite Blake Wilbur Professor in Natural Science at Stanford University.

Fellow Dick Zare (1968–1969). Fellow Adjoint (1990–2012).

Zare's and Branscomb's time at JILA only briefly overlapped that of Lineberger, who arrived in 1968. However, Lineberger has maintained lifelong ties with both of them around the shared commitment to public service originally nurtured at JILA by Branscomb and Condon.

Lineberger comments that Condon's willingness to stand up for what was right, even when unpopular, inspired him both as a scientist and a public servant. He has also benefitted from long friendships with Branscomb and Fellow Adjoint Neal Lane, whom he met during one of Lane's visits to JILA in the late 1960s. Lane

Visiting Fellow Neal Lane (1964–1965) and (1975–1976).

says he has always appreciated Carl, and the two have communicated regularly for many years.

After his second year as a JILA Visiting Fellow in 1975–1976, Lane went on to become the director of the NSF's Division of Physics in 1979–1980, the director of NSF from 1993 to 1998, and President Clinton's Science Advisor (and Director of the Office of Science and Technology Policy) from 1998 to 2001. Lane is currently a Senior Fellow of the James A. Baker III Institute for Public Policy and Professor of Physics and Astronomy at Rice University. Following his tenure as President Clinton's science advisor, Lane participated in a STEM (Science, Technology, Engineering, and Mathematics) working group of the President's Committee of Advisors on Science and Technology where he worked with JILA Fellow Carl Wieman.

Wieman, together with JILA Fellow Eric Cornell, won the 2001 Nobel Prize in Physics for creating the world's first Bose-Einstein condensate, but he also had long had an interest in improving science education. He and Fellow Dick McCray led a major effort to improve science education at CU, and then, as Wieman's work attracted national attention, he was asked to serve as the founding Chair of the National Research Council Board on Science Education. Wieman's outstanding science and his work in transforming science education led President Obama to nominate him for the position of Associate Director for Science in the White House Office of Science and Technology Policy in April of 2010. The Senate unanimously confirmed Wieman for this position in September. In this position, he plays a major role in guiding science, technology, and educational policies.

Fellow Carl Wieman (1985–2010). *Credit: JILA*

For his part, JILA Fellow Carl Lineberger has served on numerous boards and committees since the early 1980s. These include the Councils of the American Physical Society, the National Academy of Sciences, and the American Association for the Advancement of Science. In 2011, he was nominated by President Obama and confirmed by the United States Senate as a member of the National Science Board. He is the E. U. Condon Distinguished Professor of Chemistry at the University of Colorado at Boulder.

Fellow Carl Lineberger (1972–present). *Credit: JILA*

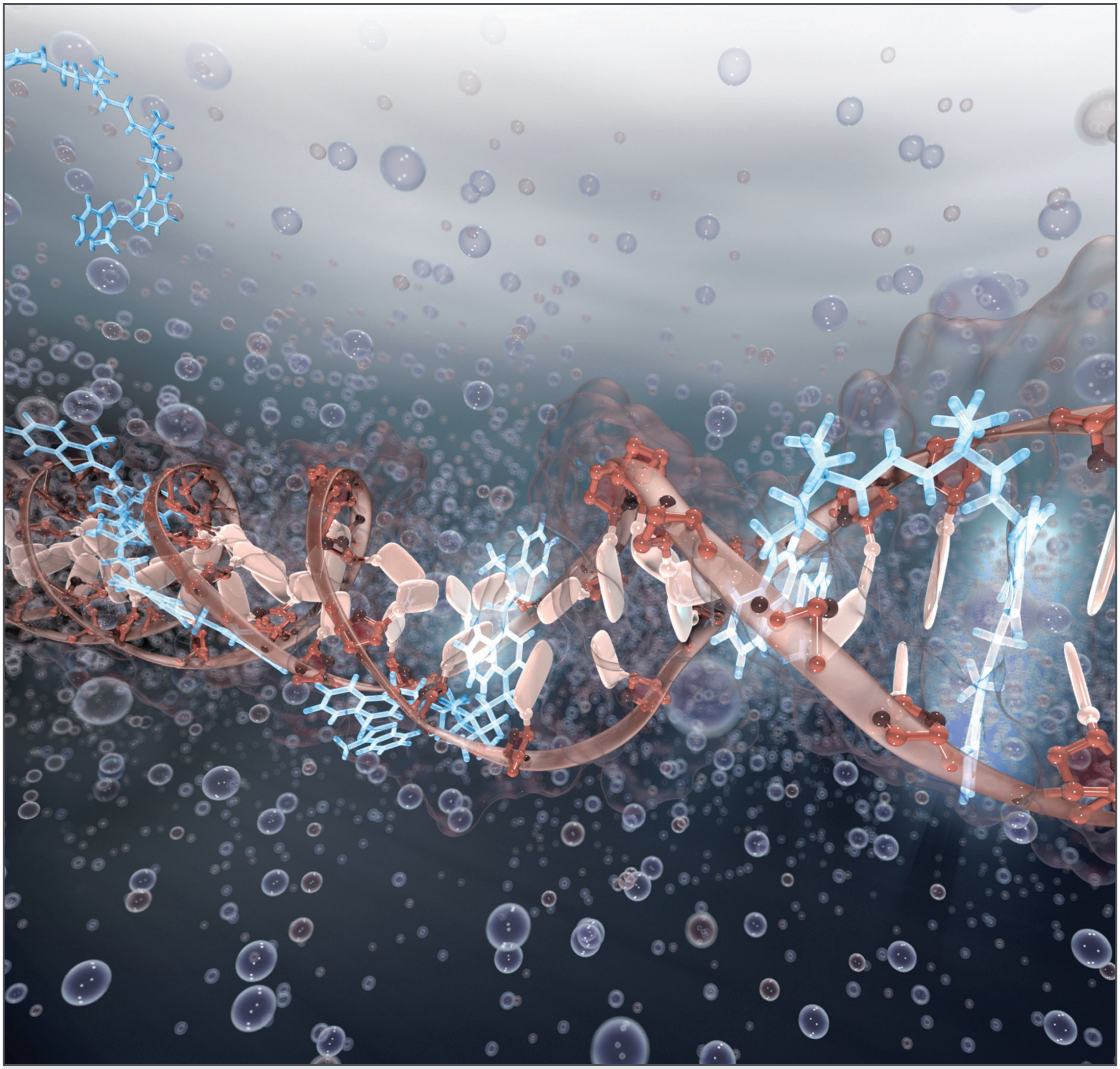
Fellow Katharine Gebbie (1974–1986) traveled a different, though equally inspirational, leadership pathway from that taken by Lineberger (See The Welcome Mat, Chapter 4). Gebbie arrived at JILA in 1968 as a postdoc in astrophysics and rose through the ranks at NBS and then NIST to found and manage NIST's Physics Laboratory and later its Physical Measurement Laboratory. From these positions, she has overseen and enthusiastically supported JILA's scientific endeavors for more than two decades.

At the time of JILA's 50th anniversary, JILA's tradition of leadership had begun to pass on to a new, younger generation of Fellows. For instance, Fellow Margaret Murnane was already nationally prominent in the effort to increase participation of women and minorities in science when, in 2012, President Obama appointed her to the chair the committee that selects the National Medal of Science recipient. Many other JILA fellows are active in service and leadership nationally and internationally.

Fellow Katharine Gebbie (1968–1986) and (1988–1991). *Credit: JILA*

JILA Fellows: 1962–2012

Anderson, Dana Z.
Armitage, Phil
Beaty, Earl C.
Becker, Andreas
Begelman, Mitchell C.
Bender, Peter L. (Chair: 1969-70)
Bohn, John L.
Branscomb, Lewis (Chair: 62-65 & 68-69)
Brittin, Wesley E.
Burnett, Keith
Castor, John I.
Clement, Tracy
Conti, Peter S. (Chair: 1989-90)
Cooper, John "Jinx"(Chair: 1975-76)
Cornell, Eric A. (Chair: 2011-12)
Cox, John
Cundiff, Steven T.
Dunn, Gordon (Chair: 1987-88)
Faller, James E. (Chair: 1995-96)
Gallagher, Alan (Chair: 1999-2000)
Garmany, Catharine (Chair: 1997-98)
Garstang, Roy (Chair: 1966-67)
Gebbie, Katharine
Geltman, Sydney
Greene, Chris H. (Chair: 2005-06)
Hall, John L.
Hamilton, Andrew J. S. (Chair: 2009-10)
Hansen, Carl
Holland, Murray J.
Hummer, David G. (Chair: 73-74 & 77-78)
Jefferies, John T.
Jimenez, Ralph
Jin, Deborah S.
Kapteyn, Henry C.
Kieffer, Lee
Lehnert, Konrad
Leone, Stephen R. (Chair: 1991-92)
Levine, Judah (Chair: 2003-04)
Lewandowski, Heather
Lineberger, W. Carl (Chair: 1985-86)
Linsky, Jeffrey L.
McCray, Richard A. (Chair: 1981-82)
Murnane, Margaret M.
Nesbitt, David J. (Chair: 2007-08)
Norcross, D. W. (Chair: 1983-84)
Oster, Ludwig
Parson, Robert P.
Perkins, Thomas
Perna, Rosalba
Phelps, Arthur V. (Chair: 1979-80)
Regal, Cindy A.
Reinhardt, William P.
Rey, Ana Maria
Richtmyer, Robert D.
Smith, Stephen J. (Chair: 1971-72)
Thomas, Richard N.
Thompson, James K.
Toomre, Juri
Uberoi, Mahinder S.
Weber, J. Mathias
Wieman, Carl E. (Chair: 1993-94)
Ye, Jun
Zare, Richard D.
Zoller, Peter
Zweibel, Ellen (Chair: 2001-02)



Four modes of interaction of a drug molecule (blue) with a strand of DNA.
Credit: The Perkins group and Brad Baxley, JILA.

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Acronym Glossary

ACTS	Automated Computer Time Service
AMO	Atomic, Molecular, and Optical
APAS	Astrophysical, Planetary, and Atmospheric Sciences
APS	Astrophysical and Planetary Sciences
APOLLO	Apache Point Observatory Lunar Laser-Ranging Operation
ARPA	Advanced Research Projects Agency
BASIC	Beginner's All-purpose Symbolic Instruction Code: A set of high-level programming languages
BEC	Bose-Einstein condensate
BITNET	Cooperative university computer network in the 1980s
C	carbon
CDC	Control Data Corporation
CPU	Central Processing Unit
CT	computed tomography
CU	University of Colorado
DARPA	Defense Advanced Research Projects Agency
DISSPLA	Fortran subroutine
DNA	deoxyribonucleic acid
DOC	Department of Commerce

D. Phil	Doctor of Philosophy (British)
ESA	European Space Agency
FORTRAN	computer programming language developed by IBM
He-Ne	helium-neon
IBM	International Business Machines
I-O	input-output
ISM	Interstellar Medium
ITS	Internet Time Services
JILA	originally, Joint Institute for Laboratory Astrophysics; Since 1995, JILA is the Institute's name
JILAn	a person who works at JILA
K	potassium or Kelvin (depending on context)
KRb	potassium-rubidium
Kr	krypton
LAG	Laboratory Astrophysics group
LAN	Local Area Network
LISA	Laser Interferometer Space Antenna
LURE	Lunar laser-ranging experiment
LSI	Networking company
MIT	Massachusetts Institute of Technology

MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NCAR	National Center for Atmospheric Research
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OSO	Orbiting Solar Observatories
PC	Personal Cosputer
Ph.D.	Doctor of Philosophy (American)
QPD	Quantum Physics Division
Rb	rubidium
REU	Research Experience for Undergraduates
SRO	Scientific Reports Office
Ti:S	titanium: sapphire
UK	United Kingdom
U.S.S.R.	Union of Soviet Socialist Republics
UFO	Unidentified Flying Object
U	uranium
VAX	family of computers
VMS	computer operating system

View from a JILA Window

Gamow Tower from my JILA windov

View of the University of Colorado at Boulder's physics complex from the JILA window of scientific visitor and artist Zdenek Herman, 1980.

JILA: The First 50 Years