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CLOSE ENCOUNTERS WITH THE CONTACT P. 2

Cover art: The contact appears in ultracold gases under conditions when the atoms are close enough to each other to collide.

Credit: The Jin and Cornell groups and Brad Baxley, JILA

CLOSE ENCOUNTERS WITH THE CONTACT

The Jin and Cornell groups have discovered irrefutable evidence for the "contact" in a Bose-Einstein condensate, or BEC. Like pressure, volume, and temperature, the contact is an important property of ultracold ensembles of atoms. The contact is particularly important when the atoms interact with each other, since the contact tells you how likely it is that an atom in the ensemble is having a close encounter with another atom.

In 2005, theorist Shina Tan (now of Georgia Tech) introduced the contact in describing an ensemble of atoms that are fermions. Two years after Tan's work was published (in 2008), the Jin group experimentally confirmed Tan's predictions — for fermions. The Jin group measured the contact in an ultracold gas of potassium atoms (^{40}K) in 2010. This work was done by former graduate students Jayson Stewart and John Gaebler, graduate student Tara Drake, and Fellow Debbie Jin.

Then in 2012, former graduate students Robert Wild and Juan Pino, graduate student Phil Makotyn, and Fellows Jin and Cornell found the contact in an ultracold gas of rubidium atoms (^{85}Rb), which are bosons. Bosons are different from fermions like ^{40}K in that bosons can occupy the same quantum state and form a BEC. The discovery of the contact in a gas of bosons really livens things up.

Tan hadn't predicted the contact in a system of bosons. So Jin and Cornell didn't know for sure whether it would exist in a gas of ^{85}Rb atoms until they found it. The JILA groups found the contact by sticking a radio-frequency (rf) microphone inside an ultracold quantum gas and "listening" for the contact. They probed the BEC with an rf pulse that selectively targeted any pairs of atoms in the gas that happened to be very close to each other; the pulse knocked anywhere from 1000–2000 atoms out of the ultracold gas. The contact signal turned out to be proportional to the number of atoms knocked out of the system.

In the process of finding the contact, the researchers developed a fast rf-based contact spectroscopy for probing strongly interacting quantum gases. Atoms rapidly disappear from strongly interacting BECs, and most other techniques are not fast enough to allow researchers to listen or look inside the BEC before it disappears. Consequently, contact spectroscopy promises to be an extremely useful new tool for the exploration of ultracold quantum gases and liquids.

The Cornell and Jin team is currently using contact spectroscopy to investigate BECs with even stronger interactions. With this new tool, they hope to look at the evolution of a BEC from a quantum gas into a quantum liquid.

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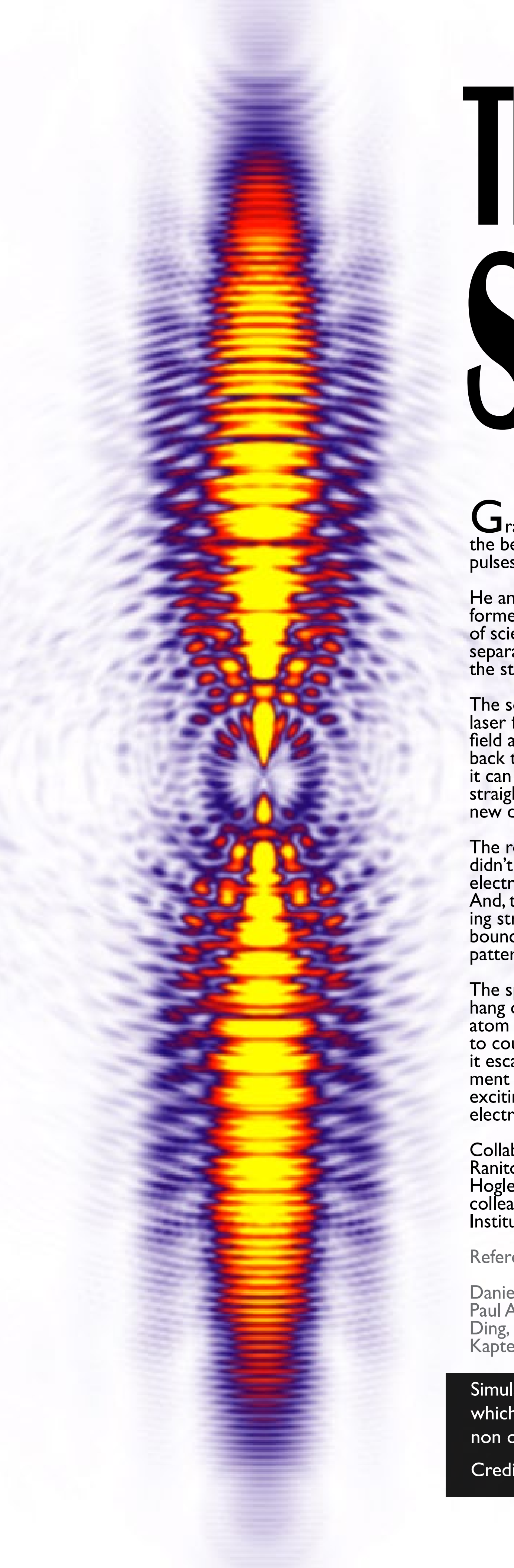

The Spider's Secrets

Graduate student Dan Hickstein (Kapteyn/Murnane group) recently investigated the behavior of electrons ripped from atoms and molecules by intense infrared laser pulses.

He and his colleagues collected the liberated electrons onto a detector where they formed intricate patterns that looked a lot like giant spiders. An international team of scientists studied these spider-like patterns to learn more about how electrons separate from atoms or molecules. They also tried to discover new information about the structure of the parent atoms or molecules.

The scientists figured out why these intriguing spider patterns are produced. First, the laser field helps an electron to tunnel out of a xenon or argon atom. Second, the laser field accelerates the liberated electron away from the parent atom before hurling it back toward the parent. At this point, one of three things happens to the electron: (1) it can crash back into its parent atom, releasing a photon of x-ray light, (2) it can fly straight past its parent atom, or (3) it can "bounce" off its parent atom, flying off in a new direction.

The researchers realized that, being a quantum mechanical particle, an electron that didn't reunite with its parent atom could be treated as a wave. The different paths this electron could take could then be treated as waves that will interfere with each other. And, that's exactly what happened to form the spider patterns. The electron zooming straight by its parent atom is traveling as a plane wave, while the electron that bounces off its parent is traveling as a spherical wave. Beautiful quantum interference patterns between these two possible pathways created the spider structures.

The spider patterns revealed that ionization does not happen abruptly. Some electrons hang out near their parent atoms for multiple laser cycles before bouncing off the atom and escaping. Details in the spider patterns made it possible for the researchers to count the number of times the laser field drove an electron past its parent before it escaped. The patterns also made it possible to make the first experimental measurement of the exact distance an electron traveled to tunnel out of the atom! These exciting results bode well for future experiments to "watch" the complex dance of electrons in atoms and molecules as chemical reactions take place.

Collaborators on this exciting project included former research associates Predrag Ranitovic and Stefan Witte, research associate Ellen Keister, graduate students Craig Hogle and Bosheng Zhang, Fellows Margaret Murnane and Henry Kapteyn as well as colleagues from VU University (the Netherlands), University of Tsukuba (Japan), FOM Institute AMOLF (the Netherlands), and the Max-Born-Institute (Germany).

Reference

Daniel D. Hickstein, Predrag Ranitovic, Stefan Witte, Xiao-Min Tong, Ymkje Huismans, Paul Arpin, Xibin Zhou, K. Ellen Keister, Craig W. Hogle, Bosheng Zhang, Chengyuan Ding, Per Johnsson, N. Toshima, Marc J. J. Vrakking, Margaret M. Murnane, and Henry C. Kapteyn, *Physical Review Letters* **109**, 073004 (2012).

Simulation of the spider structure generated by the interference of electron waves, which were created when an intense infrared laser ripped an electron from a xenon or argon atom.

Credit: Dan Hickstein, JILA, and Xiao-Min Tong, Tsukaba University (Japan)

A More *Perfectly Understood* Union

Research associate Bruno Giacomazzo recently studied the effects of magnetic fields and matter on the likelihood that the merger of two black holes will produce jets of light of different frequencies ranging from radio waves to x-rays. If such signals are generated, it may be possible to detect them with ground- or space-based observatories. Their detection would help astronomers identify and study the unions of supermassive black holes that occur after galaxies collide. Supermassive black holes are found at the centers of most galaxies in the Universe.

The exciting news is that electromagnetic signals are likely generated during some black-hole mergers, according to Giacomazzo and his colleagues from the University of Maryland and the NASA Goddard Space Flight Center. The researchers recently performed sophisticated simulations of the behaviors of magnetized plasmas interacting with magnetic fields around merging supermassive black holes.

The researchers discovered that during such a merger, interactions with a plasma increased the strength of magnetic fields a hundredfold. This increased magnetic-field strength, in turn, led to electromagnetic signals that were as much as ten thousand times stronger than previous estimates, which had not taken account of nearby plasmas and magnetic fields.

The new work means astronomers may soon be able to locate and identify jets of light emitted during black-hole mergers. Sometime in the future, however, astronomers may also be able to look for the gravitational waves produced in black-hole mergers — if and when a gravitational-wave observatory, such as the proposed Laser Interferometer Space Antenna (LISA), is launched.

An orbiting observatory that can detect gravitational waves together with observations of the predicted electromagnetic signals could help astronomers pinpoint the exact locations of black-hole mergers. Observations of jets of electromagnetic radiation and gravitational waves emitted from the same merger may also help scientists to investigate conditions around the newly merged system and determine whether gravitational waves travel exactly at the speed of light. The possibilities are mind-boggling.

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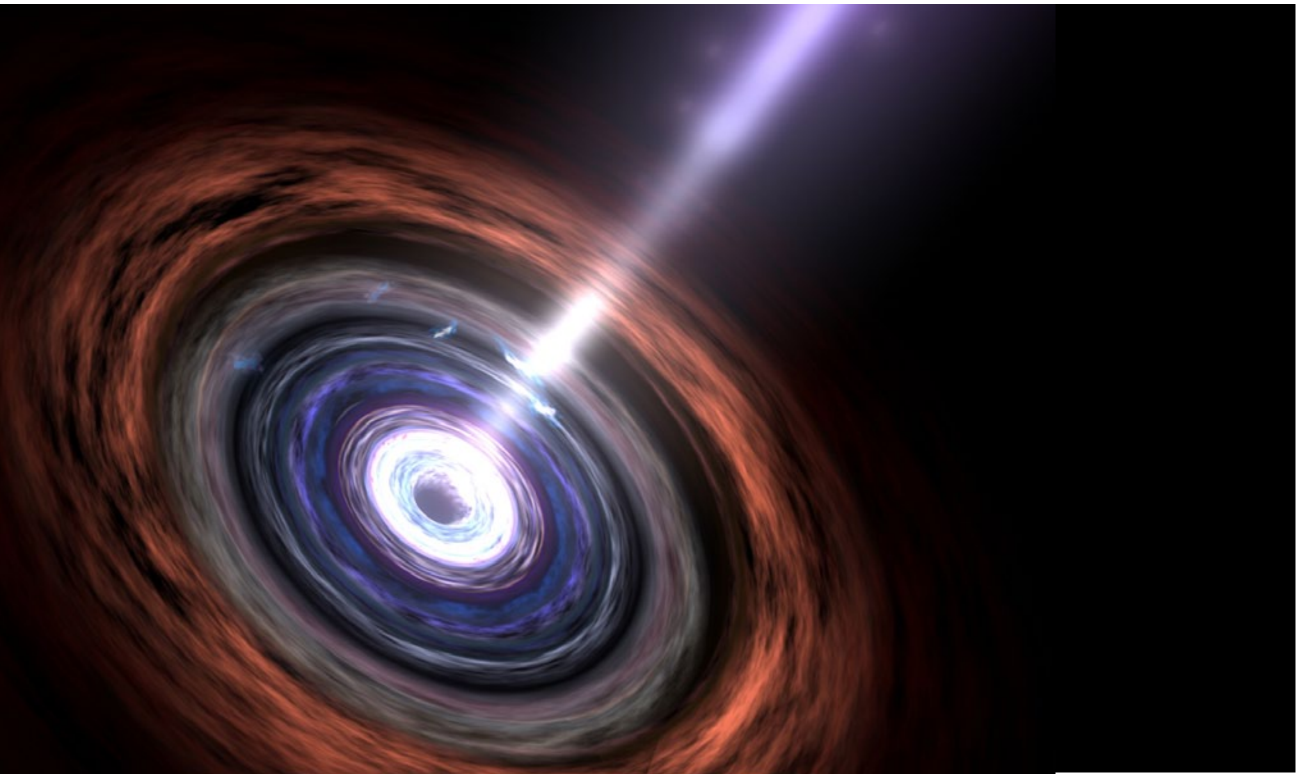
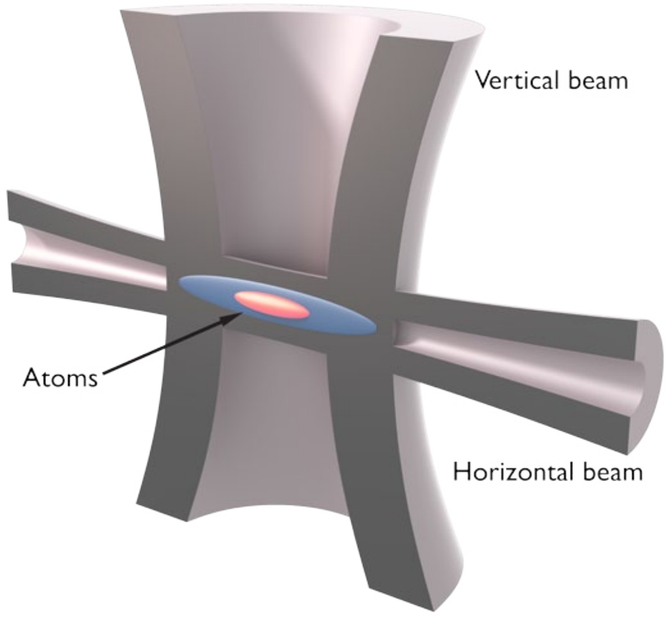


The final step in the merger of two supermassive black holes is likely to generate a jet of light with frequencies ranging from radio waves to X-rays.

Credit: NASA

SCRATCHING THE SURFACE



Artist's concept of the use of two intersecting laser beams to isolate a small "box" of atoms near the center of an ultracold Fermi gas. The Jin group probed the speeds of the atoms in this box and identified a step-like Fermi surface whose location and sharpness allowed them to determine the average density and the temperature of the atoms.

Credit: Yoav Sagi, the Jin group

Members of the Jin group found a way to measure for the first time a type of abstract "surface" in a gas of ultracold atoms that had been predicted in 1926, but not previously observed. Jin and her colleagues are leading researchers in the field of ultracold Fermi gases made up of thousands to millions of fermions.

Fermions, including electrons and some types of atoms such as potassium (^{40}K), cannot occupy exactly the same quantum state. This property leads to a unique distribution of the energy, or speed, of a collection of fermions at low temperature. The distribution has a sharp boundary called a Fermi surface. And, under the right conditions, an ultracold gas of fermions should exhibit a sharp step, or boundary, in the distribution of speeds.

Famous physicists Enrico Fermi and Paul Dirac predicted the existence of this step nearly 100 years ago. For most of a century, physicists were unable to directly see the Fermi surface by looking at the speeds of a bunch of fermions. One difficulty was that fermions interact in virtually all systems except for ultracold gases where interactions can be controlled by adjusting the magnetic field.

However, confining ultracold gas clouds in traps (using light or magnetic fields) does cause variations in the density of the gas in different parts of the cloud. These density variations wash out the sharp Fermi surface when speed distributions are averaged over an entire ultracold gas cloud. So, although physicists were sure that a Fermi surface was present in small sections of the clouds of ultracold fermions, they were unable to "see" it experimentally.

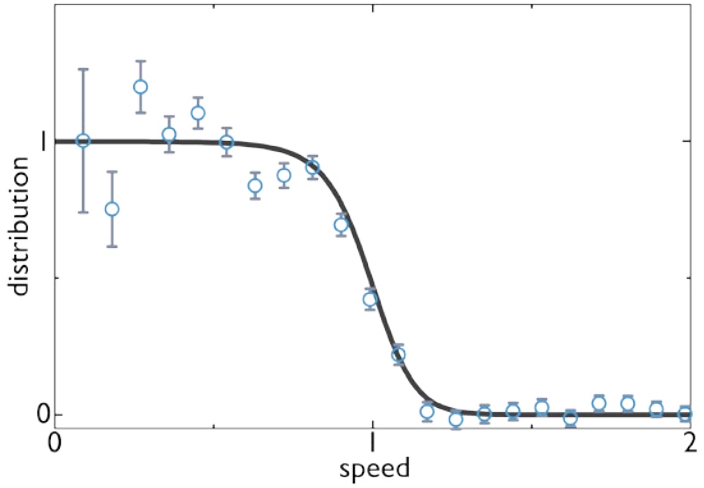
However, seeing it experimentally was exactly what the Jin group wanted to do. So research associate Yoav Sagi, graduate students Tara Drake and Rabin Paudel, former graduate students Jayson Stewart and John Gaebler, and Fellow Jin devised a clever strategy that allowed them to see a sharp Fermi surface for the first time since it was predicted in 1926. The group used two perpendicular laser beams to probe just the atoms near the center of the ultracold Fermi gas. The researchers thought there was a good chance that the density inside the tiny "box" they were targeting would be uniform enough to reveal a Fermi surface in a speed distribution.

The final step of the experiment was to turn off the lasers and measure the speed of the atoms in the box as they expanded out of the trap. These measurements revealed a clear Fermi surface. Its location and sharpness allowed the researchers to determine both the average density and the temperature of the fermions inside the box!

The Jin group is really excited about this accomplishment. It's not everyday that experimental physicists are finally able to figure out how to directly observe a 100-year old prediction.

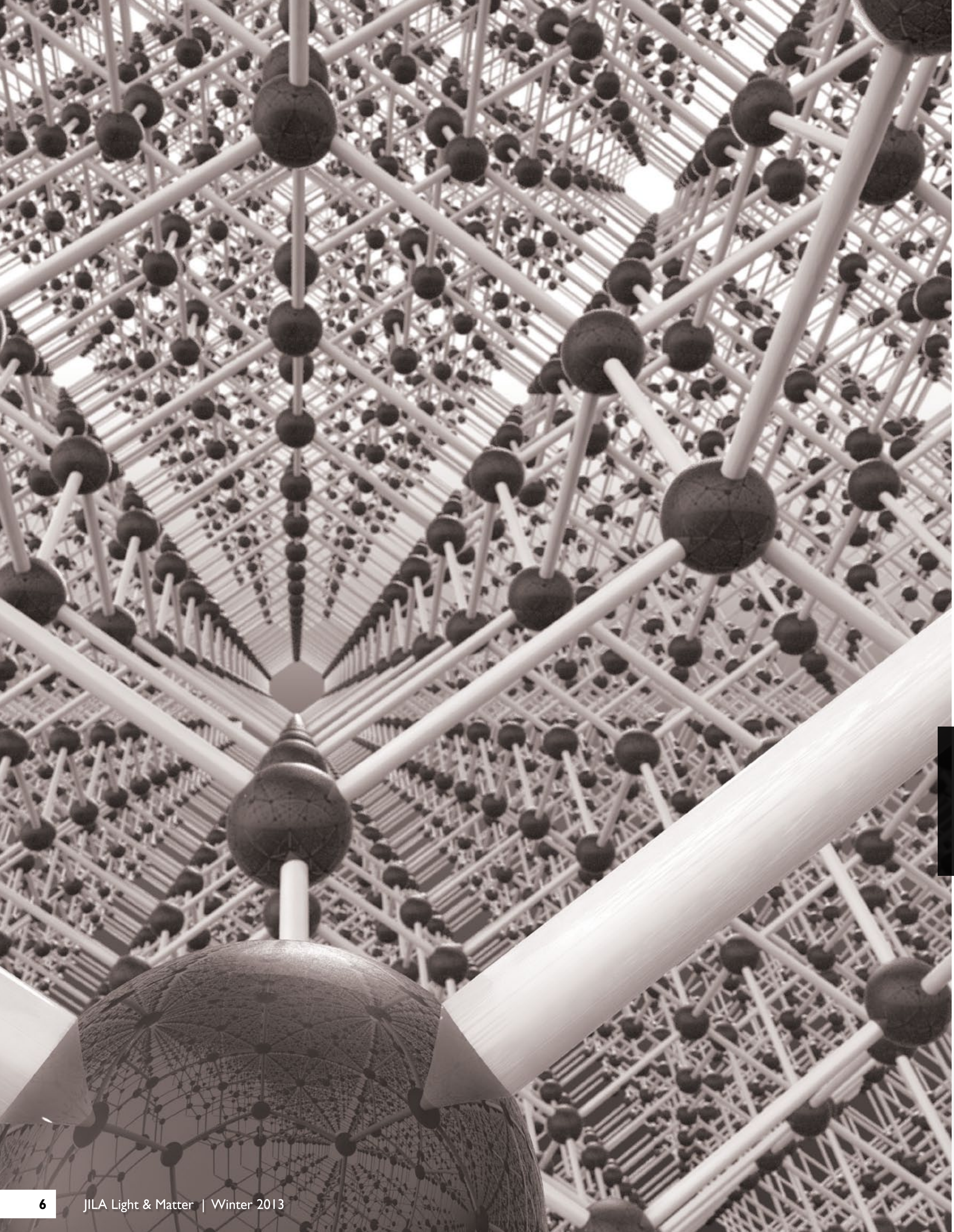
Reference

T. E. Drake, Y. Sagi, R. Paudel, J. T. Stewart, J.P. Gaebler, and D. S. Jin, *Physical Review A* **86**, 031601 (R) (2012).



Graph of the speed distribution of atoms inside the small box of atoms at the center of an ultracold gas cloud shows the predicted step-like Fermi surface.

Credit: Yoav Sagi, the Jin group



NEW SILICON CATIVY SILENCES LASER NOISE

Researchers from a German national laboratory, the Physikalisch-Technische Bundesanstalt (PTB) have collaborated with Fellow Jun Ye, Visiting Fellow Lisheng Chen (Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences), and graduate student Mike Martin to come up with a clever approach to reducing heat-related "noise" in interferometers. Interferometers are widely used measurement tools in optical atomic clocks, astronomy, and spectroscopy. Their thermal noise is due to incoherent collective motions of atoms and molecules inside them (and other material systems). Motion-related noise increases as the temperature goes up.

To reduce this noise, researchers designed an optical cavity made from a single crystal of silicon. An ultrastable laser system using such a cavity could theoretically have nearly ten times less heat-related noise than other systems employing optical cavities to stabilize laser frequencies.

Since 2008, graduate student Mike Martin, former graduate student Marty Boyd, Chen, and Ye have all worked with PTB on testing and comparing a laser using the new silicon crystal cavity with one of the best Ye group lasers, which uses a spacer made of ultralow expansion glass and mirror substrates made from fused-silica glass.

The new cavity's spacer and mirrors are made of single crystal silicon and operate at 124 K, a special temperature at which a silicon crystal's heat-related expansion is at a minimum. The cavity itself is mounted vertically in a way that is immune to additional vibrations in the surrounding environment. Only the mirror coatings contribute in a significant way to the thermal noise of the new silicon cavity system.

Recently, a laser using the new cavity was tested and compared with two ultrastable lasers, including one Martin brought to Germany from the Ye labs. All three lasers are extremely stable. For instance, both the new silicon-cavity laser and the laser from JILA can remain coherent (in sync) for distances of up to three million kilometers.

The three lasers were tested in a "three-cornered hat" comparison. In this kind of comparison, performance differences are measured between laser 1 and 2, laser 2 and 3, and laser 3 and 1. Laser 1 was built at PTB using a cavity made of ultralow expansion glass. Laser 2 was built at JILA. It uses a fiber laser stabilized to an ultralow-expansion-glass cavity and fused-silica mirrors. Laser 3 was stabilized to the ultrastable cavity made of single crystal silicon.

The tests revealed that the performance of the laser with the single-crystal silicon cavity was better than the two comparison lasers, although not yet as good as is theoretically possible. However, PTB and JILA scientists expect to be able to make further progress in improving the single-crystal silicon cavity's performance in precision metrology. A new laser using the silicon cavity will soon become the clock laser for optical atomic clocks under development at PTB. A second system will soon come to JILA for use in the strontium lattice clocks in the Ye labs.

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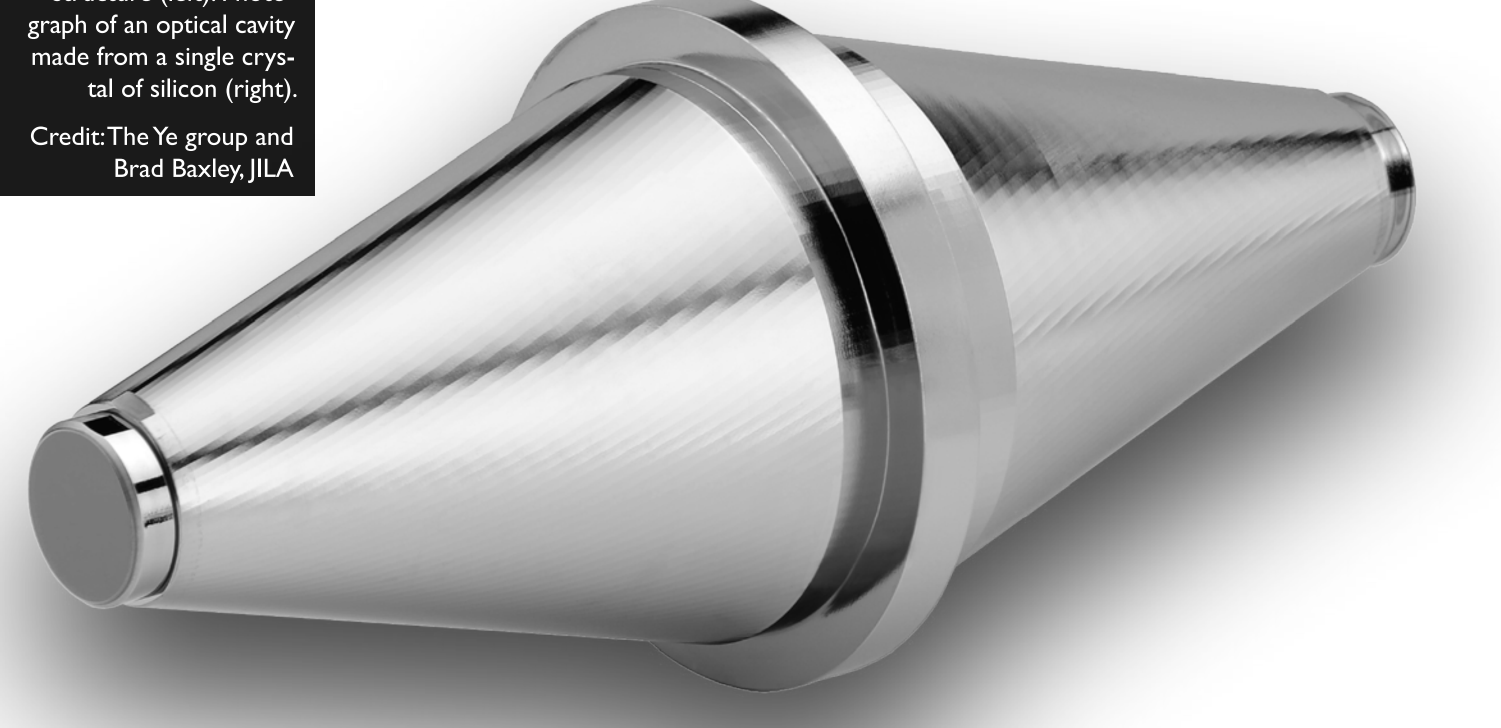


A silicon crystal's atomic structure (left). Photograph of an optical cavity made from a single crystal of silicon (right).

Credit: The Ye group and Brad Baxley, JILA

ANTARCTICA ADVENTURE

On a balmy (-30 °F) summer day in late November of 2012, Carl Lineberger stands on 9000 feet of ice at the South Pole. The South Pole visit was part of a five-day fact-finding trip to Antarctica by three members of the National Science Board, which oversees the National Science Foundation and provides policy advice to the President and Congress.

Credit: Scott Borg, NSF

Carl Lineberger joined fellow National Science Board members France Cordova (Chair of the Board, Smithsonian Institution) and Arnold Stancell (Vice President, Mobil Oil, ret.) on a whirlwind fact-finding tour of Antarctica November 26–30, 2012. The trio visited science and engineering facilities at the McMurdo and South Pole Stations, as well as field research sites in the Dry Valleys and historic huts on Ross Island.

The scientists were also given an in-depth look at logistical support facilities at the McMurdo and South Pole Stations, including base operations, water and power plants, weather, aircraft, and computing. Their charge was to identify ways for the National Science Foundation (NSF) to enhance scientific research in Antarctica by increasing the effectiveness of logistical support while lowering its costs.

Adelie penguin rookery near Shackleton's hut on Cape Royds, Ross Island, Antarctica.
Credit: Carl Lineberger

NSF is the U.S. custodian of the 1961 Antarctic treaty that provides that Antarctica shall only be used for peaceful purposes and prohibits the establishment of military bases and weapons testing. The original treaty was signed by Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, the Soviet Union, the United Kingdom, and the United States as a direct result of a successful scientific collaboration in Antarctica during the 1957–1958 International Geophysical Year. The treaty has subsequently been signed by 28 other nations. Since the treaty was signed, the United States has enforced its terms and provided logistical support for a majority of the research conducted in Antarctica.

Logistical support for Antarctic research and protection of the continent's fragile environment are major U.S. commitments. "Antarctica is roughly the size of North America and is 99% covered in ice," Lineberger says. "It's the only place on Earth where there is no native human habitation. It's a big job figuring out how to keep this environment pristine and ensure that there is no military or mineral exploitation of the continent."

Lineberger notes that even in the pitch dark and bitterly cold winter (when temperatures fall as low as -129 °F), skeleton crews man the McMurdo and South Pole stations, which are regularly subjected to gale force winds that scream across the continent at top speeds of nearly 200 mph. In this rugged climate, there is only a single landing field for wheeled aircraft — at McMurdo Station. Summer visits to other parts of the continent, such as the South Pole or the Dry Valleys, require aircraft with skis or helicopters flown by pilots trained to assess whether ice conditions allow for safe landings.

In spite of, or perhaps because of, the harsh conditions, research is flourishing in Antarctica. "The biology is very interesting because Antarctica was once part of the ancient continent of Gondwana," Lineberger says. "Species that were once common are now evolving separately in Africa, South America, Central Europe, the Arabian peninsula, India, Australia, and Antarctica." Lineberger added that conditions in Antarctica also offer excellent "seeing" for astronomers.

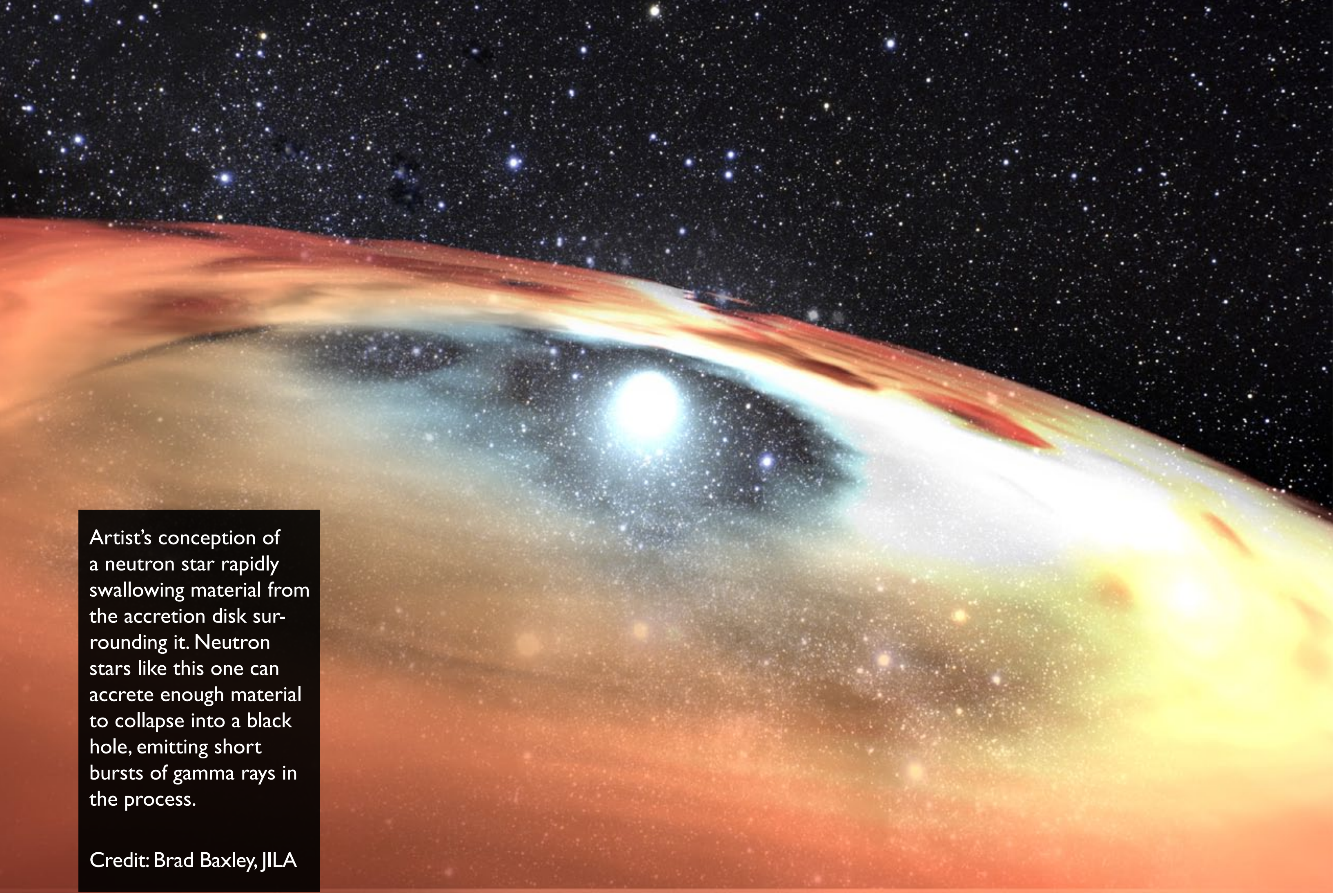
For Lineberger, one of the most fascinating regions was the Dry Valleys. These erosion-carved valleys originally sloped down to the sea in Gondwana. However, the breakup of Gondwana literally turned the valleys upside down, forming a precipitation shield that cut off rain and snow. Because the valleys receive almost no water, they've been preserved as they were 140 million years ago.

Current research in this region includes observations of penguin rookeries and studies of the internal structure and movement of glaciers, which flow like rivers through the valleys. The glacier study is crucial for determining possible changes in the amount of frozen water in Antarctica. The continent's ice pack comprises 90% of the ice found on land, or grounded ice. The melting of grounded ice makes major contributions to sea level rise in global warming scenarios.

Interior of Shackleton's hut, constructed in 1908 to support the British Antarctic Nimrod Expedition. The expedition, led by Ernest Shackleton, was the first to reach the South Magnetic Pole and came within 97 nautical miles of reaching the Geographic South Pole.
Credit: Carl Lineberger

The same day they visited research sites in the Dry Valleys, Lineberger and his colleagues were able to see historic huts, including the Shackleton hut built by explorer Ernest Shackleton and his expedition in 1908. Shackleton's crew reached the South Magnetic Pole and came within a hundred miles of reaching the Geographic South Pole. The hut they built was subsequently used by expeditions in 1911–1912 and in 1915–1916.

In addition to an overview of early Antarctic explorations, Lineberger was able to spend a day learning about the scientific research and operations support facilities at the McMurdo station. After gathering important information about the cost and complexity of logistical support for Antarctic missions, he and his colleagues headed back to Christchurch, New Zealand, and, from there, back home. The consensus was they'd learned a tremendous amount about Antarctic research and logistical support over five very intense and busy days.



Artist's conception of a neutron star rapidly swallowing material from the accretion disk surrounding it. Neutron stars like this one can accrete enough material to collapse into a black hole, emitting short bursts of gamma rays in the process.

Credit: Brad Baxley, JILA

MESSAGES FROM THE ABYSS

Many neutron stars are surrounded by accretion disks. The disks are often made up of matter pulled in by the neutron star's gravity from a companion star in a binary system. Over time, the neutron stars can swallow so much additional material that they collapse into black holes.

Recently, research associate Bruno Giacomazzo and Fellow Rosalba Perna studied this collapse process in detail. They modeled how an accretion disk affects a neutron star's collapse into a black hole. Their model included an analysis of the kinds of signals that would be emitted by neutron stars with and without accretion disks as they collapsed into black holes.

The researchers were a little disappointed to discover that the gravitational wave signal would likely be similar for an accretion-induced collapse and the collapse of a "naked" neutron star. However, they were excited to find that the two kinds of collapses would send very different electromagnetic signals such as short bursts of gamma rays.

The variations in electromagnetic signals stem from differences in what happens immediately following the collapse into a black hole. When a neutron star with an accretion disk collapses, it leaves behind some of its accretion disk. The newly formed black hole voraciously swallows the surviving disk. It can launch relativistic jets and emit short bursts of gamma rays in the process of growing rapidly. Thus, accretion-induced collapse of neutron stars could be responsible for some of the short gamma-ray bursts observed in our Universe. In contrast, when a "naked" neutron star collapses into a black hole, almost no ordinary matter is left anywhere near the new black hole. Thus, nothing happens in this kind of collapse to generate bursts of gamma rays (or any other electromagnetic signals).

By identifying and interpreting gamma-ray "messages from the abyss," researchers now have a way to locate accretion-induced collapses of neutron stars — even when they occur far outside our own Galaxy.

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SIZZLING VIBRATIONS

Former research associate Antonio Picón, research associate Agnieszka Jaron-Becker, and Fellow Andreas Becker have discovered a way to make the hydrogen molecular ion (H_2^+) fall apart into its constituent atoms without exciting or ionizing the electron. This startling finding was a big surprise for the researchers, who recently figured out how to do something that conventional wisdom said was difficult, if not downright impossible.

For starters, molecules usually don't split up into atoms unless at least one electron is excited or ionized. Rather, they dissociate into charged ions, with one negatively charged ion containing one or more extra electrons and another positively charged ion missing the same number of electrons.

Researchers thought that the only two ways to break apart a molecule into neutral atoms would be (1) to hit it with a rapid sequence of laser pulses over a wide range of different frequencies (i.e., energies) or (2) to change the frequency of the laser pulse over time, a process called chirping. Either way, the goal was to get the molecule shaking hard enough to fall apart. Either process is technically challenging since the laser frequencies needed to exactly resonate with the molecule's vibrational states to make it fall apart. And, these vibrational states get closer and closer together as they get higher and higher in energy. And, as the vibrational states get closer together, they are harder to stimulate with a single laser pulse.

Two years ago, Agnieszka Jaron-Becker and Andreas Becker weren't even thinking about getting molecules to fall apart. Rather, they were exploring the behavior of atoms and molecules interacting with infrared (IR) lasers. Their research was related to the new IR laser used to produce coherent high-energy soft x-rays in the Kapteyn/Murnane (K/M) group. They found little prior work on IR lasers because the response of matter to lower-energy light was considered less exciting than its response to visible and higher-energy wavelengths of light.

Near the end of 2010, working with Picón, Jaron-Becker and Becker discovered that IR laser pulses would greatly enhance vibrations of simple molecules such as H_2^+. They showed that when this molecule absorbs two photons of IR light, the photons excite the molecule's higher vibrational states.

Then, in an exciting new study just published in *Physical Review Letters*, the researchers showed that the absorption of pairs of photons of IR light of the right wavelength strongly favors the dissociation of molecules into atoms. A range of wavelengths is not needed! In theory, pulses of 12-μm IR light will excite all the vibrational states of H_2^+ at the same time, causing the molecule to rapidly dissociate into its constituent atoms. The molecule shakes itself apart rather than ionizing!

Unfortunately, there are not yet many IR lasers with a wavelength as long as 12 μm available to test the new theory. Consequently, the researchers are looking for a simple nonpolar molecule whose vibrational states will all resonate from the absorption of two photons of light from the 4-μm IR laser already used by the K/M group. Andreas Becker hopes it's only a matter of time until they find one.

Stay tuned for more exciting developments in the physics of molecule dissociation!

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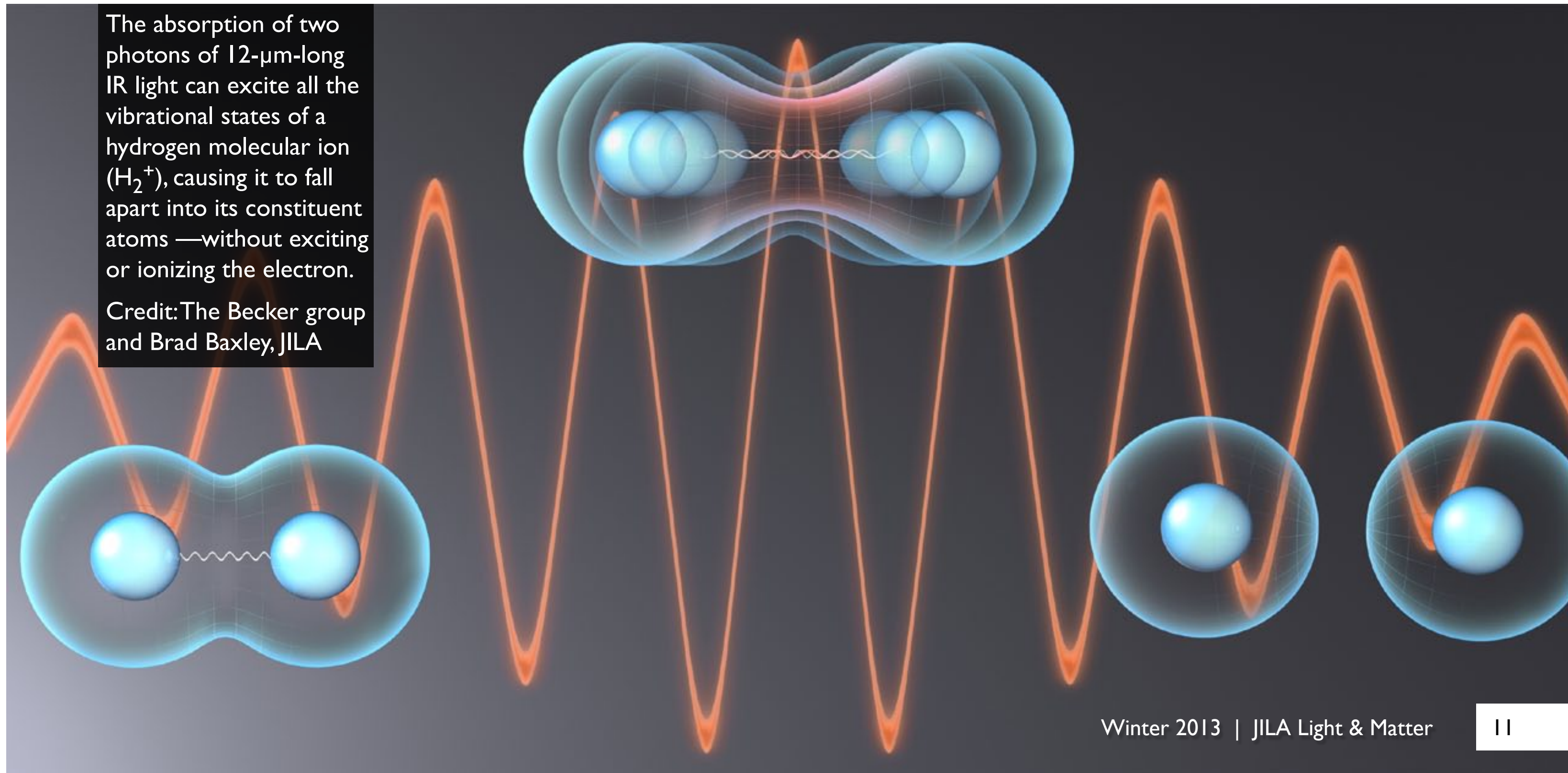

The absorption of two photons of 12-μm-long IR light can excite all the vibrational states of a hydrogen molecular ion (H_2^+), causing it to fall apart into its constituent atoms —without exciting or ionizing the electron.

Credit: The Becker group and Brad Baxley, JILA

UNDER THE COVER OF DARKNESS...

Full-grown mountain lion wearing a GPS collar transmitter pauses for refreshment at around 6:30 a.m. at the backyard pool of Jinx and Ann Cooper's Third Street home on December 5, 2012. Credit: Jinx Cooper

A second pre-dawn visitor arrives at the Cooper's pool on December 20, 2012. This young lion hasn't been tagged. Credit: Jinx Cooper.

KUDOS TO...

Former Fellow **Keith Burnett** for being awarded a 2013 knighthood for services to science and higher education. Burnett is Vice-Chancellor of the University of Sheffield in England.

Eric Cornell for winning the Ioannes Marcus Marci medal for molecular spectroscopy from the Ioannes Marcus Marci Spectroscopic Society of the Czech Republic.

Steve Cundiff for being awarded a Silver Medal from the U. S. Department of Commerce for his leadership of JILA's X-Wing project.

Research Associate **Matthew Hummon** and newly minted Ph. D. **Ben Stuhl** for winning outstanding presentation awards at the 2012 Boulder Laboratories Postdoctoral Poster Symposium.

Deborah Jin for being selected as the 2013 Laureate for North America by the International Jury of the L'OREAL-UNESCO Awards. Jin will receive the award, which includes $100,000, at a ceremony in Paris, France, on March 28, 2013.

JILA, on its 50th anniversary on April 13, dedication of the new X-Wing on April 13, and two-day anniversary celebration held July 12–13 (2012).

JILA X-Wing for being awarded a Special Judges Recognition for its outstanding craftsmanship and impact on the JILA community as part of the Best Projects competition in the Mountain States region.

Cindy Regal, JILA grad **Matthew Squires** (Anderson group, Ph.D. 2008), former postdoc **Wen Li** (Kapteyn/Murnane group), and JILA grad **Ian Coddington** (Cornell group, Ph. D. 2004) for receiving prestigious Presidential Early Career Awards for Scientists and Engineers in July, 2012. Each award is for $1 million over 5 years.

Ana Maria Rey for being selected as Woman Physicist of the Month in June of 2012 by the American Physical Society.

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The editors do their best to track down recently published journal articles and great research photos and graphics. If you have an image or a recent paper you'd like to see featured in the newsletter, contact us at communications@jila.colorado.edu.

Please check out this issue of JILA Light & Matter, Winter 2013 online at http://jila.colorado.edu/research/ where you can find supplemental multimedia that may be associtated with the articles.

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