JILA light&MATTER

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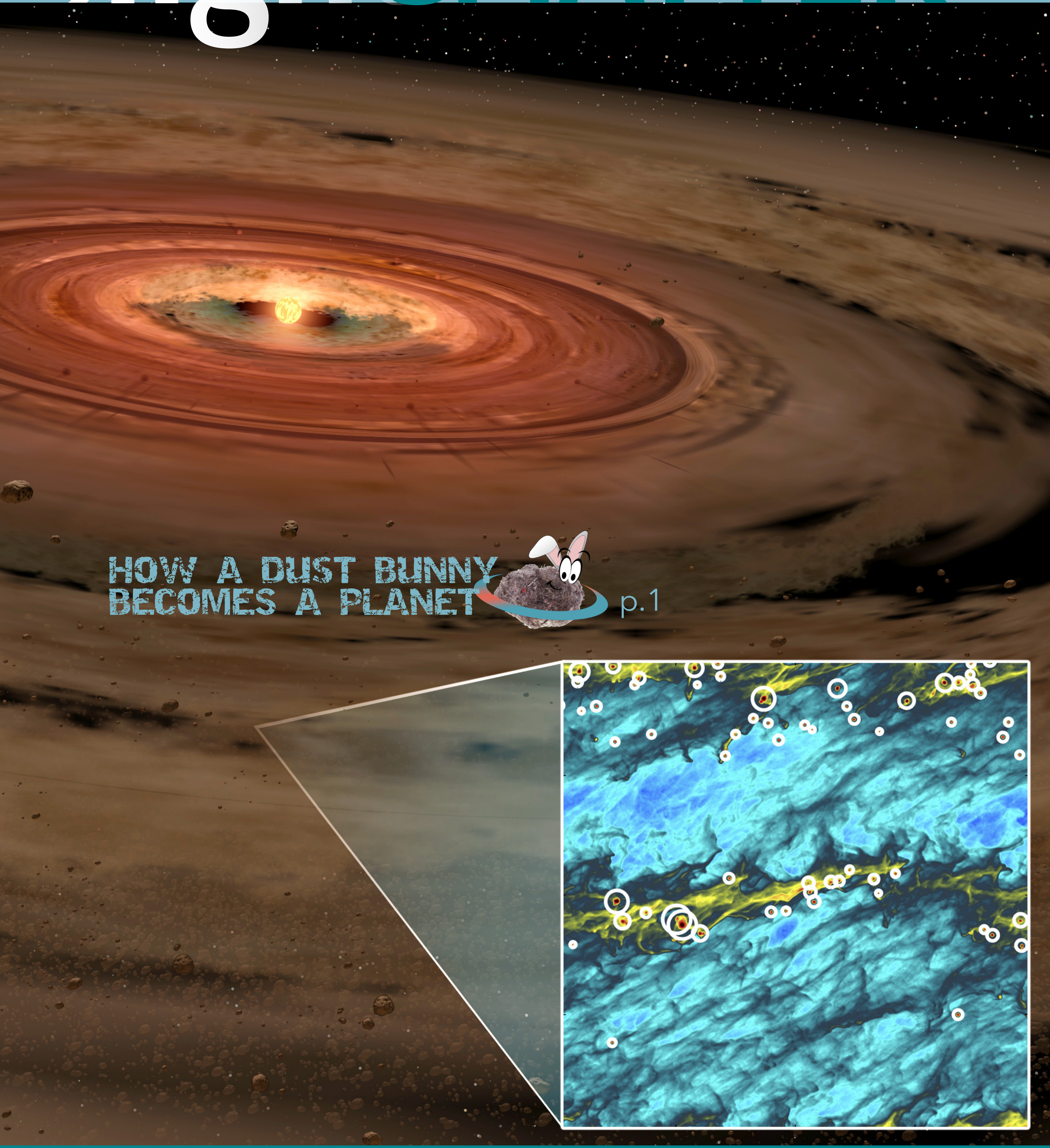
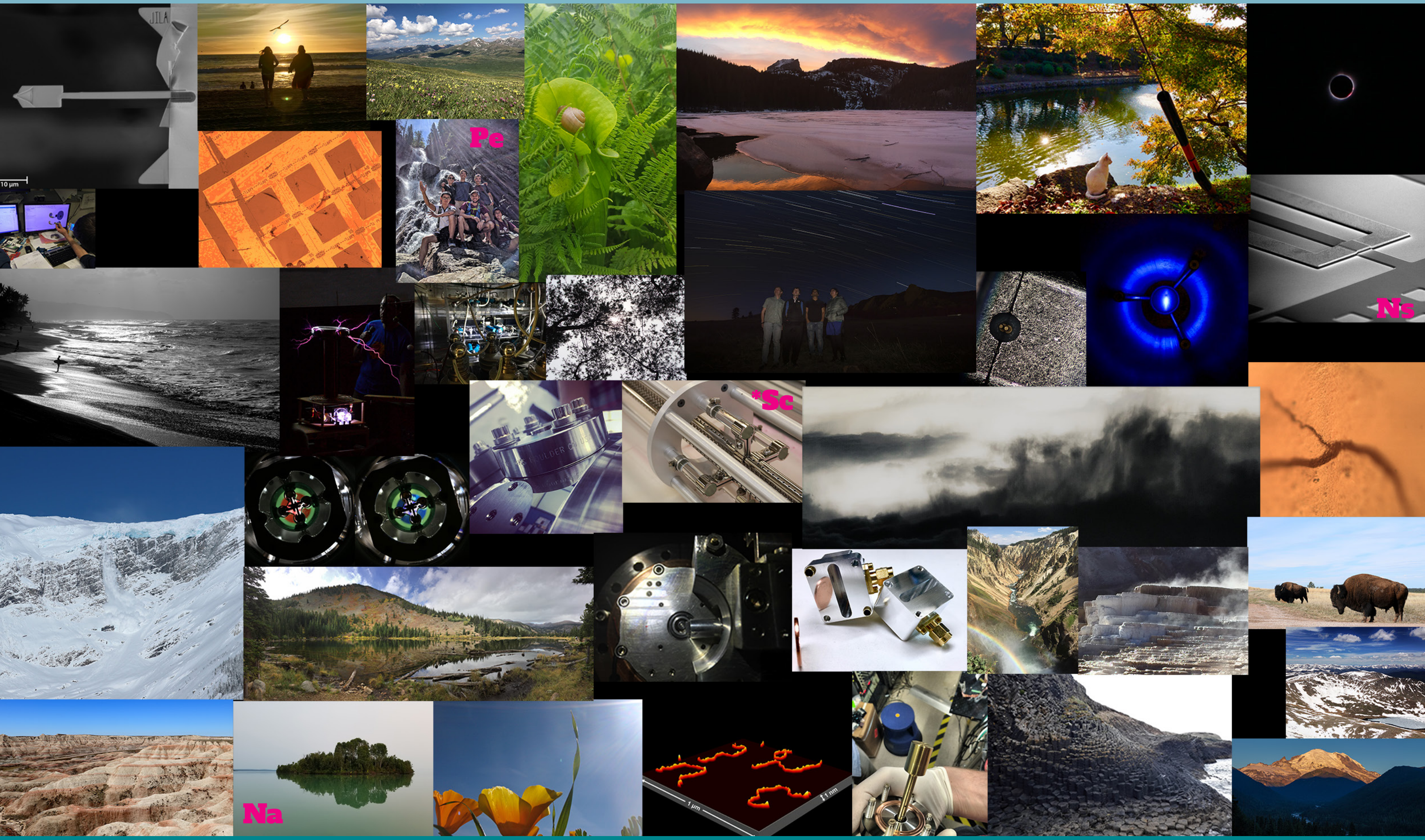


HOW A DUST BUNNY BECOMES A PLANET p.1



The many amazing submissions for the 2018 JILA Photo Contest. This year there were 42 entries, narrowed down to four category winners. Category winners are marked: Ns = Nanoscale, Na = Nature, Pe = People, *Sc = Science & Overall Winner.

JILA Light & Matter is published quarterly by the Science Communications Office at JILA, a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology.

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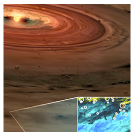
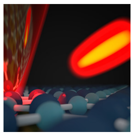
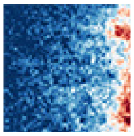
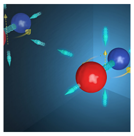
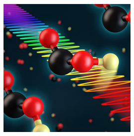










Features

HOW A DUST BUNNY BECOMES A PLANET

Jupiter is large enough to fit 1,300 Earths inside, and still have room for more. But, like all planets, Jupiter was once nothing more than a cosmic dust bunny.

A team of physicists at JILA and the University of Arizona, led by JILA Senior Research Associate Jake Simon, are studying how cosmic pebbles—starting only a millimeter in size—can lead to the formation of planetesimals, the football-field-to-Delaware-sized primordial asteroids whose development defined our solar system's architecture.

It all starts in the cosmic dust, which is composed of tiny, micron-sized particles, surrounding freshly collapsed stars. Before planets can form, planetesimals must form; and before planetesimals can form, the cosmic dust must cluster. But like all dust bunnies, cosmic dust only clusters when stirred. The technical term for this stirring is turbulence.

There are many possible sources of initial turbulence. One source, known as streaming instability, is the presence of small pebbles within the cosmic dust.

"So what's going on here is the small solids, which you might think of as the pebbles within the [protoplanetary] disk, those feel aerodynamic forces, sort-of headwind forces, against the gas. And it turns out in some circumstances that doesn't just cause them to spiral towards the star...it also causes them to cluster," says JILA Fellow Philip Armitage.

"But what is not so clear is how you make them so clustered that they actually collapse gravitationally, and that's really the point of these simulations."

Understanding the formation of these early planetesimals may reveal the architectural blueprint of our solar system. Is it a coincidence that our solar system's gas giants, Jupiter and Saturn, are fenced away from our moderately sized terrestrial planets by an asteroid belt?

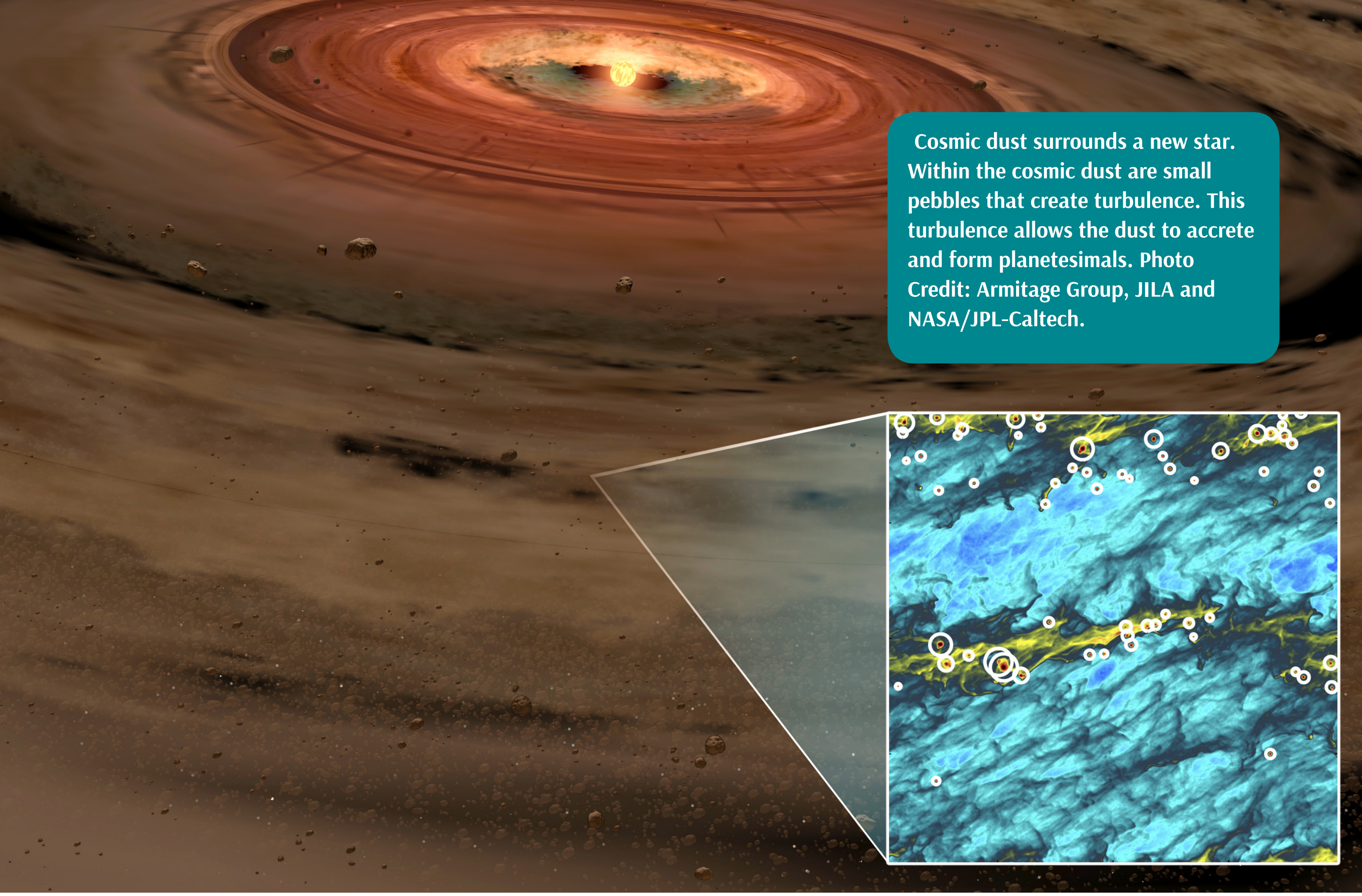
In terms of forming a giant planet, Armitage says the tinier the starting materials, the better. "If the planetesimals are small, then they themselves are damped aerodynamically by the gas disc, and so then they actually accrete faster onto the core of a forming giant planet."

The accretion of planets is not unlike the accretion of a snowball. Rolling a small snowball among the tiny snowflakes on the ground quickly generates a giant snowball. Trying to combine several snowballs, however, results in a scattered mess.

"Large objects will tend to be scattered by the growing core more," explains Armitage, and so they are not as readily accreted.

And much like snowflakes, which precipitate in different sizes, planetesimals have a wide variety of initial sizes. To quantify this variation, scientists use the mass function. The mass function describes many properties of the planetesimals, such as the average size, and the ratio of small to large particles.

Armitage and his fellow researchers wondered if the mass function of planetesimals depended on the cosmic pebbles that initiated their formation. "In a disc, you can imagine that in close to a star, where the gas is dense, the particles have quite different aerodynamic interactions. So we've been asking, do you get the same outcome whether you're forming planetesimals in the region of the terrestrial planets, in the asteroid belt, or in the Kuiper belt, where you might be forming comets."



Cosmic dust surrounds a new star. Within the cosmic dust are small pebbles that create turbulence. This turbulence allows the dust to accrete and form planetesimals. Photo Credit: Armitage Group, JILA and NASA/JPL-Caltech.

And the answer was, within error, a surprising yes. They found universality, or the idea that the slope of the mass function is the same regardless of the size of the initial pebbles. But this result is not too surprising.

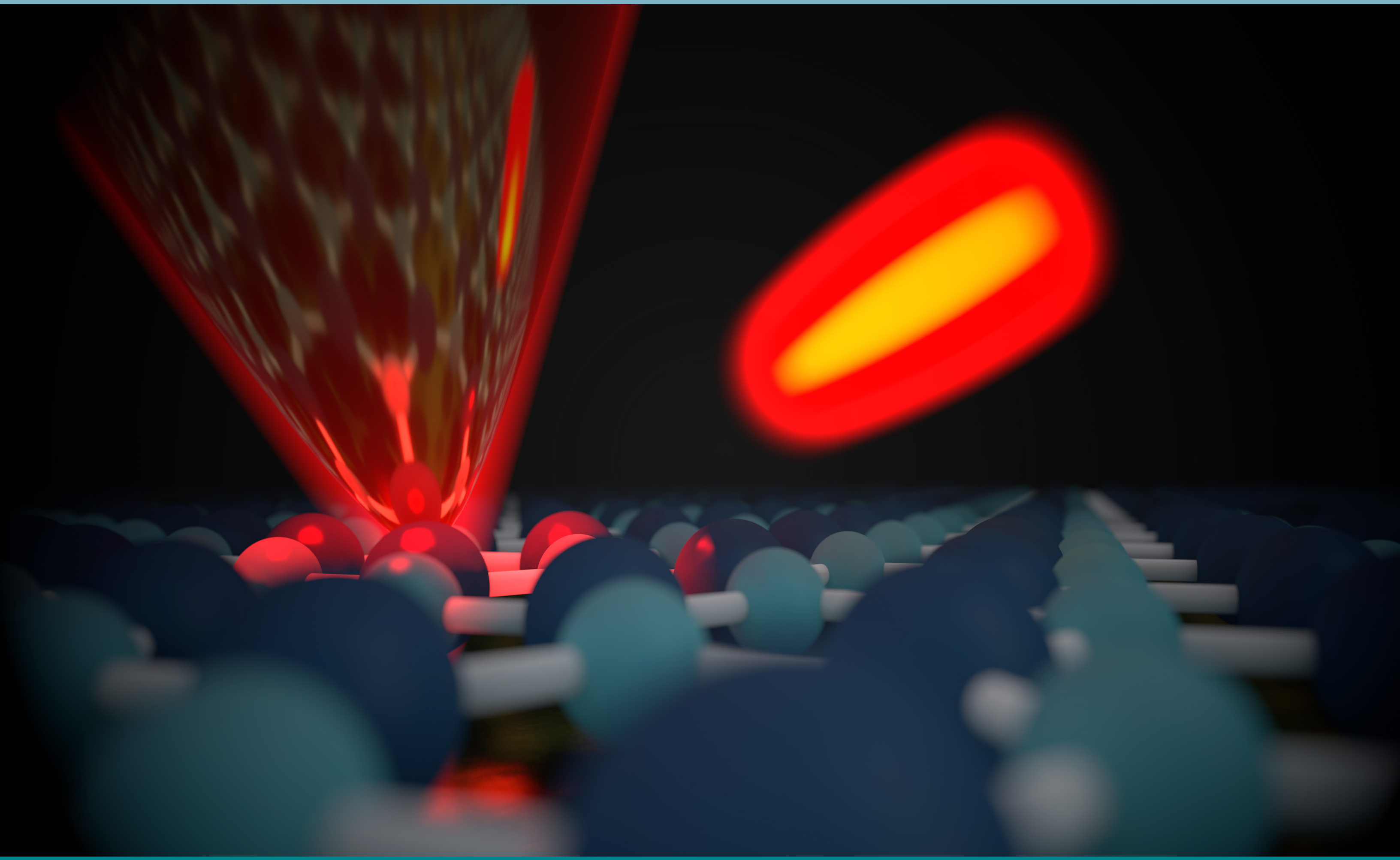
"In other astronomical situations where we have gravitational collapse, which is for example in the formation of stars, we see observationally that the distribution of stellar masses appears to be the same in many different environments. So in that case, we have a similar result," says Armitage.

This result also agrees with previous research of planetesimal formation that considers similar mechanisms, but not initial pebbles as small as one millimeter. An unexpected agreement, given that smaller particles act differently, and are more likely to form bands or rings within a disc, than large particles.

Armitage is eager to explore more sources of turbulence. "It remains the case that we've only explored a small fraction of all the conditions that might be present in disks, and it may be that some other parameter, which we vary, will eventually be shown to make a difference to the mass function."

This research was led by Jacob Simon and Philip Armitage, both of JILA, as well as Andrew Youdin and Rixin Li from the University of Arizona. The research was supported by NASA and the NSF.✴

Jacob B. Simon, Philip J. Armitage, Andrew N. Youdin, Rixin Li, *The Astrophysical Journal* **847**, L12 (2017).



A sharp gold tip acts as a nano-optical antenna to trigger light emission from dark excitons in a 2D (i.e., single atom layer) semiconductor. Photo credit: Raschke Group and Steven Burrows, JILA.

BRIGHTENING THE DARK STATE

Researchers from the Raschke group are lighting up dark excitons.

Specifically, the Raschke group developed a method to observe dark excitons in a 2D (i.e., a single layer of atoms) semiconductor at room temperature. This observation is an exciting development in the story of dark exciton applications, which includes quantum information processing and fundamental studies of complex semiconductor materials.

Bright excitons—which very rapidly emit light after forming—have long been used to probe materials and fundamental quantum processes. Now the Raschke group is seeking to make use of normally invisible dark excitons as well.

Dark excitons are bound electron-hole pairs that, unlike their bright exciton counterparts, are stifled by spin-forbidden transitions that prevent recombination through photon emission. Because these excitons are reluctant to emit a photon, they remain dark.

Darkness means stability: a dark exciton's "photoluminescence lifetime and coherence time is a thousand times longer than that of a bright exciton," says Kyoung-Duck Park, the lead graduate student on this project. These long lifetimes are what make dark excitons potential candidates for quantum computing: the state, once manipulated, can hold onto information for a long time.

But emission reluctance, or darkness, is both an advantage and a weakness.

"The problem is, how do you read it out if it is not emitting?" asks JILA Adjunct Fellow, and the principal investigator, Markus Raschke.

While dark excitons are good at holding information, they also need to release information on command in order to be useful in computing, or other opto-electronic, applications.

Previous attempts to induce dark exciton emission required both strong magnetic fields and cryogenic temperatures. But "it is really difficult to imagine devices for practical application if they require low temperature and extremely high magnetic field condition," says Park.

Park instead uses only a very sharp, gold tip to coax the dark excitons into emission.

"It's more of a piece of wire that tapers very sharp, and it's out of gold or silver, because we want very high optical conductivity," says Raschke.

Park's technique requires no magnetic fields and works at room temperature, yet sees a 600,000 times enhancement in the emission of dark excitons over previous methods.

The gold tip, carefully placed only nanometers away from the dark exciton, can then broadcast the dark exciton's signal. Much like the way a radio antenna converts electrical signals into radio waves, the gold tip acts as an optical antenna that converts the exciton's electrical information into optical waves, or photons.

And Park's technique can not only brighten dark excitons, but switch the brightness on and off. The distance between the tip and exciton acts as a nano-optical cavity. This distance determines whether the tip is coupled to the exciton, i.e., whether the tip can broadcast the exciton's signal. Therefore, by fine adjustment of this distance, a dark exciton's emission can be switched on and off, in the same way a light switch can brighten or darken a room with the flick of a finger.

This experiment was conceived and led by University of Colorado Boulder graduate student Kyoung-Duck Park and JILA Adjunct Fellow Markus Raschke, with the aid of postdoctoral associate Tao Jiang. The 2D semiconductors were prepared by Genevieve Clark and Xiaodong Xu from the University of Washington.✺

Kyoung-Duck Park, Tao Jiang, Genevieve Clark, Xiaodong Xu, Markus B. Raschke, *Nature Nano Technology* **13**, 59–64 (2018).

Same Clock. New Perspective

We all know what a tenth of a second feels like. It's a jiffy, a snap of the fingers, or a camera shutter click. But what does 14 billion years—the age of the universe—feel like?

JILA's atomic clock has the precision to measure the age of the universe within a tenth of a second. That sort of precision is difficult to intuit. Yet, JILA's atomic clock, which is the most precise clock in the world, continues to improve its precision. The latest jump in precision, of nearly 50 percent, came about from a new perspective.

"The precision of our clock is now about two and half parts in 10 to the 19. Which is an almost impossibly tiny, tiny number to actually realize or understand," says G. Edward Marti , a JILA postdoc in the Ye group, and integral member of JILA's atomic clock team. "We know we're not at the limit of this."

The atomic clock is more than just an atom. It's actually a system of thousands of atoms and a very impressive laser. This system works much like an old time-keeping system: a grandfather clock and the sun. A grandfather clock records time by swinging a pendulum back and forth. Similarly, the laser has a ticking electromagnetic field (although it ticks much faster than a pendulum clock can swing, about 10^{15} times faster).

But the swing of a pendulum (and the ticking of a laser's electromagnetic field) is not perfect, and over time, a grandfather clock's accuracy will drift off. The grandfather clock can be adjusted, however, by comparing its time to the sun at high noon. Similarly, the laser's frequency can be adjusted by comparing it to the cloud of atoms.

"The idea behind all of these clocks is that the atoms serve as a very stable frequency reference," says Marti. "And we use atoms, instead of astronomy, to be able to tweak our clock to always be the same rate." But are the atoms really a perfect timekeeper?

When measured from one day to the next, the time when the sun reaches high noon jitters. This jitter introduces error into the solar time reference. Assuming the sun revolved around the earth, the source of this jitter is untraceable, and the error remains. But, by changing perspective–is it not the sun revolving the earth, but the earth rotating beside the sun within a complicated solar system, in which the sun, moon, and sibling planets tug at the Earth's tides, thereby affecting its rotation–the jitters can be understood. When the jitters are understandable, the error they introduce can be accounted for and removed. And removing these errors results in a more precise clock.

Atoms may have similar jitters adding error to the atomic clock. But to find them, the clock team had to change their perspective quite literally.

The team built a microscope to look directly at the atoms. And when prepared correctly, the atoms divulge many secrets. For instance, the atoms were used as a prism to analyze laser properties. Much like how a prism divides white light into colors, the atoms can differentiate laser frequencies.

"The lasers we hold [the atoms] with can cause problems," explains Marti. "We decided to ask, how well can we measure that, how well can we mitigate that?"

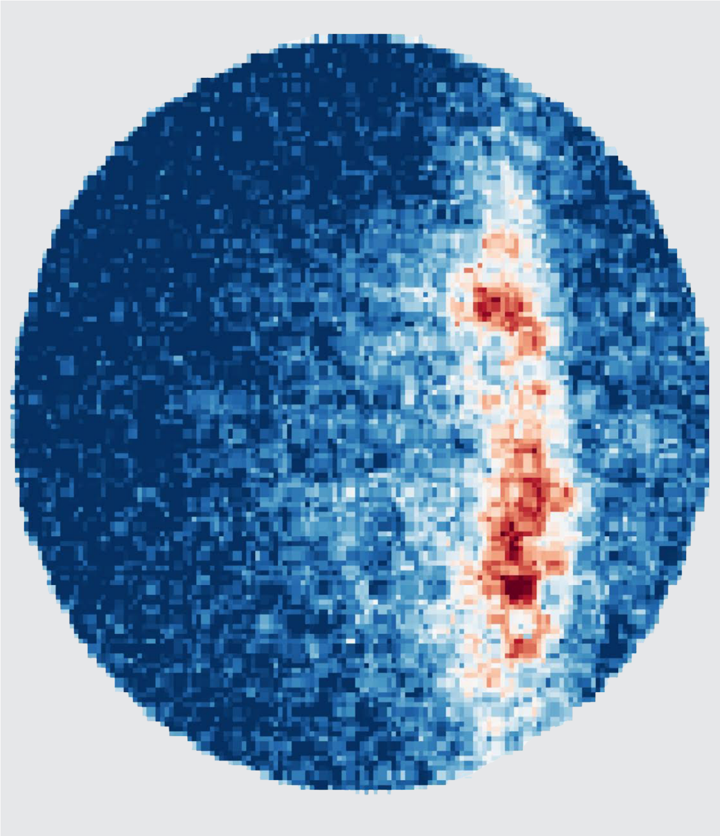
With their new imaging technique, the team was able to measure the effect of the laser holding the atoms, and how that effect could introduce errors into their system. They were also able to quantify how long their atoms remained coherent, i.e., in a quantum superposition. Specifically, their atoms were in a superposition of two atomic states useful for timekeeping, which are separated by a visible photon worth of energy. Their atoms remained coherent for up to a record-breaking 15 seconds, a near eternity for a quantum system. The new imaging technique, called imaging spectroscopy, has already reined in the clock's precision by nearly 50 percent, and the team expects their new perspective to pave the way towards future clock applications.

As the precision of the clock continues to improve, the applications for clocks continue to grow. Soon, Marti says, atomic clocks will measure gravity's influence on time using atoms separated by only a few millimeters. And searches for new forms of dark matter, changes in fundamental "constants", and possibly even quantum gravity, will soon gain new perspectives once the clock's precision realizes new experiments.

JILA's atomic clock is unique in that it uses a quantum degenerate gas and quantum many-body physics–the first for a clock system. The use of a quantum many-body system allows many more atoms, on the order of ten thousand, to be stuffed into one clock. The increased number of atoms is a big part of the clock's previously achieved precision.

This work was completed by JILA's atomic clock team, which includes G. Edward Marti, Ross B. Hutson, Akihisa Goban, Sara L. Campbell, and Jun Ye, as well as visiting JILA fellow Nicola Poli from the Università de Firenze.✺

G. Edward Marti, Ross B. Hutson, Akihisa Goban, Sara L. Campbell, Nicola Poli, and Jun Ye, *Physical Review Letters* **120**, 103201 (2018).



JILA's atomic clock has a new look.

The atomic clock consists of ten thousand atoms and a very impressive laser. The new microscope allows the clock team to see how the atoms interact with this laser. For this photo, the team has turned their atoms into a prism, which allows them to differentiate laser frequencies. Specifically, a magnetic field gradient applied horizontally across the cloud of atoms means that only atoms at a certain location will absorb the laser and jump to the excited state (red). The location and width of the excited atoms then gives information about the laser frequency, both its value and stability. The full view shown here checks the 15th digit of the laser frequency; the thin red slice demonstrates that the laser is stable to better than a few parts in 10^{16} over 8 seconds. Photo Credit: Ye Group/JILA.

IN THE NEWS

BEC HEADED FOR SPACE

JILA's favorite degenerate, the Bose-Einstein Condensate, is headed on a new adventure this week.

The BEC is going to space.

BECs became a staple for measuring quantum phenomenon when they were experimentally realized in 1995 by JILA Fellows Eric Cornell and Carl Wieman, and by Wolfgang Ketterle at MIT.

To create BECs in space, NASA's Jet Propulsion Laboratory is launching CAL, a remotely operated Cold Atom Laboratory. At the heart of CAL is a vacuum chamber ("about the size of a stick of butter," as described in *Science*) and atom chip built by JILA Fellow Dana Anderson's company, ColdQuanta. This chip helps cool and trap the atoms.

Some of the BEC experiments in CAL will be run by Prof. Peter Engels and graduate student Maren Mossman, both from Washington State University, in collaboration with JILA Fellow Eric Cornell and JILA Senior Research Associate Jose D'Incao. But the microgravity laboratory will be open to other researchers, including Nathan Lundblad from the University of California Berkeley, and Cass Sackett from the University of Virginia.

A common thread in all experiments on Earth is working around the forceful pull of gravity. In a BEC experiment, this workaround results in tight confinement for the BEC, which prevents the BEC from falling out of the experiment.

But in a microgravity environment, like the one available on the International Space Station, the pull of gravity is lessened. This will allow researchers to free the condensate from typical confinement. Like most free-range counterparts, the BECs are expected to live longer out of confinement: the BECs on board the ISS are expected to be stable for up to 10 seconds, which is much longer than the fraction of a second of the "Earth-confined" BECs.

According to the CAL website, the laboratory will launch "aboard an Orbital ATK Cygnus spacecraft, atop an Antares rocket, from NASA's Wallops Flight Facility in Virginia."

The launch, originally schedule for 20 May 2018, was delayed until Monday, 21 May 2018, due to weather concerns.

HEATHER LEWANDOWSKI ET. AL PUBLISH THE BACK PAGE OF APS NEWS

JILA Fellow Heather Lewandowski, and collaborator in the Lewandowski group Dimitri Dounas-Frazer, published an article on The Back Page of the 2018 May issue of *APS News*.

The article, entitled "Labs are necessary, and we need to invest in them", reviews the potential benefits, current goals, and cultural opinion about undergraduate lab courses, before suggesting a promising future. The article argues that broad experimental skills, such as troubleshooting, modeling, and communicating, are more effective goals of lab classes than reinforcing physics concepts.

"We imagine a promising future for physics labs. In this future, students collaborate equitably with each other and their instructors to design and conduct experiments. All lab activities would align with clearly articulated learning goals and research-based assessments—and all of this takes place in an accessible, inclusive learning environment."

To achieve this future, the authors suggest four major areas of investments.

This article was written by Marco D. Caballero of Michigan State University, Dimitri R. Dounas-Frazer of the University of Colorado Boulder, JILA Fellow Heather J. Lewandowski of the University of Colorado Boulder, and MacKenzie R. Stetzer of the University of Maine.

APS News is a monthly newspaper published by the American Physical Society. The Back Page is a forum for APS member commentary and opinion. APS News welcomes and encourages letters and submissions from APS members responding to these and other issues.

HENRY KAPTEYN ELECTED AS 2018 MEMBER OF THE AMERICAN ACADEMY OF ARTS AND SCIENCES

Henry Kapteyn has been elected as a 2018 member of the American Academy of Arts and Sciences. He joins some of the world's most accomplished leaders from academia, business, public affairs, the humanities, and the arts, including JILA Fellows David Nesbitt (2013), Margaret Murnane (2006), Eric Cornell (2005), and Carl Lineberger (1995), and such luminaries as Benjamin Franklin (1781), Alexander Hamilton (1791), Ralph Waldo Emerson (1864), Charles Darwin (1874), Albert Einstein (1924), and Martin Luther King, Jr. (1966).

"I am delighted to congratulate Henry on behalf of all of JILA," said JILA chair Thomas Perkins. "Henry, the taller half of the Kapteyn-Murnane partnership, has helped drive the development of ultrafast laser sources since graduate school. His impact is seen in the application of ultrafast lasers to diverse application in attosecond non-linear optics, molecular dynamics, and nanoscale imaging as well as the many alumni of their group that have gone on to success in both academia and industry."

The American Academy of Arts and Sciences elected 213 individuals to the class of 2018. The new members span a wide range of disciplines and professions, and include Netflix, Inc. CEO W. Reed Hastings, Jr.; actor Tom Hanks; 44th President of the United States Barack H. Obama, and CU professor of chemistry and biochemistry, Natalie Ahn.

Kapteyn joins one of the nation's most prestigious organizations, which engages its members to share knowledge and address challenges facing the world. Its members make contributions to the arts, citizenship, education, energy, government, the humanities, international relations, science, and more.

"Membership in the Academy is not only an honor, but also an opportunity and a responsibility," said Jonathan Fanton, President of the American Academy. "Members can be inspired and engaged by connecting with one another and through Academy projects dedicated to the common good. The intellect, creativity, and commitment of the 2018 Class will enrich the work of the Academy and the world in which we live."

FREQUENCY COMBS HELP DETECT METHANE LEAKS

Frequency combs, a JILA technology both pioneered and perfected by JILA Fellow and Nobel laureate John "Jan" Hall, have found yet another application: quantifying methane leaks as tiny as a quarter of a human exhalation from nearly a mile away.

The new equipment, created by CIRES, NOAA, CU Boulder and NIST scientists, ruggedized Hall's laser technology. The scientists turned the frequency comb, which is usually at least an optics table wide and very sensitive to thermal fluctuations, into a 19-inch portable unit to tote into the field. The instrument is used to detect methane leaks from oil and gas operations at a fraction of the cost of previous technologies.

More information on this new application of frequency combs can be found on the CIRES website (https://cires.colorado.edu/news/detecting-methane-miles-away).

MURNANE WINS SFI ST. PATRICK'S DAY SCIENCE MEDAL

JILA Fellow Margaret Murnane was awarded the Science Foundation Ireland's (SFI) prestigious St. Patrick's Day Science Medal on 14 March 2018 in Washington D.C., for her significant contribution to academia, research and industry.

Murnane's many achievements include designing some of the fastest lasers in the world and creating table-top affordable X-ray lasers. Applications of both works advance the wider research community.

The SFI St. Patrick's Day Science medal is awarded annually to distinguished Irish scientists, engineers, or technology leaders living and working in the US.

Murnane was born and raised in County Limerick, Ireland, before moving to the US to complete her Ph.D. in physics at the University of California at Berkeley. She continues to play a significant role in research and the promotion of science in Ireland, in her keen and ongoing support of the Tyndall National Institute of Cork.

From the SFI website: On accepting her SFI St. Patrick's Day Science Medal, Prof Murnane said: "My passion and love for physics first came from my father who was a teacher, and this grew when I attended University College Cork and completed my Bachelors there. Today I am proud to say that the education I started in Ireland and continue to develop in the US has allowed me to follow my interests and create technology and systems which can be used across different areas of research in both countries today. In my work with the Tyndall Institute, I have seen first-hand the fantastic research taking place in Ireland which has applications around the world. As an Irish citizen living in America, it heartens me to see the continued collaboration between the two countries to ensure the research community in both Ireland and the US can produce the very best work. Today, I am very honoured to receive the SFI St. Patrick's Day Science Medal."

The award was presented by Taoiseach Leo Varadkar to both Murnane and David McCourt, Founder and CEO of Granahan McCourt Capital. Read more about the award on the SFI website.

YE WINS 2018 I.I. RABI AWARD FOR RESEARCH ON OPTICAL LATTICE ATOMIC CLOCKS

JILA Fellow Jun Ye was named the 2018 winner of the I.I. Rabi Award by the IEEE Frequency Control Symposium. Ye was recognized "for the development of stabile, reproducible, and accurate atomic clocks based on optical lattices, and the use of those clocks to probe fundamental atomic interactions and quantum many-body systems."

The award recognizes Ye's sustained leadership in perfecting optical lattice atomic clocks as the most accurate and precise timekeepers in the world, and Ye's continual pioneering of new physics, such as his recent first-in-the-world Fermi degenerate gas atomic clock using quantum many-body physical principles to dramatically improve clock accuracy and stability.

The IEEE Frequency Control Symposium is the world's largest and most important scientific society dealing with atomic timekeeping and related topics. The I.I. Rabi Award is the Symposium's highest award for scientific research in atomic timekeeping. Award namesake Isidor Rabi was the 1944 Nobel Physics Laureate for his invention of the resonance technique in molecular beams. In 1945, Rabi was the first to suggest this method could be used to make atomic clocks, and indeed Rabi's method was adopted for the best atomic clocks for several decades. More recently, Ye and other scientists perfected the new and more precise method of optical lattice atomic clocks.

Previous I.I. Rabi Award winners at JILA have included JILA Fellows Jan Hall and Judah Levine.

The award was formally presented to Ye at the International Frequency Control Symposium in Squaw Creek, CA, May 21–24, 2018.

KARL WINS BEST STUDENT PAPER AWARD AT SPIE ADVANCED LITHOGRAPHY CONFERENCE

JILA graduate student Robert Karl, Jr. won the 2018 Karl Urbanek Best Student Paper award at SPIE Advanced Lithography Conference.

Karl is a graduate student in the Kapteyn-Murnane group at JILA. His paper was entitled, "Characterization and Imaging of Nanostructured Materials using

Tabletop Extreme Ultraviolet Light Sources". The award was presented by Metrology, Inspection, and Process Control for Microlithography Conference Chair Vladimir Ukrainsev, and Conference Co-chair Ofer Adan.

Graduate Student Christina Porter, also from the Kapteyn-Murnane group at JILA, received an honorable mention.

This annual award is sponsered by KLA-Tencor.

PAT MCINERNY, JILA'S FORMER EXECUTIVE OFFICER, DIES AT 77

William Patrick (Pat) McInerny passed away on May 4, 2018 after a long battle with kidney disease. He was 77.

McInerny was the National Institute of Standards and Technology's Executive Officer for JILA from 1971 to 2003. He loved working at JILA, and managed all staff and finances while the institute developed much of the scientific reputation it enjoys today.

Pat is survived by his wife of 55 years, Jacqueline McInerny, and their three children and seven grandchildren. Jackie and Pat enjoyed Colorado life, embracing an outdoor-focused lifestyle full of weekend hiking, camping and ski trips.

Those that knew Pat say he had an infectious personality and an unending sense of humor. He was caring and thoughtful, and always willing to lend a hand to family, friends, and strangers alike.

More information about Pat McInerny's life, as well as space to share condolences, can be found at: https://www.drinkwinemortuary.com/notices/William-McInerny.

A funeral mass was held on Friday, May 25th at 1:00 p.m. at St. Thomas Aquinas Catholic Church, 898 14th Street, Boulder, CO, 80302. A Celebration of Life will be held followed the Mass in the St. Thomas community center.

In lieu of flowers, Pat's family requests that donations be made to the Denver Hospice Center (http://giving.thedenverhospice.org/site/Donation2?2180.donation=form1&df_id=2180&mfc_pref=).

JEN HARLOW, JILA GRADUATE, DIES AT 33

JILA graduate, Dr. Jennifer (Jen) Wightman Harlow, died in a rockfall accident on May 14, 2018. She was 33.

Jen came to JILA in 2007 after earning her A.B. in physics from Harvard University.

As a graduate student, Jen studied ultrasensitive measurement at the limits imposed by quantum mechanics in the lab of Konrad Lehnert. She graduated with her Ph.D. in physics from the University of Colorado Boulder in 2013. Her thesis was entitlted, "Microwave Electromechanics: Measuring and Manipulating the Quantum State of a Macroscopic Mechanical Oscillator."

After graduating from JILA, Dr. Harlow moved to Dar es Salaam, Tanzania, to work for EGG-energy, a solar energy company. In 2015 she moved to Cape Town, South Africa, to join Dimagi as a field technology leader. There she provided technical solutions and capable building for various development organizations across Southern and Eastern Africa.

Coming from the mountains of California, Jen grew up with a love for hiking, running, swimming, and skiing. For much of her time in the U.S., Jen raced in cross-country skiing at the national level. Once in South Africa, she joined the Hiker's Search and Rescue team, excited to spend time outdoors and keep others safe.

Friends of Jen at JILA knew her to be a steadfast individual with an infectious laugh. On top of spending time outdoors, Jen also enjoyed dancing, board games, and cooking. She formed many close friends at JILA.

HOW MAGNETISM MELTS AWAY

A Super-Excited Spin State Thaws Magnetic Order

Magnets hold cards to your fridge and store data in your computer. They can power speakers and produce detailed medical images. And yet, despite millennia of use, and centuries of study, magnetism is still far from fully understood.

Members of the Kapteyn-Murnane group at JILA recently discovered that the underlying cause of magnetism—the quantum spin of the electron—can be manipulated 10 times faster than previously thought possible. And while this result may be very useful in practice, the causes are not yet understood.

Magnetism, while complicated in detail, has simple origins: it arises from electric charges moving in a circle. Creating a weak magnet is as simple as looping a current-carrying wire. And the magnetism intrinsic to materials, like that in your fridge magnet, also arises from circulating charges, albeit very small ones.

Every electron has a quantum property, called spin, that generates a tiny magnet. Quantum law dictates that no two electrons can have the same spin alignment while in the same location. This law encourages nearby spins in most materials to pair in opposite alignment—one spin is up, the other spin, down. These pairings cancel out the electrons' magnetism, and are the reason why most materials are not magnetic. But in the strongest of magnetic materials, the spins of all the electrons align in the same direction, resulting in a net magnetic field.

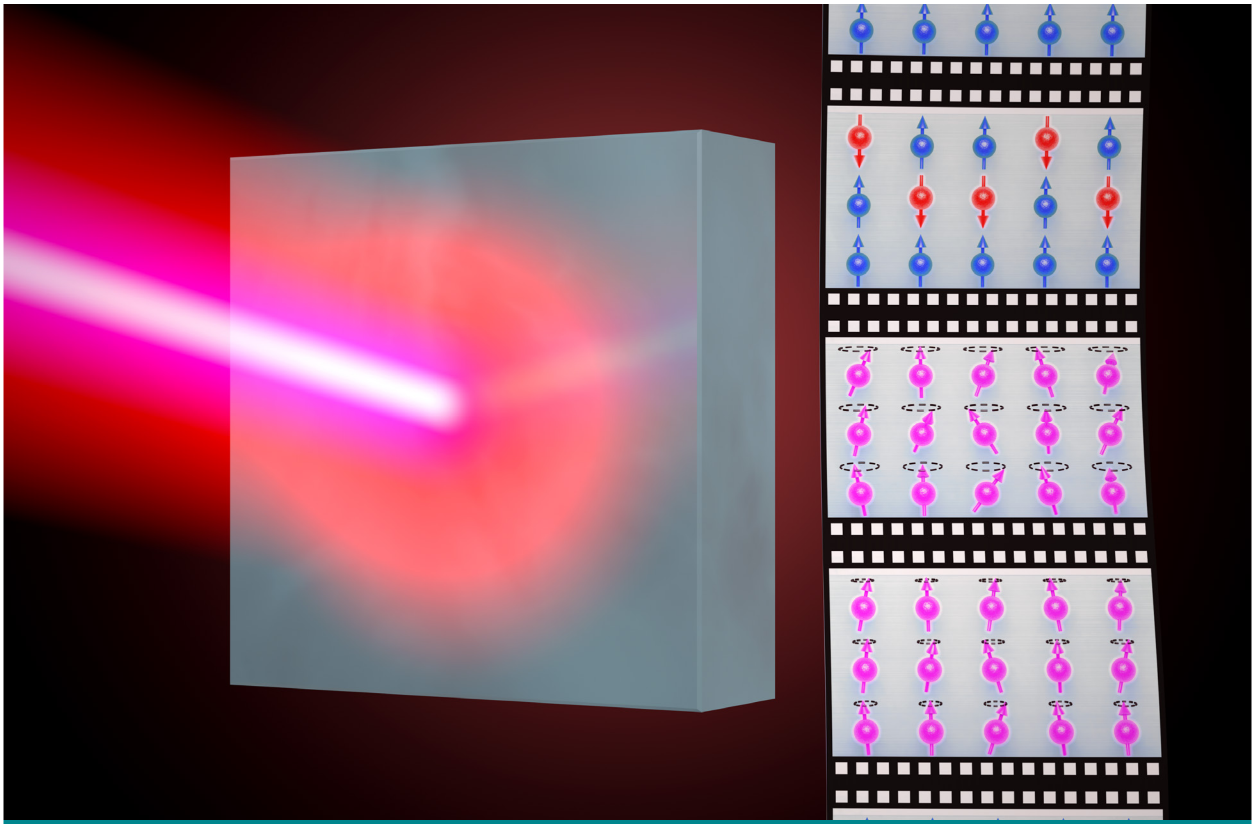
These strong magnetic materials, officially called ferromagnets, are often called "permanent magnets" due to their ability to retain magnetism. A ferromagnet can lose its magnetism, however, if the electron spins are randomized. The spins of a ferromagnet will transition from aligned to randomized if heated. The temperature at which the spins transition, and the magnetism melts away, is called the Curie temperature.

While ferromagnets can be heated through conductive (e.g., hot plate) or convective (e.g., oven) means, it is also possible to heat them with radiation (e.g., laser pulse). And with the evolution of rapid, femtosecond (1 fs = 10^{-15} seconds) laser pulses, the timescale on which ferromagnets can be demagnetized is decreasing rapidly. So rapid, in fact, that laser demagnetization is now relevant to fast, energy-efficient electronics and data storage.

But understanding exactly how fast magnetism can melt away is complicated. Because electrons are very small, very fast, and interact on very short (fs) timescales, we simply did not have tools capable of capturing the fast melt of spin alignment—at least until very recently.

A team of students and scientists at JILA made a series of surprising discoveries using femtosecond bursts of visible and X-ray laser light. Most recently, they showed that the electron-spin system in a laser-heated ferromagnet can be driven into a previously unknown super-excited state, where the spins of some of the electrons flip to opposite alignment. This can happen on timescales 10 times faster than previously realized, within a fleeting 20 fs.

Several spins flipping to opposite alignment is not the same as the spins randomizing, a process which the team observed later, at about 200 fs.

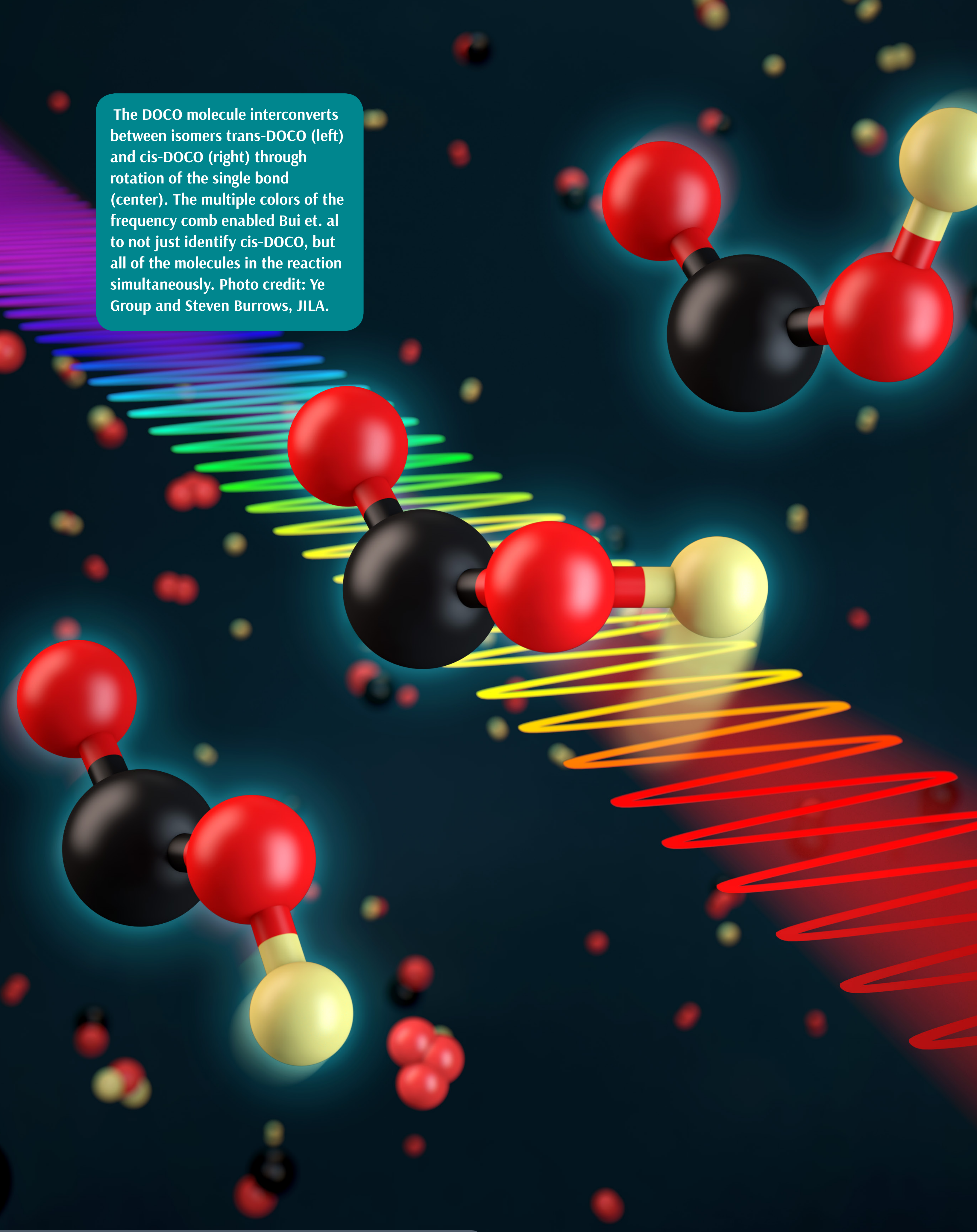


If the electrons in a ferromagnet are heated above the Curie temperature by a femtosecond laser, the spins also become excited. This heating process creates a previously unobserved super-excited magnetic state within 20 fs. Excess energy acquired during the heating process gets deposited into the spin system (2nd frame). The spin alignment later randomizes, within ~ 200 fs (3rd frame). Photo Credit: Kapteyn-Murnane Group and Steven Burrows/JILA.

These new observations of how magnetism melts away can be compared to the much slower process of heating ice water. If we add heat to a mixture of ice and water, the temperature of the water does not initially rise above the freezing point (0˚C), because the heat energy must first melt the ice. Similarly, in a laser-heated magnet near the Curie temperature, the spin alignment does not immediately randomize because the laser energy must first flip individual spins.

Specifically, research by graduate students Phoebe Tengdin and Wenjing You, in collaboration with Postdoctoral Researchers Dr. Zhensheng Tao and Dr. Xun Shi, all in the Kapteyn-Murnane group at JILA, indicates that there is an as-yet not understood spin state in ferromagnetic systems that can soak up energy on 20 fs timescales. This finding also demonstrates that spins can be manipulated 10 times faster than previously thought.✺

Phoebe Tengdin, Wenjing You, Cong Chen, Yun Shi, Dmitriy Zusin, Yingchao Zhang, Christian Gentry, Adam Blonsky, Mark Keller, Peter M. Oppeneer, Henry C. Kapteyn, Zhensheng Tao, and Margaret M. Murnane, *Science Advances* **4,** eaap9744 (2018).



The DOCO molecule interconverts between isomers trans-DOCO (left) and cis-DOCO (right) through rotation of the single bond (center). The multiple colors of the frequency comb enabled Bui et. al to not just identify cis-DOCO, but all of the molecules in the reaction simultaneously. Photo credit: Ye Group and Steven Burrows, JILA.

The Energetic Adolescence of Carbon Dioxide

Researchers at JILA unraveled the multistep process behind the formation of atmospheric carbon dioxide.

The reaction, at first glance, seems simple. Combustion engines, such as those in your car, form carbon monoxide (CO). Sunlight converts atmospheric water into a highly reactive hydroxyl radical (OH). And when CO and OH meet, one byproduct is carbon dioxide (CO_2)–a main contributor to air pollution and climate change.

But it's more complicated than that. Before CO_2 is formed, a short-lived, intermediate molecule, called the hydrocarboxyl radical (HOCO), is formed. The existence of HOCO was first proposed over 40 years ago, but the unstable nature of the molecule made it difficult, nearly impossible, to observe. The Ye group of JILA, however, has been closing in on the impossible.

The deuterated version of HOCO, called DOCO, was observed by Bryce J. Bjork, Thinh Q. Bui, Jun Ye, and their collaborators in 2016. Deuteration is the process of replacing the hydrogen atom with deuterium, a heavier version of the hydrogen atom. Dueteration reduced signal contamination from the atmospheric water in the system.

Yet their understanding of the reaction was incomplete. The version of DOCO that the Ye group observed did not dissociate into carbon dioxide. "There were a lot of missing details in the reaction pathway" said Thinh Bui, a postdoctoral researcher in the Ye group.

In their new paper, published in *Science Advances*, every step of the reaction, starting from the reactants, OD and CO, all the way to the final product of CO_2, and every intermediate in between, is finally accounted for.

> The frequency comb not only enabled Bui et. al to identify cis-DOCO, but simultaneously observe all the molecules in the reaction in real-time. Through this simultaneous observation, they discovered that the cis- and trans- populations were interconverting, i.e., the molecule was rotating between either orientation, on a rapid microsecond timescale.

Specifically, the group detected the two variations of DOCO, trans-DOCO and cis-DOCO. The cis- and trans- prefixes denote different geometric isomers, or arrangements of the atoms within the molecule. The two isomers differ by only a single bond rotation, with cis-DOCO resembling a boat, and trans-DOCO resembling a chair.

Cis-DOCO is the more elusive of the two isomers because it is more energetic. Like a child running around, the high-energy cis-DOCO rotates, vibrates, and generally evades detection. Remove this high energy with a molecular collision and the cis-DOCO calms down. Let cis-DOCO run around however, and something more interesting happens: cis-DOCO will dissociate into deuterium and CO_2, a trick that the calmer trans-DOCO cannot do.

The original work by the Ye group identified only the trans-DOCO variation. To identify cis-DOCO, the group had to wade through heaps of overlapping molecule signals.

"We didn't know where the cis-DOCO signal would appear, and we didn't know what it would look like," said Bui. "When you are searching for something exciting that no one has ever seen before, you wish to have a tool that simplifies the problem."

The tool that Bui alludes to is the frequency comb. "It's rising fairly fast to be a rock star in the spectroscopy world," said Bui.

Bui describes the frequency comb as a million lasers in one. Whereas a standard (continuous wave) laser is a single color, a frequency comb can have up to a million colors. Unlike white light, the colors in a frequency comb are not continuous, but discretely, and precisely, spaced. The result is a tool that is both broad yet fine, like a net meant for catching (sight of) molecules.

The frequency comb enabled Bui et. al to not only identify cis-DOCO, but simultaneously observe all the molecules in the reaction in real-time. Through this simultaneous observation, they discovered that the cis- and trans- populations were interconverting, i.e., the molecule was rotating between either orientation, on a rapid microsecond timescale.

Now that all the molecules present during the formation of carbon dioxide are accounted for, the Ye group can begin exploring how to control this reaction. If the Ye group can find a way to stop the interconversion between cis- and trans-DOCO, (possibly by operating at lower temperatures), the group may be able to control the reaction pathway, thereby decreasing or increasing the production of CO_2.

This work was done by JILAns Thinh Q. Bui, Bryce J. Bjork, and Bryan P. Changala, from the group of JILA Fellow Jun Ye. The group worked with T. L. Nguyen and J. F. Stanton from the University of Florida, as well as M. Okumura from the California Institute of Technology.

This research was supported by the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency (Spectral Combs from UV to THz), the National Institute of Standards and Technology, and the National Science Foundation's JILA Physics Frontier Center.✺

Thinh Q. Bui, Bryce J. Bjork, P. Bryan Changala, Thanh L. Nguyen, John F. Stanton, Mitchio Okumura and Jun Ye, *Science Advances* **4**, eaao4777 (2018).

Puzzle Instructions

Find all the chemical elements in the puzzle on the next page. The first JILAn to turn in a correct puzzle to Kristin Conrad, JILA X415, you will receive a $25 gift card.

Element Word Search

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B M M U E A L M I M D T M C L M M T C E R E S B T M P M
M R U M O E M M M X T C M U M U I C L A C U E I U G H M
I A M M K U U U E G I M M U I D N A C S Z T F I L E O N
E D U C I I I N N N U P I R L N N E O N A O L L M V F I
O O I B L S O C E I I L T B G A E T G C C E R I U M E C
A N R L E N T S B G E T L E N P T H U O H P P U I S R R
N E A C M S R R E B Y I N R C O S N R S R R M L B I M T
I G B L A A E U O U X X I K N H G M A O O T U O O U I E
S O M L U T G N T N C U O E U N N R M T M U I D I B U R
U R U I T M U N A H T N A L N O U E A H I U D N N I M B
M D I Y M E I C E G E I R I E O T C T E U R O P I U M I
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D H A F N I U M U D I A I M I I A P F L U O R I N E S M
T I R P N E O D Y M I U M U N E D B Y L O M I E E E U C
N M U I C N A R F L M U M I M R T E P R I R T N P I O N
R R U R D E I M L R R A U C G M N L N M K I I L D P M N
M M M I L U M M B R O M I N E U U N M U I D A N A V O D
M I M M N U U M U G U A M E R I C I U M O I I E E B N C
S M O U U A I U U I A E Y R L N R A D I U M G U R T O N
G N M B I I M I N I N D D W M U I S S A T O P A T H S C
M T U E E N L R R D D I O A M T T D S I L I C O N T M U
M U I R M N O U E O U O E L D P Z E L D N L T R H U I R
Y S R Y U F H L H G N A S T I E N I T A T S A A U M U I
M K A L I C E L O T M I A I S N M U N I T A L P N S M U
E U M L D V L E R P Z I R C O N I U M C U L I T H I U M
I R A I I E E T L D Y S P R O S I U M U I M D A C B U L
T C S U R O H P S O H P O H M L P E M U I N E L E S M M
M M M M I I D M O M O B T H O R I U M E R C U R Y A U O
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Actinium
Aluminum
Americium
Antimony
Argon
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Barium
Berkelium
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Bismuth
Boron
Bromine
Cadmium
Calcium
Californium
Carbon
Cerium
Cesium
Chlorine
Chromium
Cobalt
Copper
Curium
Dysprosium
Einsteinium
Erbium
Europium
Fermium
Fluorine
Francium
Gadolinium
Gallium
Germanium
Gold
Hafnium
Helium
Holmium
Hydrogen
Indium
Iodine
Iridium
Iron
Krypton
Lanthanum
Lawrencium
Lead
Lithium
Lutetium
Magnesium
Manganese
Mendelevium
Mercury
Molybdenum
Neodymium
Neon
Neptunium
Nickel
Niobium
Nitrogen
Nobelium
Osmium
Oxygen
Palladium
Phosphorus
Platinum
Plutonium
Polonium
Potassium
Praseodymium
Promethium
Protactinium
Radium
Radon
Rhenium
Rhodium
Rubidium
Ruthenium
Samarium
Scandium
Selenium
Silicon
Silver
Sodium
Strontium
Sulfur
Tantalum
Technetium
Tellurium
Terbium
Thallium
Thorium
Thulium
Ytterbium
Titanium
Tungsten
Uranium
Vanadium
Xenon
Yttrium
Zinc
Zirconium

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University of Colorado **Boulder**

National Institute of Standards and Technology
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About JILA

JILA was founded in 1962 as a joint institute of CU Boulder and NIST. JILA is located at the base of the Rocky Mountains on the CU Boulder campus, next to the Duane Physics complex.

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry and Biochemistry; and Molecular, Cellular, and Developmental Biology as well as in the School of Engineering. NIST's Quantum Physics Division members hold adjoint faculty appointments at CU in the same departments.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and x-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

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