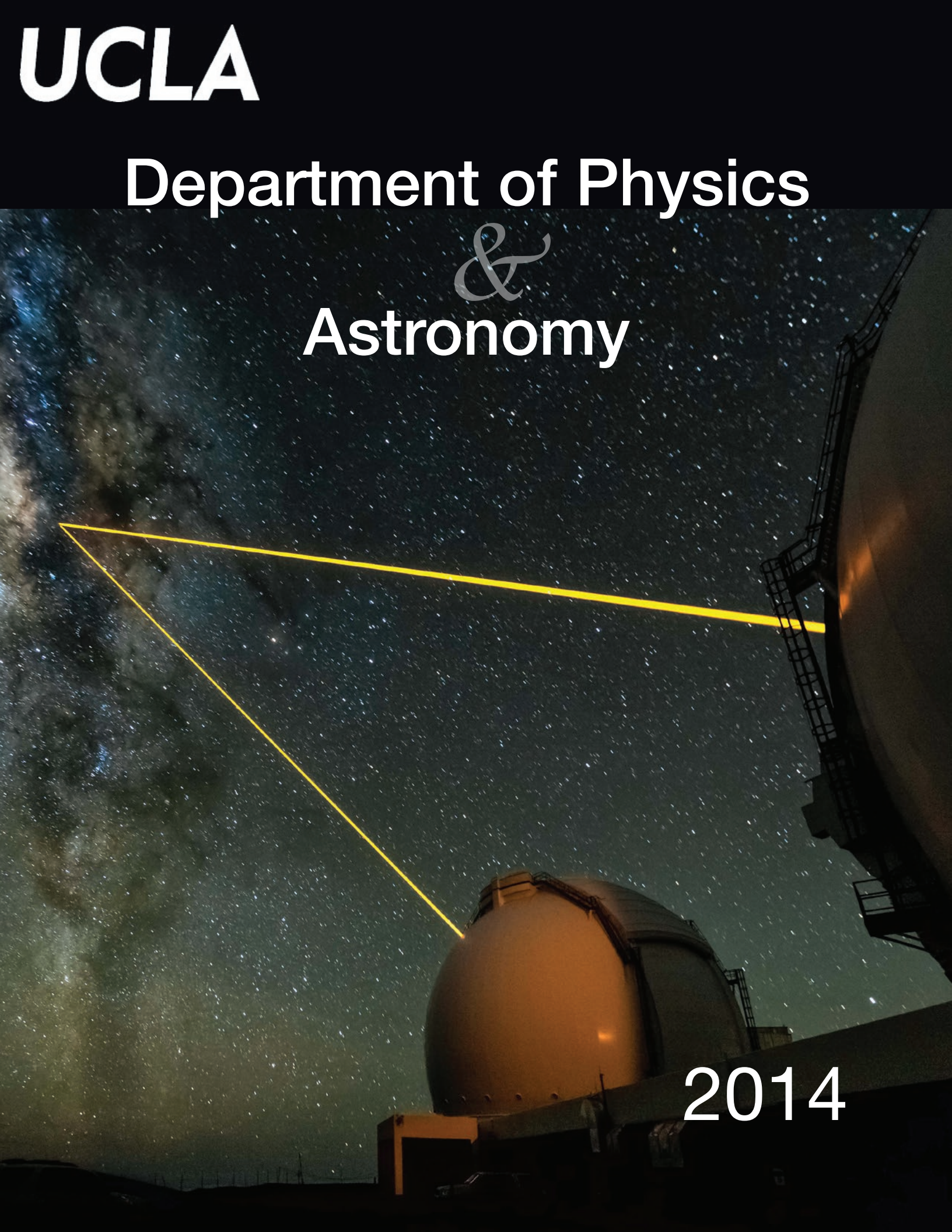


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**Department of Physics  
&  
Astronomy**

**2014**



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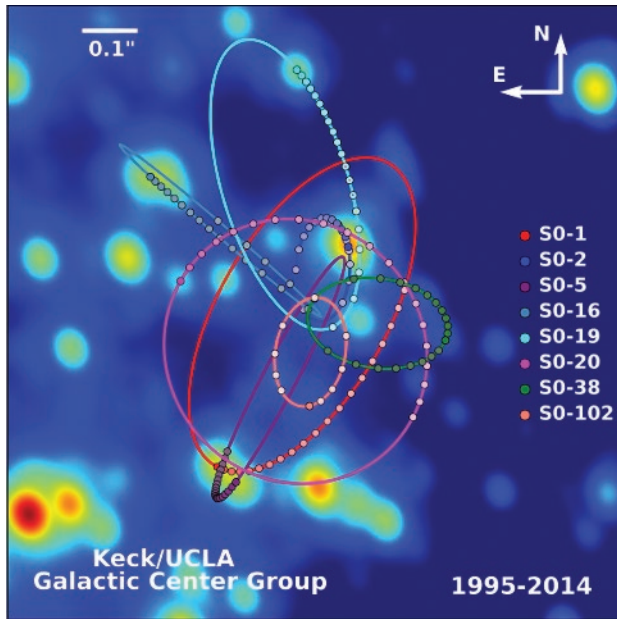
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DEPARTMENT OF  
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&  
ASTRONOMY

2014  
Annual Report

UNIVERSITY OF CALIFORNIA, LOS ANGELES





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# CHAIR'S MESSAGE

It is my privilege to present, in the waning days of my four and a half years of service as Chair, the 2013-14 Annual Report of the UCLA Department of Physics and Astronomy. We have been producing this document for over a decade now to capture in a compact volume the most exciting developments here in the department. It permits us a chance to reflect on the previous year, and bask momentarily in the glow of our collective and individual accomplishments. Given that this report is by nature a snapshot that captures a transient picture of the myriad activities in education and research in our department, it is not a deep treatment of the subject; the Annual Report should instead serve as a stimulating introduction to our programs. Much more information can be found on the departmental web site, as well as the sites dedicated to the faculty and research groups. The interested reader is encouraged to explore these sites in depth, as in them one finds a wealth of resources for obtaining a deeper understanding of our efforts.



James Rosenzweig, Chair

We may also profit and learn from looking at the image of this department as seen from our colleagues worldwide. UCLA has recently been placed in a rarefied position among the leading research universities, and in this year's Times of London rating we note that UCLA has been named the highest-ranking public university program in the world in the physical sciences. Indeed, for the first time, UCLA has edged its sister campus, UC Berkeley, for this coveted position. We can all be extraordinarily proud of this designation, as it represents the cumulative achievements of present and past students and faculty.

This high level of esteem from colleagues and competitors is paralleled by progress in widening and deepening the scope of our educational programs. We note that the number of undergraduate majors — a unique mix of physics, astrophysics, and biophysics students — has increased by a factor of two in recent years. Similarly the recruited classes for our graduate programs in the past two years have expanded commensurately. In order to support this expanded cohort of emerging research scholars in an age of stressed state funding and instability in federal research investments, we have turned increasingly to gifts and grants from private sources. An excellent example of this phenomenon is found in the Schwinger Graduate Fellowship, funded as a gift from the Julian Schwinger Foundation (Professor Seth Putterman, board president), named after our own Nobel Prize-winning theorist. This endowed position enables the department to offer a prestigious named fellowship to an elite incoming graduate student.

We are very excited to have welcomed three new faculty members to our ranks this year. Smadar Naoz is a theoretical astrophysicist specializing in both cosmology and planetary dynamics, who has arrived as an Assistant Professor at UCLA from the Harvard Center for Astrophysics, where she held the prestigious Einstein Fellowship. The Astronomy Division was also greatly strengthened by the addition of noted observational astronomer Professor Tommaso Treu, previously of UC Santa Barbara. Professor Treu has made essential contributions in numerous areas in extragalactic astronomy, including dark matter, star formation, and black holes. The third new faculty member added this year is Professor Frank Jenko, who is coming to UCLA from the Max-Planck-Institut für Plasmaphysik in Garching, Germany. Professor Jenko is a computational plasma physicist with internationally recognized expertise in turbulence as well as in plasma simulation methods, a field that originated at UCLA.

The bulk of the Annual Report consists of short reports from the various research groups, providing a glimpse of the most exciting research projects in the department today, and the results they have uncovered in the past year. We also shine a spotlight on one particular subject in the Annual Report, in the form of a featured article that explores this subject in considerable further depth. This year the focus falls on the achievements of the first 20 years of the Galactic Center Group (GCG), led by Professor Andrea Ghez, and the prospects for further breathtaking discovery in its investigations. The questions being studied in the GCG center on the nature of gravity, elucidated by the black hole at our galaxy's center and its fascinating effects on intricate environment around it. This compelling work involves many of our astronomers, who utilize advanced instruments developed at UCLA and collaborating institutions. These tools included infrared "eyes" installed in large telescopes such as the Keck Telescopes that can see into the past, or the optics created in our IR Lab (Professor Ian MacLean, director), as well as the corrective "glasses" of the adaptive optics utilized to make images with unprecedented

resolution. Even as stunning results pour in from today's astronomical instruments, the next generation Thirty Meter Telescope (TMT) with dramatically higher resolution and light collection capabilities is proceeding, with strong UCLA leadership involved. The featured article gives a concise introduction to this exciting research.

The rest of the Department's research portfolio is well represented in the brief reports from the various research groups. The variety of topics covered in a single department is quite striking, as it illustrates the increasingly multi-disciplinary nature of scientific research in general, and the broadening definition of physics in particular. Physics now has boundaries that extend from the infinitesimal scales of elementary particles and their interactions, to the macroscopic and complex phenomena investigated by biophysicists. UCLA has great strength in these areas, and nearly all others in between: the curious behavior of new quantum materials in condensed matter physics; four-dimensional imaging at the atomic-molecular level based on new types of accelerator-based X-ray sources; new energy frontiers being explored in large-scale plasma physics experiments; the fundamental physics underpinning quantum computers in atomic-molecular-optical physics laboratories, and more. I urge you to explore the diversity of this research in more detail in the research group reports.

The research outlined above proceeds hand-in-hand with our academic programs. The graduate course curriculum in both physics and astronomy have been revamped in recent years, and we are turning our attention to reform of undergraduate courses both inside and outside of our majors. We are now studying the introduction, jointly with Electrical Engineering, of an honors version of introductory physics for scientists and engineers. This is complemented by revisions of the introductory physics for life sciences labs, as well as the initiation of an analysis of the reform of this course series with the involvement of the Department of Mathematics and the Division of Life Sciences. In order to meet the demands of dramatically increased upper division class enrollment, we are examining the optimized use of online resources in teaching.

The UCLA Physics and Astronomy family suffered two losses in the past year, with the deaths of two emeriti: Professor Bernard "Ben" Nefkens and Professor Nina Byers. Professor Nefkens is remembered through donations to the Ben Nefkens Memorial Fund, which is dedicated to student support in his research specialization of intermediate physics. The estate of Professor Byers has, per her wishes, bequeathed money to fund a yearly Nina Byers Lectureship, which will enable a short residence at UCLA by an eminent outsider academic who is on the cutting edge of research in fundamental areas of physics.

This endowment, as well as the Schwinger Fellowship, reminds us of the critical advantage that gifts can make in reshaping departmental programs. As the funding environment within the department remains challenging, with modest increases in state support offset by diminishing of federal support, the generosity of private donors takes on increasing importance. As such, I encourage all who are interested in enabling the department's mission of educating the next generation of physicists and astronomers, while pushing back the frontiers of current knowledge — in both applied and basic science — to consider deepening their involvement in the department. Let this report be a starting point.



Ian McLean  
Vice Chair Astronomy

As hinted at above, I will be leaving the Chair's office at the beginning of the new year. The reins of the department will be placed in the capable hands of Professor Jean Turner, a noted radio-astronomer. While I look backward at the rewarding experience of helping the department define its collective future, I also look forward to a return to academic life. I will be fully engaged in teaching and research, occupying myself in the development — in collaboration with Professors Pietro Musumeci and Rob Candler — of an exciting new type of miniaturized soft X-ray free-electron laser, in a project funded by the Keck Foundation. It is the opportunity to develop high-risk initiatives such as this that make me profoundly grateful to be part of both a university and a department that appreciate and support such efforts.



# UCLA GALACTIC CENTER GROUP 20 YEARS OF DISCOVERY

- *What can our Galaxy tell us about our universe?*
- *What is gravity: was Einstein right?*
- *How do black holes grow?*
- *How does a black hole shape our Galaxy?*

The UCLA Galactic Center Group (GCG), led by Professor Andrea Ghez, is hoping to be able to answer these and other fundamental questions in the not-too-distant-future.



Founded 20 years ago by Andrea Ghez, Eric Becklin and Mark Morris, the GCG is one of the most active and most respected groups in infrared astronomy. It is dedicated to researching the innermost regions of the Milky Way at the highest angular resolution possible to understand the formation and evolution of supermassive black holes and their interaction with their surrounding environment.

*“When we first started out, people didn’t think our approach would work,” Ghez said. “Not only did it work but the technology has progressed so much in the last 20 years that we are now asking questions we simply couldn’t have conceived of asking when we first started. We set out to answer a straight-forward question – Do Supermassive Black holes exist? – and what we found was not only the answer but a whole host of unexpected results that have propelled us into many new and exciting lines of inquiry and discovery. It was been tremendously exciting to be part a new field that has been opened up with new technology. Taking the risk of investing in the development of new technologies has really been a key part of our success.”*

## QUEST FOR DISCOVERY

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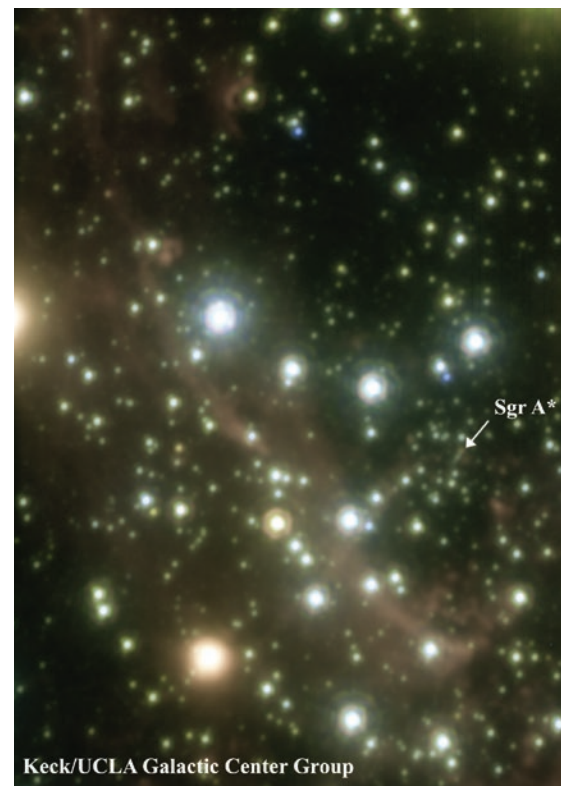
Preston Family Endowed Graduate  
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1994: Ghez was the first to deliver images from Keck observatory that were corrected for the blurring effects of the Earth’s atmosphere, breaking a fundamental barrier and delivering images sharper than those from Hubble Space Telescope by more than a factor of 10.

1998: By tracking the motions of stars, Ghez, Morris and Becklin proved the existence of a supermassive black hole at the center of our Milky Way galaxy, 26,000 light years away and with a mass approximately 4 million times that of the sun.

2000: GCG astronomers were the first to report that stars were accelerating around the supermassive black hole. This research provided the best evidence to date for the existence of black holes.

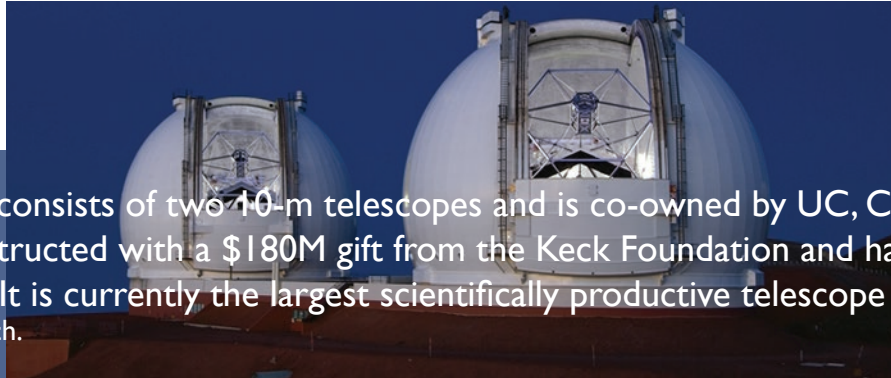
2005: Ghez and her colleagues improved the quality of sharp pictures of the center of the Milky Way by a factor of 100, by using the powerful new technology of Adaptive Optics. With these clear pictures, the GCG uncovered many unexpected discoveries in subsequent years about the environment around black holes, which informs the role black holes play in the evolution of galaxies. This included the presence of young stars, where none were expected, and the lack of old stars, where many were predicted, and an unexpectedly faint, but highly variable emission associated with the accretion flow.



2014: Using more than a decade of Adaptive Optics data, the GCG discovered what appears to be a new class of stars: what may be pairs of stars forced to merge by the black hole's gravitational field. This provides a new possible solution to the mystery of G2, gas cloud falling into the black hole, and points to an important physical process that can influence the long-term growth of the black hole.

2018: The star 'S0-2' is expected to pass closest to our Galaxy's supermassive black hole, enabling precision measurements that will test Einstein's General Theory of Relativity in an unexplored regime (100 times closer to an event horizon and on a mass scale that is a million times larger).

2024 & Beyond: First light on the Thirty Meter Telescope, allowing the GCG to address new scientific frontiers of black hole research, including the first measurement of black hole spin from an orbiting star and catching the first glimpse of the birth of stars in the hostile environment near a black hole.



Keck Observatory consists of two 10-m telescopes and is co-owned by UC, Caltech, and NASA. It was constructed with a \$180M gift from the Keck Foundation and has an operation budget of \$28M/yr. It is currently the largest scientifically productive telescope in the world. Image credit: Laurie Hatch.

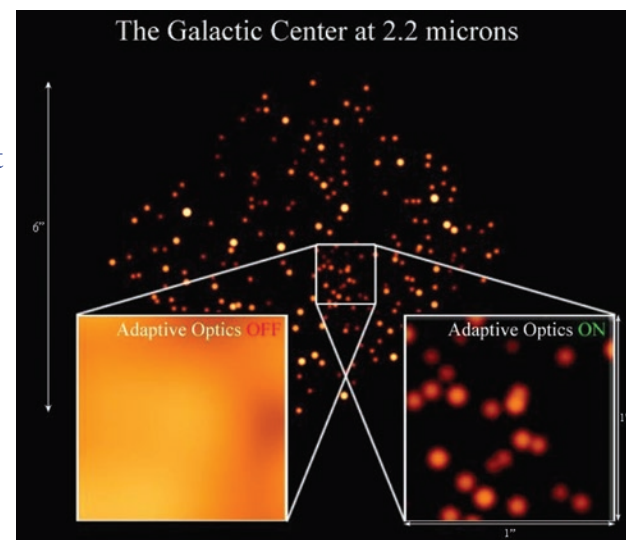
**A NATIONAL PRIORITY** The work of the GCG has been highlighted as a national priority in several high-level reports. For example, it was listed as #7 in NSF's "Nifty 50," which identifies the top 50 "NSF-funded inventions, innovations and discoveries that have become commonplace in our lives," and was also featured in a recent National Academy of Sciences assessment of future opportunities in astronomy.

*"It's been very gratifying to see that scientists throughout the world, including non-astronomers, are aware of our UCLA research effort, and they are always eager to hear the latest news from our group. We're happy to try to meet their expectations that exciting new results will always be forthcoming."* Mark Morris

**TOOLS OF DISCOVERY** Researchers in the GCG use the W. M. Keck Observatory atop Hawaii's dormant Mauna Kea volcano, along with a powerful technology called Adaptive Optics (AO) that Ghez helped pioneer for use in astronomy. AO corrects the distorting effects of the Earth's atmosphere in real time. The clear pictures that AO provides have shown that what happens near a supermassive black hole is quite different than what theoretical models have predicted, challenging many of our notions of how black holes shape our galaxy. In addition to their science goals, the GCG are dedicated to advancing the next generation of high resolution imaging technology through the creation of new data analysis and simulation tools, which are essential for carrying out more sophisticated orbital analysis and informing the design of future instruments.

## THE BENEFIT OF ADAPTIVE OPTICS

Ghez and her colleagues are poised to capitalize on advances in science and technology in order to explore new frontiers of physics and arrive at fundamental new theories of how the universe works and they invest significantly in the development of new data analysis and simulation tools, which are necessary to plan for the next generation of instrumentation and experimentation on both Keck and the Thirty Meter Telescope.



## A COMMITMENT TO EDUCATION AND PUBLIC OUTREACH

The GCG is highly committed to education and public outreach. It strives to inspire and educate the general public about the importance of cutting-edge research and technology by broadly disseminating discoveries about black holes, which have immense popular appeal. Members of the GCG give frequent public talks and their work has been featured in many textbooks, museums, and documentaries (including a documentary released this fall as a companion to the feature film *Interstellar* by Chris Nolan). The group actively trains the next generation of scientists about emerging methods for studying black holes and emerging technologies that are essential for the next generation of telescopes, and is committed to supporting women and others who are poorly represented in the physical sciences through mentoring.

## A LEAN OPERATION

The GCG has made its extraordinary discoveries through a combination of UCLA support, federal grants, foundation grants and private donations. It is a lean, well-run operation, and every dollar is stretched as far as possible. By contrast, the GCG's main research competition, the Max Planck Institute in Germany, is supported by a large, steady supply of guaranteed public funds.

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The GCG hopes to attract additional major philanthropic investment to enable the Group to expand the scope of its exciting research, develop new technologies, and uncover the mysteries of black holes and galaxies in our universe.

*"The Galactic Center Group plays a key role in the Astronomy Division," said Ian McLean, Vice Chair for Astronomy. "Galactic Center research provides many synergistic opportunities for other areas of astronomy. For example, all four infrared cameras and spectrometers in use at the W. M. Keck Observatory were developed entirely, or in part, by the UCLA Infrared Lab, and this group is also involved in new instrumentation for the Thirty Meter Telescope. In addition, the detailed study of the Galactic Center black hole, the nearest supermassive black hole to us, impacts our understanding of the role of supermassive black holes in distant galaxies and the early universe, another major area of research at UCLA. And finally, the gravitational motion of stars around our central black hole has many similarities to the motion of planets around stars; our experts in orbital dynamics can contribute to both fields. The Division of Astronomy has a remarkably effective research program."*

For more information, please visit  
<http://www.galacticcenter.astro.ucla.edu/>



# UCLA'S WORLD-CLASS EXPERTISE

Director and founder of the GCG, **ANDREA GHEZ** is Distinguished Professor in Physics & Astronomy, the Lauren B. Leichtman & Arthur E. Levine Chair in Astrophysics, and a world-leading expert in observational astrophysics. She has used the Keck telescope to demonstrate the existence of a supermassive black hole at the center of our Galaxy. She has received many honors, including election to the National Academies of Science and the American Academy of Sciences in 2004, a MacArthur Fellowship 2008, and she was the first woman to be awarded the prestigious Crafoord Prize in Astrophysics in 2012.



The GCG's Associate Director (and co-founder) is **MARK MORRIS**, Distinguished Professor of Physics & Astronomy and an internationally renowned expert on our Milky Way Galaxy. This relatively extreme environment is characterized by high densities of stars, gas and energy, as well as very strong magnetic fields. All of this gives rise to a variety of phenomena not evident elsewhere, including stellar collisions, large-scale shocks, powerful magnetohydrodynamic displays, and a central, supermassive black hole. He has been a member of the UCLA faculty since 1983, and is former chairman of the Department. He received the UCLA Distinguished Teaching Award in 2004.

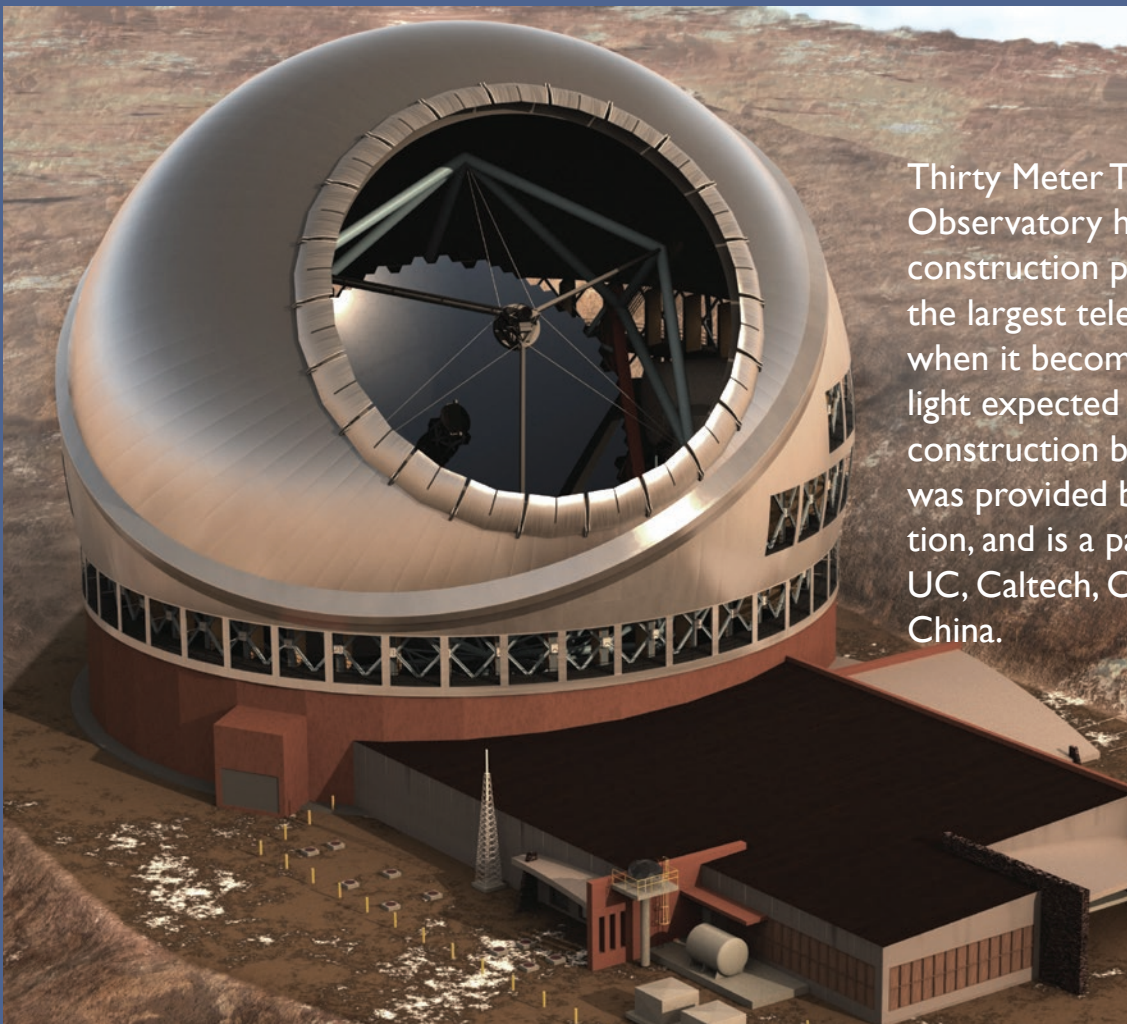


**ERIC BECKLIN** is co-founder and Distinguished Professor of Physics & Astronomy and a pioneer of infrared astronomy. Over his career, he has focused on the search for Brown Dwarfs (objects that do not have sufficient mass to sustain nuclear burning and are the missing link between stars and planets), the detection of dust rings around stars that are related to planet formation, the dynamics and compositions of the center of our Galaxy, and the nature of luminous infrared galaxies. He was the first person to detect infrared light from the center of our Galaxy more than 40 years ago and was elected to the American Academy of Arts & Sciences in 2009.



## ADDITIONAL GCG TEAM LEADERS:

- Tuan Do, Research Scientist and stellar evolution & spectroscopy expert
- Michael Fitzgerald, Assistant Professor of Physics & Astronomy; instrumentation expert
- Brad Hansen, Professor of Physics & Astronomy; theory expert
- James Larkin, Professor of Physics & Astronomy; instrumentation expert
- Francis Longstaff, Professor and Finance; time series analysis expert
- Jessica Lu, Assistant Professor of Astronomy (Univ. of Hawaii); star formation & imaging expert
- Keith Matthews, Lead Instrumentation Specialist at California Institute of Technology
- Smadar Naoz, Assistant Professor of Physics & Astronomy; theory expert
- Matthias Schoeck, Instrument Scientist at Thirty Meter Telescope International Observatory; adaptive optics expert
- Peter Wizinowich, Head of Adaptive Optics Team at W. M. Keck Observatory



Thirty Meter Telescope International Observatory has just entered the construction phase and will become the largest telescope in the world when it becomes operational (first light expected 2024). It has a \$1B construction budget, of which \$200M was provided by the Moore Foundation, and is a partnership between UC, Caltech, Canada, Japan, India, and China.

TO LEARN MORE ABOUT THE **UCLA GALACTIC CENTER GROUP**, PLEASE VISIT [HTTP://WWW.GALACTICCENTER.ASTRO.UCLA.EDU/](http://WWW.GALACTICCENTER.ASTRO.UCLA.EDU/)

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Lauren B. Leichtman and Arthur E. Levine Astrophysics Endowed Chair  
UCLA Galactic Center Group Fund

Jerry Magnin  
UCLA Galactic Center Group Fund

Janet Marott  
Janet Marott Student Travel Awards  
UCLA Galactic Center Group Fund

Howard and Astrid Preston  
Howard and Astrid Preston Graduate Colloquium Fund  
Preston Family Endowed Graduate Fellowship in Astrophysics  
Physics and Astronomy Capital Support  
UCLA Galactic Center Group Fund

Shirley Saxon  
David Saxon Physics Graduate Fellowship Fund

Robert and Jane Schneider  
Physics and Astronomy Graduate Award

Dorothy P. Wong  
Eugene Y. Wong Physics Graduate Fellowship



Alumni and supporters celebrate the UCLA Centennial Campaign launch with a Royce Hall light show.

## THE CENTENNIAL CAMPAIGN FOR UCLA

UCLA has launched the \$4.2 billion Centennial Campaign to celebrate the anniversary of its founding in 2019. In less than a century, UCLA has emerged as a world renowned university, and the Centennial Campaign seeks to secure UCLA's future as a groundbreaking center for higher education. With California state general appropriations now accounting for only 7 percent of the university's revenues, UCLA must increase its endowment and discretionary funds to compete with other top institutions for the most exceptional students and faculty.

The UCLA Department of Physics and Astronomy seeks philanthropic partnerships to support the groundbreaking research of outstanding faculty and students in its next 100 years in the following high-priority areas: .....

**"We invite our Physics and Astronomy alumni and friends to imagine what's possible in UCLA's next century. To learn more about giving options and how you can make a difference, please contact: Brooke Sanders at 310-794-9045 or [bsanders@support.ucla.edu](mailto:bsanders@support.ucla.edu).**

### **Chair's Discretionary Fund**

An unrestricted gift of any size helps the Chair meet the department's most pressing needs.

### **Endowed Chairs**

Endowed Chairs help recruit and retain the highest caliber faculty, and allow faculty to undertake innovative research not supported by federal grants.

### **Prize Postdoctoral Fellowships**

Due to lack of federal funding, there is a critical need to attract top post-doctoral researchers with a competitive and prestigious prize.

### **Undergraduate Scholarships & Graduate Fellowships**

Scholarships support the most deserving graduate and undergraduate students based on merit, financial need, or a combination of both. Student support has a tremendous impact on our students' lives and future careers.

### **Lab Equipment Upgrades**

Investment in highly technical lab equipment can help our faculty and students perform cutting-edge research for years to come.

### **Public Outreach Support**

You can have a major impact on the department's ability to engage the public in science education by supporting the Astronomy Live! graduate student outreach group and upgrades to the UCLA Planetarium.



## DONOR IMPACT STORY: MICHAEL AND GRETCHEN KRISS

“We have a fundamental belief that basic research is the start of all good things,” said Michael Kriss. Michael and his wife Gretchen have been long-time supporters of UCLA Physics & Astronomy. They decided to renew their commitment to the Michael and Gretchen Kriss Teaching Assistant Award this year after consulting with Department Chair James Rosenzweig on the department’s greatest needs. “We want to support students and ongoing research in physics,” Michael said. “We agreed that the best way to use our contribution was to help support the recruitment and retention of talented graduate students.” Michael is passionate about basic research and physics thanks to his time at UCLA, where he received his bachelor’s, master’s, and PhD in physics working with influential physical acoustician and low temperature expert Isadore Rudnick. Michael’s physics education at UCLA gave him the background he needed to succeed in his career at Eastman Kodak Laboratories, both in the era of chemical film processing and as the company moved toward digital imaging as well as his years at the University of Rochester where he taught and ran the Center for Electronic Imaging Systems. Michael also gives back to UCLA by serving on the Physical Sciences Board of Advisors. We extend our deep thanks and gratitude to Michael and Gretchen for helping UCLA Physics & Astronomy provide needed support for the next generation of scientists, which will have a lasting impact on their careers.



## ALUMNI OPPORTUNITIES

We love hearing about our alums and what they are doing now! Throughout the UCLA Centennial Campaign, we will be reaching out to our alumni to learn more about their personal and professional successes. Alumni are always welcome back to the department. Please email the Chair’s Office to share an update: [chair@physics.ucla.edu](mailto:chair@physics.ucla.edu)

You may also enjoy the UCLA Planetarium’s public shows on Wednesday evenings at 7:00 p.m. (8:00 p.m. during daylight savings).

For more information visit - <http://www.astro.ucla.edu/planetarium/>

As an alumnus, you are eligible for lifetime @ucla.edu email forwarding. Please visit this website to learn more: <https://www.bol.ucla.edu/services/accounts/lifetime>

## INFRARED LABORATORY GROUP:

Ian McLean, James Larkin and Mike Fitzgerald

During the past year UCLA's Infrared Laboratory for Astrophysics (IR Lab) achieved several new milestones in its long run of successes since the lab was founded in 1989 by Professors Becklin and McLean. In the fall of 2013, a powerful new instrument called the Gemini Planet Imager (GPI) obtained "first light" on the 8-m Gemini South telescope in Chile. The IR Lab team designed and built GPI's integral field spectrometer, which allows astronomers to capture images and spectra of planets orbiting other nearby stars.

In February 2014, FLITECAM, the UCLA-built infrared camera for NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA), was successfully commissioned in flight. Another major milestone was reached in May 2014 with the announcement of the formation of an international observatory consortium to move forward on the construction of the proposed Thirty Meter Telescope (TMT) in Hawaii. This news was significant because the IR Lab is the lead organization for IRIS, the Infra-Red Integral-field Spectrograph, which will be the first infrared instrument on the new telescope. The IR Lab also continued its support of the Keck Observatory. Grants were obtained to upgrade OSIRIS, which the lab delivered in 2005. Details on all these stories are given in the paragraphs below.

To image planets more than 10 million times fainter than their host stars, the Gemini Planet Imager employs a high-contrast adaptive optics (AO) system to overcome air turbulence, plus special masks to suppress the host starlight. But planets can remain hidden in the residual light that is dominated by small "speckles" that dance around the field due to irregularities in the optics and in the atmosphere.

These speckles have a strong wavelength variation, and so the Infrared Laboratory designed an integral field spectrograph that simultaneously constructs images of the field in 15-20 different wavelength channels. The spectrograph development was led by Professor James Larkin. The device not only separates the planet from the speckles, but also produces a spectrum of the planet! Like the OSIRIS instrument Professor Larkin delivered to the Keck Observatory in 2005, GPI's integral field spectrograph employs a lenslet array to dissect the image and create 36,822 spectra simultaneously over a square field of view.

The "trick" of speckle suppression with a spectrograph was first demonstrated with the OSIRIS instrument in 2006 by Mike McElwain, then one of Professor Larkin's graduate students. Later OSIRIS was used by Brendan Bowler at the University of Hawaii to take the first spectrum of a directly imaged planet in 2009. The GPI spectrograph is optimized for speckle suppression and this optimization adds another factor of 10 to 100 of contrast relative to the central star, depending on the location of the planet. GPI was shipped to the telescope in Chile in August, 2013 and "first light" on the sky occurred in November 2013. The results were spectacular! Some of the early measurements of the planet Beta Pictoris b contributed to the PhD thesis of UCLA student Jeff Chilcote. Jeff graduated in June 2014 and is now a postdoctoral fellow at the Dunlap Institute, University of Toronto. Jeff Chilcote, James Larkin, and Mike Fitzgerald are members of the GPI science team. The team will begin a large three year survey of nearby young stars in November 2014. In particular, Professor Fitzgerald is leading a group studying circumstellar debris disks, which are tracers of solar systems in formation.

NASA's Stratospheric Observatory for Infrared Astronomy – SOFIA – is a modified Boeing 747 jumbo jet with a 2.5-meter telescope in a cavity towards the rear. The plane can reach altitudes of 45,000 feet, where it is well above most of the water vapor in the atmosphere. Absorption by water vapor, a greenhouse gas, impedes most ground-based observations in the infrared. UCLA's FLITECAM was the last of four specialized instruments needed for the flying observatory to

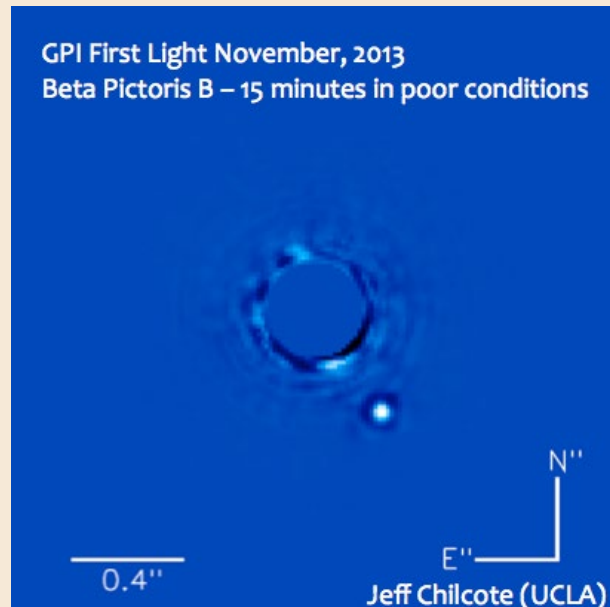


Fig. 1. A reduced image from the "first light" run of GPI in November 2013 showing a very clean detection of the planetary object Beta Pictoris b.

achieve Full Operational Capability. This goal was achieved in February 2014 with six successful missions. On board was UCLA professor and principal investigator, Ian McLean, UCLA emeritus professor Eric Becklin, and UCLA graduate student Sarah Logsdon. IR Lab team members Chris Johnson and Ken Magnone also participated. Nature cooperated by providing a remarkable target of opportunity.

A type IA supernova, the kind used as a standard light source for distance measurements, exploded in the galaxy M82, which is relatively nearby at about 12 million light-years. FLITECAM will have an Acceptance Review in September 2014 and then remain part of SOFIA's suite of instruments.

In collaboration with Caltech and with initial funding from the Moore Foundation, the University of California has established an international partnership with Canada, Japan, China, and India to construct an extremely large telescope on the summit of Mauna Kea, Hawaii. The proposed new telescope will have an effective collecting aperture 30 meters in diameter. The mirror will have the same segmented construction as the successful telescopes at the Keck Observatory, also in Hawaii. A major step towards construction of the TMT was announced in May 2014 when the consortium formed a limited corporation known as the TMT International Observatory. One of the first two instruments to be used on the new telescope will be an integral field spectrograph (IRIS). Professor James Larkin is the principal investigator of the international team tasked with building this huge, adaptive-optics-based instrument. IRIS will provide unprecedented detail on objects ranging from the solar system to the galactic center to the high redshift universe. IRIS is currently in the early stages of its preliminary design phase.

Now with 20 years of scientific history behind them, the twin 10-meter telescopes of the W. M. Keck Observatory in Hawaii continue to be the most productive ground-based telescopes in the world. UCLA's IR Lab contributed to all four of the currently operational infrared instruments in use at the observatory. NIRSPEC, the first high-resolution infrared spectrograph, was delivered in 1999 by Professor McLean. Professors Larkin and McLean assisted Caltech to deliver the first diffraction-limited infrared camera (NIRC2) in 2001. Then in 2005 Professor Larkin delivered the first integral field spectrograph (OSIRIS). Most recently, in 2012, Professor McLean delivered the first multi-object infrared spectrometer (MOSFIRE).

It is therefore not surprising that our group has been asked to propose upgrades to these powerful and successful instruments in order to keep pace with detector technology. During the past year we sought funding to implement detector upgrades for NIRSPEC and OSIRIS. Partial funding was obtained by Professor Michael Fitzgerald to develop a prototype of the NIRSPEC upgrade, and full funding from the NSF was obtained by Professor Larkin to replace the spectrometer detector in OSIRIS. A separate large grant from the Moore Foundation was obtained by Professor Fitzgerald and Professor Andrea Ghez for the purpose of completely replacing the wide-field imager within OSIRIS. Each new detector for OSIRIS will be similar to those already employed in MOSFIRE and GPI.

In other news, during this past year the IR Lab hired a junior software engineer (Ji Man Song), but said farewell to our most experienced engineer George Brims, who retired in June 2014. We celebrated George's 25-year contribution to the IR Lab with a review of his role in all our scientific instruments, followed by a party, and the presentation of mementos on the 3rd floor patio. George will be missed but we wish him well and thank him for his outstanding service. Finally in October 2013 Professor McLean was the opening speaker at the international Scientific Detector Workshop in Florence, Italy. The organizers surprised him with a lifetime achievement award. Asteroid (249544) 2010 HQ44 is now known as Ianmclean.



Fig. 2. On board SOFIA during one of FLITECAM's commissioning flights in February 2014. FLITECAM's display screens are in the foreground. Professor McLean (lower left) and UCLA graduate student Sarah Logsdon (lower right) are at the controls as the bright supernova in the M82 galaxy is moved onto the slit of the spectrometer.



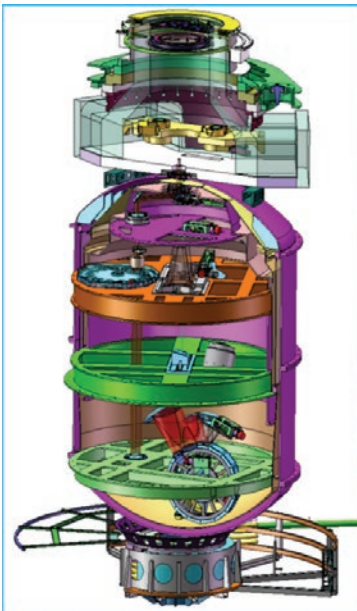


Fig. 3. Conceptual designs for the Thirty Meter Telescope International Observatory and its first infrared camera/spectrometer (IRIS). The IRIS instrument is much larger than previous instruments in this class, and the combination of telescope size, and adaptive optics for the correction of air turbulence, will result in unprecedented image resolution.

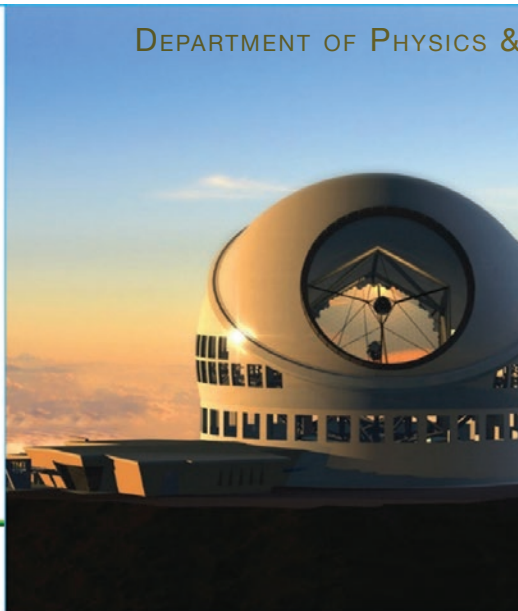
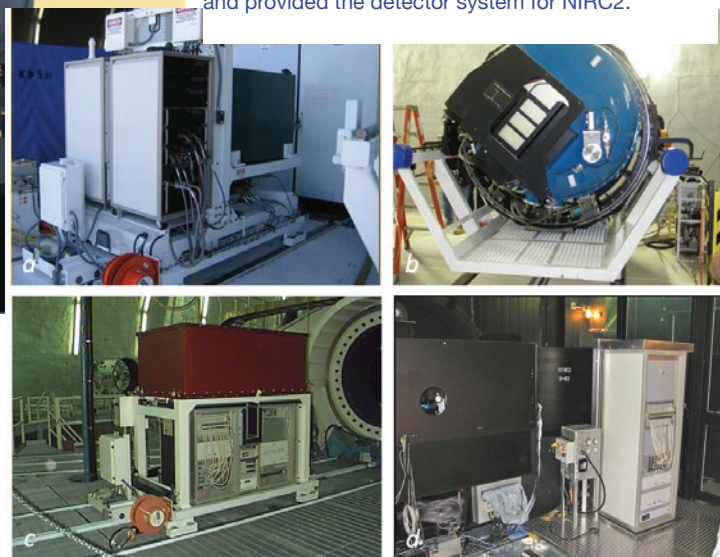


Fig. 4. The four currently operational infrared instruments at the W. M. Keck Observatory on Mauna Kea, Hawaii. (a) OSIRIS, (b) MOSFIRE; both on the Keck I telescope. (c) NIRSPEC, (d) NIRC2; both on the Keck II telescope. UCLA's Infrared Laboratory led the OSIRIS, MOSFIRE and NIRSPEC projects, and provided the detector system for NIRC2.



**Ian McLean** has continued as Vice Chair for Astronomy, Director of the Infrared Lab and Associate Director for the University of California Observatories (UCO). He also continued as co-chair for the bi-annual international conference series on astronomical telescopes and instrumentation sponsored by the society of photo-electronic instrumentation engineers (SPIE). During this reporting period, McLean supported graduate students Gregory Mace, Sarah Logsdon and Emily Martin. Mace obtained his PhD with in June 2014, and is now a postdoctoral researcher at the University of Texas (Austin) and McDonald Observatory. Using NIRSPEC and MOSFIRE at the Keck Observatory, and FLITECAM on NASA's SOFIA, McLean's research includes the study of the coolest sub-stellar objects known as brown dwarfs, as well as star formation in the local and high-redshift universe.



**James Larkin** focuses on the early development of galaxies like our own Milky Way. Using his instrument OSIRIS at the Keck Telescopes, he and his former graduate student Shelley Wright (now a faculty member at University of Toronto transitioning to a faculty position at UCSD) measure the internal motions of galaxies more than 9 billion light years away at a time soon after their formation. A primary goal of this research is to learn when and how these vast structures began to mature into the stable rotating disk galaxies we see in the Universe today. As a byproduct of these measurements they are also able to identify black holes growing at the galaxy centers and can measure the composition of the gas going into the early generations of stars. Larkin's effort to construct the Gemini Planet Imager spectrograph has been assisted by graduate student Jeffrey Chilcote. Chilcote obtained his PhD in June 2014 and is now a postdoctoral researcher at the University of Toronto. Larkin also supports graduate student Anna Boehle, who is working on the OSIRIS upgrade and measurements of local active galaxies.



**Mike Fitzgerald** studies the relationship between exoplanets and dusty circumstellar debris disks, which act as tracers of planet formation processes. He has applied the NIRC2 camera and the Keck AO system to search for faint emission from planets and disks around nearby stars, and has developed similar techniques for the Gemini Planet Imager (GPI). He has worked with graduate students Jeffrey Chilcote, Thomas Esposito, and Li-Wei Hung to develop and apply high-contrast imaging techniques to these systems. He is now applying these methods to observations with the Gemini Planet Imager, and received NSF funding to support this research. Meanwhile he is also leading the upgrade of the OSIRIS imager for the Keck Observatory and the proposed upgrade for NIRSPEC. He is also working with the Professor Ghez's group to model the field-dependent aberrations in Keck AO imaging via the AO Optimization project.

## Mark Morris

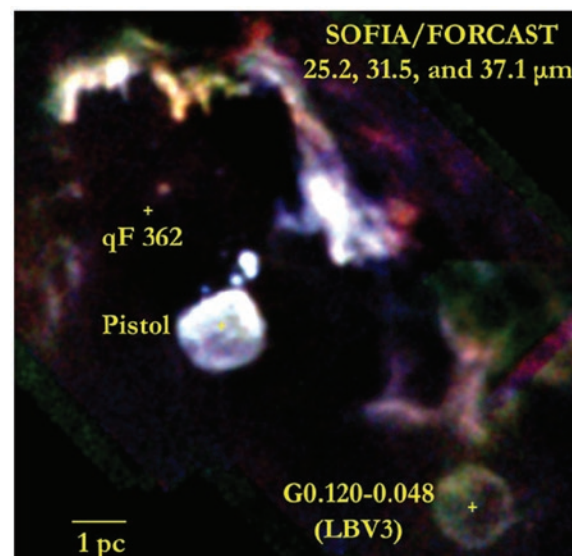
The research of Professor Mark Morris has focused on the central region of our Galaxy, and employed a variety of observational techniques at wavelengths from radio to X-ray. Working with recent UCLA research scientist Zhiyuan Li (now a professor at Nanjing University) and with Fred Baganoff at MIT, Morris combined data from NASA's Chandra X-ray Observatory with radio data from the Jansky Very Large Array (JVLA) to propose that an energetic jet arises from the accretion flow onto the Galaxy's central supermassive black hole. The proposed jet is aligned with the Galaxy's rotation axis, and could be revealing that the spin of the black hole is aligned with that of the Galaxy. Further work is under way to gather additional evidence for this hypothesis.

Morris has also been studying mid-infrared data on the Galactic center from the SOFIA airborne observatory in collaboration with colleagues at Cornell University. They have shed new light on the remarkable bubbles blown by Luminous Blue Variable stars, including the Pistol Nebula, discovered by Morris in the 1980's (see figure). These massive stars shed most of their mass before ending their brief lives as supernovae.

Working with colleagues at the University of Paris 7, Morris has been studying X-ray emission from the Galactic center. Over the past 15 years, this group has witnessed the propagation of extremely luminous X-ray flares through the central zone of molecular clouds at the Galactic center. When energetic X-rays hit neutral iron atoms in the clouds, they eject the most tightly bound electron, leading to a fluorescent cascade that emerges as a series of characteristic X-ray spectral lines. The fluorescent lines move outwards from the central black hole, strongly indicating that the flares arose from dramatic accretion events that took place on the order of 100 year ago. A recent analysis indicates that there have been at least two such flares, one of which

lasted one year or less. As this project continues, Morris and colleagues hope that the temporal profile of the flares can be determined with sufficient detail to be able to perform tomography on the clouds in the Galactic center, and thereby to infer their line-of-sight distance.

As one of the founding members of the Galactic Center research group, now led by Andrea Ghez, Morris has continued to participate in the investigations of the central black hole and the stars surrounding it, carried out at the Keck Observatory for the past 20 years. Several new results have been published by the group during this past year, culminating in a paper on the dust-enshrouded star G2, which went through its point of closest approach to the black hole in early 2014. While other groups have argued that G2 is a small gas cloud that could be pulled apart by the black hole's tidal forces, thus leading to a possible outpouring of accretion energy as the gas falls into the black hole, the UCLA group has found compelling evidence that G2 is a star with an extended, dusty atmosphere. How this came about has been answered by hypothesizing that G2 is the result of a recent merger of two stars in a binary system. The extended, dusty envelope that hides the star might be subject to partial removal by the tidal forces of the black hole.



## EXTRAGALACTIC ASTRONOMY

### Jean Turner

Professor Jean Turner has been studying the efficiency of star formation in regions forming super star clusters in local galaxies. The molecular clouds forming these immense clusters are unlike any clouds known in our Galaxy: they are hot, dense, and unusually dusty.

Professor Turner employs kinematic methods and high spatial resolution to obtain gas masses since standard techniques for finding mass fail in these clouds. She finds star formation efficiencies that are nearly 100 times higher than

in Milky Way gas clouds, and has proposed that the high efficiencies are due to fueling by accretion of circumgalactic streamers of gas.

Professor Turner has been using the Submillimeter Array for this work, and is currently obtaining data with the new Atacama Large Millimeter/Submillimeter Array, working in collaboration with students S. Michelle Consiglio and Joe Izaguirre.



## EXTRASOLAR PLANETARY SCIENCE

### Brad Hansen

Brad Hansen continued his studies of the formation of extrasolar planetary systems. He extended the formation and assembly models previously developed for sun-like stars to study the consequences for low mass stars. Such objects are favored targets for ongoing transiting-planet searches and offer the best chance to study the atmospheres of habitable planets by the transit technique. An encouraging outcome of this study is that it suggests that habitable planets should be common around such stars, which helps to motivate the ongoing searches.

Professor Hansen has also examined models for the early evolution of solid material in protoplanetary disks in order

to understand the initial conditions under which the planetary assembly process occurs. By examining the circulation of small particles (dust) in the disk, such models can provide a natural explanation for the distribution of material that we ultimately see combined together into planets.

Hansen and graduate student Shane Frewen have also completed a study of the effect of stellar evolution on asteroids in extrasolar planetary systems. They find that the mass loss from the central star causes planetary orbits to move sufficiently to destabilize the orbits of some asteroids, perturbing them onto eccentric trajectories.

Some of these asteroids approach close enough to the central star to be disrupted and accreted, which can help to explain the origin of the heavy elements that are observed to be accreted by some white dwarfs.

## HIGH-REDSHIFT GALAXIES

### Alice Shapley Group

A few billion years after the Big Bang, the growth rates of galaxies and the supermassive black holes that they host were at their peak levels.

Currently our knowledge of fundamental galaxy properties is extremely limited during this important epoch. Key questions include: What are the physical processes driving star formation in individual galaxies? How do galaxies exchange gas and heavy elements with the intergalactic medium? How are stellar mass and structure assembled in

galaxies (in situ star formation vs. mergers)? What is the nature of the co-evolution of supermassive black holes and galaxies?

Starting in spring 2013 Alice Shapley and collaborators at the University of California embarked upon the MOSFIRE Deep Evolution Field (MOSDEF) survey (<http://mosdef.astro.berkeley.edu/Home.html>) to address these questions. The MOSDEF survey has been awarded 47 nights from

2013-2016 to use the MOSFIRE near-infrared spectrograph on the Keck I telescope (built here at UCLA, with Professor Ian McLean as co-PI). With MOSDEF, we are collecting rest-frame optical spectra and observe the stellar, gaseous and chemical content of ~1500 galaxies when the Universe was only 1.5 to 4.5 billion years old. So far, we have obtained spectra for more than 600 galaxies. In our early science results, we have already uncovered important evidence that the cycle of gas and heavy elements operates in different manner in high-redshift galaxies relative to what is observed in the local universe. We have also discovered a powerful method for estimating the heavy element content of galaxies based on the strong emission lines observed in MOSFIRE spectra.

Additionally we have determined how to use MOSFIRE spectra to effectively identify the galaxies hosting actively accreting supermassive black holes.

Ongoing work on high-redshift galaxies addresses the nature of dust, the build up of total and stellar mass, and the incidence of large-scale outflows of material. With its rich dataset, MOSDEF will transform our

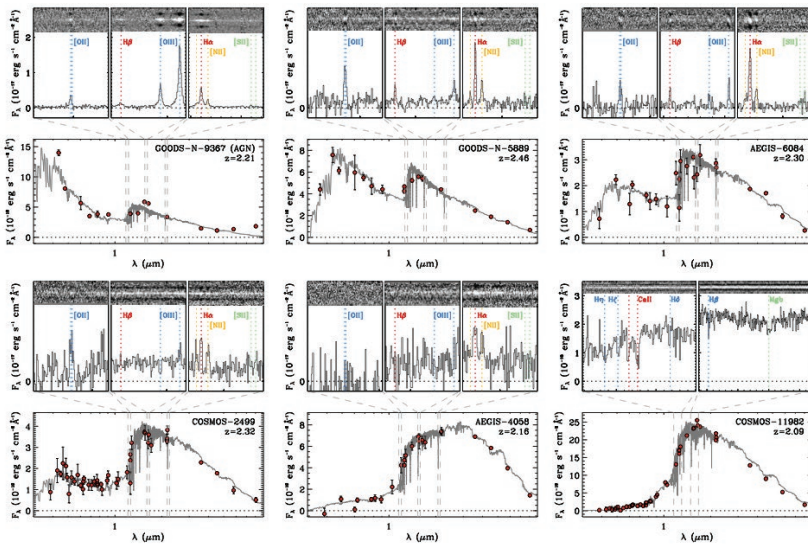
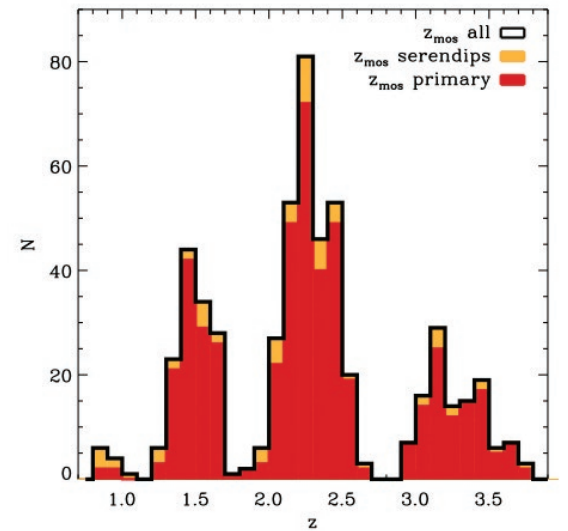


Fig. 1. In the first figure, we show the histogram of >600 redshifts collected thus far in the MOSDEF survey. In addition to galaxies that we target (indicated in red), galaxies fall serendipitously on our MOSFIRE slits. We can also obtain useful information for these “serendips” (shown in yellow).

knowledge of basic galaxy properties in the early universe. The MOSDEF survey is supported by a ~\$1M grant from the National Science Foundation as well as funding from the Space Telescope Science Institute.

Fig. 2. In the second figure, we show examples of spectra collected as part of the MOSDEF survey, along with spectral energy distributions (SEDs) showing the multi-wavelength electromagnetic output of each galaxy. The overall spectral shape highlights the relative importance of young, massive stars, relative to older stellar populations, as well as the effects of dust attenuation. Both the presence of dust and old stars tend to redden the SEDs. The MOSDEF survey covers galaxies with a wide range of stellar populations, spanning from young, blue galaxies to old, red galaxies. Accordingly, we are obtaining a representative sampling of galaxies in the early universe. The MOSFIRE spectra typically show emission lines from ionized hydrogen, oxygen, nitrogen, and sulfur gas. In one case (lower right), we observe stellar absorption lines from hydrogen and calcium.



## COSMOLOGY

### Edward (Ned) Wright

Edward L. (“Ned”) Wright has been working on WISE, with the big news of 2013-2014 being that the spacecraft has been reactivated with funding from the planetary division of NASA to search for asteroids.

After pointing away from the Earth for 2 months, the telescope and detectors cooled to 73 K, colder than liquid air, and started surveying the sky. Notable discoveries so far include 2013 YP139 which is a big potentially hazardous asteroid, and 2014 HQ124 which came within a million miles of the Earth two months after WISE discovered it.

In addition, Professor Wright spent a quarter on sabbatical at the Johns Hopkins Physics and Astronomy department where he had a chance to interact people in the Space Telescope Science Institute across the street. He served on a National Research Council committee that studied whether the proposed use of one of the “free” telescopes from the NRO to make WFIRST-AFTA would be responsive to 2010 decadal survey recommendation of WFIRST.

We concluded that the larger telescope could do the science, even though it is hampered by the warm mirror technology; but that the cost was unlikely to fit within the budget wedge envisioned by the decadal panel.

## PLANETARY SCIENCE AND ASTRONOMY

### David Jewitt

David Jewitt used observations from the Keck and the Hubble Space Telescope to investigate two extraordinary objects discovered in late 2013. Known, somewhat uncomfortably, as P/2013 P5 (Fig. 1) and P/2013 R3 (Fig. 2), both objects are “active asteroids,” meaning that they are asteroids by their dynamics but comet-like by their appearance.

P5 and R3 appear to be the first ever recorded examples of asteroids losing mass through rotational instability. Torque exerted on small asteroids by the momentum of escaping thermal radiation can accelerate the spin on million year timescales. Above a critical spin rate, a sufficiently weak asteroid will begin to fall apart, rotationally.

Jewitt and colleagues attribute the different morphologies of the objects to mass-shedding (regolith falling off the rotational equator in a series of small avalanches) in the case of P5 and true break-up of the body in R3. Although never before directly observed, rotational breakup may be the dominant method of destruction of sub-kilometer asteroids, and a significant contributor to dust production in the inner solar system.

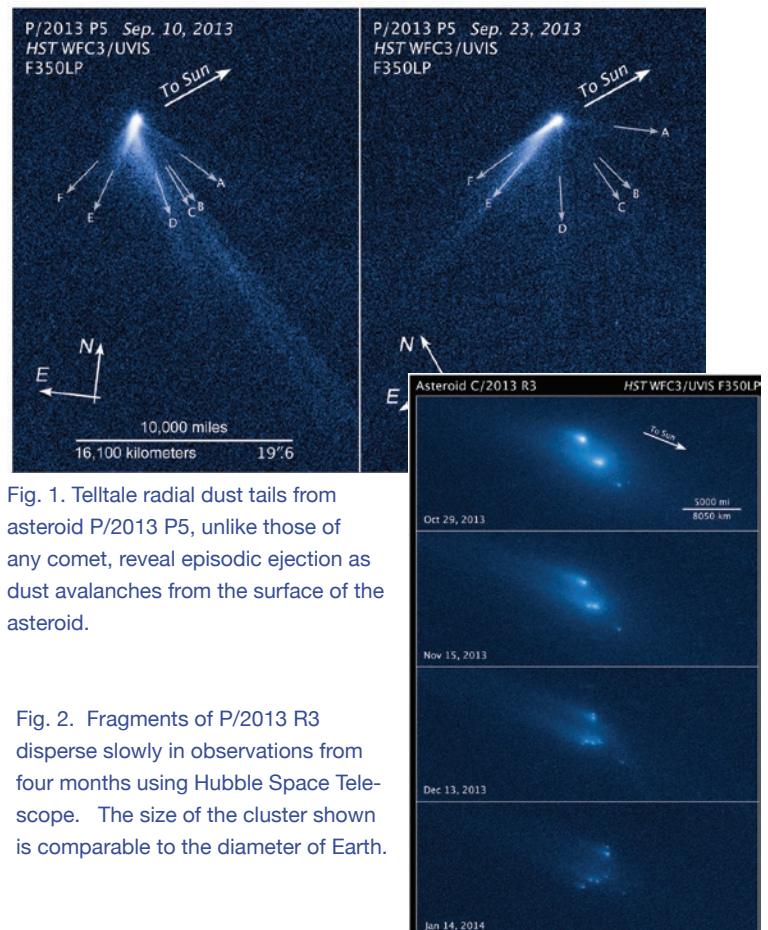


Fig. 1. Telltale radial dust tails from asteroid P/2013 P5, unlike those of any comet, reveal episodic ejection as dust avalanches from the surface of the asteroid.

Fig. 2. Fragments of P/2013 R3 disperse slowly in observations from four months using Hubble Space Telescope. The size of the cluster shown is comparable to the diameter of Earth.



## PLANETS AND EXOPLANETS

### Jean-Luc Margot

Our research group performs high-precision measurements of the shapes and motions of planets, satellites, and asteroids. This work allows us to better understand the interior structure of these bodies and the processes that affect them. The ultimate goal is to help address fundamental questions related to the formation and evolution of habitable worlds.

In the past year graduate student Adam Greenberg enhanced our algorithms for 3D shape reconstruction of asteroids, improving both the speed and the rigor of the modeling procedure. Knowledge of asteroid shapes helps not only with key science questions, but also with trajectory predictions, impact risk assessments, and spacecraft proximity operations. It also allows graduate student Shantanu Naidu to model the complex spin-orbit dynamics in binary systems.

Graduate student Sebastiano Padovan improved our ability to determine the interior structure of the planet Mercury by modeling the response of the solid planet to solar tides. The periodic deformation exceeds a meter and can be detected by tracking the motion of the MESSENGER spacecraft, a task that postdoc Ashok Verma is pursuing.

Professor Margot continues to secure high-precision astrometry of asteroids that orbit deep within the gravitational well of the Sun using the Arecibo telescope (Fig. 1). In the next few years, the data should yield improved tests of general relativity and a purely dynamical measurement of the oblateness of the Sun.

In Summer 2014 our group reviewed 20 articles con-

cerning the search for extraterrestrial intelligence. Recent discoveries about the abundance of planets compel us to seriously consider SETI studies.

In a departure from typical publication venues, Professor Margot published an article in a nursing journal. This article (“No Evidence of Purported Lunar Effect on Hospital Admission Rates or Birth Rates”) counters the persistent but erroneous beliefs that bleeding incidents and human births correlate with the phases of the Moon. George Abell (UCLA) published a similar report in 1979.



Fig. 1. Satellite view of the Arecibo telescope, the largest telescope on Earth. Margot and his group use the 1,000-foot diameter telescope to measure the 3D shapes of near-Earth asteroids and their trajectories with exquisite precision.

## ASTROPARTICLE PHYSICS

### Alexander Kusenko

Warren Essey and Alexander Kusenko have clarified an intriguing connection between gamma rays and cosmic rays that are produced by distant blazars, which are believed to be supermassive black holes accreting matter and accelerating particles in a powerful jet. The highest energy gamma rays observed from most distant sources in the universe appear to be generated not at the source, but in the cosmic ray interactions with photon backgrounds along the line of sight.

This explanation solves a long-standing astrophysical problem and opens a way to measure the magnetic fields in deep voids, away from galaxies. A recent measurement of

the redshift of a very distant blazar, PKS 1424+240, combined with the observations of its gamma-ray spectrum, makes it an excellent testing ground for understanding secondary gamma rays and for measuring the extragalactic magnetic fields.

A recent paper by Warren Essey and Alexander Kusenko shows a good agreement between theory and observation. In a separate paper, Susumu Inoue and Alexander Kusenko make predictions for future observations of Cherenkov Telescope Array (CTA). Thanks to the secondary gamma rays, CTA will be able to observe more distant TeV sources than was originally expected.

UCLA graduate student Lauren Pearce and Alexander

Kusenko, in collaboration with Kalliopi Petraki (a UCLA PhD now working in Amsterdam), have explored a new class of dark matter candidates. In this model the dark matter particles exhibit some properties similar to ordinary

matter. For example, there is an asymmetry between particles and antiparticles, just as there is an asymmetry between matter and antimatter in the universe. The properties of this dark matter allow new approaches for its detection.

## THEORETICAL ASTROPHYSICS

### Steven Furlanetto

Steven Furlanetto's research focuses on the formation of galaxies, quasars, and other luminous sources and their interactions with their environments and each other.

Professor Furlanetto's research group has been exploring the interaction of these sources with the intergalactic medium. Graduate student Fred Davies has examined the prospects of detecting the "reionization era," when light from the first galaxies ionized the hydrogen pervading the universe, by imaging the interface between neutral and ionized gas in the early universe. Former graduate student Lauren Holzbauer and postdoc Joseph Muñoz have examined the rich astrophysics of early galaxies and made novel predictions of

their observability with new and future telescopes, like the Atacama Large Millimeter Array.

Professor Furlanetto is also closely involved in the development of new observational facilities. He is Theory Lead for the Hydrogen Epoch of Reionization Array (HERA, PI: Aaron Parsons, Berkeley), a next-generation radio array that will observe neutral hydrogen in the first billion years of the Universe's history. HERA has received initial funding from the NSF and will begin construction in 2015. Furlanetto is also Theory Lead for the Dark Ages Radio Explorer (DARE; PI: Jack Burns, Colorado), a NASA mission concept to observe this signal via a radio telescope orbiting the moon.

## VERY HIGH-ENERGY (VHE) ASTROPHYSICS

### Rene Ong and Vladimir Vassiliev

The VHE astrophysics group led by Rene Ong and Vladimir Vassiliev carries out research in a broad range of science topics at the intersection between physics and astronomy. The main focus of their studies involves exploring violent phenomena in the Universe, which are capable of producing high-energy (100 MeV – 100 GeV) and very high-energy (>100 GeV) photons. Such gamma rays are emitted in physics processes far from thermal equilibrium, which take place in the vicinities of supernova remnants (SNRs), pulsars and their nebulae, black holes, such as in centers in active galaxies, and in enigmatic gamma-ray bursts.

At these energies gamma rays can also be created in physics processes beyond the standard model of particle physics, such as from the annihilation of unknown particles composing dark matter in the universe, or from the evaporation of primordial black holes if they were produced during early stages of universe evolution. Through their interac-

tion with the cosmological low energy (radio through UV) diffuse radiation fields, very energetic photons also provide unique opportunities to probe cosmologically important backgrounds as well as the very weak intergalactic magnetic fields. These studies could provide key information about the UV/infrared diffuse radiation produced throughout the history of the universe and about the origin of magnetic fields in the galaxies and other astrophysical systems.

The VHE gamma astronomy and astrophysics have been greatly advanced by the relatively recent development of imaging atmospheric Cherenkov technique. VHE gamma rays interacting in the upper atmosphere create showers of relativistic particles that are beamed towards the ground. These particles emit Cherenkov light that can be detected on the ground by large optical reflectors that focus the light onto imaging cameras at the focal plane. The major benefit of this technique is due to very large area of Cherenkov light pool on the ground, ~105 m<sup>2</sup>, comparing to a 1 m<sup>2</sup> – scale area of a satellite, which enables the detection of very low astrophysical fluxes of gamma-rays.

UCLA is a major partner in the Very Energetic Radiation Imaging Telescope Array System (VERITAS), which is located at the Whipple Observatory in southern Arizona and consists of an array of four 12m-diameter imaging

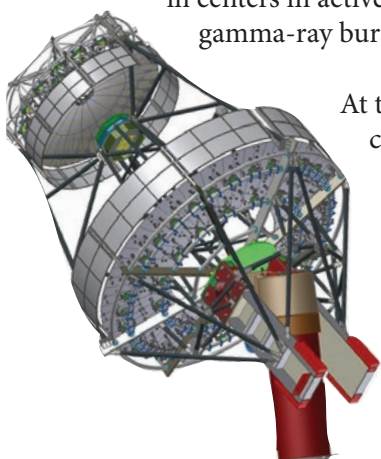


Fig. 1. SC Telescope construction model. Prototype SCT is scheduled for construction at FLWO in early 2015.



atmospheric Cherenkov telescopes (IACTs). VERITAS has been operating very successfully since 2007 and has detected many dozens of sources and produced a number of important discoveries. Within the last year the UCLA group contributed significantly to several new publications and continued analysis work on several topics, including a comprehensive study of observations taken in the Cygnus region of the Galaxy, a search for the evaporation of primordial black holes and a study of effects of weak intergalactic magnetic fields on propagation of gamma-rays from cosmological sources.

The research with VERITAS is substantially augmented by the observations made at lower gamma-ray energies by the Large Area Telescope (LAT) of the Fermi satellite. UCLA scientists use the Fermi-LAT data to provide broader spectral coverage of gamma-ray sources. In the last year, PhD student Timothy Arlen, Vassiliev, and co-workers published a significant new study on constraining the intergalactic magnetic field, using observations of distant active galaxies made by VERITAS and Fermi-LAT. In other work, PhD student Alexis Popkow is producing a map of the Cygnus region at Fermi-LAT energies to correlate with data taken by VERITAS in the same region.

The VHE astrophysics group is heavily involved in the plans for the next-generation ground-based gamma-ray observatory called the Cherenkov Telescope Array (CTA). CTA is expected to have an array in both the northern and southern hemispheres, with each array consisting of up to 75 imaging atmospheric Cherenkov telescopes (IACTs) covering an area greater than 1 square kilometer. UCLA has made a significant effort led by Rene Ong to propose two possible sites in Arizona to host the CTA-North facility.

U.S. members of the large international CTA consortium, including nearly 30 countries, are working on the development of the novel Schwarzschild-Couder Telescope (SCT) for CTA, designed to achieve superior performance and wider field of view compared to conventional designs of IACTs such as used by VERITAS. The group organized by Vladimir Vassiliev at UCLA pioneered this new instrumentation development for VHE gamma-ray astronomy and is now leading the effort of more than a dozen institutions to construct the prototype SCT at the VERITAS site location (see Figure 1). A recent multi-million dollars award from the NSF under the MRI program (PI Vladimir Vassiliev) supports this work. SCT construction and commissioning is planned for the next two years.

Both VERITAS and CTA related activities of the UCLA astrophysics group are expected to provide exciting

research and instrumentation development opportunities for both graduate and undergraduate students. The group is responsible for design and delivery of pSCT optical system and significant efforts are now devoted to prototyping of pSCT alignment system and metrology of segments of primary and secondary mirrors. Figure 2 shows a picture of Very High Energy Astrophysics Lab, where this work is conducted. We are looking for interested gifted graduate and undergraduate students to join our activities.

The nature of astrophysical dark matter is one of the most compelling mysteries facing physics and astronomy today. There are strong arguments that a new particle (or particles) comprises the bulk of the dark matter. One highly motivated candidate is the weakly interacting massive particle (WIMP). Many experiments worldwide are searching for WIMPs utilizing various techniques, among which a unique signature for WIMP annihilation could come from the detection of anti-deuteron particles in the cosmic rays. Astrophysical anti-deuterons have never been detected but UCLA is working with the other groups to develop the first dedicated search experiment, called the General AntiParticle Spectrometer (GAPS). In the GAPS instrument, an anti-deuteron would be detected through its interaction in lithium-drifted silicon detectors (Si(Li)). The GAPS team developed a prototype instrument that had a successful flight in June 2012 from the Taiki launch facility of the Japanese Aerospace Exploration Agency (JAXA) in Hokkaido, Japan. The team is now proposing to build a science payload that would fly on a long-duration balloon around the Antarctic.

Currently the VHE astrophysics group consists of Professors Rene Ong and Vladimir Vassiliev, postdoctoral researchers Taylor Aune, Issac Mognet and Julien Rouselle, and graduate students Matt Buchovecky, and Alexis Popkow.



Fig. 2. Very High Energy Astrophysics Lab where prototyping and integration of pSCT alignment and optical system is taking place.

## KATSUSHI ARISAKA GROUP

The Arisaka Group leads the design and construction for the XENON1T dark matter experiment, the largest and most promising dark matter project in the world, currently under construction at LNGS (Italy). The experiment will involve the search for so-called Weakly Interactive Massive Particles (WIMPs.) Alexey Lyashenko is responsible for design and construction of the photosensor arrays for the XENON1T detector. For test purposes he has manufactured a prototype that comprises one quarter of the complete XENON1T photosensor array, representing the exact geometry of the detector. Performance of the prototype array was successfully tested in liquid Nitrogen on a dedicated setup designed and constructed at UCLA for that purpose. After this successful test of the prototype the next step will be manufacturing the actual XENON1T photosensor arrays

The Arisaka Lab is also active in photon detector development for the future dark matter experiments. The low internal radioactivity Photo-Multiplier Tubes (PMTs), R11410-10, were designed by Hamamatsu Photonics in close collaboration with UCLA. One of the most critical characteristics of the PMT is the so-called Quantum Efficiency (QE), a probability used to convert incoming photons into photoelectrons for subsequent amplification. Alexey Lyashenko has recently measured the absolute QE in

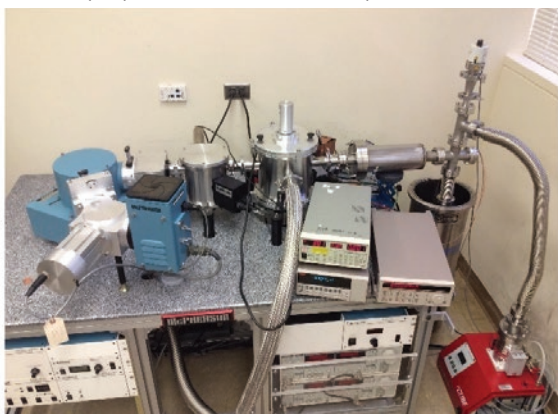


Fig. 3. The vacuum UV cryogenic spectrometer to measure Quantum Efficiency.

a spectral range between 150 nm to 400 nm at low temperatures down to -110 oC, a typical PMT operation tempera-

ture in liquid Xenon detectors. It was shown that at -110 oC the absolute QE increases by a factor of 1.15 at 175 nm. It will result in the improved single photon sensitivity, allowing for lowering of the energy threshold improving the detector sensitivity to the low energy WIMPs.

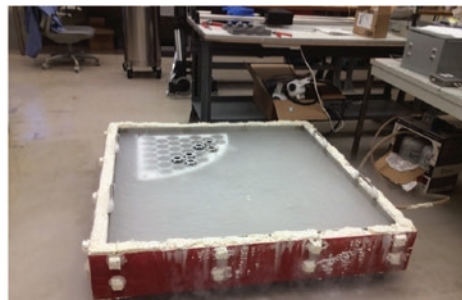


Fig. 1. One quarter of the PMT support structure, tested under liquid Nitrogen bath.

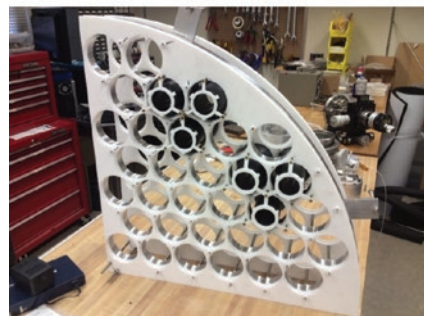


Fig. 2. One quarter of the PMT support structure for the XENON1T dark matter experiment.

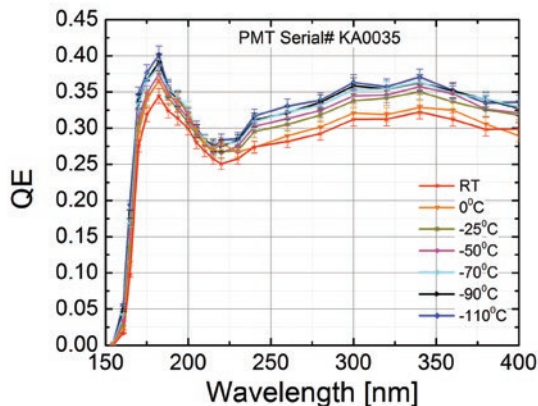


Fig. 4. The Quantum efficiency as a function of wavelength and temperature.

## RARE EVENT SEARCHES WITH NOBLE LIQUID DETECTORS

David Cline

The UCLA group has had a prominent role in the direct dark matter detection community starting with the development of two-phase liquid xenon detectors in the 1990s. Our first detector, Zeplin II, was the first such detector constructed at UCLA. Currently we are working on the XENON100 and XENON1T detectors at Gran Sasso National Laboratory (LNGS) in Italy. XENON1T is expected to take

data starting in 2015 and will be the largest detector in the world. We are also working on the DARWIN detector concept that has come out of the EU science studies. This detector will be 25 tons.

From the 2014 UCLA Dark Matter Symposium held at UCLA in February we learned that one key candidate for





Fig. 1. XENON1T under construction under-ground at Gran Sasso National Laboratory.

the dark matter is the supersymmetric Higgs called the Higgsino. Since we have helped discover the Higgs particle at the LHC, detection of the Higgsino would be a great breakthrough.

We have worked for many years on the 600 ton ICARUS detector at LNGS. The experiment is now finished. The neutrino beam traveled 734 km from CERN to LNGS. Final results, including about 2000 neutrino events, showed the great discrimination power

in the ICARUS technology. We were the first to make a direct measurement of the velocity of the muon neutrino.

ICARUS is the model for the proposed Long Baseline Neutrino Experiment (LBNE) detector with a 30 kiloton liquid argon volume to be constructed in South Dakota 1300 km from FNAL.

We are carrying out R&D on smaller liquid argon detectors in collaboration with Los Alamos National Laboratory (LANL). We helped conceptualize a 5 ton portable liquid argon detector called CAPTAIN. A smaller version called mini-CAPTAIN uses a large dewar from UCLA. Mini-CAPTAIN is ready to be filled at LANL now.



Fig. 2. CAPTAIN cryostat at Los Alamos National Laboratory.

## NOBLE LIQUID DETECTOR LAB FOR RARE EVENT SEARCHES

### Hanguo Wang's group

One of the biggest open questions of modern astrophysics is the nature of an invisible form of matter called dark matter. It is five times more abundant than ordinary matter in the Universe but has so far eluded all direct detection efforts, which has pushed physicists to build more massive and more sensitive detectors.

Hanguo Wang's group participates in two of the major efforts: XENON and DarkSide, both international collaborations utilizing dual-phase (liquid-gas) noble liquid time projection chambers (TPCs). They detect scintillation and ionization signals induced by possible dark matter interactions in a target volume instrumented with highly sensitive photodetectors.

The XENON program, located underground at Gran Sasso National Laboratory (LNGS) in Italy, has been the world leader in direct dark matter detection. The latest iteration, XENON1T, is a fully approved next generation detector with a 3.5 ton liquid xenon target mass. Wang's team, in close collaboration with postdoc Alexey Lyashenko of Professor Arisaka's group, is responsible for designing the TPC, designing and testing the photosensor assembly system, and designing and constructing the high voltage feedthrough (HVFT). XENON1T is deep in the construction phase and is expected to start data-taking in late 2015.

The DarkSide program is similar to XENON, but uses liquid argon as the target mass. DarkSide-50, also located

at LNGS, is the first physics detector of the DarkSide family, featuring a dual phase underground argon TPC of 50 kg active mass surrounded by an organic liquid scintillator neutron veto and a water-Cherenkov muon detector. Members of the UCLA team were on site at LNGS during 2013 to assemble and install the TPC. DarkSide-50's high voltage feedthroughs and cryogenic system were designed at UCLA in collaboration with Fermi National Accelerator Lab (FNAL) and have been operating flawlessly for almost 1 year, helping the detector to accumulate more than 50 live days of data. Postdoc Yury Suvorov resides full time at LNGS and had a pivotal role in installation and operation of all three sub-detectors. The team is also heavily involved in a variety of aspects of the analysis effort, from data processing to reconstruction to cut development to detection limits to paper writing. The first physics results of DarkSide-50 will be published in the fall of 2014, putting the strongest WIMP exclusion limit to date for liquid argon detectors.

A comprehensive understanding of the scintillation and ionization signals from noble liquids is crucial for extracting a possible dark matter signal from the monumental backgrounds present in XENON, DarkSide, and other experiments. To that end, Wang's group has undertaken two parallel R&D efforts to study the intrinsic properties of liquid xenon and liquid argon. Graduate student Yixiong Meng is responsible for the xenon system, which is currently running smoothly. Forthcoming measurements will

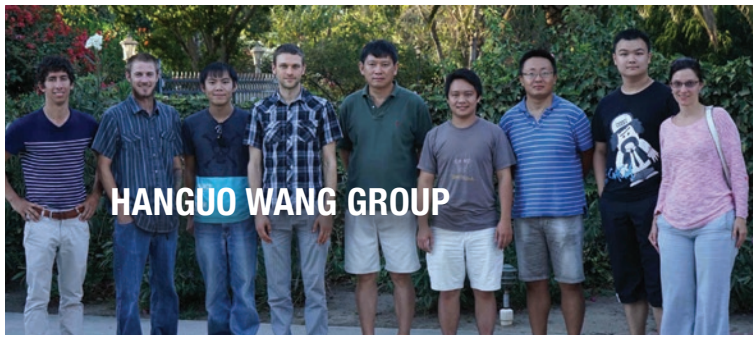


Fig. 1. Left to right: Alec Stein, Andrew Renshaw, Tam Nguyen, Alexey Lyashenko, Hanguo Wang, Alden Fan, Yixiong Meng, Yi Wang, Emilija Pantic. Missing: Yuri Suvorov, Artin Teymourian, and Eric Zhou.

help to clarify the dark matter search results from liquid xenon detectors such as XENON and LUX. Graduate student Alden Fan is responsible for the argon system, which is designed to fully map the parameter space that affects the electroluminescence signals coming from dual phase TPCs. A small TPC, along with custom high voltage feedthroughs and gas and cooling systems, have been fabricated. First operation is expected in late 2014. The effort will inform design parameters and operating conditions for next generation dual phase liquid argon detectors.



Fig. 2 The DarkSide-50 dark matter detector has been taking data since October 2013.

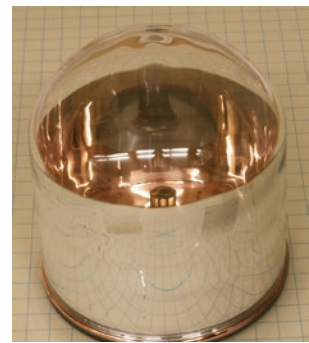


Fig. 3. A prototype of a new photosensor technology, SiGHT, is almost complete.

Wang's team is also developing a new ultra-low background photosensor technology, called Silicon Geiger-mode Hybrid Tube (SiGHT), for use in noble liquid detectors. Conventional photomultiplier tubes produce the dominant neutron background in noble liquid dark matter detectors, and SiGHT will be a viable alternative when scaling up to future generation detectors. It is similar to the QUPID technology jointly developed by Professor Arisaka, Wang and Hamamatsu. The key feature of SiGHT is the use of silicon photomultipliers (SiPMs), which have been characterized at low temperature by postdocs Andrew Renshaw and Artin Teymourian and undergraduate Tam Nguyen. Visiting graduate student Yi Wang from IHEP, Beijing is largely responsible for development of all other aspects of SiGHT. Assembly of the first prototypes is expected within the end of 2014.

Suvorov and Wang are also members of the Borexino collaboration. In August 2014, the Borexino collaboration published a Nature article detailing the first detection of pp solar neutrinos, particles which are born inside the core of the Sun during the primary reaction of pp-cycle fusion. Suvorov and Wang are also participating in the SOX (Short distance neutrino Oscillations with Borexino) experiment, which aims at the complete confirmation or clear disproof of the so called neutrino anomalies, using two powerful and innovative neutrino and antineutrino generators made of Cr-51 and Ce-144.

Finally, Wang's team is heavily involved in the Long Baseline Neutrino Experiment (LBNE) and its associated programs such as the 35 ton technical test at FNAL and the mini-CAPTAIN and CAPTAIN programs at Los Alamos National Laboratory. The team provided key technical support for design and construction of a 200 kV feedthrough, as well as the liquid argon condenser and 50 kV feedthrough for mini-CAPTAIN. Wang's team has been developing and manufacturing the HVFTs for the XENON1T, DarkSide, mini-CAPTAIN, CAPTAIN and LBNE experiments. Each detector has different voltage requirements and unique geometrical constraints, demanding custom designs for each. In addition to providing high voltage, each HVFT must hold an ultra-high vacuum seal to prevent contamination of the detectors. All feedthroughs have been constructed and are being tested up to their maximum design voltage. These were the main focus of Renshaw, Teymourian and researcher (now professor) Emilija Pantic.

High school senior Eric Zhou interned with the group in the summer of 2013. He is attending UC Berkeley in the fall with plans to major in physics. In January 2014, Pantic took a faculty position at UC Davis, where she continues to work as a member of the DarkSide collaboration. As of September 2014, Teymourian works at Hai Tech Lasers, Inc. developing custom laser engravers and laser welders.

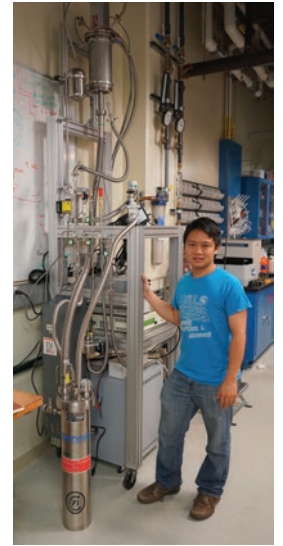


Fig. 4. Complete systems built to study intrinsic properties of liquid argon and liquid xenon in the context of dual phase dark matter detectors.



Fig. 5. Custom designed 200 kV high voltage feed through for use in LBNE.



# Atomic-Molecular-Optical Physics

## QUANTUM PHYSICS WITH ATOMS AND MOLECULES

### Wes Campbell

Research in the Campbell group this year has been centered on preparing trapped ultracold atoms to explore quantum many-body effects. The neutral molecule work led by postdoc Andrew Jayich has resulted in a publication describing how to use pulses from ultrafast lasers to decelerate molecular beams. In the lab, we have been able to demonstrate a novel trapping technique using a single mode-locked laser that will allow laser cooling and trapping of complex species that normally require too many lasers to make this feasible. This may also open the door to trapping using light in the deep UV where laser sources are difficult to produce. Along with REU student Alisa Babcock, we have constructed a thermally-insensitive reference cavity for stabilizing the mode-locked laser's optical frequencies to 1 part in  $10^9$ .

The trapped ion quantum simulator has progressed to trapping Coulomb crystals of many ions at once, which will be used to simulate electron spins in many-body systems. A new monolithic trap designed by undergraduate Danio Dadic has been machined from a single piece of

fused silica and is being assembled for testing. This new trap will allow us to create 2D Coulomb crystals to simulate many-body physics in 2D systems, where geometric frustration leads to large degeneracy in the vicinity of the ground state.

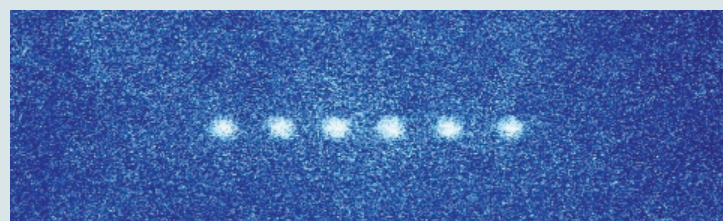


Fig. 2. False-color image of a Coulomb crystal of six singly-ionized atoms. Each atom will be programmed to store the quantum state of a simulated electron spin, and the mutual repulsion between atoms will be used to program the spin-spin interaction we wish to simulate.

## COHERENT DIFFRACTIVE IMAGING (CDI)

### Jianwei (John) Miao

Coherent diffractive imaging (CDI) using synchrotron radiation, X-ray free electron lasers (XFEL), high harmonic generation, optical lasers, and electrons is a rapidly growing area of research that has found applications across several disciplines. The conventional approach to achieve three-dimensional (3D) CDI is through collecting multiple coherent diffraction patterns by varying the orientation of a sample.

In 2010, Professor John Miao and collaborators developed a novel imaging method, termed ankylography (derived from the Greek words ankylos meaning 'curved' and graphein meaning 'writing'), which under certain circumstances enables complete 3D structure determination from a single view utilizing the curvature of the Ewald sphere and additional constraints (K. S. Raines et al, "Three-dimensional structure determination from a single view," *Nature* 463, 214-217 (2010)).

An important implication of this work is its ability to achieving single-shot 3D structure determination with XFEL pulses. However this paper created a big debate in the CDI community, and some believed that single-shot 3D structure determination would never be experimentally achieved on realistic samples.

Facing skepticism of this method, Professor Miao led an international team that has recently demonstrated single-shot 3D structure determination of high-index-faceted nanocrystals at  $\sim 5.5$  nm resolution using  $\sim 10$  femtosecond XFEL pulses. Coherent X-ray diffraction patterns were collected from the gold nanocrystals using the Japanese XFEL, each struck by an XFEL pulse based on the diffraction-before-destruction scheme.

Using the symmetry of the nanocrystals and the curvature of the Ewald sphere, his team reconstructed the 3D structure of individual nanocrystals from single-shot diffraction patterns and determined their exposed high index (661) facets. Furthermore, the single-shot diffraction patterns of identical gold nanocrystals were selected to assemble a 3D diffraction pattern, from which an average 3D reconstruction was achieved with a resolution presently limited by the detector geometry.

The significance of this work is twofold. First, as symmetry exists in many nanocrystals and virus particles, this single-shot 3D imaging method can be applied to 3D structure studies of such particles at the nanoscale resolution with

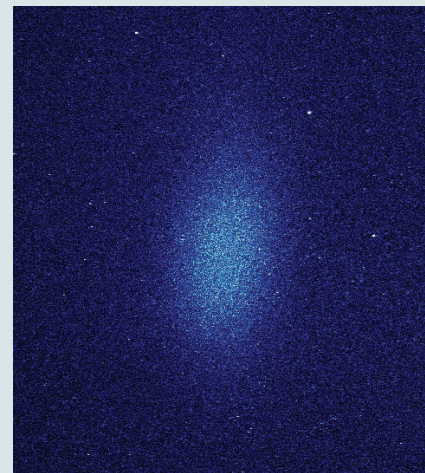


Fig.1. A cloud of ultracold rubidium atoms emitting blue light after being excited on a two-photon transition. Since the blue light is a different color than the excitation laser beam, the atoms can be detected with high sensitivity due to the low backgrounds.





Fig.1. Professor John Miao delivered a Plenary lecture at the 23rd Congress and General Assembly of the International Union of Crystallography in Montreal in August 2014.

femtosecond time scales. Second, with enough copies of identical nanocrystals, the combination of symmetry, the curvature of the Ewald sphere and CDI can potentially be used to determine the 3D structure of nanocrystals at atomic resolution.

This work has recently been published in Nature Communications (R. Xu. et al, "Single-shot three-dimensional structure determination of nanocrystals with femtosecond X-ray free-electron laser pulses," Nature Commun. 5, 4061 (2014)).

Professor John Miao has also delivered a Plenary lecture at the 23rd Congress and General Assembly of the International Union of Crystallography (IUCr) in Montreal, Canada entitled "Beyond Crystallography: Coherent Diffraction Imaging and Atomic Resolution Electron Tomography." Because 2014 is the International Year of Crystallography, there were about 3,000 attendants of this conference and his lecture was very well received.

## ARISAKA NEURPHYSICS GROUP

### Katsushi Arisaka

The Arisaka Lab is investigating the biophysical principles behind sensory integration and directed behavior through the study of the model organism, *Caenorhabditis elegans*. This is a 1 mm long transparent nematode with only 302 neurons. However it has a mapped connectome and is currently the only model organism amenable to complete systems-level analysis. In the laboratory our research is focused on the visualization and analysis of the organism in response to modulation of its physical environment. Since Summer 2013 close to one hundred undergraduate students have joined the Arisaka Lab, and formed a student-run scientific club, called the "Elegant Mind Club" (<http://www.elegantmind.org>). They have constructed unique experimental devices, exposing *C. elegans* to various external stimulations such as electrical and magnetic fields, temperature, humidity, and UV photon. In Spring 2014 club members began observing interesting behaviors that had not been reported previously. These research efforts were integrated into a novel laboratory course as a part of Physics

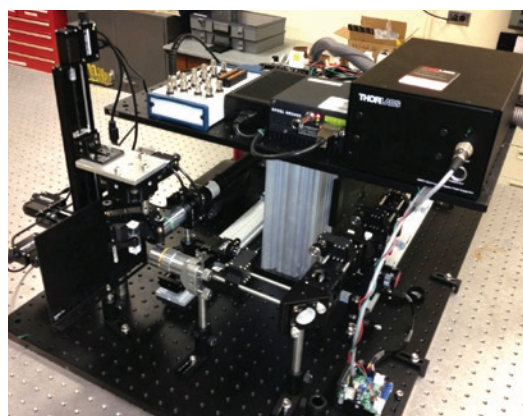


Fig. 2. A Bessel beam sheet illumination microscope for 3D high-speed, super-resolution observation of neural networks.

6C, enabling undergraduates to learn fundamental physics through their direct application of lecture-acquired knowledge of biophysical research.

Several advanced optical imaging systems have been constructed, enabling the recording of the development and function of the neural circuits in model animals, such as *C. elegans*, zebrafish and mice, from embryo to adult. The most advanced system is a radical, high-speed, super-resolution 3D microscope utilizing Bessel beams. This project was recently funded by the NSF and NIH. The prototype has been successfully constructed and installed at the CNSI Advanced Light Microscope user facility.



Fig. 1. A group meeting of the Elegant Mind Club, discussing their own projects.

## BOZOVIC LABORATORY

### Dolores Bozovic

Our laboratory studies the nonlinear dynamics of inner ear hair cells. Mechanotransduction converts mechanical stimuli into electrochemical cellular signals, a phenomenon which occurs in various sensory biological systems. Despite its importance, tools that provide non-invasive manipulation of this process are still fairly limited. Hence we developed a new technique that allows of fast and reversible control of mechanosensitive hair cells.

Cube-shaped magnetic nanoparticles, manufactured in Cheon laboratory at Yonsei University, bind to components of cellular membranes and can be controlled with an electromagnet to exert pico-Newtons of mechanical force on the cells. The cubic nanoparticles can thus be used for non-contact mechanical control of the position of the stereocilia of an inner ear hair cell, yielding displacements of tens of nanometers, with sub-millisecond temporal resolution. Such mechanical stimulation switches ion channels from open to closed state, with the concomitant  $\text{Ca}^{2+}$  influx into the cell during the open state. Our magnetic manipulation technique opens new opportunities for high-speed and non-invasive control of mechanotransduction in hair cells.

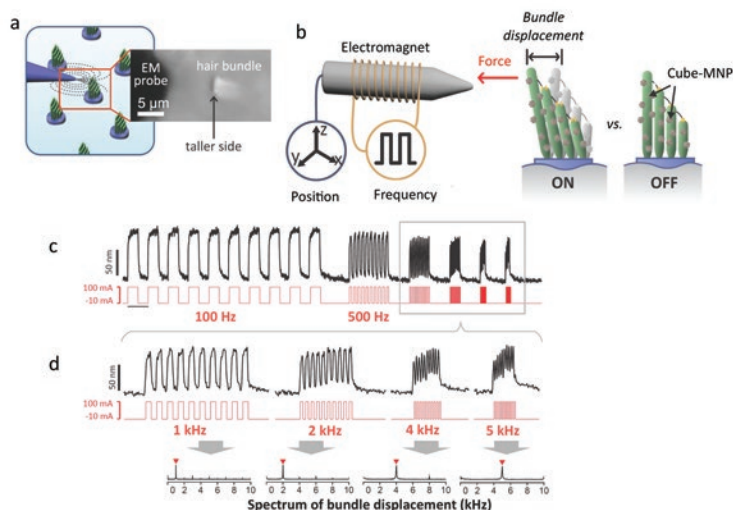


Fig. 1. Entrainment of hair bundle oscillation with a magnetic switch: a. Schematic drawing of a magnetic probe activating a single hair bundle and a bright-field microscope image in top-down view. b. Schematic diagram of the EM probe stimulating a single hair bundle with c-MNPs attached. c and d. Stimulation frequency variation: pulse frequencies of 100, 500, 1000, 2000, 4000, and 5000 Hz are applied to entrain bundle motility. Lee et al, ACS Nano, 8, 6590 (2014).

## MOLECULAR BIOPHYSICS

### Giovanni Zocchi

Research in the Zocchi Lab is concerned with mesoscopic physics. We bring a materials science, physics based approach to the study of biological macromolecules and the design of new supramolecular constructions. We are specifically interested in enzymes as chemo-dynamics machines.

### *Equilibrium mechanics of enzymes.*

We use our supra-molecular constructions consisting of an enzyme coupled to a DNA “molecular spring” (Fig. 1) to explore the equilibrium mechanical response of the enzyme [Tseng and Zocchi, Appl. Phys. Lett. 104, 153702 (2014)]. Having previously established quantitative knowledge of the mechanics of the DNA spring in the

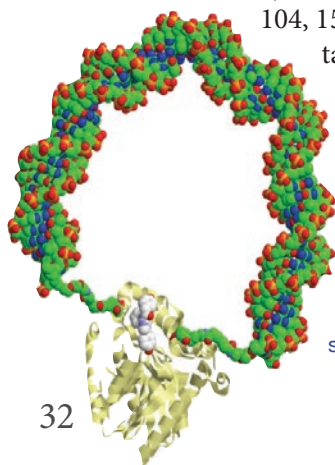


Fig.1. Cartoon of a Luciferase–DNA chimera; these constructs are used to study enzymes under stress. The Luciferase structure is from PDB 2PSJ and DNA is from the nucleosome structure 1KX5. The enzyme and DNA spring are drawn approximately to scale.

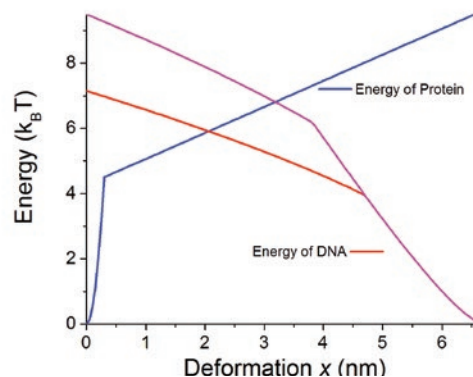


Fig. 2. Elastic energies vs. deformation of the enzyme, for the construction of Fig. 1. The proposed energy function for the enzyme (blue) features a softening of the parabolic (linear elasticity) profile beyond a few Angstrom deformation. The energy function of the DNA spring (red and pink: shown for two different configurations) has been directly measured in experiments.

relevant nonlinear elasticity regime, we extract from the measurements of enzymatic activity under stress features of the mechanics of the enzyme. We find evidence that the enzyme undergoes a softening transition for deformations beyond the linear regime (Fig. 2), similarly to the DNA spring. This softening transition may be a generic mechanical feature of hydrogen bonded macromolecular structures.

The catalytic cycle of enzymes is often coupled to a mechanical cycle of conformational changes of the enzyme. Here we use mechanical stress to probe properties of the cycle not naturally accommodated by simple transition state theory. We find that mechanical stress has different effects on the forward and backward reaction catalyzed by the same enzyme (Fig. 3). This is a direct demonstration that forward and backward cycles are not time reversal symmetric [Joseph et al, PLoS ONE 9, e101442 (2014)].

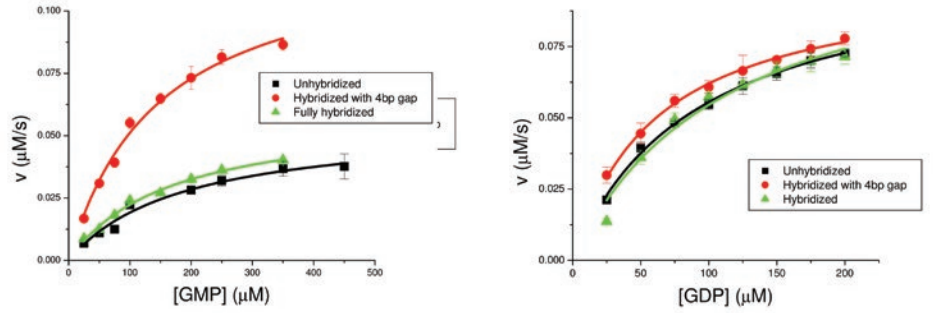


Fig. 3. Reaction speed vs. initial substrate concentration for the yeast Guanylate Kinase chimera in the absence (circles) and presence (triangles) of mechanical stress, for the forward (left) and backward (right) reaction.

## Experimental Elementary Particles and Nuclear Experimental Physics

### NUCLEAR PHYSICS GROUP

Huan Huang

The UCLA Nuclear Physics Group (Huang Group) has established research programs on studies of hot QCD (Quantum ChromoDynamics) matter of quarks and gluons and on searches for neutrinoless double beta decays. The group is active in the STAR (Solenoidal Tracker at RHIC) experiment at Brookhaven National Laboratory Relativistic Heavy Ion Collider (RHIC) and CUORE experiment at Gran Sasso Underground Laboratory in Italy. The CUORE experiment is under construction and data-taking is expected to commence in early 2015. We highlight here our recent work on studies of novel phenomena in heavy ion collisions due to possible topological excitation of QCD vacuum in the presence of a strong magnetic field.

The formation of the Quark-Gluon Plasma (QGP) in high-energy heavy ion collisions may lead to domains of distinct topological Chern-Simons charge where quark chirality symmetry (left-right handedness) is broken. These quarks can couple to strong magnetic field (1015Tesla) generated

by the passing of spectator protons in non-central collisions resulting an electric current along the direction of the magnetic field. As a result there is charge separation across the reaction plane and a dynamical breakdown of the P and CP symmetry in heavy ion collisions. This is the so-called Chiral Magnetic Effect (CME).

The CME assumes the formation of the deconfined QGP where quarks can travel over distances greater than the scale of a nucleon. Observation of the CME at the top RHIC energy [1-3] and its beam energy dependence could potentially reveal the absence of the QGP at lower energies. Fig. 1 shows our recently published result of the charge separation signal as a function of the beam energy at RHIC [4]. The signal approaches zero at the lowest energy of 7.7 GeV indicating a possible transition from the QGP to a system dominated by hadron degrees of freedom. Our future RHIC Beam Energy Scan (BES) phase II program is expected to significantly reduce the statistical errors of the measurement.

In addition, a long-wavelength hydrodynamic mode for the charge densities, the so-called Chiral Magnetic Wave (CMW), has also been proposed theoretically. The CMW manifests itself as a finite electric quadrupole moment resulting in a charge asymmetry dependence of collective motions between negative and positive charged particles in the final state. Fig. 2 shows the slope parameter from a linear dependence on the charge asymmetry as a function of collision centrality at various beam energies [5]. The slopes are significantly reduced at lower energies that is consistent with the expectation of CMW. Definitive observation of the CME and CMW will be the first experimental confirma-

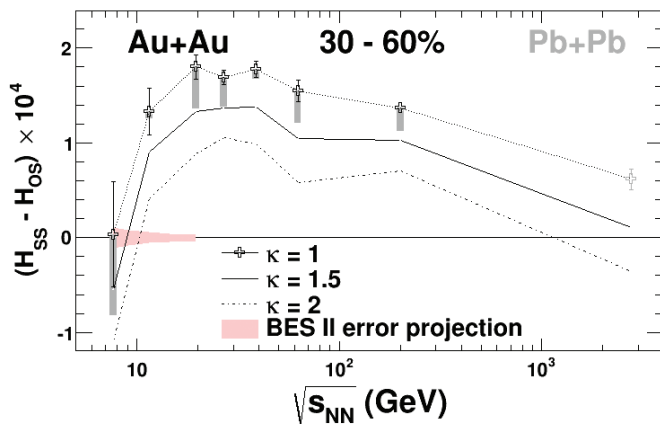


Fig. 1 shows result of the charge separation signal as a function of the beam energy at RHIC.



tion of topological excitation of the QCD vacuum, an intrinsic characteristic of the non-Abelian gauge field theory. The UCLA nuclear physics group will continue to explore this physics topic in the coming years.

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- [3]L.Adamczyk et al. [STAR Collaboration], Phys. Rev. C 88 (2013) 64911.
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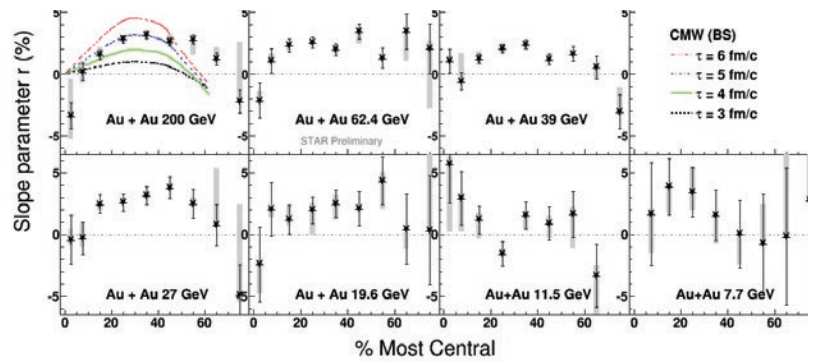


Fig. 2 shows the slope parameter from a linear dependence on the charge asymmetry as a function of collision centrality at various beam energies.

## PARTICLE PHYSICS ENERGY FRONTIER GROUP

Robert Cousins, Jay Hauser, David Saltzberg

*Experimentalists at Large Hadron Collider prepare for dramatic increase in beam energy*

As described in past annual reports, UCLA physicists play a variety of crucial roles in the Compact Muon Solenoid (CMS) collaboration at the Large Hadron Collider (LHC) at the CERN laboratory outside Geneva. Anticipation is high for data-taking in the year 2015, when the energy of the colliding beams will be close to the LHC design energy foreseen 20 years ago.

The years 2010-2012 were already a “smashing” success, highlighted by the discovery of the Higgs boson in 2012. However, the LHC has operated thus far with a maximum of only 8/14 of the design energy of the beams, a precaution necessary due to flaws in the magnet connections that caused the major breakdown in 2008, delaying data-taking until 2010. In the past year, thousands of connections have been retrofitted so that it is safe to energize the magnets to levels that can contain beams close to (at least 13/14) of the LHC design energy, thus allowing searches for “new physics” to scan much greater regions where now particles or forces may be lurking.

Meanwhile, during the 2013-2014 LHC shutdown for

repairs, the collaboration has worked hard to improve the CMS detector in numerous ways. One of the largest improvements was in the system that detects penetrating particles (muons) in the endcaps of the detector. Professor Jay Hauser is the international project manager for this system, and Professor David Saltzberg oversaw the assembly and testing of many new detectors and their electronics that were added to the system. Almost all UCLA researchers, postdocs, and students contributed to this project, which was completed while the UCLA group was also putting the finishing touches on physics papers analyzing the existing data.

Looking even further ahead, major efforts are underway to plan for much higher LHC beam intensities later in the decade. Professor Robert Cousins served on a blue-ribbon Particle Physics Project Prioritization Panel that advised the U.S. Dept. of Energy and the NSF on strategic planning for the field. The panel assigned top priority in the near term to the upgrades of the detectors needed for the LHC intensity upgrade projects.

## DAVID CLINE AND THE UCLA DARK MATTER TEAM

*The 2014 Dark Matter Symposium: Possible Evidence for Dark Matter*

The 2014 symposium, “Sources and Detection of Dark Matter and Dark Energy in the Universe,” is one of the most famous Dark Matter Symposia in the world. In 1998 the two groups studying the acceleration of the universe presented their evidence for an “accelerating universe” for the first time. This concept of dark energy was invented shortly after.

This year’s meeting was held on the UCLA campus. For the first time we had 190 participants. The meeting covered the full range of proposals for dark matter, LHC data, WIMPs, axions, dark photons, sterile neutrinos, as well as details of the search for dark matter signals from Fermi LAT data. Direct dark matter searches continue to be negative.

Larger detectors are being constructed and UCLA is part of this program. One set of data stood out: the data from the Galactic Center observed by Fermi. There is clearly an excess of MeV to GeV particles produced in the Galactic Center. In many ways, these particles behave like the results of WIMP annihilation. The signal peaks at the very center of the galaxy.

Two independent groups report similar conclusions. However there is not a “smoking gun” to prove this is due to dark matter. A press release from the meeting was released by UCLA. Over the next two years, additional data and analysis will be very interesting and we intend to hold Dark Matter 2016 at UCLA.

## RADIO DETECTION OF HIGH-ENERGY PARTICLES

### David Saltzberg

This year this group, researching the detection of high-energy particles by their radio emissions, went on the road. Professor David Saltzberg, Researcher Dr. Konstantin Belov, and Postdoc Dr. Stephanie Wissel and several UCLA physics undergraduates, Kyle Borch, Kyle Kuwatani, Joe Lam and UCLA REU student Rachel Hyneman, went to the SLAC National Accelerator Laboratory to emulate the emission from cosmic rays using a particle beam.

They were joined by over a dozen collaborators from labs and universities around the world. Despite decades of detection in remote environments, this emission had never been produced in well-understood laboratory conditions.

The theoretically predicted emission had undergone major revisions and the data clearly supported the modern incarnation over the models that were used for the previous several decades.



Fig. 1. Dr. Konstantin Belov works with graduate students building the four-ton magnetized target in the SLAC National Accelerator Laboratory's famous Endstation A.

Later Dr. Stephanie Wissel and incoming “zero-year” (entering September 2014) UCLA graduate students Steve Emmel and Alex Wickes traveled to NASA's Columbia Scientific Ballooning Facility in Palestine, Texas to help complete the construction of the ANITA scientific payload for its upcoming flight in Antarctica. In collaboration with JPL scientist Dr. Andres Romero-Wolf, they and the UCLA machine shop also built a new drop-down antenna that will deploy mid-flight and will increase the largest detectable wavelength for ANITA by a factor of four, thereby reaching into the heart of the cosmic-ray radio-emission spectrum.



Fig. 2. Dr. Stephanie Wissel (center) and collaborators complete the Anita Low Frequency Antenna (ALFA) that will drop down and hang from the ANITA payload at an altitude of 120,000 feet above Antarctica. Also shown (l to r) are graduate student Alex Wickes, chief machinist Harry Lockart, professor David Saltzberg and JPL scientist Andres Romero-Wolf.

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*Eric D'Hoker was appointed a "KITP Simons Distinguished Visiting Scholar" at the Kavli Institute for Theoretical Physics at UCSB for Winter 2014.*

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## THEORETICAL AND MATHEMATICAL PHYSICS

### Eric D'Hoker

Research highlights: In collaboration with Michael Green, Boris Pioline, and Rodolfo Russo, Professor D'Hoker proved various remarkable matches between superstring perturbation theory results at two loop order

and predictions from supersymmetry and S-duality in Type IIB superstring theory. These results have implications in number theory, and a part of the work will be published in the Journal of Number Theory.

# Experimental Plasma and Beam Physics

## INVERSE FREE ELECTRON LASER (IFEL)

Pietro Musumeci

Professor Musumeci's group strengthened UCLA's leadership position in the field of Inverse Free Electron Laser (IFEL) with a successful experiment carried out at the Accelerator Test Facility in Brookhaven National Laboratory. Among different laser-based high gradient accelerators, unique advantages of the IFEL include the fact that the laser-electron interaction happens in a vacuum (no plasma or nearby structures) and there is no need for a tight laser focus (far-field interaction). This implies extended interaction lengths and very high efficiency of energy transfer between the laser and the electrons.

The combination of ATF's high brightness electron linac and a TW-class CO<sub>2</sub> laser systems has enabled a new world record for the IFEL acceleration scheme. Past IFEL experiments utilized planar undulators to induce sinusoidal transverse motion in order to couple to the laser electric field.

A drawback of this approach is that the electrons' transverse motion is reduced to zero two times per period, effectively halting energy transfer there. Introducing a circularly polarized undulator field improves this situation by causing the beam to move along a helix, thereby providing continuous energy transfer and significantly improving the gradient.

Using a helical geometry strongly tapered undulator built at UCLA, the Rubicon experiment led by UCLA graduate student Joe Duris under the supervision of Professor Musumeci demonstrated high quality high gradient IFEL acceleration of electrons, doubling the energy of the ATF beam from 50 MeV to 100 MeV in 50 cm with more than 20% of the injected electron charge trapped with an rms final energy spread of 1.8 %. These results which have been published in Nature Communications (Duris et al. Nat. Comm. 5, 4928, 2014) demonstrate that the helical IFEL mechanism is a viable avenue for achieving compact accelerators and pave the way towards a meter-long GeV IFEL driver for compact light sources.

Professor Musumeci and his group have also made important progress in the field of transmission electron microscopy with the proposal of a revolutionary design for a TEM that would improve temporal resolution over current instruments by three orders of magnitude. Researchers have adapted the microscopes to capture fast changes in materials by using short, intense pulse of electrons—the

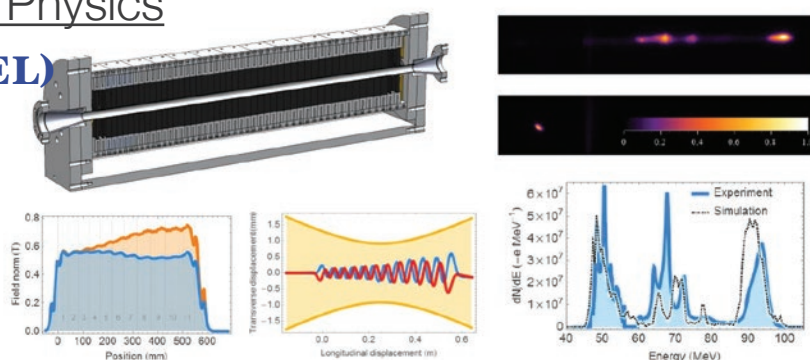


Fig. 1. Top left. Cutaway view of Rubicon IFEL undulator. On the bottom left magnetic field tapering for two different experimental tuning setups and in the center electron trajectory. Top right. Raw images of laser-on and laser-off shots for the Rubicon IFEL experiment. Bottom right. Comparison between measured energy spectrum and 3D simulations.

equivalent of taking photographs with a brief, bright flash.

But these microscopes often have to trade spatial resolution for speed: a shorter pulse has to carry more electrons to produce a sharp image, and repulsion between the charges causes the beam to spread. Professor Musumeci's group proposes an electron microscope design that—at least in theory—is capable of capturing, in a single shot, images of 10-nanometer-sized objects within 10 picoseconds—about 1000 times faster than the highest-speed microscopes in operation today. As reported in Physical Review Applied, 2 024003 (2014) the proposed microscope would allow researchers to study how shock waves or temperature gradients affect a material's structure.

The key component in the UCLA proposal is a relativistic electron source, called a radio-frequency photoinjector, in which electrons are stripped by a laser from a metal cathode and quickly accelerated to relativistic energies. These sources, which are similar to those used to seed some x-ray free-electron lasers, are capable of emitting high peak currents in tight bunches. Moreover, relativistic electrons experience a lower charge density in their rest frame because of time dilation. Li and Musumeci's simulations show that an

electron microscope equipped with a photoinjector source and special quadrupole magnet lenses is able to image a test pattern of nanometer-sized bars within 10 picoseconds.

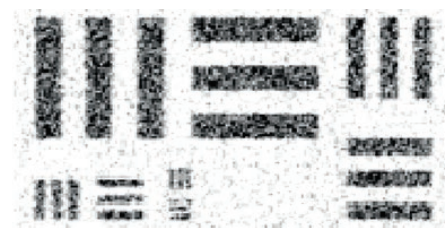


Fig. 2. Simulation of the image formation for a test pattern showing 10 nm resolution. The electron bunch length used in the simulation is 10 ps.



## BASIC PLASMA PHYSICS EXPERIMENTS

Walter Gekelman, Steve Vincena, Bart Van Compernelle, Patrick Pribyl, Yuhou Wang. Graduate Students: Tim DeHaas, Nathaniel Moore, Jeff Bonde, Mike Martin, Alexandra Latshow, Dooran Hong

### *Tearing of a Current Sheet*

Walter Gekelman, Tim DeHaas, Bart Van Compernelle, Steve Vincena

A long-standing issue in plasma physics is the stability of sheets of current in magnetoplasmas. Tearing modes in plasmas have been a great interest for both the fusion community as they can lead to disruptions in Tokomaks [1] and to the plasma physics community as the process is of importance in the earth's magnetotail [2]. A long-standing issue in plasma physics is the stability of sheets of current in magnetoplasmas. Tearing modes in plasmas have been a great interest for both the fusion community as they can lead to disruptions in Tokomaks [1] and to the plasma physics community as the process is of importance in the earth's magnetotail [2].

Tearing mode theory has been around since the 1970s [3]. When a current sheet tears into filaments they can interact with one another if the magnetic field of one is large enough to affect the next via the force. The currents are then interacting magnetic flux ropes. This is a fully three-dimensional process as demonstrated in PIC simulations [4].

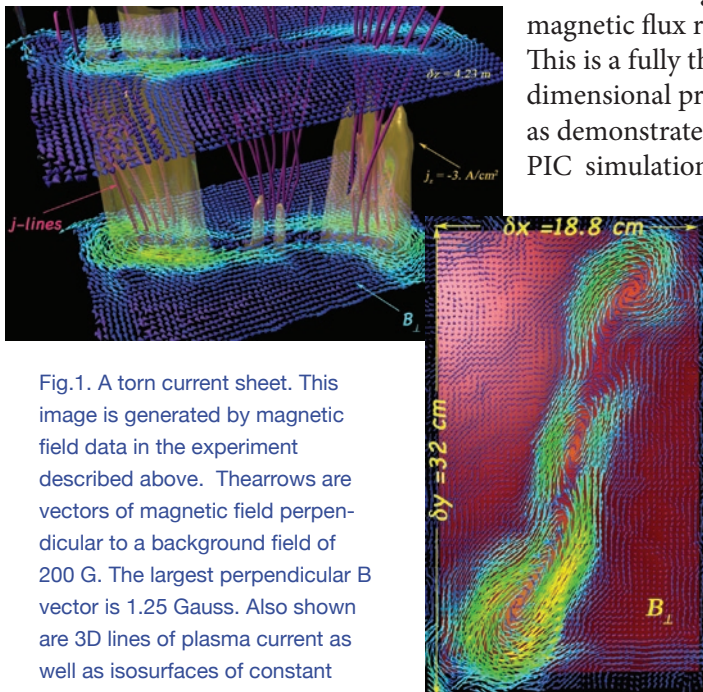


Fig.1. A torn current sheet. This image is generated by magnetic field data in the experiment described above. The arrows are vectors of magnetic field perpendicular to a background field of 200 G. The largest perpendicular B vector is 1.25 Gauss. Also shown are 3D lines of plasma current as well as isosurfaces of constant magnetic field ( $J_z = -3.3 \text{ A/cm}^2$ ). The total current in the plane is  $-350 \text{ A}$  (negative indicates it is carried by electrons). The current comes through a narrow slot 7 meters below the lower plane. The dimensions of the planes are  $\delta x = 18.8 \text{ cm}$ ,  $\delta y = 32 \text{ cm}$ .

Fig. 2. Vectors of perpendicular magnetic field in a plane 6.83 meters from the start of the current sheet. The data is shown for  $t = 411.2 \text{ ms}$  after the current was switched on. Three magnetic islands are visible as "O" points in the magnetic field perpendicular to the device axis.

Tearing has been experimentally observed before in a current sheet with unmagnetized ions [5].

Both theory and simulation indicate that in order to tear the sheets they must have a large transverse aspect ratio, at least 10. In this experiment a sheet was formed in the background plasma (He,  $T_e = 4 \text{ eV}$ ,  $T_i = 1 \text{ eV}$ ,  $B_0z = 200 \text{ G}$ ,  $n = 1 \times 10^{12} \text{ cm}^{-3}$ ) of the LAPD [6] device at UCLA [6]. A second LaB6 cathode made a discharge, which went through a narrow slot (1 cm thickness, 20 cm height) and produced a current sheet 8 m long. A three-axis B-dot probe was used to measure the magnetic field as a function of time on 5 planes, which were 65 cm apart. Data was acquired at 3888 locations on each plane with 4 mm separation between data points and 10 "shots" at every location. Data was acquired at 12,288 timesteps,  $\delta t = 0.16 \text{ ms}$ .

The tearing is observed to be fully three-dimensional. If one plots the magnetic field in a plane it is difficult to make out the "X" and "O" points because the currents are inclined to the normal vectors to each plane. The red lines in figure 1 are the current field lines. The tearing is obvious when one plots  $J_z$ . (The current is calculated from which is justified as the structures change rapidly transverse to  $B_0z$  and slowly along it.) This may be resolved by using the law of Biot and Savart to calculate in each plane from  $J_z$ . This vector field is shown in 3D relief in fig. 1 and in a plane in fig. 2.

The brighter the vectors, the larger the perpendicular field. In Fig. 2 three magnetic islands are clearly visible. In figure 1 there are three islands visible at  $\delta z = 6.83 \text{ m}$  but only two at  $4.25 \text{ m}$ . An isosurface of constant  $J_z$  confirms this. In figure 2, two magnetic "X" points, possible site for magnetic field line reconnection are clearly visible.

As the experiment progresses the islands come and go indicating an interaction between the flux ropes associated with them. A detailed paper about the experiment with simulation results is in process [7]. These data sets are very large and can only be understood using visualization techniques. The acquired data is first processed using IDL™ and then converted to a format that MAYA™, visualizing software used in the entertainment industry, accepts. Ray traced images and movies are then generated. Professor Gekelman has a research grant from Los Alamos National Laboratory along with William Daughton, a research scientist at LANL. The Los Alamos group is performing 3D particle in cell simulations of the experiment using some of the world's largest supercomputers.

### Three-dimensional electromagnetic structure of a laser-produced plasma

Stephen Vincena, Walter Gekelman, Jeffrey Bonde

Our visible universe is primarily composed of matter in the plasma state, and invisible lines of magnetic field thread much of this plasma. Violent and sometimes beautiful events can cause rapid expansions of one region of dense plasma into a rarified ambient magnetoplasma; these events range from the explosive deaths of stars, to the ephemeral glow of a comet in the solar wind, to the brief life of a frozen fuel pellet injected into the core of a fusion research tokamak.

At UCLA's Basic Plasma Science Facility, aspects of such events have been successfully modeled over the past 15 years by using lasers to irradiate solid targets that are immersed in the 20-meter plasma column of the Large Plasma Device. Depending on the setup geometry, the resulting laser-produced plasmas (LPPs) can be directed to expand either across or along the background magnetic field.

This year, with funding from the U.S. Department of Energy, Dr. Stephen Vincena, Professor Walter Gekelman, and graduate student Jeffrey Bonde have made detailed measurements of the electric and magnetic fields within such an LPP. In this way the roles of the electrostatic and inductive electric fields can be evaluated, not only on the dynamic evolution of the LPP but also on the transfer of energy and

momentum to the ambient plasma. Although ignored in some models of LPP expansion our recent measurements show that electric fields arising from charge separation are of comparable

magnitude to the inductive fields. The figure right (Fig. 3.) illustrates the three-dimensional structure of the measured electric and magnetic fields

for just a single snapshot in time ( $t=200\text{ns}$  after the laser.)

Unseen in this image is a background plasma of argon with a density of  $4 \times 10^{12}/\text{cm}^3$  and a confining field of 750G.

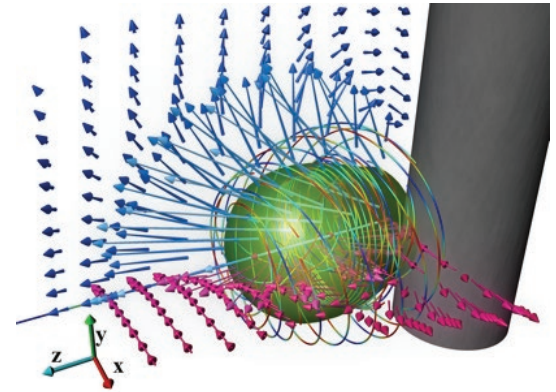


Fig. 3. A snapshot ( $t=200\text{ns}$ ) in the evolution of a laser-produced plasma. Data visualization includes blue magnetic field vectors in the  $yz$ -plane (300 G max); pink electric field vectors in the  $xz$ -plane (100V/cm max); semi-transparent green iso-surface of 200 G magnitude; rainbow-colored streamlines of induced plasma currents. Shown for scale is the 2-cm diameter carbon target rod.

### Ion beam generated modes at high ion cyclotron harmonics

B. Van Compernelle, S.K.P. Tripathi, W. Gekelman

Ion beam generated modes enjoy great interest in the plasma community. In fusion plasmas, injected ion beams or alpha-particles from fusion reactions can couple to a multitude of waves[8]. In the magnetosphere ring current ions[9] are unstable to electromagnetic ion cyclotron waves[10]. In astrophysical plasmas cosmic rays are thought to excite waves through a gyroresonant instability which leads to self- confinement and isotropy of the cosmic rays[11]. The interaction of a fast ion beam with a low beta magnetized plasma has been studied in the LAPD.

The experiments were done in a Helium plasma ( $n \sim 1 \times 10^{12} \text{ cm}^{-3}$ ,  $B_0 = 1500 \text{ G}$ ,  $f_{pe}/f_{ce} \sim 2$ ,  $T_e \sim 0.25 \text{ eV}$ ). Helium ions with energy of 15 keV are injected from the end of the machine at an angle to the machine axis. The fast ions spiral down the machine with a pitch angle on the order of 40 degrees. Waves were observed below  $f_{ci}$  in the shear Alfvén wave regime, and in a broad spectrum above  $f_{ci}$  at numerous cyclotron harmonics.

The power spectra of the electric field fluctuations exhibits

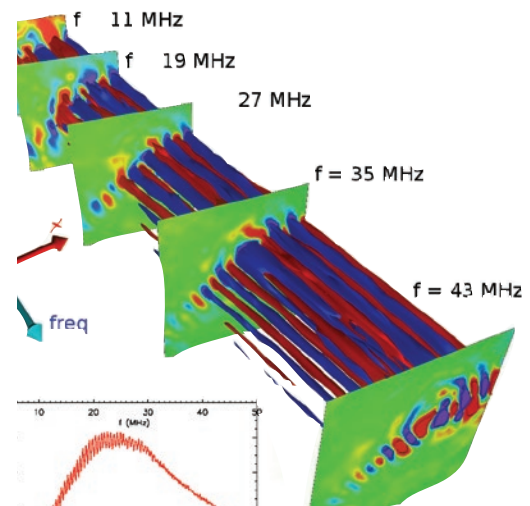


Fig. 4. shows the mode structure of the  $E_x$  component as a function of frequency in 2D planes perpendicular to the guide field. The mode structure is shown in five  $x-y$  planes at different ion cyclotron harmonics with the highest frequency modes in the foreground and lowest frequency modes in the background. Isosurfaces of positive and negative  $E_x$  show the monotonic evolution of the perpendicular wave number, i.e. mode wave number increases linearly with mode frequency. In the low frequency mode two wavelengths were captured in the measurement plane.



tens of peaks at high ion cyclotron harmonics. Mode frequencies range from a few fci, going up to 70-80 fci, which ranges from below to above the lower hybrid frequency. Mode structure of the beam modes at different frequencies can be obtained by cross correlation analysis of the signals on the moving probe with signals on a reference probe. whereas at the highest frequency seven to eight wavelengths are distinguishable.

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## TROY CARTER GROUP

Professor Troy Carter and his group led research on fundamental processes in magnetized plasmas, in particular waves, instabilities and turbulence. Motivation for their work comes from terrestrial applications of magnetized plasmas, in particular magnetic confinement fusion energy, as well as natural plasmas found in space and astrophysical settings, for example accretion disks. Experimental work performed by the group makes use of national facilities, such as UCLA's own Basic Plasma Science Facility and tokamak experiments including the DIII-D experiment operated by General Atomics Corporation in San Diego.

A recent research highlight from the Carter group concerns

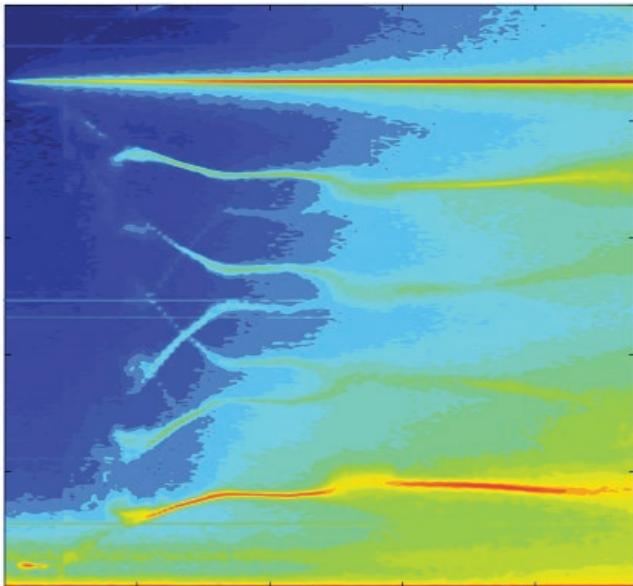


Fig. 1. Magnetic fluctuation spectrum in LAPD during experiments in which an Alfvén wave (the pump wave) is launched with increasing amplitude (Antenna Current). Above a threshold amplitude, daughter waves are observed.

so-called nonlinear instabilities. Turbulence in magnetically confined plasmas is often attributed to linear instabilities, which can grow from infinitesimal initial perturbations (e.g. thermal noise). However it is well known in the hydrodynamics community that linear instability (normal mode) analysis fails at predicting turbulent onset for a number of physical situations, for example water flow in cylindrical pipes (Poiseuille flow). In these cases, turbulence arises even though all linear modes are stable, meaning infinitesimal perturbations on the laminar state cannot grow exponentially. Nevertheless, finite amplitude perturbations can still excite turbulence.

We have found that the same can be true in pressure-gradient-driven turbulence in magnetic confinement devices. This fact makes prediction of turbulence and turbulent transport in fusion experiments difficult as linear instability calculations, which are relied on quite heavily in the fusion community, can be misleading. Using input from analysis of massively-parallel simulations of turbulence in the Large Plasma Device at UCLA, postdoc fellow Brett Friedman developed a technique that enables the prediction of the nonlinear properties of a turbulent system using simple linear, but "nonmodal", calculations. The technique successfully predicts the structure of the nonlinearly-saturated state in LAPD turbulence simulations and provide a linear technique to estimate turbulent saturated amplitude and particle transport [B. Friedman and T.A. Carter, Physical Review Letters 113, 025003 (2014)].

A second highlight concerns the observation of a decay instability of Alfvén waves in LAPD. Alfvén waves are low-frequency modes in magnetized plasmas that can play fundamentally important roles in laboratory, space, and astrophysical plasmas. One important process, called the parametric decay instability, results from the decay of



a large-amplitude Alfvén wave into a daughter Alfvén wave and a sound wave. This process could play a role in heating the solar corona, which is observed to be as hot as three million degrees (compared to the 6,000 degree solar surface). Postdoc Seth Dorfman has led a study looking for this decay instability in LAPD. This work has built on earlier work led by Dr. Dorfman that demonstrated a three-wave interaction between two antenna-launched Alfvén waves which resulted in the generation of damped sound waves [S. Dorfman and T.A. Carter, *Physical Review Letters*, 110, 195001 (2013)].

In recent experiments, observations consistent with the decay of a single, large-amplitude Alfvén wave have been

## UCLA PLASMA DIAGNOSTIC GROUP

**William A. Peebles, Edward J. Doyle, Terry L. Rhodes, Lothar Schmitz, Neal A. Crocker, Troy A. Carter**

### *Advanced Plasma Diagnostic Systems*

The UCLA Plasma Diagnostic Group (PDG) has developed and deployed a wide range of advanced mm-wave plasma diagnostic systems for leading fusion research facilities, both nationally and internationally. Activities expanded during the year, and the Group now has significant research and development involvement with each of the following four fusion research facilities:

The DIII-D National Fusion Facility, operated by the General Atomics (GA) company in San Diego, CA.

- UCLA operates five key diagnostic systems on DIII-D: an ITER-like profile reflectometer system to measure electron density profiles, two multi-channel Doppler backscattering systems to provide wavenumber resolved measurements of turbulence flow velocities and amplitudes, a correlation electron cyclotron emission system to measure plasma electron temperature fluctuations, and a new, novel cross-polarization scattering system to measure internal magnetic field fluctuations. These diagnostic systems support physics studies across a wide range of DIII-D operational regimes.
- The NSTX-U spherical torus facility, located at the Princeton Plasma Physics Laboratory (PPPL), in Princeton, NJ. As on DIII-D, UCLA provides and operates profile reflectometer, Doppler backscattering and polarimeter/interferometer systems to support wide-ranging physics studies on NSTX-U. UCLA also recently obtained funding to investigate the role of energetic ion driven Alfvén eigenmodes in causing plasma transport in NSTX-U. [see e.g. N. A. Crocker, et al., *Nucl. Fusion* 53,043017 (2013)].

made, as shown in the Fig.1. This figure shows the spectrum of magnetic fluctuations in the experiment as the amplitude of the “pump” Alfvén wave is increased (x-axis). Above a threshold amplitude, two new coherent waves appear spontaneously; the waves have frequencies and wavenumbers consistent with a three-wave decay process. Dr. Dorfman will give an invited presentation at the upcoming APS Division of Plasma Physics meeting on this topic and a manuscript is in preparation for submission to *Physical Review Letters*. Dr. Dorfman was the recipient of the 2013 Fred L. Scarf Award and Basu United States Early Career Award, both from the American Geophysical Union, in recognition for his work on Alfvén waves while at UCLA and on Magnetic Reconnection during his graduate work at Princeton University.

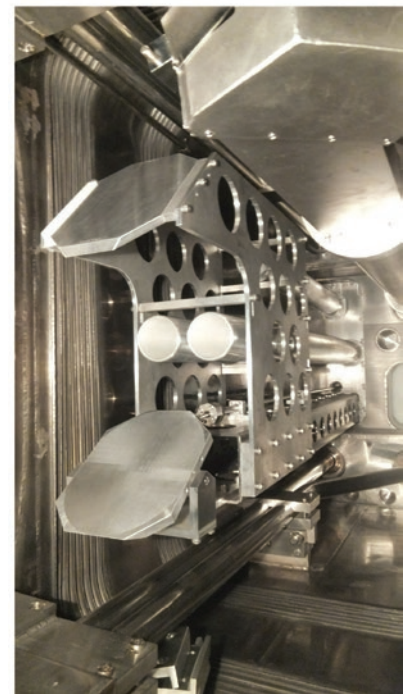


Fig. 1. Photograph showing a new UCLA designed and constructed microwave antenna and mirror system for profile reflectometer and Doppler backscattering measurements, installed inside a midplane port on the EAST tokamak, located at ASIPP, Hefei, China.

- UCLA is now a key member of a U.S.-funded team to design and develop the main Low-Field Side Reflectometer System (LFSR) for the ITER facility, a \$30-50 billion tokamak device under construction in Cadarache, France. The other U.S. team members on this project are PPPL, GA and ORNL.
- UCLA is collaborating with the University of Science and Technology of China (USTC), to develop and deploy profile reflectometer and Doppler backscattering systems for use on the EAST Tokamak, operated by ASIPP, in Hefei, China. During the year, UCLA designed, constructed and delivered a new integrated microwave front-end antenna system for EAST (see Fig. 1), as well as an 8-channel mm-wave source/receiver system for Doppler Backscattering measurements.

These projects include significant student involvement. In October 2013, Jie Zhang successfully completed his PhD thesis on the “Study of Internal Magnetic Field via Polarimetry in Fusion Plasmas.” Two new graduate students have started PhD thesis work with the group; Laszlo Bardoci will be studying the influence of turbulence on Neoclassical Tearing Mode instabilities in DIII-D and Shawn Tang, will participate in the investigation of Alfvén eigenmode induced transport in NSTX-U.

### ***Diagnostic Development and Physics***

UCLA is developing a new internal magnetic field fluctuation diagnostic utilizing cross-polarization scattering (CPS), a process where magnetic fluctuations scatter EM radiation into the perpendicular polarization. CPS is based upon the process where magnetic fluctuations scatter electromagnetic radiation into the perpendicular polarization. The unique scattering geometry offered by Doppler backscattering (DBS) probe beams is utilized to improve the spatial localization and wavenumber range compared to previous implementations. When fully developed, the system will measure magnetic fluctuations in the core and edge of high-performance DIII-D tokamak plasmas with cm spatial and microsecond time resolution, and wavenumber range 0.25–9 A DOE Diagnostic Grant is funding the development of this system on the DIII-D tokamak.

More information on this diagnostic can be found in “Development of a cross-polarization scattering system for the measurement of internal magnetic fluctuations in the DIII-D tokamak” by T.L. Rhodes, et al, in Rev. Sci. Instrum. 85, 11D838 (2014).

A new frequency-modulated profile reflectometer system, featuring monostatic antenna geometry (using one microwave antenna for both launch and receive), has been installed on the DIII-D tokamak, providing a first experimental test of this measurement approach for profile reflectometry. Fig. 1. shows the system layout and also includes a photograph of the in-vessel antennas. More information can be found in “Performance and data analysis aspects of the new DIII-D monostatic profile reflectometer system” by L. Zeng, et al, in Rev. Sci. Instrum. 85, 11D843 (2014). Fig. 2. shows schematic overview of new DIII-D monostatic profile reflectometer system. The embedded photo shows both Q- and V-band antennas located in the DIII-D port.

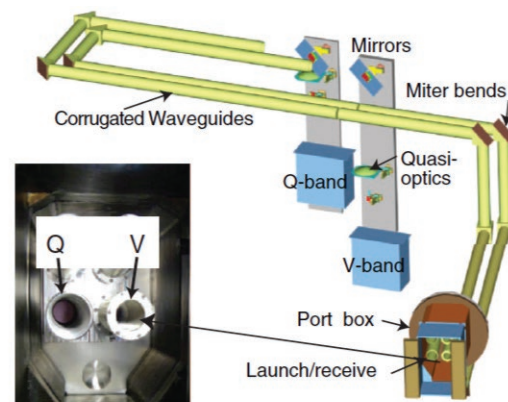


Fig. 2. Schematic overview of new monostatic profile reflectometer system. The embedded photo shows both Q- and V-band. antennas located in the DIII-D port.

## **RESEARCH ON RADIATION BELT REMEDIATION**

**Y. Wang, W. Gekelman, P. Pribyl, B. Van Compernelle**

We are engaged in experiments related to ionospheric modification using RF waves. Related experiments at UCLA involve the focusing of high power microwave on a plasma layer within the Large Plasma Device. A mega-Watt solid-state pulser was constructed and is capable of firing rapid high power energy pulses at tunable modulation frequencies ( $\Delta\tau \sim 1 \mu\text{s}$ ,  $P = 1 \text{ MW}$ ,  $f_{\text{modulation}}$  as high as 200 kHz). The pulses were converted into X-band microwaves by a magnetron and delivered into the plasma transverse to the background magnetic field. The electromagnetic energy was deposited into a narrow plasma layer determined by the plasma density profile and the background magnetic field (Fig. 1). By generating super-thermal electrons and current channels, the high power microwave pulses created a virtual antenna inside the plasma (Fig 2). An initial experiment, just completed,

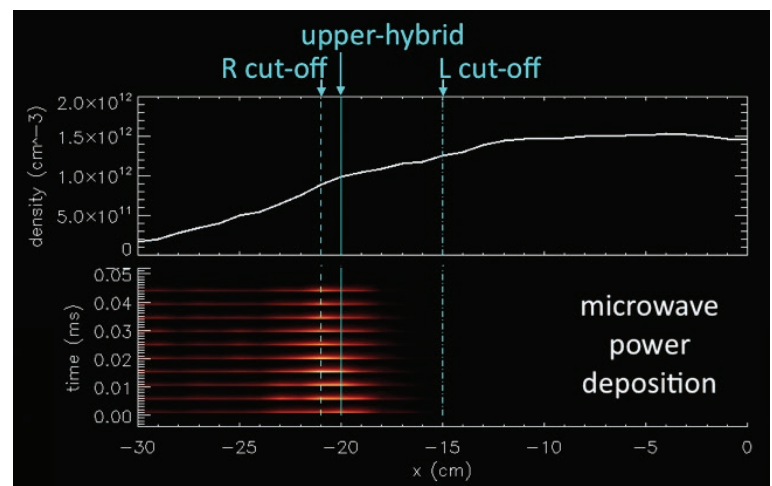


Fig. 1. The location of microwave power deposition (shown on bottom) is largely determined by plasma density profile (shown on top).

showed generation of a coherent shear Alfvén wave at a frequency determined by the pulse spacing. This wave driving mechanism may have important application in terrestrial radio communications by low-frequency waves, which at the present time are difficult to launch directly due to their enormous wavelengths.

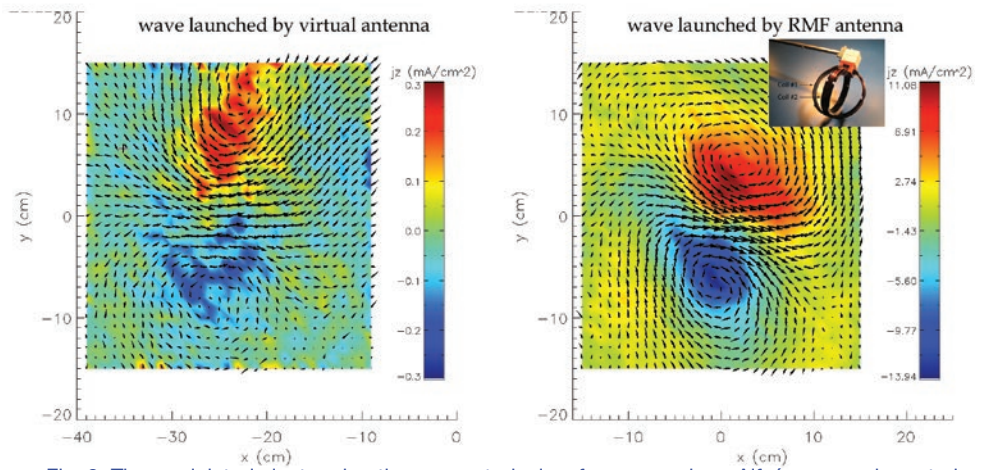


Fig. 2. The modulated electron heating generated a low frequency shear Alfvén wave, characterized by an oscillating magnetic field (shown on top). The wave launched by this virtual antenna is very similar to that launched by a physical antenna.

## THEORETICAL PLASMA PHYSICS

George Morales

### *Ion-ion hybrid Alfvén resonator in fusion plasmas*

Graduate student William Farmer and Professor George Morales recently published a comprehensive study [Phys. Plasmas 21, 062507 (2014)] of a shear Alfvén wave resonator expected to arise in the ITER tokamak being constructed in France. This major international project aims to create a plasma in which alpha particles, produced by the fusion of deuterium and tritium nuclei, provide the heating power to achieve burning conditions. The shear Alfvén mode, which propagates predominantly along the magnetic field direction, experiences a parallel reflection where its frequency matches a unique frequency, the ion-ion hybrid frequency, which is proportional to the magnetic field strength. In a tokamak operating with a D-T fuel this effect forms a resonator because of the variation in local field-strength along a field line. The characteristic propagation bands for this mode are illustrated in Fig. 1.

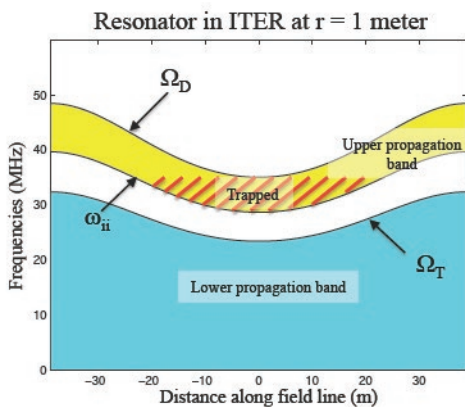


Fig.1. Propagation bands for ITER. Red dashes correspond to the trapped resonator modes.

The study found that the resonator modes can be driven unstable by energetic alpha particles. A high level of resonator fluctuations can result in enhanced energy transport, and the unique spectral and spatial localization of the resonator modes can provide useful diagnostic signatures.

### *Statistical properties of turbulent fluctuations in the DIII-D tokamak*

Dr. James Maggs and Professor George Morales are collaborating with senior UCLA researcher Dr. Terry Rhodes stationed at the DIII-D tokamak in San Diego. This device is the largest fusion research device operating in the U.S. The goal is to apply permutation entropy analysis techniques, previously used by Maggs and Morales, to study chaotic transport in LAPD experiments (Plasma Phys. Control. Fusion 55, 085015 (2013)), to the turbulent fluctuations detected by the Doppler Backscattering System (DBS). This is a novel microwave diagnostic tool developed at UCLA by Dr. Tony Peebles' group. An important feature of DBS is that it provides simultaneous sampling of the fluctuations at several radial locations, and measures the plasma flows in which the fluctuations are embedded. The project aims to determine if the underlying dynamics are chaotic or stochastic. The answer to this question will provide constraints and guidance for theoretical and numerical studies of the turbulent nature of fusion plasmas.



### Nonlocal transport in magnetized plasmas

A joint experimental, theory and computer simulation project involving Dr. Bart Van Compernelle, Dr. James Maggs and Professor George Morales at UCLA, and Professor Richard Sydora, at the University of Alberta in Canada, is investigating nonlocal transport in magnetized plasmas. By nonlocal we mean that the transport of fundamental macroscopic parameters of a system, such as temperature and density, does not follow the behavior predicted by a Fokker-Planck equation. The core of the project is a novel experimental arrangement implemented in the LAPD device at UCLA. It consists of the injection of relatively low energy electrons into a cold magnetized plasma. As these electrons slow down by Coulomb scattering they provide a simple heat source, akin to a candle, that heats the cold background plasma. To explore the role of nonlocal transport, the spatial distribution of the injected electrons is designed to be a hollow ring. The goal is to determine the

rate of heat transport across the magnetic field into the cold hollow center of the ring. A possible origin of the nonlocal transport is chaotic motions induced by plasma modes, which are driven unstable by the temperature gradient. An example of a measured spatial distribution of electron temperature in such a system is shown in Fig. 2.

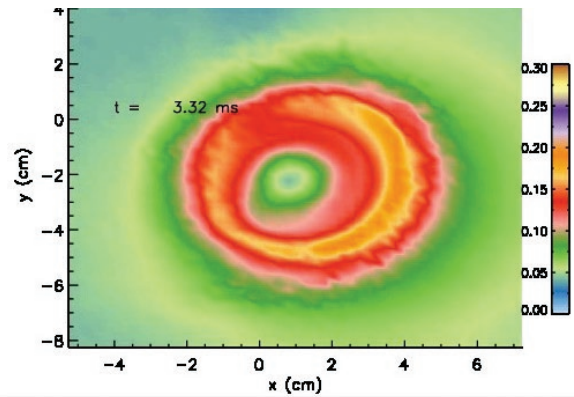


Fig. 2. Contours of constant electron temperature on a plane perpendicular to the magnetic field.

### SPACE PLASMA SIMULATION GROUP (SPSG)

Maha Ashour-Abdalla

The Space Plasma Simulation Group (SPSG) has continued to carry out cutting edge research on a number of different problems in space physics. The overall theme in these projects is to use various types of numerical plasma simulation codes in close coordination with observations made by NASA satellites at the Earth and at other planets. The satellite data is used both to initialize the simulations and to validate the results. The simulations are then used to determine the physical mechanisms that are operating and also to put the single point satellite measurements in a global context. The goal is to achieve a better understanding of the space plasma environment and determine the important physical processes at play. As such the SPSG works closely with NASA and NSF to carry out this research that involves both observational data and simulations that are performed on massively parallel supercomputing systems.

A longstanding unsolved question in magnetospheric physics is the problem of where and how electrons are accelerated up to 100's of keV in the magnetotail from initial temperatures of about 1 keV in the magnetotail lobes. The conversion of magnetic energy to particle energy will occur and accelerate electrons and protons near regions

where the particles are demagnetized, i.e., the electron and ion diffusion regions, respectively. Understanding particle acceleration in the magnetotail during substorms requires knowledge of changes in the global magnetospheric configuration and the local regions of microinstabilities caused by reconnection. To this end, the SPSG simulated a substorm

on February 15, 2008 by coupling the UCLA global magnetohydrodynamic (MHD) simulation code and a two dimensional version of the iPIC3D implicit particle-in-cell code (Fig. 1). In the iPIC3D simulation after a few seconds an active X-point forms and dipolarization front (DF) like structures form about every two seconds and propagate earthward. In the near-Earth magnetotail the earthward moving fronts combine to form larger structures. The presence of the macroscopic scale magnetic field, featuring a significant dipolar component nearer the Earth affects the reconnection process, choking the flow Earthward flow and causing the produc-

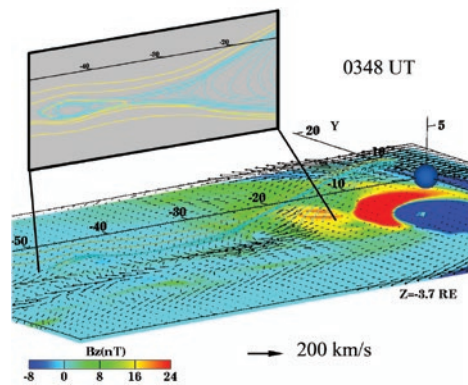


Fig. 1. A 3D perspective of a combination of field lines,  $B_z$  and flow vectors is shown at 0348 UT from the MHD simulations, which was used as input to the iPIC3D simulation. The color shading gives the component of the magnetic field, and the black arrows are flow vectors at  $z = -3.7$  RE. Closed field lines are blue and open field lines are yellow. The field lines originate from a region bounded by  $x$  from  $-9$  to  $-32$  RE,  $y = -3$  RE and  $z = -3.7$  RE. The insert shows 3D field lines in the region  $-15$  RE  $> X_{GSM} > -45$  RE, projected onto the plane at  $y = -3$  RE.

tion of multiple repeating DFs. In the region away from the equator but equatorward of the separatrices, the DFs become associated with a series of spatial stripes that are visible in the electron temperature and the magnetic and electric fields and are also caused by the unsteady nature of the process of reconnection (Fig. 2). The electrons are preferentially accelerated in the dipolarization region in the extension of the dipolarization field lines to high latitudes and reach energies of 100 keV or more. A streaming instability may be responsible for the parallel acceleration. This acceleration of the plasma associated with the DFs is greater than that occurring near the X-point for this sub-storm [Ashour-Abdalla et al., 2014].

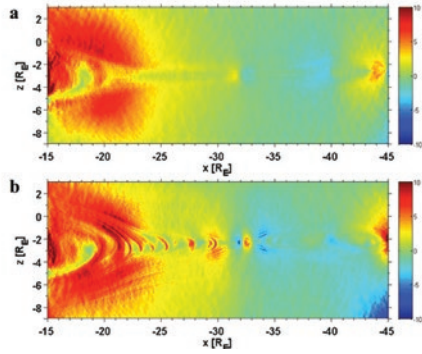


Fig. 2. The normal magnetic field ( $B_z$  in GSM coordinates) is shown at  $t = 14.4$  s (panel a) and  $t = 57$  s (panel b), corresponding to the global MHD/iPIC3D simulation run.

Members of the SPSG, in collaboration with colleagues from ESA, IRAP (France) and Johns Hopkins University have also been investigating the interaction of solar wind ions with the dayside magnetospheric boundary (magnetopause). Recently, they carried out numerical simulation studies of that interaction for southward interplanetary magnetic field (IMF). Results of global MHD simulations in conjunction with large-scale kinetic (LSK) calculations revealed the development of a strong dawn-dusk asymmetry in the ion entry over the high-latitude dayside magnetosphere. This is illustrated in Fig. 3 that shows the locations of the solar wind ion crossing a spherical detector used in the simulation. The detector shows that the most energetic ions (red crossings) are precipitating at the lowest latitudes while the less energetic ones (blue crossings) are seen over a large range of high latitudes. This energy dispersion results from the time of flight effect in the entry of the ions accelerated toward Earth by the reconnection process. The detector also reveals a strong asymmetry in the ion precipitation. Most of the precipitation occurs in the morning and pre-noon sectors. This dawn-dusk asymmetry is also visible in the southern hemisphere and has been shown to be consistent with statistical studies of low-altitude spacecraft observations. Analysis of the simulations indicates that the asymmetry results from the dawn-dusk reversal of the electric field associated with the component of the magnetopause current parallel to the magnetic field. In the northern pre-

noon-morning sector, the parallel electric field is positive so it accelerates solar wind ions reaching the magnetopause toward the ionosphere, whereas the electric field is negative in the afternoon-evening sector and accelerates the ions outward toward the magnetotail, creating the asymmetry. The same dawn-dusk asymmetry is found in the southern hemisphere because both parallel electric field and magnetic field reverse direction [Berchem et al., 2014].

In another project, the SPSG has studied how plasma is transported in the Earth's magnetotail and how this transport relates to turbulent flow. A significant part of

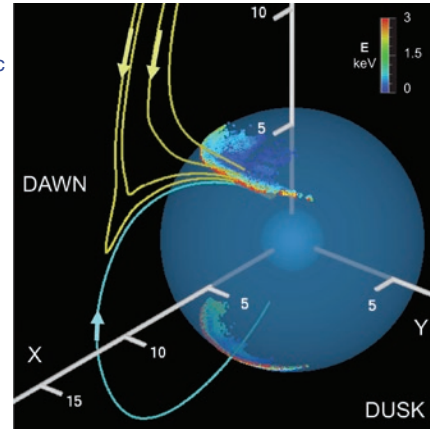


Fig. 3. This figure shows the locations of the solar wind ions crossing a spherical detector used in the simulation. The transparent blue sphere represents the detector viewed from about 15:00 local time and above the ecliptic plane; the X-axis is aligned with the Sun-Earth direction and distances are measured in Earth radius ( $\approx 6400$

km). The solid blue sphere seen inside the transparent one represents Earth. The location of each crossing has been color coded according to the particle's energy using the scale displayed on the upper-right inside of the figure. The blue line shows the last closed geomagnetic field line. Yellow lines are magnetic field lines that have been opened by magnetic reconnection during the merging of the IMF with the geomagnetic field.

the transport in the magnetosphere is due to turbulence on large-enough scales that the plasma can be treated as a fluid and described on large scales MHD formalism. We have performed MHD simulations of the magnetosphere and its interaction with the solar wind to model this turbulence focusing on the night side of the Earth, i.e., the magnetotail. The simulation reveals numerous eddies nested at smaller and smaller scales (Fig. 4). We have found that the simulation reproduced the spectrum of fluctuations in the magnetosphere and that the transport it provides is critical for establishing the magnetosphere's configuration and evolution. The process of magnetic reconnection in the magnetotail ultimately drives the turbulence but it is also controlled by the spectrum of eddies [El Alaoui et al, 2013].

The group has also continued to make progress in understanding Mercury's magnetosphere using a first of its kind global hybrid simulation that fully resolves the ion gyro-radius. This research effort provides theoretical support for



the MESSENGER spacecraft mission, which became the first orbiter of Mercury upon successful insertion in March 2011. The focus of the research has continued to be on the transport and acceleration of electrons in Mercury's magnetosphere using hybrid simulation results with the electron LSK simulation method. One of the main results has been to determine electron precipitation profiles onto Mercury (Fig. 5). When a particle precipitates at Mercury it collides directly with the planet since there is no atmosphere or ionosphere. The results show that a type of "auroral oval" pattern is formed by the precipitation of keV electrons at higher latitudes in the north and south, however, the entire precipitation pattern is shifted to the north due to the northward offset of Mercury's magnetic dipole. An important consequence of electrons precipitating at these energies is the formation of x-rays when electrons interact with planetary surface elements. There is very good correspondence between the precipitation of the electrons and the emission of X-rays as shown by the X-ray Spectrometer (XRS) instrument (gray shaded regions). Thus at Mercury an X-ray aurora is formed analogous to the visual aurora formed at the Earth [Domingue et al., 2014].

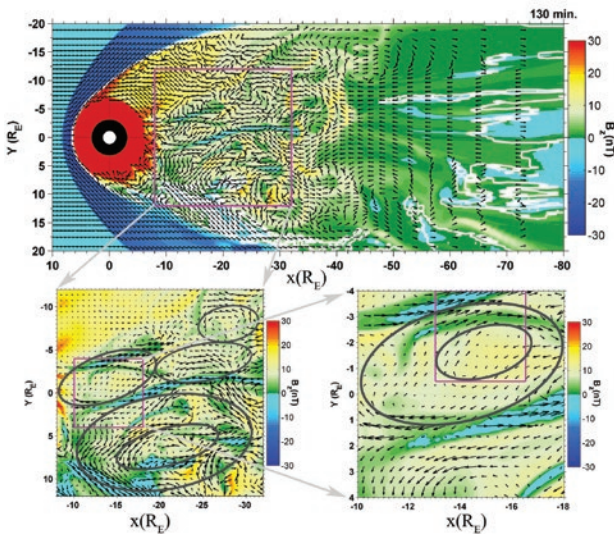


Fig. 4. A snapshot of the MHD solutions in the equatorial plane is shown. Superimposed are unit flow vectors in the plane and white solid lines showing the positions of the outermost field lines connected to the Earth at both ends. The color contours indicate the magnitude of the north-south component of the magnetic field. The part of the top large-scale panel has been expanded on the lower left to show finer scale structures in the convection, and then further expanded on the lower right. Gray ovals indicate turbulent eddies.

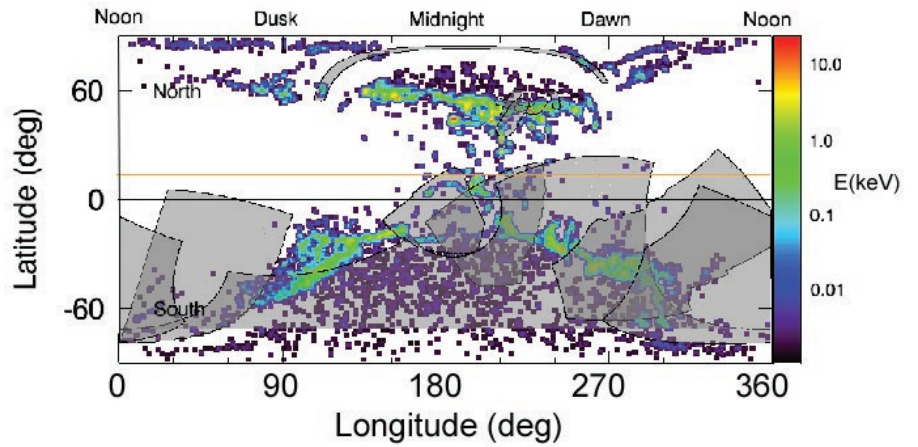


Fig. 5. This figure shows the latitude-longitude precipitation profiles for electrons at Mercury for a northward IMF solar wind: The color coding is in energy with 0.0 latitude corresponding to the geographic equator and the gold horizontal line at about 11° latitude corresponding to the location of the geomagnetic equator. Midnight is 180° longitude. The gray shading corresponds to where the XRS instrument observed x-ray fluorescence emanating from the planet.

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# Experimental Condensed Matter Physics

## STUART BROWN

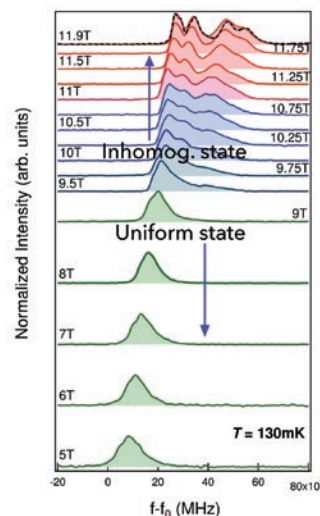
Electronic correlations in materials are associated with a wide range of phenomena of interest to condensed matter physicists, such as high temperature superconductivity, Mott insulators, and novel ordered and quantum disordered ground states. The research activities

of Professor Brown's group are focused on several aspects associated with strong correlations, including molecular superconductors, intermetallic heavy fermion compounds, and frustrated quantum magnets from both organic and inorganic families. Typically, the materials are probed using nuclear magnetic resonance methods, often applied under extreme conditions such as low temperature, high magnetic fields, and under high pressure or strain. NMR is sensitive to the electronic degrees of freedom via interactions between the electronic and nuclear spins, and to the local charge environment when the nucleus under study exhibits an electric quadrupole moment. Here we highlight some recent work in which NMR is used to probe a new superconducting phase which is stabilized at high magnetic fields.

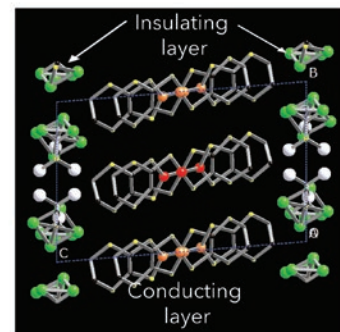
One of the spectacular properties we associate with superconductivity is the Meissner Effect, which is the exclusion of magnetic fields from the interior of a superconductor. When a superconductor is placed in a magnetic field, surface currents are generated in response, which in turn produce a field



The mixing chamber of the dilution refrigerator is equipped with a piezo-rotator of millidegree precision.



$^{13}\text{C}$  NMR spectra, showing the formation of the high field phase. The line broadening is associated with inhomogeneous electronic spin polarization.



Depicted is the layered structure of an all-organic superconductor. The magnetic field is confined to the insulating spacers.

cancelling the applied field in the interior. As the field is increased, the associated cost in energy eventually destroys the superconducting properties and ordinary metallic behavior is restored. Superconductivity can persist to higher fields by allowing for the creation of magnetic field penetration in the form of lines of circulating currents, known as quantized vortices. Layered superconductors can avoid these effects completely, allowing for the flux to penetrate between the conducting layers and generating only insignificant currents. In that case, the magnetic field penetrates easily into the material while maintaining superconducting coherence. However, high magnetic fields are still the enemy, because eventually the effects of the field coupling to the electron spin drives the system to the normal state. An intermediate state, still superconducting but with inhomogeneous spin polarization was predicted in the 1960s, but only now being identified and studied in our laboratory in

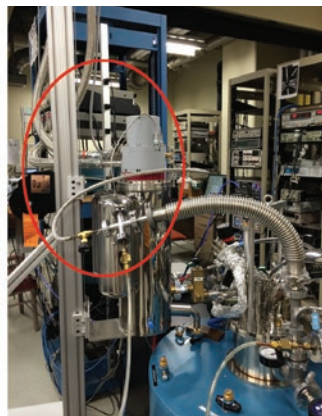
layered molecule-based superconductors. In the spectra shown, magnetic fields up to 12T are applied precisely in-plane to within approximately .01 degrees, at temperatures of order 100mK. We use NMR to probe the local spin polarization, which is modulated in space, as well as associated fluctuations.



The collection bag is partially full in this photograph. The table it sits on is flush with the A-level of the PAB, and the liquefier and purifier is accessible from the B-level.



The helium liquefaction facility used by Prof. Brown's group is located in the shaft between Knudsen Hall and the PAB.



One of the pulse tube units (circled) in Prof. Jiang's laboratory, for reliquifying helium as it boils from the cryostat.





nary materials subjected to intense electrical and/or thermal biases. Such driven states exhibit dynamic symmetry breaking and manifest critical behavior with continuous as well as hysteretic phase transitions, which bear intriguing analogies to lasing and equilibrium condensation of quantum liquids. An ability to engender a bosonic condensate by thermal gradients opens exciting possibilities for the nascent field of spin caloritronics, which strives to control spin transport by thermal means as well as employ its utility in thermoelectric applications.

Finally, in collaboration with experimentalists at the UCLA Department of Electrical Engineering, we studied topological insulators that were magnetically doped into a ferromagnetic state. We showed that such materials can exhibit a remarkably strong spin Hall effect, which allows for a strong coupling between charge currents flowing along the surface and magnetic dynamics in the doped region (see *Nature Materials* 13 (2014) 699). As a result, a weak electrical current can leverage an efficient transfer of angular momentum from the atomic crystal to the collective magnetic dynamics, which can induce a full reversal of the magnetic order. Further progress in fabricating and im-

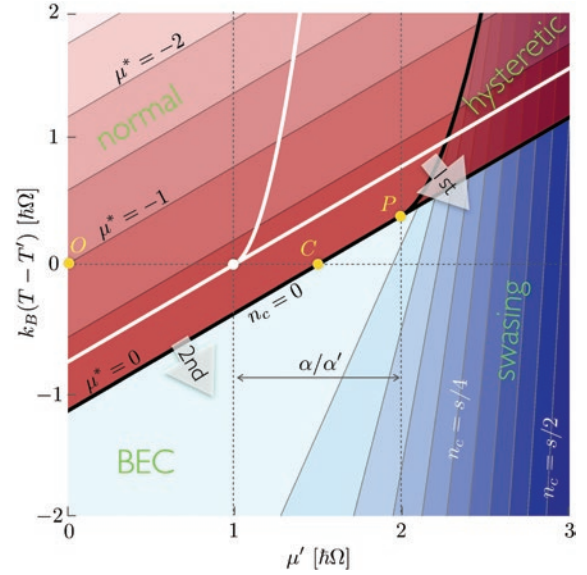


Fig. 2. Dynamic phase diagram for the magnonic Bose-Einstein condensate and “swasing” states (cf. *Phys. Rev. B* 90 (2014) 094409).

proving this and similar heterostructures based on materials with strong spin-orbit interactions may lead to innovative spintronic applications, such as nonvolatile memory and logic devices with ultralow energy dissipation.

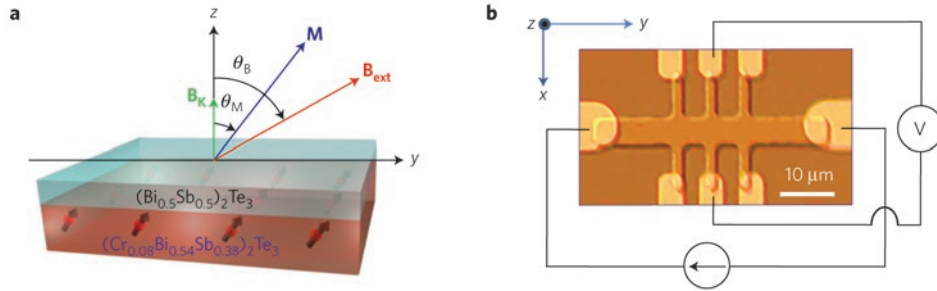


Fig. 3. Three-dimensional schematic of the magnetically-doped topological-insulator heterostructure (a) and micrograph of the Hall bar device (b).

## RAHUL ROY

Most of the observed phases of electronic matter can be understood in terms of patterns of symmetry and symmetry breaking. Since the 1980s a number of new types of phases have been discovered where the pattern of order cannot be described in terms of a local function such as polarization or magnetization, but rather is topological in nature. These include the integer and fractional quantum Hall effects, as well as the more recently discovered topological insulators.

Fractional Chern insulators are a class of lattice models which display quantum-Hall-like behavior without the need for a large external magnetic field. For this reason, developing laboratory realizations of these systems has been a subject of intense interest recently, and one aspect of Professor Rahul Roy's work over the past year has been

developing a theoretical understanding of the new degrees of freedom these systems offer over the continuum quantum Hall effect.

In particular his group, in collaboration with Dr. G. Moller at Cambridge, has performed large-scale numerical simulations which verified previous theoretical work by Professor Roy on conditions contributing to the thermodynamic stability of these phases. Professor Roy has also collaborated with Professor S. H. Simon at Oxford University and his student, F. Harper, to explore a perturbative approach for the Berry curvature and many-body physics in the Hofstadter model. He has also studied analogs of quantum Hall ferromagnetism in fractional Chern insulators with higher Chern numbers in collaboration with Professor S. L. Sondhi and A. Kumar at Princeton University.



## SUDIP CHAKRAVARTY

My research interest involves quantum theory of collective behavior of electronic systems. I am interested in theories of high temperature superconductivity, dissipative quantum systems, quantum phase transition and criticality, localization transition in interacting systems, and the concept of von Neumann entropy in quantum phase transitions. I am currently actively interested in competing electronic states in high temperature superconductors. I have written four papers in the past year. One particular paper, involving a heavy fermion material, is a new direction of research that I would like to highlight here. This work was carried out in collaboration with my student Chen-Hsuan Hsu and will be published shortly in Physical Rev. B and at arXiv:1308.5357.

In the heavy fermion material, URu<sub>2</sub>Si<sub>2</sub> (URS), the identity of the order parameter in an enigmatic phase, known as the hidden order (HO) phase below the temperature 17.5 K, is not known despite a quarter century of its discovery. Buried deep inside this phase lies a much less-explored unconventional superconducting state at a temperature 1.5 K that was our central interest.

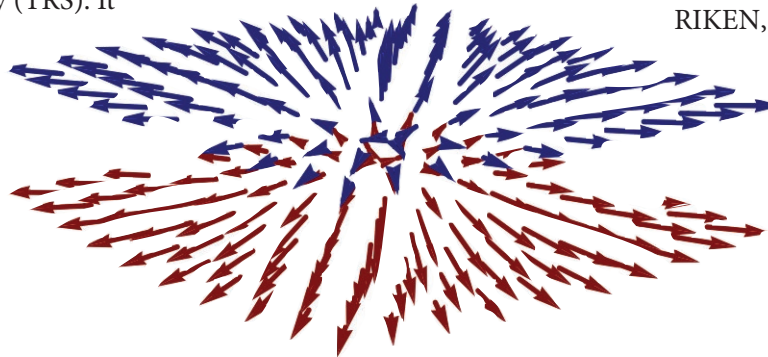
We identified a special density wave to be the hidden order state. It has no net charge or spin modulations and does not break time reversal symmetry (TRS). It does have topological order

with quantized spin Hall effect. Thus it is naturally impervious to common experimental probes and is an excellent candidate for HO.

We then constructed a global phase diagram in which there is a deconfined quantum critical point, ultimately responsible for the basic mechanism of superconductivity. We argued that the skyrmionic spin texture in the HO state ultimately fractionalizes into fermionic merons and anti-merons, which results in two copies of unconventional chiral d-wave BCS superconductors, consistent with experiments.

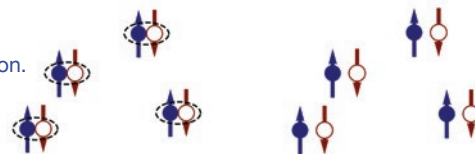
The superconducting state breaks TRS, which can be directly detected by polar Kerr effect (PKE) measurements; in contrast HO itself should not exhibit PKE except perhaps for magnetic impurities. In a more general context, our work reflects the rich possibilities of emergent behavior in condensed matter systems.

This past year I have co-organized the 2014 Aspen Winter Conference on “Unconventional Order in Strongly Correlated Systems,” held in Aspen, Colorado. During 2013-2014 I had three graduate students at various stages of their careers. One student, Chen-Hsuan Hsu, graduated in June 2014 and is a postdoctoral fellow at RIKEN, Japan.

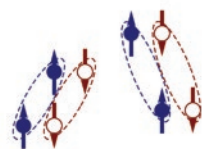


Merons with fluxes  $\pm 2M$

Merons and antimerons are bound in a skyrmion.  
The arrows denote the gauge flux not spin



Merons and antimerons unbound at  
the deconfined quantum critical point



Bound pairs of merons and anti-merons in  
the superconductor

# Faculty 2013-14

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 Lindley Winslow

## Professors Emeriti

Ernest S. Abers  
 Eric Becklin  
 Rubin Braunstein  
 Charles Buchanan  
 Marvin Chester  
 Gilbert W. Clark  
 John M. Cornwall  
 Robert Finkelstein  
 George Igo  
 Steven Moszkowski  
 C. Kumar N. Patel  
 Roberto Peccei  
 Claudio Pellegrini  
 William E. Slater  
 Reiner Stenzel  
 Roger Ulrich

Alfred Wong  
 Chun Wa Wong  
 Byron T. Wright  
 Benjamin Zuckerman

# Researchers 2013-14

## Researchers

Jean Berchem  
 David Brower  
 Viktor Decyk  
 Weixing Ding  
 Mostafa El Alaoui  
 Samim Erhan  
 Terry Rhodes  
 R. Michael Rich  
 Robert Richard  
 Lothar Schmitz  
 Gil Travish  
 Steven Trentalange  
 Stephen Vincena  
 Hanguo Wang

## Associate Researchers

Gerard Andonian  
 Neal Crocker  
 Mikhail Ignatenko  
 Shreekrishna Tripathi  
 Frank Tsung

## Assistant Researchers

Xiaoping Ding  
 Atsushi Fukasawa  
 Liang Lin  
 Alexey Lyashenko  
 Sebastiaan Meenderink  
 Brian Naranjo  
 Gregory Rakness  
 Shoko Sakai  
 So Takei  
 John Tonge  
 Bart Van Compernelle  
 Gang Wang  
 Jingwen Wu  
 Jeffrey Zweerink

# New Faculty 2013-14

## FRANK JENKO



Frank Jenko received his PhD from the Technical University of Munich in 1998. As a postdoc at Garching, Maryland, and Princeton, he co-pioneered the development and application of grid-based numerical techniques for the investigation of kinetic turbulence in magnetized plasmas. Since then, his code GENE has been playing a key role for analyzing both laboratory and natural plasmas, standing at the forefront of High Performance Computing. Since 2005, he has been the leader of an independent research group at IPP, gradually broadening his scientific interests and organizing many interdisciplinary workshops and conferences. From 2005-2011 he was the head of a Helmholtz Young Investigators Group, and since 2011 his work has been supported via a prestigious €1.45M Starting Grant from the European Research Council. Professor Jenko has authored or co-authored about 150 papers in peer-reviewed journals, including one of the most cited articles in "Physics of Plasmas" and 20 papers in "Physical Review Letters." Among other accomplishments he has been serving on the Editorial Board of "Computer Physics Communications," as co-director of the Helmholtz Graduate School for Plasma Physics, and on the Steering Committee of the Max-Planck/Princeton Center for Plasma Physics.

## SMADAR NAOZ



Smadar Naoz began her studies in Physics at Hebrew University of Jerusalem, where she received her B.S. in 2002 and her M.S., Magna Cum Laude, in 2004, and where she was awarded the 2003 Arnold Rosenblum Prize, for outstanding achievement as a graduate student in Astrophysics and the 2004 Rector's Prize, for top 5% of master's students in the science faculty. Professor Naoz earned her Ph.D. in Physics at Tel Aviv University, where she was awarded the 2006 School of Physics & Astronomy Award for outstanding achievements, a 2007 Don & Sera Marejn Scholarship, the 2007 Ilan Ramon Award, the 2008 John Bahcall Graduate Student Prize, and the 2009 Dan David Prize Scholarship. Since completion of her Ph.D., she was postdoc, first at Northwestern as a Gruber Fellow, an international fellowship awarded annually by the International Astronomical Union, and then at Harvard where she held a prestigious Einstein Fellowship. Professor Naoz's research expertise is in two distinct areas in theoretical astrophysics -- cosmology and planetary dynamics. Her highest impact work thus far is in the arena of extra-solar planets, where there has been tremendous growth in knowledge due

to rapid advances from several different observational approaches. Professor Naoz is also exploring stellar dynamics near supermassive black holes, and is interested in applying this work to studies of the Galactic Center, which is an area of great interest to our department.

## TOMMASO TREU



Tommaso Treu received his PhD in Physics at the Scuola Normale Superiore in Pisa in 2001. He was a postdoctoral scholar at the California Institute of Technology until 2003, and held a prestigious Hubble Postdoctoral Fellowship here at UCLA from 2003-2005. In 2005, he joined the Department of Physics at the University of California, Santa Barbara as an assistant professor, and then rose through the ranks and was promoted to full professor. In Summer 2014 Professor Treu joined our faculty. His research involves several distinct areas of extragalactic astronomy. These include: a robust description of elliptical galaxy evolution; the use of strong gravitational lensing to obtain constraints on the dark matter distribution and stellar initial mass function (IMF) in elliptical galaxies; the use of strong gravitational lensing to obtain tight constraints on cosmological parameters; the measurement of the co-evolution of supermassive black holes and their host galaxies; and the identification of the highest redshift galaxies observed during the "Epoch of Reionization." Professor Treu is particularly focused on questions of fundamental importance in the field of galaxy formation and cosmology: What is the

nature of dark matter? What is the formation history of elliptical galaxies? What is the initial mass function of star formation? When do supermassive black holes grow relative to their host galaxies? What is the nature of the reionization of the universe? His use of high-angular-resolution adaptive optics (AO) techniques, and his active role in the maintenance and enhancement of these capabilities at the Keck Observatory, make him an especially important addition to the astronomy division at UCLA.



# BERNARD MARIE KAREL NEFKENS

## JULY 27, 1934 - JANUARY 10, 2014



Experimental Nuclear and Particle Physicist Bernard M. K. (Ben) Nefkens died peacefully at his home in Sherman Oaks, CA, January 10, 2014, at the age of 79 after a long illness.

Ben was born in the Netherlands where he received his PhD from the University of Utrecht before moving on to research faculty positions at Purdue University and the University of Illinois. In 1966 he settled at UCLA where he remained for the next 45 years.

At UCLA Ben taught both on the undergraduate as well as graduate levels. He had a strong interest in improving the quality of the physics laboratories and created a popular laboratory course that deals with the measurement of the properties of everyday objects around the UCLA campus instead of standard textbook measurements, which may at times seem rather dull to some students. As a teacher, he had an infectious enthusiasm and a caring empathy for his students. Rigorous training in the fundamentals is the sign of a Nefkens PhD student.

- Authored over 250 scholarly publications
- Fellow of the American Physical Society
- Corresponding member of the Royal Academy of the Netherlands
- Member APS
- Member European Physical Society,
- Saclay Visiting Scientist (1978-79 and 1988-89)
- CERN Visiting Scientist (1972-73)
- recipient of a Fulbright Travel Grant (1959)
- Program Advisory Committee and member CELSIUS/WASA project at the University of Uppsala, Sweden
- Co-founder and editor of the Pion-Nucleon Newsletter
- Co-founder of the International Conference on Meson and Nucleon Physics (MENU) series

Ben's research involved the study of the structure of the nucleon and probing the Standard Model via tests of broken symmetries such as P, C, T, and CP. Throughout the 1980s, this work was carried out in large part at the Los Alamos National Laboratory, where he led a collaboration of several universities in a series of experiments that resulted in the complete high-precision measurement of the pion-nucleon scattering process at intermediate energies. In a second experimental study at LANL he produced the most complete study to date on time-reversal invariance in pion-3-body nucleus system during which he coined the term "superratio". At TRIUMF, in Vancouver, Canada, he was responsible for a unique set of neutron detectors that were used to study charge-symmetric reactions around the Delta resonance – these detectors are still in use at PNPI. At Saclay, near Paris, France, his research group studied decay modes of the eta meson, and at ELSA in Bonn, Germany, he worked on the photoproduction of the eta near threshold.

One of Ben's greatest achievements was the acquisition and refurbishing of the famous SLAC Crystal Ball multi-photon detector that was used extensively at SLAC and HERA. Ben took the "Ball" to Brookhaven National Laboratory to use at the AGS until the fixed target program ended in 2002. There, he formed and spearheaded an international collaboration of over 30 faculty and students from 12 institutions to carry out a program of pion-nucleon and kaon-nucleon scattering. In 2002, the Crystal Ball detector was once more moved to the MAMI facility in Mainz, Germany, where he formed a new collaboration consisting of over 50 faculty and

students from 17 institutions. That research program continues on to this day.

Besides physics, Ben was interested in music and the arts. He gave wonderful colloquia on symmetries in nature, art and music. While at travel he always looked for local concerts and art expositions to go to. He judged the local churches by the quality of their organist and choir. Above all, Ben loved his family and, as he would say to his collaborators "highly recommended having and playing with grandchildren".

He is survived by his wife, Helen; his children: Julie, Karla and Chuck; their respective spouses: Jim, Toby and Jill; his grandchildren: Tyler, Kate, Millie and Julia; and his sisters, Anny and Jos. His other sibling, Riet Nefkens (Sister Joan), preceded him in death. His passions were his family, physics, swimming, music, and traveling the world, always with his wife Helen at his side.

A memorial for Ben was held at UCLA in March 2014. Donations in his memory can be made to The UCLA Foundation. In the memo field indicate "Ben Nefkens Memorial Fund" and mail to Kerri Yoder, Director of Development; Div. of Physical Sciences; College of Letters and Science; 1309 Murphy Hall; Box 951413; Los Angeles, CA 90095. Further information is available at <http://www.pa.ucla.edu/content/professor-bernard-nefkens>

## NINA BYERS

JANUARY 19, 1930 - JUNE 5, 2014



Nina Byers, a prominent theoretical physicist, passed away at her home in Santa Monica on June 5, 2014 succumbing to a haemorrhagic stroke. She was a pioneering physicist, contributing to the understanding of both particle physics and superconductivity.

Nina was born in Los Angeles to Irving and Eva Byers on January 19, 1930. She received her BA with highest honours from the University of California, Berkeley. After Berkeley she became a graduate student at the University of Chicago where she was Murray Gell-Mann's first and last Chicago student before he moved on to Caltech. When Gell-Mann left Chicago, Nina became Gregor Wenzel's student and eventually wrote a thesis on pi-mesic atoms, obtaining her PhD in 1956. Her thesis work is the basis of her first publication "Interactions of Low-Energy Negative Pions with Nuclei," which appeared in the Physical Review in 1957.

After Chicago, Nina had a postdoctoral period at the University of Birmingham, England in R.E. Peierls' group in the Department of Theoretical Physics. She then moved to Stanford University in 1958, where she worked on superconductivity. Nina joined UCLA in 1961

where she turned her attention to particle physics, collaborating on studies in CP-violation and pion-nucleon charge-exchange scattering. In the late sixties and early seventies, Nina was offered a position at Oxford University and split her time between Los Angeles and Oxford. At Oxford, she was the Jane Watson Visiting Fellow in Somerville College and, for a period, a Science Research Council Senior Scientist.

She returned to UCLA in Fall 1973, where her focus in physics had moved to the new gauge theories of the electroweak interactions. Nina's interest in quarkonium and bound state systems was rekindled in the early 1980's, spurred. She was the first female assistant professor in the physics department at UCLA and the only one for more than 20 years. At UCLA, she collaborated at first on studies in CP violation and pion-nucleon charge-exchange scattering. In the 1970s, her interests turned to the new gauge theories of electroweak interactions, quarkonium and bound-state systems.

This was a very active time in Byers' life, for not only was she doing forefront research with her students, but she was also heavily committed to the affairs of the American Physical Society (APS). Of particular note during this period was the role she played in the Panel of Public Affairs and in the Forum of Physics and Society of the APS, an organization which she chaired in 1982. Her leadership in the AAAS was also notable and she was named a fellow of both societies. Nina served as President of the APS Forum on History of Physics, a position earned through her dedication to promoting the understanding of two weighty subjects: the role of women in physics, and the examination of physicists' role in the development and deployment of nuclear weapons.

She retired in 1993, but was an active professor emeritus until the end. During her long career, she was a visiting scholar at Harvard and Oxford, and held several fellowships and published numerous papers. Partly spurred by her interest in the role of women in academia, soon after retirement, Nina seriously began contemplating establishing a website that would detail the contributions of women to 20th Century physics. After considerable difficulties at first, and with the help of a significant grant from the Sloan Foundation, Nina was finally able to establish this scholarly archive in 1996. She also worked to document the accomplishments of women physicists, culminating in the book "Out of the Shadows: Contributions of Twentieth-Century Women to Physics," co-edited with her colleague at UCLA, Gary Williams.

In addition to her passion for physics, Nina never stopped learning about the world around her. She was politically aware, advocating against the proliferation of nuclear weapons for more than six decades, and was a staunch anti-war activist. She also supported many social-justice and environmental causes. Her passions included the arts, with a love of classical music and film, and an inclination towards modern art and theatre.

Married to Arthur Milhaupt Jr until his death, Nina is survived by her step-children Gretchen, Merimee, Anthony and Anne, her niece Morissa, nephew Mark, and a multitude of extended family, colleagues, students and lifelong friends scattered throughout the globe. A truly independent and inspirational woman, she will be missed greatly by her global family.

A memorial service was held for Nina Byers on Friday, October 24, 2014 at Woodlawn Cemetery in Santa Monica, California.



# OUTREACH

## ASTRONOMY LIVE!

## THE UCLA PLANETARIUM

On November 16th and 17th, 2013 we hosted the fourth and fifth annual Exploring Your Universe events. These free public events included talks, demonstrations, exhibits, and hands-on activities from the Departments of Physics and Astronomy, Earth and Space Sciences, Atmospheric and Oceanic Sciences, Chemistry, the Center for Environmental Implications of Nanotechnology, as well as several student groups, including AXE, SMACS, ESSN, OSA/SPIE, BEAM, IEEE, along with the Neuroscience “Brain Readers,” ELFIN, CIAN, CBGSA, and the departments of Math, Statistics, and Ecology and Evolutionary Biology (added in 2013). This event has grown dramatically over the past few years and has tripled in attendance since its inaugural year. Visitors come from all over the Los Angeles area, including many students, staff, and faculty of local schools and UCLA. This EYU 2014 promises to be even larger—we will be incorporating more student groups and departments than ever before and have three simultaneous lecture series highlighting topics across the science fields.

In 2014, Astronomy Live! created a new summer observing workshop for high school students here at



UCLA. In its pilot year, 6 students were chosen (high school juniors and seniors) based on their applications. Over the course of 8 weeks, students learned the basics of observational astronomy. They learned to use the 14-inch and 16-inch telescopes at UCLA, took their own data, and used that data to complete research projects relating to astronomy and astrophysics. Workshop participants also heard short research talks from graduate students at UCLA. As a part of this program Astronomy Live! was granted two nights on the Lick 1-meter Nickel telescope to observe remotely. During one of these observing runs, the students were able to sit in and even control the telescope. In the process of learning to do data reduction, the workshop participants used reduction scripts written in Python. At the end of this workshop, one of our community partners - Celestron Telescopes - generously donated 6 small telescopes for the student participants. We hope to make this workshop an annual event, and expect it to grow in size in the years to come.

In addition, the UCLA Planetarium has had another very successful year. The graduate student-led planetarium saw 103 shows given over the 2013-2014 school year, with 5,123 attendees (our third year over 5,000) and shows given to 38 different schools. It played a major role in Exploring Your Universe 2013 and our High School Summer Program, along with an event centered around the eclipsed that occurred April 14-15, where ~250 people over 3 hours came between 10 pm and 1 am, despite cloud cover.





## Can Zvi Bern calculate with increasing precision the behavior of gravitons?

Zvi Bern is riding a winning streak more befitting a poker shark in Vegas than a theoretical particle physicist at the University of California, Los Angeles. He is famous in his field for betting colleagues that he can calculate with increasing precision the behavior of gravitons, hypothetical particles that are believed to impart the force of gravity. At stake in each wager is a fine bottle of wine. Against all odds, Bern's wine collection is growing.

For the latest wager with Kelly Stelle, a professor of particle physics at Imperial College London, Bern and his collaborators will subject  $N = 8$  supergravity to an unprecedented test. If they can calculate what happens when gravitons collide to a level of precision known as "five loops" in a fictional world with 4.8 space-time dimensions, then Bern wins. In that case, Stelle must give

him a bottle of Flint Dry from the Chapel Down Winery in England. "It's the wine that was served at William and Kate's wedding," Stelle explained.

For the whole story go to <http://www.wired.com/2014/03/quantum-supergravity/>



## Ni Ni, has received a 2014 Early Career Research Award from the U.S. Department of Energy

Ni Ni, UCLA assistant professor of physics and astronomy, has received a 2014 Early Career Research Award from the U.S. Department of Energy for her proposal "Exploring Superconductivity at the Edge of Magnetic or Structural Instabilities. The Early Career Research Program aims to strengthen the nation's scientific brainpower by supporting researchers during their early years, when many scientists accomplish their most formative work. It awards university-based researchers with at least \$150,000 per year to cover summer salary and research expenses.

Professor Ni joined the UCLA faculty in 2013 to help build new efforts in experimental condensed matter physics, with particular emphasis on the rapidly growing field of quantum materials.



## Michael Rich, astronomer receives funding from National Science Foundation

UCLA astronomer Michael Rich and an international team of collaborators have been awarded funding from the National Science Foundation to map the central

bulge of the Milky Way. The 400 square degree Blanco DECam Bulge Survey (BDBS) will map the bulge from the ultraviolet to the infrared.



## UCLA Physics and Engineering Team Awarded \$1 Million Grant by the W. M. Keck Foundation

A team consisting of Professor Robert Candler of Electrical Engineering and Professors Pietro Musumeci and James Rosenzweig from Physics and Astronomy has received a prestigious \$1 million research grant from the W. M. Keck Foundation, funding a proposal entitled "Ultra-compact X-ray Free Electron Laser."

This is a 2-year program which aims to miniaturize free electron lasers (FELs) by combining novel nano-fabrication techniques to produce extreme short period undulator magnets, with cutting edge beam physics, enabling access to new physical regimes of the FEL. This scenario will enable low energy accelerators to be used to produce coherent, short pulses of X-ray radiation for use in biology, condensed matter physics, medicine and ultrafast chemistry.

## THE JULIAN SCHWINGER FELLOWSHIP AWARD

A first-of-its-kind graduate fellowship in the UCLA College of Letters and Science will transform the department of physics and astronomy by enabling it to attract some of the world's best students in physics, thanks to a \$1.2 million gift from the Julian Schwinger Foundation for Physics Research.

The Schwinger Foundation expects that the comprehensive fellowship will enable students to focus on their research without undue financial pressure by providing, for a maximum of four years, full tuition and fees, along with an inflation-protected stipend of \$42,000 a year. An additional \$3,000 a year will be provided for professional and travel expenses.

Former UCLA physics professor Julian Schwinger shared the 1965 Nobel Prize with Richard Feynman and Sin-Itiro Tomonaga for their research on quantum electrodynamics. In 1971, he joined the faculty at UCLA, where he taught and carried out research until his death in 1994. At Schwinger's request, his wife, Clarice, and his colleague Seth Putterman, a UCLA professor of physics, collected the Schwinger assets into a charitable foundation.



JUSTIN KAIDI is a fourth-year undergraduate student at UCLA, majoring in physics (with a focus on mathematical physics), and minoring in math and Japanese. He is most interested in high energy theory or Topological Quantum Field Theory. Justin also has an interest in formal logic which he hopes to incorporate into his formal studies.

**\$1.2 MILLION GIFT FROM THE  
JULIAN SCHWINGER FOUNDATION  
FOR PHYSICS RESEARCH.**

"Knowledge creation is the key product of the university, and this fellowship will enable generations of young physicists to pursue their passions and make a difference," Putterman said on behalf of the foundation directors. "I can think of no better way to honor the monumental legacy left by Dr. Schwinger, who is considered one of the finest physics scholars of the 20th century."

The inaugural Julian Schwinger graduate fellowship, which could be the first of several fellowships established by the Schwinger Foundation at UCLA, was awarded in April to fourth-year UCLA undergraduate student Justin Kaidi, a physics major with a focus on mathematical physics and minors in math and Japanese.

"This tremendous gift not only emphasizes the strength of our physics program here at UCLA but also highlights the philanthropic spirit of our faculty," Rudnick said. "Dr. Putterman and Dr. Schwinger are shining examples of the kind of investment our faculty are willing to make in our students and in the future of this institution."

## RESEARCH EXPERIENCE FOR UNDERGRADUATES (REU) 2014

Summer 2014 saw the 12th year of the Research Experience for Undergraduates program sponsored by NSF and run by the department. Fourteen students coming from every corner of the country assembled in our department for an intensive 10-week immersion in research supervised by some of our best faculty. Each student is paired with a faculty and their group and works on a well-defined research project and participates in academic and social activities all aimed at giving the students a taste of what a research career might be and the sense of science as a community. The program is challenging as the students

present the results of their research at an end-of-program symposium and write a paper in a professional format and a few of them go present their results at professional conferences around the country. To date, 167 students have participated in our program and our data indicate that over 85% of them go on to pursue graduate studies in a STEM discipline indicating that our program has had a strong impact on the next generation of this country's scientists.

**KEYNOTE SPEAKER**  
**2014 PHYSICS & ASTRONOMY COMMENCEMENT**  
**CLAUDIO PELLEGRINI**

Commencement ceremonies took place on June 14, 2014. Claudio Pellegrini, Distinguished Professor Emeritus of UCLA Physics & Astronomy was the keynote speaker. Professor Pellegrini's area of research is electron and photon beams physics, coherent X-ray sources, particle accelerators and their applications, novel accelerators using lasers and plasmas.

Professor Pellegrini received the "Laurea" award in 1958 "Libera Docenza" in 1965 University of Rome Fulbright Fellow in 1997.

**Awards:**

1999 International Free-electron Laser (FEL) Prize

2001 Robert R. Wilson Prize for Achievement in the Physics of Particle Accelerators.

**Committees:**

National Research Council, on the International Executive Committee for Free-Electron Lasers

International Committee on Future Accelerators Panel on Novel Light Sources.

**2001-04 Chair of the Department of Physics and Astronomy.**

During his tenure as Chair many initiatives were launched including a Graduate Assistants in Area of National Need (GAANN) Fellowship for the department, an REU program grant and corresponding program was put in place which continues to this day, and a new undergraduate major, biophysics, was developed.



**UCLA PHYSICAL SCIENCE #1 IN U.S.A.**

UCLA remains in the top tier of all universities in the world, according to the 2014–15 Times Higher Education World University Rankings. The Times ranked UCLA No. 12 among the top 400 universities worldwide.

Physical Sciences was ranked No. 1 among U.S. publics and ninth overall.

**Awards 2013 - 14**

**RUDNICK-ABELMANN SCHOLARSHIP**

Rodrigo Lara  
Rosalinda Lopez  
Alexis Popkow  
Dylan Rees

**WINSTEIN AWARD**

Kyle Christopher Borch

**CHARLES GEOFFREY HILTON AWARD**

Rachel Lauren Theios

**E. LEE KINSEY PRIZE**

Prateek Puri



## BACHELOR OF SCIENCE IN ASTROPHYSICS

Michael Kenneth Benner  
 Matthew Kyle Davis  
 Christopher Art Dolan  
 Erika Marie Holmbeck  $\Phi$  \* ‡  
 Christopher James Johnson  
 Mohammed Sharjeel Khan  
 Ha Son Le  
 Jeongho Lee  
 Shahriyar Philip Mavlan  
 Maksim Viktotovich Nikiforov  
 Adam Thomas Quaal  
 Rodd Talebi  
 Rachel Lauren Theios  $\diamond$  \*\* ‡‡  
 Andrew Mario Torricelli  
 Phuong B. Vo  
 Conrad Wilson  
 Nicole Rowley Wolters  
 Jonathon Zink

Christopher Alexander Martinez  
 Michael Morag  
 Alexander Grant Newell  
 Man Dinh Nguyen \*  
 Sean S. Niizawa ‡  
 James R. Petersen  
 Rafael Plascencia  
 Amir Pourhamzeh  
 Prateek Puri \*\*\* ‡‡  
 Peter Charles Racioppo  
 Tyler John Ryan \*\*\* ‡‡  
 Nicholas Andre Searle  
 Maria Sergeeva  
 Christopher Allen Spencer  
 Kije Sung  
 Li-Chia Tai \*\*\* ‡‡  
 Hiu Ching Tang  
 Jeffrey Jae Taulbee  
 Salvador Torres  
 Alan D. Tran \*\*\* ‡‡  
 Wayne Tran  
 Jan Clark Van Bruggen ‡  
 Jiechuan Wang  
 Tyler Anthony Willms  
 Zhuo C. Zhang  
 Brian Xie Zhu

## BACHELOR OF SCIENCE IN PHYSICS

Yonathan Alon  
 Krish Ashvin Bhutwala ‡  
 Kyle Christopher Borch  $\Phi$  \*\* ‡‡  
 Jessi Rene Bustos  
 Gavin Edwards Carlson  $\diamond$  \*\*\* ‡‡  
 Elizabeth Hillary Case  
 Paokuan Chin \*\*\* ‡‡  
 Ashley Clarke  
 Matthew James Copperman  
 Christopher Michael Coy ‡  
 Danilo Dadic ‡‡  
 Tyler J. Dawson  
 Amirari Diego  
 Paul Dupenloup  $\diamond$  \*\*  
 George Ian Dyckes \*  
 Nicole Frances Echterling  
 Ruben Gutierrez Martinez  
 Elisabeth Magdalen Heinrich-Josties \*  
 Uriel Fernando Hernandez  
 Long Van Ho \*\*\* ‡‡  
 Winson Huang \*\*  
 Julianne Hui  $\Phi$  \* ‡  
 William Michael Johnson  
 Jennifer Yukari Kadowaki  
 Justin Kamyar Kaidi \*\*\* ‡‡  
 Alexander Kerelsky  $\Phi$   $\diamond$  \* ‡‡  
 Tae Hyun Kim  
 Kyle Steven Kuwatani  
 Joe Lam  
 Christopher Henry Lee  
 Ryan Ming Yun Leong \*  
 Jiahao Lin  
 Andreas Mengyang Liu  $\diamond$   
 Nicholas Antonio Macro ‡

## BACHELOR OF ARTS IN PHYSICS

Margaret Mary Jamison  
 Jeongho Lee  
 Jae Hyun Park  
 Walid Ur Rahman  
 Scott Warren Snyder

## BACHELOR OF SCIENCE IN BIOPHYSICS

Christian Orbita Chua  
 Keenan Ming Faix  
 Blake David Franey  
 Charles Theodore Hohenschuh  
 Jihyeung Jang  
 Vasilis Michael Karagiannis  
 Benjamin Lee \* ‡  
 Alex Chang Leu

## MEANING OF SYMBOLS

- $\Phi$  PHI BETA KAPPA
- $\diamond$  COLLEGE HONORS
- \* CUM LAUDE
- \*\* MAGNA CUM LAUDE
- \*\*\* SUMMA CUM LAUDE
- ‡‡ HIGHEST DEPARTMENTAL HONORS
- ‡ DEPARTMENTAL HONORS

## DOCTOR OF PHILOSOPHY ASTRONOMY

### Jeffrey Chilcote

Advisor: James Larkin

### Gregory Mace

Advisor: Ian McLean

### Siyi Xu

Advisor: Michael Jura

## DOCTOR OF PHILOSOPHY PHYSICS

### Daniel Aharoni

Advisor: Katsushi Arisaka

### Syed Amir Ahsan

Advisor: Robijn Bruinsma

### Alexander Bataller

Advisor: Seth Putterman

### Scott Davies

Advisor: Zvi Bern

### Ian Ellis

Advisor: Warren Mori

### William Farmer

Advisor: George Morales

### Brett Friedman

Advisor: Troy Carter

### Chen-Hsuan Hsu

Advisor: Sudip Chakravarty

### Seung Keun Ji

Advisor: Robijn Bruinsma

### Devin Kachan

Advisor: Alex Levine

### Andrey Knyazik

Advisor: James Rosenzweig

### John Koulakis

Advisor: Karoly Holczer

### Adam Kullberg

Advisor: George Morales

### Sean Lake

Advisor: Edward Wright

### Joshua McNeur

Advisor: James Rosenzweig

### Emin Menachekanian

Advisor: Gary Williams

### Hong Pan

Advisor: Hong-Wen Jiang

### Lauren Pearce

Advisor: Alex Kusenko

### Yuttana Roongthumskul

Advisor: Dolores Bozovic

### Sara Salha

Advisor: Jianwei Miao

### Joshua Samani

Advisor: Michael Gutperle

### Derek Schaeffer

Advisor: Christoph Niemann

### Chiao-Yu Tseng

Advisor: Giovanni Zocchi

### Yuhou Wang

Advisor: Walter Gekelman

### Edward White

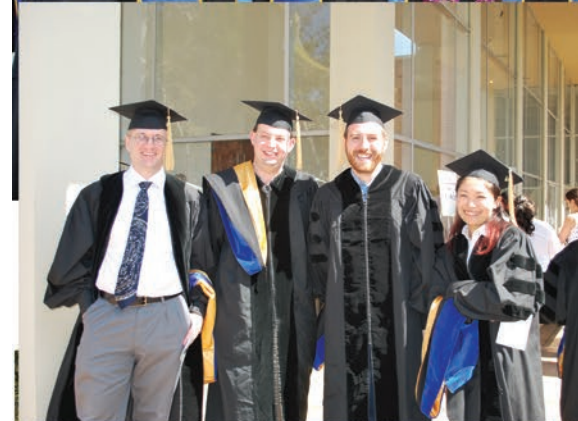
Advisor: B. Chris Regan

### Jie Zhang

Advisor: Troy Carter

### Chun Zhu

Advisor: Jianwei Miao





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