the SPS Observer

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Who is in this house?

the SPS Observer

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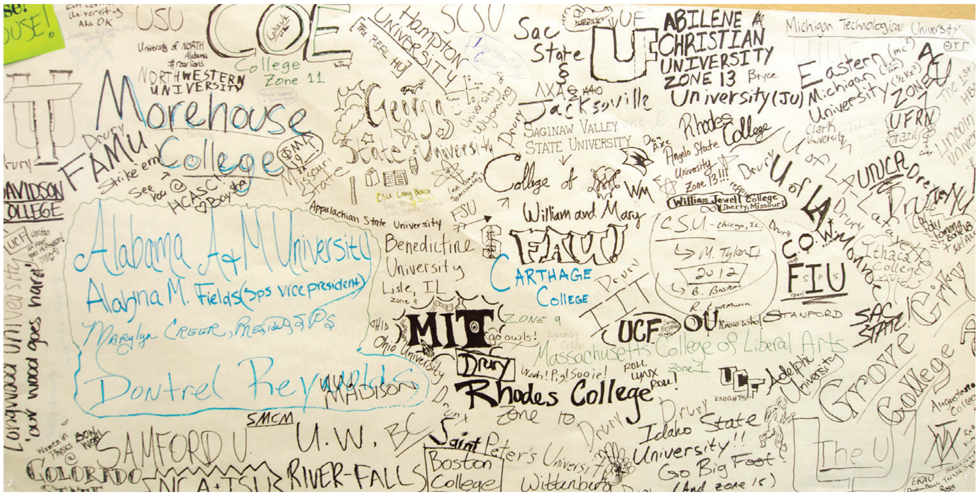
Special Feature: PhysCon 2012

About the Cover

More than 120 schools were represented at the 2012 Quadrennial Physics Congress held in Orlando, FL, November 8-10, 2012. See the special congress section beginning on page 8.

Image credit: Ken Cole.



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Failure in Physics

by John Mather of NASA's Goddard Space Flight Center, a speaker at the 2012 Physics Congress

What a Nobel Laureate Learned from his Failed Thesis Project

Failure is the essence of progress, in a particular way; if we never fail, then we just aren't trying very hard. But "failure" isn't real, like a proton is. It's only a label. And it seems a little unnecessary for a physicist to decide that a certain subset of all the possible configurations of the natural universe qualifies for that label.

Abstraction aside, though, the failure of my thesis project on its first flight was pretty darned important to me. The project was conceived by my adviser, Paul Richards, and I worked on it at the University of California, Berkeley, along with two other grad students: David Woody and Norman Nishioka. It was a balloon-borne, far-infrared spectrometer designed to measure the spectrum of the cosmic microwave background radiation (CMBR), and it was quite ingenious.

"...failure is an essential part of research."

The CMBR was predicted in 1948 and would become the strongest proof yet that the expanding universe theory is correct. (The name "big bang" implies to most people that there was a time before time, which is linguistically meaningless and not implied by the observations.) But to know that the CMBR is a predicted remnant of the big bang, we needed to confirm that it has the right spectrum and that it comes almost equally from all directions, not from a local source.

Top: Dr. John Mather delivers his plenary talk, "The James Webb Space Telescope: Science Opportunities and Mission Progress," at the 2012 Quadrennial Physics Congress, November 9, 2012. Bottom: Dr. Mather answers questions from students following his plenary talk. Image credits: Ken Cole.

The CMBR had been discovered in 1965, but its status as evidence of the early universe was a little uncertain, since a number of faulty measurements had already disagreed dramatically with the predicted 3 kelvin blackbody spectrum. Our payload was to rise above 99 percent of the Earth's atmosphere to get a look between the atmospheric emission lines using a polarizing Michelson interferometer immersed in liquid helium to suppress thermal emission from the instrument and enable sensitive detections.

After working on the project for what seemed like forever, in the fall of 1973 we decided that it was time to try a launch, which our team had never done before. David and I drove the payload to the balloon base in Palestine, TX. With help from Paul and professional engineers from Berkeley and the balloon base, we prepared it for launch. The launch was successful. The payload went up and up, and then let down 2,000 feet of unrolled cable that should have allowed the payload to observe the sky, not just the balloon overhead.

Imagine our chagrin when the instrument did not work. There was nothing we could do except sit in the control

More than three decades after his botched thesis project, John Mather would have cause to smile when he received the Nobel Prize in Physics for his studies of cosmic microwave background radiation. Image credit: NASA.

room and watch the data come in. The motor that was to move the interferometer did not turn, and the detector reported an oscillating signal that should not have been there.

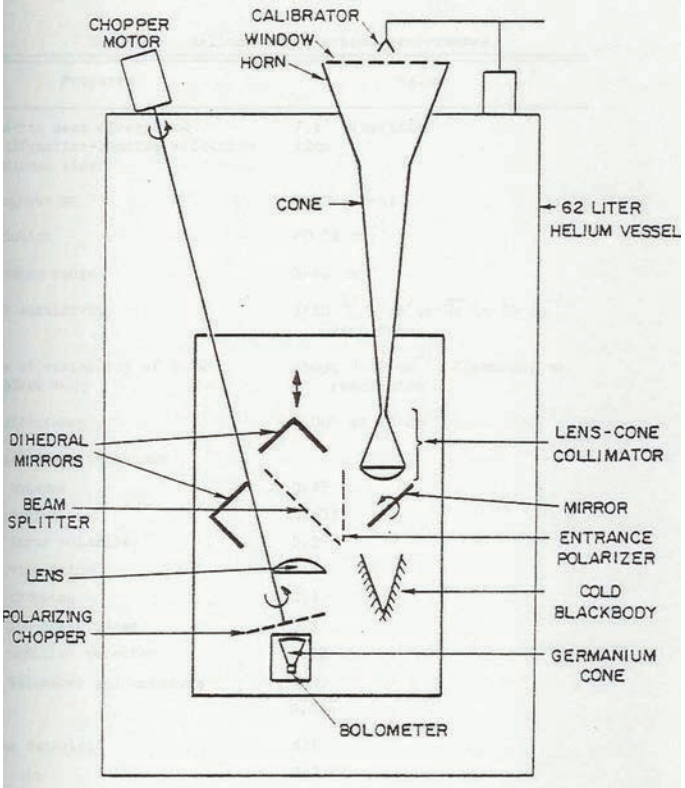
As I recall, we were all too tired to display a lot of emotion; the job at hand was now to retrieve the payload and figure out what happened so we could fly again. Paul was very generous and let me write a thesis about the instrument that did not work (and about a ground-based instrument that did work). I hurried off to my upcoming postdoctoral position with Pat Thaddeus at the NASA Goddard Institute for Space Studies in New York City, convinced that this CMBR work was much too hard for a young person.

Meanwhile, David Woody conceived of an inexpensive environmental test chamber (made of plywood and Styrofoam and filled with dry ice) for the payload and quickly discovered what our problems were. The motor didn't turn because it had rusted on the ground in the moisture of Texas and because its control electronics wouldn't work cold. The oscillating signal likewise appeared because the detector preamplifier was too cold. David, Paul, and Norm fixed the problems with better electronics and better protection for the motor, flew the payload again, and it worked that time. Later, they upgraded the instrument with liquid helium-3 cooling for the detectors and flew it two more times. The instrument now resides in the Smithsonian National Air and Space Museum in Washington, DC, not far from an overhead model of the Cosmic Background Explorer (COBE) satellite.

What did I learn? Number one, if you do not test something, it will not work. Some people think it's worth a try anyway, but I think it's not a matter of chance at all. Nature knows when we are trying to cheat, and Murphy was an optimist. Even if you are tired (or broke), you should not skip the testing.

This came back to me much later when my luck had turned and I was working at NASA's Goddard Space Flight Center with a huge team of scientists, engineers, and technicians, preparing the COBE for launch. The COBE carried a new and greatly improved version of the balloon-borne instrument, along with two other instruments built to examine the early universe. Over and over I had to resist the temptation to think that I really knew that something was okay to launch.

With a big budget at stake, the temptation to capitulate to management pressure to launch on time was pretty strong. Conversely, after all the expenditure of personal time and public money, we owed it to the taxpayers to get it right and not take chances with their funds. So we tested adequately, and we found some faults and fixed them.



This diagram from John Mather's PhD thesis details the anatomy of a balloon-borne spectrometer that failed to collect accurate data after being exposed to moisture and chilled high in the atmosphere. Image credit: John Mather.

One was particularly important and was found with a test I might have skipped. The moving calibrator body for the space version of my thesis experiment did not work properly and would have wrecked the mission. I thank my lucky stars every day for (a) my experience of failure with my thesis project and (b) my brilliant colleagues at NASA who knew quite well why we had to test, and didn't give up. Just about 33 years after that balloon payload failure, I got a call from Stockholm, as did my colleague George Smoot, for our work on the COBE.

Part of the point of this story is that failure is an essential part of research. My friend and noted astrophysicist Harvey Moseley grew up on a farm and describes life there as endlessly fixing broken things. On a farm, you're pretty much on your own. There is no instruction book and no handy stockroom of spare parts. He says scientific research is much the same, always fixing broken things without an instruction book.

I like to think that we are puzzling out the giant crossword puzzle of the universe, putting in letters and getting them wrong and finding out and fixing them. I imagine the general public thinks our lives are quite different, as brilliant scientists who must know so much. But on the cutting edge of research, we are always looking for things that don't fit, and the minute we understand something, we go on to the next thing we don't understand. It takes a certain degree of nerve to do it, considering how little we know. But if you like it, welcome to a thrilling life in science! ●

Shouvik K. Bhattacharya. Image credit: Tracy M. Schwab.

My First Visit to a Job Fair

Reflections from a Novice Job Fair Attendee

by Shouvik K. Bhattacharya of Minnesota State University Moorhead, a 2012 SPS Summer Intern who explored how physics departments can help their students be better prepared to enter the workforce upon graduation.

I take a deep breath and step inside the fair pavilion at the Ronald Reagan Building in Washington, DC. There are about 30 small booths occupied by prospective employers at this summer career expo sponsored by the magazine *Equal Opportunity*, and already four of them are crowded. The University of Virginia booth looks less crowded, so I decide to visit it first.

An official welcomes me with a warm smile and gives me a pen with the university's name printed on it. She says that the human resources department recruits applicants from diverse academic backgrounds, including physics. An applicant with a STEM (science, technology, engineering, and mathematics) background is expected to have the ability to effectively coordinate and collaborate with others. These are valuable skills that employers care about. She shares her contact information and also requests my resume in turn.

I wander off for a bit and then enter the US Bureau of Labor Statistics booth. Many who complete bachelor's degrees in physics have taken some statistics courses, and that is what motivates me to stop by this particular booth. But the representative informs me that a physics major should apply only if he or she has a strong mathematics and statistics background.

> "I know what I have to do when I attend my next job fair."

The next representative I speak with, at the Boeing Company's booth, sounds very positive and enthusiastic. She tells me that the company has many entry-level openings. She advises me to create a profile on Boeing's career website and to prepare a resume based on the jobs that are available. She emphasizes that being flexible about relocation and having a positive attitude toward learning new things are essential to an employee's job security. I realize that all the representatives at the job fair are actually there to help applicants, and I feel confident thereafter.

Then I stop by the job booth of the US Nuclear Regulatory Commission, where I am handed a job list. This government agency definitely hires physics undergraduates. The representative asks me to share this information with anyone who would be interested in applying for the entry-level openings. Job titles include general engineer and scientist, both of which require a minimum cumulative GPA of 2.8 overall and 3.4 in the applicant's major. The job descriptions include writing, critical thinking, decision making, inspection, and conformity research as the integral duties that employees would have to perform. I get a little excited seeing all these details. So far this has to be my best experience of the job fair, as I get to see an example of how a physics major can start working after a successful degree completion.

The US Air Force posts its jobs on the USAJOBS website, which I learn at its booth. The representative at the Internal Revenue Service booth tells me that living in a big city can seem tough and challenging, but ultimately it often turns out to be beneficial, as dynamic city life motivates employees to perform better. He also tells me that it never hurts to be ambitious. A representative from the Defense Intelligence Agency asks me why I have not highlighted in my resume the electronics courses that I have taken. The resume I had handed him focuses on my research background in observational astronomy. I realize that having a few different versions of my resume would be beneficial.

In the beginning, I felt a little overwhelmed, but I soon realized that all of the representatives are there to help and answer questions. Looking back at it now, I know what I have to do when I attend my next job fair. The role I played at this fair might be considered that of a surveyor, rather than that of a potential job seeker. I didn't prepare different versions of my resume, highlighting different skill sets. That is the first thing one should do before attending a fair, as the resume serves the role of a conversation starter. Wearing business clothes is also a must, because it shows how interested and serious one is about finding a job. I made a few new connections at the job fair, and I've now sent follow-up emails to each, conveying my thanks for spending time with me. The job fair visit was an absolutely amazing learning experience for me. ●

SPS Jobs

Remember to make SPS Jobs, the official online job site of the Society of Physics Students and Sigma Pi Sigma, an essential part of your career planning!

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Worldwide, Galileoscopes have had great impact. Here's a picture of a group of children in Tanzania using a Galileoscope brought by Chuck Ruehle (left), a pastor from Racine, WI. Image credit: Chuck Ruehle.

Galileoscopes in Classrooms

Exciting Kids about Astronomy and Physics

by Coty Tatge, KelliAnn Anderson, and Zach Troyer, Carthage College

Four hundred years after Galileo's first telescope observations, the year 2009 was celebrated as the International Year of Astronomy (IYA). Several big, worldwide initiatives were launched to engage people with astronomy. Ranking among the largest was the Galileoscope Project (http://galileoscope.org). One of our physics professors, Doug Arion, helped start Galileoscope, which is still going strong three years later.

You may be familiar with the inexpensive telescopes sold in stores. They're often difficult to use and don't give good viewing. That's the kind of experience that won't turn anyone on to astronomy. Well, the Galileoscope team realized how big a problem this is and developed a new telescope to get people excited—one that has high optical and mechanical quality, comes with an educational kit, and is very inexpensive so that people all over the world can afford it.

There are now more than 200,000 Galileoscopes in use in more than 100 countries! Members of our SPS chapter used the telescopes for astronomy outreach programs this summer, and it was great to hear people looking through Galileoscopes exclaim, "Wow, I really can see Saturn's rings!"

Galileoscope continues today as a legacy project of the IYA, manufacturing and distributing telescopes for individuals, schools, and other science education organizations. One new project called Telescopes 4 Teachers (T4T, www.telescopes4teachers.org) lets people make tax-deductible donations through Astrosphere New Media, a nonprofit astronomy outreach group. The donations pay for Galileoscopes to be sent to teachers or schools designated by the donors.

T4T isn't the first such donation program. During the IYA more than 7,000 Galileoscopes were put into use in developing nations. An observatory in South Africa distributed the donated telescopes. But other requests came in from people who wanted to send telescopes to schools. T4T is the best way to make that happen.

The T4T program isn't the only way we've been working with Galileoscopes to help improve science education. A new astronomy education and outreach program partners Carthage College and the Appalachian Mountain Club (AMC), one of the largest and oldest outdoors and nature education organizations in the country. The three of us, all Carthage physics students and SPS members, worked with Prof. Arion and spent the summer in New Hampshire, helping out with programs that included solar observations, night sky observations, and public lectures at AMC lodges and high mountain huts.

It's fun to hike telescopes up into the mountains and show people the sky from dark, beautiful sites. In the first year we talked about the sky with more than 2,000 visitors!

In addition to using larger, commercial telescopes to do sky shows, we also used Galileoscopes in workshops with scout groups, camp groups, and kids of all ages, promoting T4T to as wide an audience as possible. Guests have been surprised at how well the Galileoscopes work, especially given how inexpensive the devices are. We're hoping that the visitors have great experiences at our workshops, continue to be interested in astronomy, and maybe purchase a Galileoscope (or two!) so they have a great tool with which to observe the sky.

It has been a great experience working with the public, especially with kids, and getting people excited about the sky. SPS chapters can get involved by using Galileoscopes for their own outreach programs and fund-raisers, and by promoting the T4T program. The telescopes make great Christmas gifts, too! ●

Right: Authors KelliAnn Anderson '14, Coty Tatge '12, and Zach Troyer '14 were 2012 summer astronomy interns working with the Appalachian Mountain Club. Here they are near the summit of Mount Washington above the Lakes of the Clouds Hut after doing an astronomy program for the nearly 100 hut guests. Image credit: Doug Arion.

Beyond Borders, with a BANG!

Above: Water and packing peanuts erupt from a trash can during a Peer Pressure demonstration, the "nitrogen trash can blast," at one of the many elementary schools visited by Angelo State University SPS members during their annual road trip. Image credit: Hardin Dunham.

Peer Pressure Team Helps Bring Physics to All

by Blake McCracken, Angelo State University

Our time at Yeso Elementary School in Artesia, NM, was almost over. Standing in front of a group of 3rd and 4th graders, we got ready to close our physics demo show with a bang . . . literally! The students were silent in anticipation, as were we.

Then, all of a sudden, a loud boom from a rubber trash can broke the silence. Water, packing peanuts, and a white haze shot into the air. As the excited students yelled, screamed, and clapped, a confused and distraught teacher bolted out of a nearby building to see what all the ruckus was about—only to find teachers, administrators, and 200 students enthusiastically applauding for some college students from Texas.

Memorable events such as this one are why SPS members in the Angelo State University (ASU) Peer Pressure Team continue the Physics Road Tour year after year. The tradition began in 2003 and has continued to be a great success every year since. During the week after university classes end, we spend hours driving from school to school. Each day is booked with at least two shows.

The continuous hustle and bustle is well worth it. By targeting schools with significant populations of underprivileged students, we can make a meaningful impact on students who might not otherwise be exposed to the possibilities of physics. Usually, the schools we visit lack the funds and resources needed to provide their students with a robust science curriculum. The enrichment the schools receive from our exciting demonstrations is welcomed, especially when they learn that our program comes at no cost to them.

This past year, in conjunction with the national SPS theme “Science Beyond Borders: Physics for All,” we decided to take our road trip out of Texas and into New Mexico. At 7:30 in the morning on Monday, May 14, our 700-mile journey began. We visited three schools in Texas on the way to New Mexico. Then, on Wednesday morning, the ASU SPS Peer Pressure Team made its out-of-state debut in eastern rural New Mexico. Five elementary schools welcomed us with excited groups of students and teachers. The students filed into gymnasiums, cafeterias, and libraries, where our team of 13 college students and two physics faculty members from Texas was ready and waiting to wow the kids with both familiar and unfamiliar equipment.

During our shows, physics concepts such as pressure, light, sound, and temperature were explored using marshmallows, fire, liquid nitrogen, lasers, and other props. Our team created a custom laser light show for each school, much to the delight of the children. We finished each show with one of our more boisterous demonstrations, either a nitrogen trash-can blast or a nitrogen thunder cloud.

We always make sure to provide students with some time to ask questions. That's the time we value most, because that's when the true interest of the students shows. Oftentimes we're unable to answer all of the questions in the time we have. Some students are so interested and inquisitive that they get back to class late.

SPS volunteers have noticed the children’s eyes, glued with anticipation to the presenter, just waiting for the climax of the demonstration. The soft and long “wooooooow” that follows, spoken by the students in unison, gives us an immediate satisfaction born from the impact we are having on these children. We also receive hundreds of thank you letters from students saying they want to be scientists just like us when they grow up. This is extremely rewarding, and we anticipate that ASU physics will find a way to continue these annual outings. The value of introducing children all across the state, and even the nation, to the wonderful world of physics is well worth the trip. ●

SPS members in Angelo State University’s Peer Pressure Team prepare to cross into New Mexico during their annual Physics Road Trip. Image credit: Hardin Dunham.

Students and Stardust

Experiencing the 2012 Quadrennial Physics Congress

by Lily Udumukwu, University of Miami

More than 800 students, alumni, and professors participated in the 2012 Quadrennial Physics Congress. Image credit: Liz Dart Caron.

On November 8, 2012, the University of Miami's SPS chapter arrived at the Sigma Pi Sigma 2012 Quadrennial Physics Congress (PhysCon)—just in time for what would be a once-in-a-lifetime affair for many of the participating students.

Held in Orlando, FL, the conference brought together people of different backgrounds and social circles, linked by one common interest: a passion for physics. The diverse menu of world-class speakers at the event included a Nobel laureate, an astronaut, a sitcom contributor, and a Fellow from the US Department of State. All were luminaries in physics. All were an honor to experience.

Some students at the congress embarked on a "behind-the-scenes look" at the NASA Kennedy Space Center on Merritt Island. The tours were specially arranged by Space Center staff, and ours was hosted by a comical (yet committed) retired NASA firefighter. Though he didn't major in science, our host admitted there's something electric about the human drama of the island, a treasured piece of history he's been a part of for many years.

It was not the numbers—more than 800 students, faculty, alumni, and professionals who traveled from as far away as China—that made the most profound impression at the congress. Instead, it was the gravity of the attendees' accomplishments, imparted in a series of inspirational anecdotes of immeasurable value. It was enthralling. Strangers only the night before engaged in constructive debates over the importance of science to public policy, in workshops that highlighted science's potential to improve our ever-changing society. Omnipresent was the murmur of excitement and intrigue, as a sea of hundreds broke into resounding applause at the conclusion of yet another anticipated guest speaker's talk highlighting his or her esteemed contributions to the world of physics.

Quadrennial Physics Congress attendees tour NASA's Kennedy Space Center. Image credit: Ken Cole.

Dialogue took place over buttered bagels. Earnest and eager students discussed the secrets of the universe with practicing scientists during "Breakfast with the Scientists." Confident handshakes brought together admissions personnel from top-tier universities and prospective candidates presenting their exceptional resumes at the exhibit hall. In one corner, professors and professionals huddled around a poster presentation. Off-the-cuff conversations with students ensued.

Reverberating throughout the days of this unique and incredible meeting was the theme of "Connections." Transcending expertise, school, region, and even language, we were united. At the close of this event, the physics students of UM left as a community with newly formed intangible connections, fueled by Nobel laureate John Mather's parting words: "We are all made of stars." ●

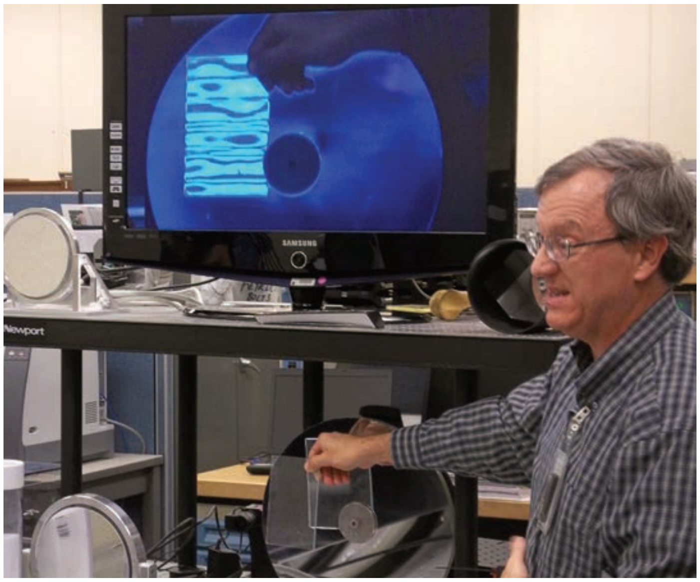
Solving NASA's Problems

A Behind-the-Scenes Look at NASA's Kennedy Space Center

by Kevin Rhine, Idaho State University, who joined dozens of other SPS reporters for a special tour of NASA's laboratories and launch pads. All Congress attendees were treated to a general tour.

As a child, I frequently heard about the achievements of our impressive space program but found it difficult to imagine what really goes on at NASA—aside from sending rockets beyond our atmosphere. After seeing for myself during a behind-the-scenes tour of the Kennedy Space Center, it all seems quite clear now. NASA is a place for problem solvers.

This organization reaches not only into the sky, but deep into the general physics community. Bob Youngquist, a NASA scientist who gave us an extremely enjoyable and informative demonstration, has for decades found solutions to problems for which other NASA departments are not specialized. One such problem stemmed from the need to closely examine the space shuttle, liquid fuel tank, and solid rocket boosters prelaunch. Measuring the size and severity of blemishes from the ground is difficult. So NASA scientists arranged two laser pointers with parallel beams a fixed distance apart in a portable box. This box could be mounted on a camera, allowing a photographer to document any faults from the ground with two pinpoint laser dots providing a sizing scale. This simple device has been used not only to further space exploration, but to improve crime scene investigations.



NASA's Bob Youngquist demos a device for detecting leaks.
Image Credit: Michael Harrington.

During another presentation, we learned of a technology being developed to clear sand and dust from a glass pane without the use of mechanical wipers. Nearly invisible electrodes embedded in the glass create electromagnetic pulses to disperse the pesky particles. This approach would be especially useful for cleaning the camera of a rover exploring a planet that has little or no atmosphere, where dust interacts with other matter in ways it doesn't here on Earth. With more progress, this may be a technology we will begin seeing in terrestrial vehicles and eyewear.

Another endeavor underway at NASA is the pursuit of efficient lunar mining. The low-gravity environment of the Moon makes a normal dozer or drill design impractical. On Earth we can make tractors as big and heavy as needed in order to perform in whatever environment they are designed for. But this brute-force approach isn't cost effective on the moon, since lifting the extra pounds into space is very expensive. The solution being developed is a lunar tractor that lowers counter-rotary drilling buckets at both of its ends, lifting up the entire machine. All weight goes into the drilling process, rather than just a fraction. Interestingly, due to buoyancy, underwater robotic drilling can result in some of the same problems as in the lunar situation.

I came away from this trip to NASA with a renewed sense of clarity and a new motivation for tackling the problems I sometimes face in my own life. During the final night of the conference, a friend and I found ourselves stuck in the sand in a rented jeep that lacked four-wheel drive. After several hours of digging, lifting, and experimenting with various makeshift wooden ramps and levers, we might have lost morale. But we worked with the determination and deliberate thoughtfulness of the NASA scientists who spoke to us. We resolved our problem.

To many, the technologies that come out of the NASA space program are indistinguishable from magic. To me, they are simply outgrowths of concepts and applications we already understand, constructed by people not much different from myself, and held together by ingenuity. ●

Moon Makers

At NASA many different fields of science are being utilized to further human space exploration. I noticed lots of effort going into cutting the costs of and increasing the efficiency of space travel, specifically by extracting oxygen, hydrogen, and other elements from regolith (lunar soil) to use as fuel, water, and air for the next leg of the journey into space. The first lab we went to was the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) lunar rover development lab. There, the focus was on combining robotics and chemistry to extract, analyze, and produce water from regolith. Another lab we visited develops automated and remote-controlled mining techniques for missions to the Moon and to Mars. Much effort is also going into testing to determine the best material to build launch and landing pads on low-gravity bodies. In the last lab we visited, projects varied from the detection of minerals while a rover is in motion to the effects of LED light color temperatures on the sleep cycles of astronauts.

by Michael Harrington, Appalachian State University

Biased Results

Prejudice Damages Academia, James Stith Warns

by Jennifer Rehm, Georgia State University

"The subject of race and gender is systematic in our community," said James Stith, Vice President Emeritus of the American Institute of Physics. He opened the November 8 workshop "Connecting Diverse Perspectives in Science" with astonishing findings from studies of unconscious bias. During blind, randomized trials, evaluators assigned the exact same job performance a lesser score if told it was completed by a woman rather than a man. Ratings of verbal skills were lower when evaluators were told an African American wrote a piece of text as opposed to a white person. In another study, employers were more likely to hire an applicant if the name on a real woman's CV was changed to that of a man. Every study showed a significant bias due to race or gender, but most interestingly, the race and gender of the evaluator from which the bias came did not play a significant role.

Stith illustrated this concept using a story told by one of the great civil rights leaders, Desmond Tutu. Archbishop Tutu boarded a plane in Johannesburg one day and, upon noticing that both of his pilots were black, felt so proud to see the day in which this equity was possible. When the plane later hit turbulence, he found himself wishing that his pilots were white. "At that point he realized how damaged he was," said Stith.

In a later interview, Stith emphasized the importance of discussing diversity among colleagues and the steps all members of a department (students and faculty) should take to ensure their environment is growing toward a diverse perspective. "There should be at least one person in every department to whom reports of discrimination can be made; this should be known by everyone," said Stith. Those in positions of power who have nothing to lose professionally should speak up and empower those that feel powerless. Said Stith: "Not saying something is a way of condoning the behavior. We need to create a culture of openness. Students and faculty need to have these conversations." ●

The Physics of Physical Comedy

David Saltzberg on Science Outreach Via *The Big Bang Theory*

by Jeni Hackett and Elana Urbach, The College of William and Mary

Jokes that mention non-inertial reference frames were once relegated to laboratory lunches and meetings between undergraduate science majors. Complex mathematical formulas tended to be feared by the general public. References to cutting-edge science were for science fiction. But now, millions tune in weekly to watch the exploits of four scientists on the sitcom *The Big Bang Theory*, in which all of the above occur regularly and, more impressively, accurately. Suddenly, physicists are in the spotlight, as entertainers rather than educators.

Ensuring the soundness of the science in *The Big Bang Theory* is David Saltzberg, a high-energy physicist who studies the particles that rain down on Antarctica from space. He doesn't write the jokes or have a hand in shaping the show's characters. Instead, he links the writers to the scientific community.

Saltzberg found himself working as a science consultant by chance, through a friend of a friend. "The writers are big geeks," says Saltzberg. They want, first and foremost, to make the show entertaining but also strive to do it right, to never let bad science slip in, he says.

Listening to his talk, I realized just how much effort is put into making the sitcom not only scientifically accurate, but full of background nods to the scientific community. Whiteboards covered in equations are just the tip of the referential iceberg. According to Saltzberg, if you send in a research poster, it could be used in the background of a scene. We did spot him picking up some PhysCon fliers, and PhysCon did host a poster session... material for the university set's message board, perhaps?

"We're broad but not very deep," Saltzberg explained during our interview with him. This breadth exposes the audience to a wide variety of scientific terms and experiments. What viewers choose to do with this exposure is up to them. One fan actually performed the calculations to fact check a joke. When she got a different answer than the one in the show, she struck up a conversation with Saltzberg about it!

The fact that *The Big Bang Theory* has become such a hit indicates a shift in the perception of scientists in the popular media. They're no longer relegated to lab coats (Saltzberg took the writers on a tour of UCLA, where they saw that none of the physicists wore lab coats) and no longer background characters, but are instead brought to the forefront as main characters.

The characters provide an accessible point of reference for the general audience as to what a physicist is. "For people to tune into a sitcom, they have to like the characters," Saltzberg reiterated throughout his talk and our interview. Penny, the girl next door, also plays an important role. "Every science show has that one character that isn't a scientist, so [the scientists] can turn to that character to explain what's going on." The physicists have to learn to communicate with Penny, and in so doing they gradually expose her to scientific ideas. By explaining science to her, they explain science to the audience.

"It's pretty clear what I'll be remembered for at this point," says Saltzberg. He says he doesn't find that frustrating. By being involved in the show he helps spread awareness in a subtle way. Anything that gets the general public captivated with (or even just a little bit more understanding of) science is something that we welcome in a prime-time sitcom spot. ●

Chandeliers and Space Gas

Mercedes Richards Sees the Universe in 3D

by Katrina Hanson and Theodore McDonough, University of Wisconsin–River Falls

What do chandeliers and extraterrestrial bodies have in common? Both are objects of interest for Mercedes Richards, whose childhood fascination with her neighbor's illuminated fixtures was a mere antecedent to her now-preeminent knowledge of binary star systems and the gas flows between those stars. The Penn State Department of Physics and Astronomy professor joined us in Orlando, FL, as one of PhysCon's noteworthy plenary speakers.

As Richards presented her talk, "The Incredible Tomography Imaging Technique," it became evident that both her topic and the woman herself truly embody the 2012 congress theme: "Connecting Worlds." A Jamaican native, Richards completed her undergraduate work at the University of the West Indies. She then traveled to England to earn her master's degree from York University, before completing her doctoral requirements at the University of Toronto. She is a living example of the importance of promoting diversity in science.

Her technique of choice, tomography, is itself a tool for connecting and communicating. This approach to imaging pieces together two-dimensional projections to create 3D images. Humans already use a form of tomography in their everyday lives, Richards pointed out. When we see the shadow of a wolf on a tent wall while camping, our brains conjure up the animal's real-space stature. We immediately identify the flat shadow as a projection of the fully fleshed-out being. Science has adapted and advanced this natural survival skill into a relevant and useful imaging method.

Group photo of several UWRF students with Richards immediately after her presentation. From left to right: Wesley Barnes, Tyler Capek, Katrina Hanson, Mercedes Richards, Alesha Radke, Samantha Oswald, and Philip Middlemiss. Image credit: Ken Cole.

The intrinsic value of tomography is being realized through major applications in the fields of medicine, oceanography, geophysics, archaeology, and even art. The healthcare industry relies on tomographic technology every time a CAT (computed axial tomography) or MRI (magnetic resonance imaging) scan is ordered. Similarly, artist Louis Tiffany incorporates layers of stained glass into his pieces to create a three-dimensional effect. Seismic tomography applies tomography to primary and secondary waves moving through Earth to scan the center of the planet which cannot be reached. Radar (radio detection and ranging) and Sonar (sound navigation and ranging) are critical imaging techniques that provide the means for using tomography to map geological and oceanic Earth and even led to the rediscovery of the sunken Titanic.

Now Richards and other scientists are applying the far-reaching abilities of tomography to yet another field: astrophysics. Aristotle's rationalization of Earth's spherical shape, based on the projection of its curved shadow on the moon's surface, can be considered an early application of tomography. Nevertheless, astronomy is considered to be one of the last scientific disciplines to realize the imaging technique's full modern usefulness. Despite its belated introduction, tomography has now become a staple within astrophysics' technological arsenal.

Richards uses Doppler tomographical imaging to study binary stars. About 70 percent of stars that appear to be single are actually binary or multiple star systems. Stars in such systems transfer gas from one to the other, typically forming rings of gas around recipient stars.

When white-dwarf stars lose their ring of gas, tomography can produce three-dimensional images of the gas. The orbital motion of the stars leads to cyclic Doppler shifts in their spectra. This characteristic allows scientists to obtain views of a star from a vast range of angles and superimpose these projections into a representative figure. Richards initiated the use of this technique when she collaborated with Russian scientists to produce the first three-dimensional velocity images of magnetically threaded gas streams. This application of tomography is truly incredible, as the name of her plenary talk suggests.

After Richards' presentation, we shared a meal with her. She was very accommodating in our requests for material, and her willingness to work with students was encouraging. The conference brimmed with inspiring moments and learning opportunities, but it was Richards who truly embodied the heart of PhysCon's motto. Not only does she connect worlds, she gives the next generation of scientists the courage to be fascinated with its own personal "chandeliers." ●

Connecting WORLDS 2012 through science & service


SPS Zone 9 Associate Zone Councilor Brandon Clary (left) inducts Freeman Dyson (right) as an honorary member of Sigma Pi Sigma.

I loved that many of the speakers stayed around for the entirety of the conference so we were able to talk with them in a smaller group setting.

– Grove City College


Participants in the "Connecting Physics and the Public" workshop explore the theme "Connecting Worlds."


Yashashree Jadhav (
GradSchoolShopper
Greenberg.

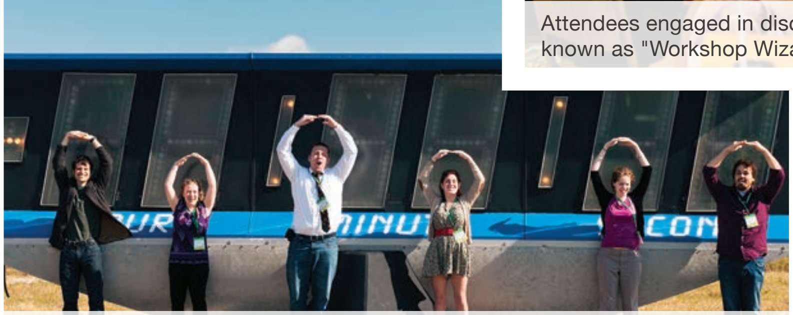

Students from
Space Center V


"Connecting Academia and Industry" workshop leader Shelly Arnold (center) engages with students at the Breakfast with the Scientist event.


Attendees engaged in discussions at various workshops, while moderators known as "Workshop Wizards" wandered around facilitating discussions.

It was surprising to see the diversity of groups at the Conference. Freeman Dyson himself even noted that there were nearly 50 percent women!

– University of Central Florida

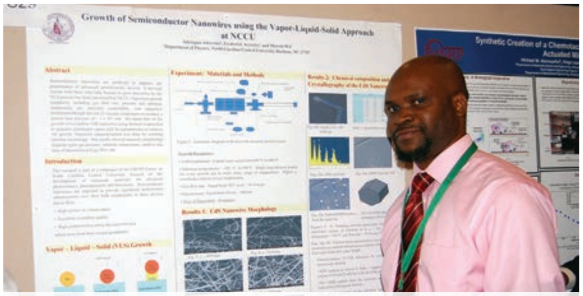

Filling in the famous countdown clock during their tour of NASA's Kennedy Space Center are (left to right), former SPS Associate Zone Councilor (AZC) Chris Faesi, Zone 11 AZC Audrey Burkart, Zone 15 Dayton Syme, Zone 4 AZC Mary Clare Roche, former Zone 10 AZC Jenna Smith, and Zone 18 AZC Chad Garrison.

We would be lying if we said we weren't geeking out in the extreme as our bus drove up to the famous shuttle launch countdown clock.

– The College of William and Mary

(right) learns more about
from Exhibitor Daniel

Sarah Reiff and Sylwia Ptasinska from the University of Notre Dame speak with a student in the Exhibit Hall.



Poster presenter Adetogun Adeyemo received an Honorable Mention for the Outstanding Student Poster Award, sponsored by the Optical Society (OSA).

Much of what we experienced will help us in the future whether we wish to enter directly into the workforce or pursue further learning in graduate school.

– The College of Wooster

Southeast University in China enjoy the Kennedy
Visitor Complex.

We hope that those that come after us will follow in our footsteps and be part of the 2016 PhysCon in San Jose.

– Roberts Wesleyan University

For more information & PhysCon photos, visit: www.spscongress.org

Attending the conference for us was like meeting a long lost family. The love, support and friends that we made during the conference will last with us forever.

– St. Peter's College

Throughout the conference, one theme surfaced repeatedly in almost every lecture and workshop. Outreach to the public is crucial for the advancement of physics.

– Marquette University

Students take advantage of some time to socialize between sessions.

I for one was very surprised and impressed at the turnout and dance skills of an all physicist dance party.

– Michael Harrington, Appalachian State

The dance floor at the "Club Congress" party sponsored by the American Physical Society was packed all evening.

Image credits: Ken Cole.

Reflections on the Sigma Pi Sigma 2012 Congress

An Old-Timer's Perspective

by Dwight E. Neuenschwander, Southern Nazarene University

I have been privileged to attend every Quadrennial Congress of Sigma Pi Sigma since the first one of the "modern era," which took place in Dayton, OH, in 1992. What a ride it has been! I recall how the organizing committee of the 1996 Congress worried whether even 100 people would show up. Several members of that committee were present at the 2012 Congress, which drew more than 600 students and another 200 faculty members and alumni to Orlando, FL. Much has changed. Our hearts were glad.

Sigma Pi Sigma has made a place for itself in the wider physics community. This year's congress overflowed with not only a passion for physics and a spirit of sheer joy, but also with a combination of activism and a willingness to serve the larger society. Yes, a good time was had by all. But more importantly, Sigma Pi Sigma, in partnership with the Society of Physics Students and other organizations, is now poised to make an indelible contribution to the culture of physics.

The proactive enthusiasm exhibited during the congress and the broad range of support it enjoyed from institutional cosponsors suggest that the physics community may be ready to encourage not only those who invest their lives in research, but also those who want to use a physics education to reduce poverty, ignorance, and despair. Critically placed in the landscape of physics society meetings, the congress provides an effective venue for a wider democracy in physics, by helping such people find one another. Let us keep that ball rolling!

Dwight E. Neuenschwander (right), a former director of SPS and the at large member of the SPS Executive Committee, is pictured at the 2012 Quadrennial Physics Congress with another former SPS director, George Miner. Image credit: Ken Cole.

Relationships hold communities together. For large communities to remain stable and authentically alive for long timescales, those relationships must be based on openness, diversity, and respect. Over the decades physicists have sometimes appeared to be rather exclusive. Agendas within the community deemed worthy of respect have often been quite narrow, dictated by esoteric problems in elite laboratories. But physics is too important and too powerful and too beautiful to be owned by a small number of experts talking mostly with each other. The Sigma Pi Sigma Congresses can revitalize how the physics community sees itself.

Most of the congress attendees were young. The youthful exuberance that filled this congress revitalized us old-timers, reminding us of the values and passions that drew us into physics in the first place. Conversely, the advice and wisdom of senior physicists was clearly valued and appreciated by the young. It was heartwarming to see the likes of Jocelyn Bell Burnell and John Mather surrounded by crowds of young people. Freeman Dyson was particularly amazing. Eighty-eight years old, he stood patiently for three days, facing long lines of people waiting to shake his hand, turning no one away. He was essentially the last congress participant to leave on Saturday night.

A workshop coordinated by David Mosher, director of the National Security Division of the Congressional Budget Office, tested the physics students with a model exercise that bridged science and society. He asked groups to decide how to cut more than $80 billion of spending from federally funded science programs. As you know, physics students are always up to a challenge! But the sobering exercise made everyone realize the difficulty of such a task, ponder the consequences of different choices, and consider how science interacts with politics—which can be just as complex as physics itself.

Revolutions are almost always started by young people who eagerly want to change the world. Those with physics-trained habits of mind are especially well equipped to enact those changes responsibly and sensibly. Both the physics enterprise and society at large would be well served by incorporating those who have a passion for physics and are willing to strive earnestly for competence. That is where Sigma Pi Sigma and the Society of Physics Students come in. As in baseball or in music, physics will always have its legendary superstars. But physics needs a deep bench, a broad base of informed appreciators.

The 2012 Congress showed how young people who carry this tremendous reservoir of enthusiasm, talent, willingness to serve, and passion for physics—all spiced with a joyful love of life—can find one another and work creatively in the interest of improving the well-being of civilization and life on our planet. ●

Experiencing Another Continent

A Shared Love of Physics Breaks Down Barriers

by Christopher Frye, University of Central Florida, reporting on the International Conference of Physics Students (ICPS), August 4–10, 2012, Utrecht and Enschede, the Netherlands

Dormitories at Utrecht University campus in the Netherlands. Image credit: Christopher Frye.

Upon arriving overseas for the 2012 International Conference of Physics Students (ICPS) in the Netherlands, I immediately encountered a language barrier. It would be a constant reminder during my stay that I was a visitor in a foreign country and culture. I developed an envy of European students proficient in two, three, or even four languages, having spent their lives in multicultural environments.

The event fell at the end of my summer studentship at CERN in Geneva, Switzerland, so I had already enjoyed nine weeks immersed in a European environment. But at ICPS I met students coming from an especially diverse collection of countries. Some had just entered university. Others were nearly finished with doctorates. The friendliness with which all attendees treated one another took me by surprise. Each encounter with a new group of students gave me the impression that they had all come from the same university, even though they had often just met the previous day on the bus. A shared love of physics quickly broke down the barriers between students of different cultures.

Learning about other countries' approaches to studying physics forced me to analyze my own opinions about the US education system. Many of the students I met last summer specialized in physics immediately upon entering their universities, which made me slightly jealous; their demanding high school curricula made further general education in college unnecessary. Such a system lets students progress quickly to explore quite advanced material by the third year. However, I do prefer the American system's approach of absorbing the master's degree into the PhD program. This allows students to build strong relationships with professors at their universities and provides undergraduate research opportunities quite uncommon throughout Europe.

The opening night of the conference began with a welcome lecture by the Dutch physicist-turned-politician Jan Terlouw. Speaking in a cathedral built shortly after the turn of the first millennium, he described his love for the beauty of physics and the search for truth, and stressed the responsibility all physicists hold as citizens. He emphasized that those who quantitatively understand the laws of nature must admonish their leaders and their peers when policies seem doomed for failure. Terlouw warned the audience that current economic models, upon which governments base decisions, assume infinite growth can be achieved; however, we live on Earth, which is essentially a closed system once one includes the Sun. Because infinite growth cannot occur in a finite system, he fears society may soon collapse and calls on scientists to spread the word.

In a fascinating two-hour lecture, Hitoshi Murayama of the University of California, Berkeley, spoke about neutrinos and why they might be the reason that stars, planets, and humans are all made of matter. He discussed theories that combine ideas about antineutrinos, extra

More Information

Christopher Frye received an all-expenses paid trip to ICPS as a winner of the 2012 SPS Outstanding Student Award for Undergraduate Research, along with fellow winner Rachel Ward from Utah State University. Read their research abstracts and full meeting reports at www.spsnational.org/programs/awards/2012/osa.htm. Interested in applying for the 2013 Outstanding Student Award? Visit www.spsnational.org/programs/awards/student.htm. Applications are due March 15, 2013.

Next up

{ICPS} Heriot-Watt 2013

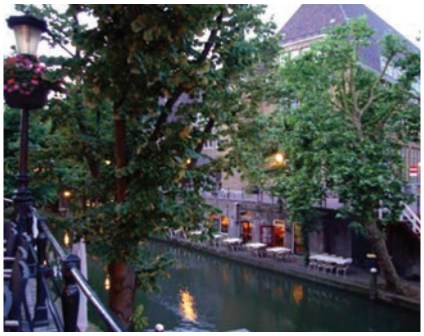
The next ICPS will take place
August 15–21, 2013
Edinburgh, Scotland
www.iaps.info/icps/scotland-2013

dimensions, and asymmetries between matter and antimatter. These theories attempt to explain why shortly after the big bang, the universe consisted mostly of matter instead of antimatter. Bill Unruh of the University of British Columbia, Vancouver, spent the majority of his lecture explaining an illuminating analogy between photons traveling near a black hole and water waves traveling on the surface of a stream with varying current speeds. It surprised me to discover that experiments done with water waves have provided insights into black hole thermodynamics.

During the conference, I also enjoyed hearing about the research projects of the new friends I made during the student lecture sessions. I especially enjoyed talks about knot theory and the foundations of quantum mechanics. During the poster session, I had an illuminating discussion with a student studying tachyons, hypothetical particles that travel faster than light.

I also had the privilege of giving a talk about my latest research at the European laboratory CERN—a new method for beam splitting in a machine called the Proton Synchrotron. With 20 minutes allotted for my presentation, I went into detail, describing the theory and the calculations behind my work. I enjoyed the challenge of making the talk understandable to those in the room with a knowledge of only elementary physics.

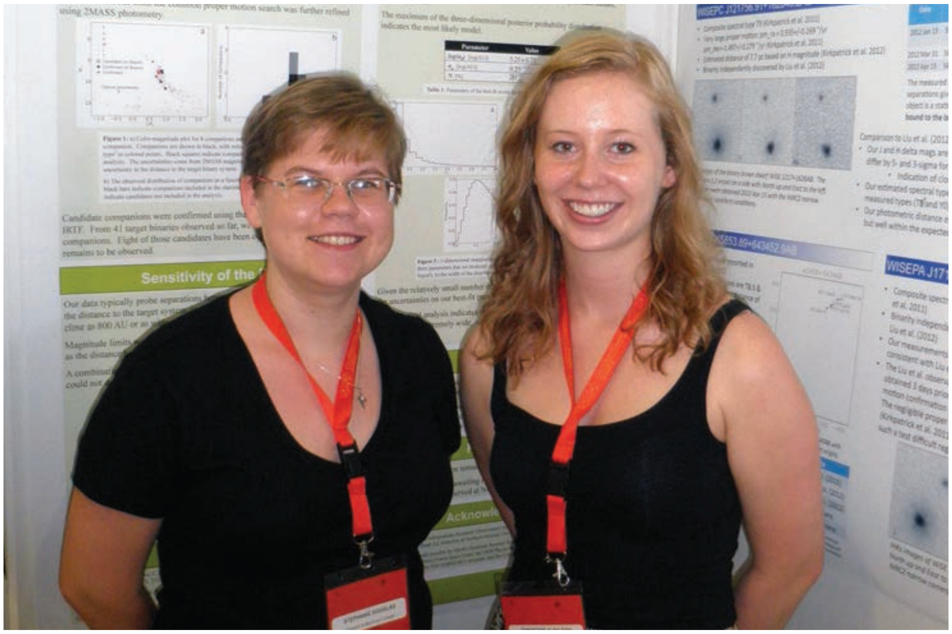
All together, ICPS was a wonderful learning opportunity. Not only did I gain experience in presenting a lecture on my own research and finding out about neutrinos in the early universe, but I also came to appreciate the rich diversity of cultures and perspectives exemplified by the new friends I made from around the world. ●



Utrecht, the Netherlands.
Image credit: Christopher Frye.

Cool Stars in the Summertime

by Stephanie Douglas, Franklin & Marshall College, reporting from Cool Stars 17, The Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, June 24–29, 2012, Barcelona, Spain



Stephanie Douglas (left) poses in front of the poster she presented at Cool Stars 17, joined by Christine Wilson (right). Image credit: Stephanie Douglas.

During his talk at Cool Stars, Todd Henry of Georgia State University had the entire audience stand up and participate in an exoplanet dance. It was, quite possibly, the funniest moment of the conference.

Astronomers were told to perform different motions depending on what exoplanet search method each was most involved in. Those participating in the Kepler mission and other transit searches, which wait for planets to pass in front of stars and block the starlight, stood with their hands clasped behind their backs. Those using radial velocity searches, which look for the gravitational wobble of a star induced by a planetary companion, moved their heads back forth in “what we in America call 'the funky chicken,'” said Henry. The remaining members of the audience were instructed to move side to side and shake their heads back and forth while twisting their arms around in a circle to represent all the effects that could show up in a third, lesser-known method for finding planets around nearby stars: astrometry, or the precise measurement of stellar positions.

Cool Stars 17 provided a new meeting experience for me, and not just because of the dancing. I had been to the large winter meetings of the American Astronomical Society (AAS), but Cool Stars was smaller, more focused, and much more international. The conference is held every two years, alternating between the United States and Europe. This year 433 attendees gathered in Barcelona to discuss pretty much any star-like object that astronomers consider "cool" . . . everything from recently discovered room-temperature Y dwarfs, to old giant stars that measure a toasty 6,000 Kelvins.

The coolest hydrogen-burning stars, M dwarfs, are gaining a lot of attention. Bárbara Rojas-Ayala of the American Museum of Natural History explained to me that the details of M dwarfs were largely ignored for a long time. The stars were thought of as small, boring, and unimportant. But they are ideal hosts for detectable planets, and as Caltech's Kaspar von Braun stated during his talk, “You understand the exoplanet only as well as you understand the parent star.” In light of this, the entire last day of the conference was dedicated to M dwarfs as exoplanet hosts. M dwarfs make good hosts for detectable exoplanets because they are relatively dim compared to Sun-like stars. A planet transiting the face of a dimmer star will block a higher percentage of the starlight, making it easier to detect.

Antoni Gaudí designed this unusual structure in Barcelona's Park Güell, not too far from the site of the Cool Stars meeting. Image credit: Stephanie Douglas.

Victoria Meadows of the University of Washington spoke about the habitability of exoplanets and explained that there are a huge number of factors that affect a planet's ability to harbor life. Her talk focused on biosignatures that might signify life, as well as the effects of the host star's spectrum and magnetic activity on habitability. She cautioned that we can only be sure that a planet is inhabited if we detect modulated electromagnetic signals coming from it; otherwise, we can only determine the probability that the planet hosts life.

Another area of interest at Cool Stars was the transition from M dwarfs down through the different classes of less massive brown dwarfs. Brown dwarfs have the same composition as stars but don't have enough mass to ignite hydrogen fusion. Due to their cool temperatures, brown dwarfs have cloudy atmospheres. Atmospheric models usually assume a uniform atmosphere, but that's probably not the case for many brown dwarfs. Several astronomers presented evidence that brown dwarfs vary over time as the objects rotate, indicating that, like Jupiter, brown dwarfs may have nonuniform bands or patches of clouds.

Very few undergraduates attended Cool Stars. I met only one other! Christine Wilson, from Saint Mary's University in Halifax, Nova Scotia, presented her research on the supergiant star Epsilon Aurigae. We met because we were both staying in the same hostel, and we stuck together at many events throughout the week. The lack of other undergraduates made the meeting slightly more intimidating than the AAS winter meeting, where undergraduates make up a significant fraction of attendees. There were a good number of graduate students, however, and each of the three splinter sessions I attended included a graduate student talk.

Outside of the conference, there was plenty to see in Barcelona. The city is host to a myriad of buildings designed by the architect Antoni Gaudí. Christine and I, along with City University of New York graduate student Kay Hiranaka, spent an afternoon exploring two of Gaudí's works: La Sagrada Familia and Park Güell.

Between the city, the astronomy, and the dancing, I had a great time at Cool Stars. ●

Next up

The next Cool Stars meeting
will take place
June 8–14, 2014
Flagstaff, Arizona
www2.lowell.edu/
workshops/coolstars18/

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What's Cooler than Being Cool? Ultracold Physics!

by Patrick Donnan, Auburn University, reporting on the 43rd Annual Meeting of the American Physical Society (APS) Division of Atomic, Molecular, and Optical Physics (DAMOP), June 4–8, 2012, Orange County, CA

Author Patrick Donnan gives his talk during the undergraduate session at DAMOP. Image credit: Patrick Donnan.

On the last night of this year's DAMOP conference, the speaker came from beyond the grave. In a recording made before he passed away last year, Norman Ramsey talked about his interactions with famous scientists such as Rutherford, Thompson, Rabi, and Dirac. It was fascinating to hear about the personalities and quirks of scientists whose names often remain associated with concepts in textbooks but never quite come to life. Ramsey, a Nobel laureate, was no slouch himself. His work contributed to the development of MRI machines and GPS systems. He had his share of quirks as well and was a very entertaining lecturer. The previous night had featured a session commemorating his contributions to AMO physics, and it was great to see the community honor the passing of one of its greatest.

DAMOP is a conference largely composed of younger scientists and has a tutorial on the first day to orient graduate students new to the field. The conference was very lively; there were always physicists gathered in the lobby, discussing their research and the talks they had attended or were planning to attend.

Philip Burke of Queen's University Belfast gave a talk about R-matrix colli-

Next up

The next DAMOP conference
will take place
June 3–7, 2013
Quebec City, Quebec, Canada
www.aps.org/units/
damop/meetings/annual/

sion calculations that was particularly of note; he could not attend due to health issues and instead presented a recorded talk. I emailed him during the conference to thank him for going the extra mile to present, and he responded within a day, sending me a long list of papers about the R-matrix method. Gestures like this help make DAMOP much less imposing for younger students, especially when a lot of the material is going right over your head!

Other talks I enjoyed included those of Charles Adams, Ian Spielman, and Rudi Grimm. Charles Adams from Durham University spoke about electromagnetically induced transparency in frozen Rydberg gases, a phenomenon that has great potential for use in quantum information science. Ian Spielman of the Joint Quantum Institute, the National Institute of Standards and Technology, and the University of Maryland talked about recent breakthroughs in spin-orbit coupling in ultracold atomic systems. These systems provide a great way to test condensed matter theories in the highly controllable environment of atomic ensembles. Lastly, Rudi Grimm of the University of Innsbruck discussed universality and its relation to his work in ultracold cesium. Universality is a fascinating phenomenon that allows you to work out certain properties of how few-body systems behave, regardless of what the actual bodies are. You just need to know if they are bosons or fermions.


DAMOP attendees peruse one of the meeting's three poster sessions. Image credit: Patrick Donnan.

Of particular note to undergrads is the special undergraduate session at DAMOP. Undergraduates apply to speak, and six are selected to give talks that are slightly longer than contributed conference talks. This year's undergraduate session was incredibly diverse. It opened with one of last year's LeRoy Apker Award winners, Bethany Jochim. She gave a great invited prize talk on the dissociation of the molecule NO^{2+}. I was very excited to be presenting my work on calculations of antihydrogen spectroscopy in this session with other undergrad researchers in my field. The work I presented was part of a larger effort by the Antihydrogen Laser Physics Apparatus (ALPHA) Collaboration that resulted in the first measurements of the antihydrogen spectrum. I made it through my talk, and, perhaps more importantly, I wasn't drilled in the post-talk question session! The DAMOP community supports its undergrad speakers; quite a few people came up to me afterward with complimentary remarks. A lunch social was also provided for the presenters. Comparing this experience to other experiences I've had at universities across the United States, I learned that universality isn't restricted to atoms!

There is lots of exciting research going on in AMO physics today. I'd highly recommend that undergrads trying to figure out what subfield of physics they want to enter give AMO a look. The community is lively and highly receptive, and the excitement is infectious. Personally, I hope to be attending DAMOP meetings for years to come. ●

Upcoming Physics Meetings

American Association of Physics Teachers 2013 Winter Meeting
January 5-9, 2013, New Orleans, LA, www.aapt.org/conferences/wm2013

2013 Annual Meeting of the American Association for the Advancement of Science
February 14-18, 2013, Boston, MA, www.aaas.org/meetings

March Meeting of the American Physical Society
March 18-22, 2013, Baltimore, MD, www.aps.org/meetings/march

April Meeting of the American Physical Society
April 13-16, 2013, Denver, CO, www.aps.org/meetings/april

222nd Meeting of the American Astronomical Society
June 2-6, 2013, Indianapolis, IN, aas.org/meetings/aas222

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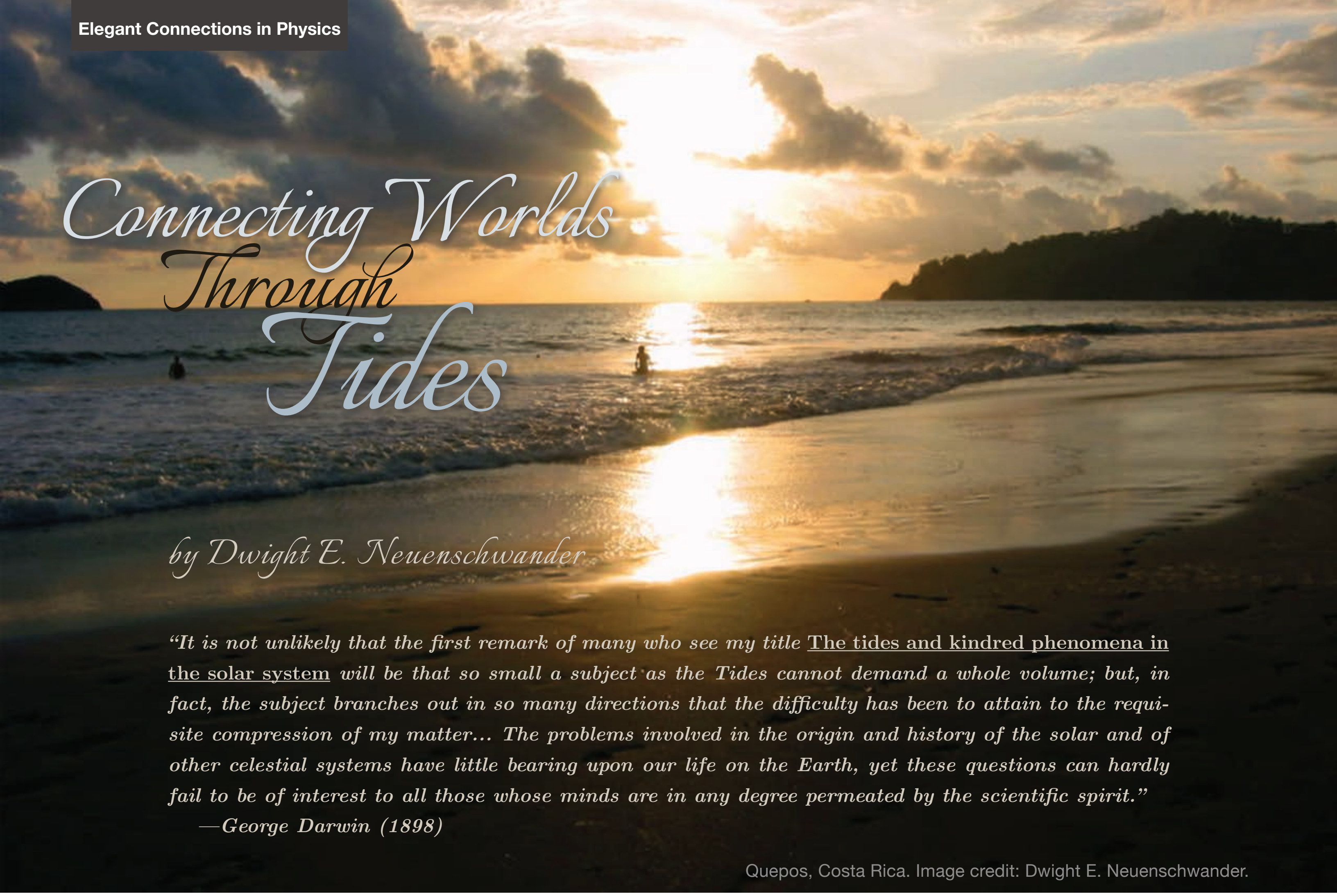

Connecting Worlds Through Tides

by Dwight E. Neuenschwander

> *"It is not unlikely that the first remark of many who see my title The tides and kindred phenomena in the solar system will be that so small a subject as the Tides cannot demand a whole volume; but, in fact, the subject branches out in so many directions that the difficulty has been to attain to the requisite compression of my matter… The problems involved in the origin and history of the solar and of other celestial systems have little bearing upon our life on the Earth, yet these questions can hardly fail to be of interest to all those whose minds are in any degree permeated by the scientific spirit."*
>
> *—George Darwin (1898)*

Quepos, Costa Rica. Image credit: Dwight E. Neuenschwander.

Our obligation to the Sun as the source of energy for life on this planet needs no elaboration. Should our appreciation also extend to the Moon? A journalist once said, "We live with the Moon, but not by it."[1] That may be true of our attitudes toward our Moon and our awareness of it, but if the Moon did not exist, how different would life on this planet be?[2]

Astronomical bodies are connected by gravitation, which holds satellites in their orbits about stars and planets. To understand the orbits themselves we initially model these bodies as point masses. But planets and moons have finite sizes. Gravitational forces vary with distance, and gradients in the field produced by one body generate internal stresses in other bodies. For instance, the Moon's gravity is slightly stronger on the Moon-facing side of Earth than on the opposite side, producing strains throughout Earth, the "tidal forces." The distortions produced by these stresses show up most dramatically in the oceans, forming two bulges of water on opposite sides of the planet. The bulges lie approximately on the line connecting the centers of the Earth and the Moon.

The bulge on the side of the Earth facing the Moon makes intuitive sense, but why is there a bulge on the *opposite* side? The authors of one introductory astronomy textbook write that the second bulge exists "because the Moon pulls more strongly on the Earth's center than on the far side. Thus the Moon pulls the Earth away from the oceans, which flow into a bulge away from the Moon...."[3] Other authors write that "the high tide on the far side of the Earth from the Moon occurs because the water there is 'left behind' as the Moon pulls the solid center of the Earth toward it."[4] Such explanations were written for nonmathematical audiences, so the authors had to resort to plausibility arguments. "Elegant Connections" readers may prefer discussions linked directly to elementary but quantitative physics. Let's have a go at it.

To get at the essentials of the tidal mechanism and the appearance of two tidal bulges, we will begin with an oversimplified model of the Earth. Then we will add realistic complications, including friction created by the Earth's crust rotating beneath the oceans. The friction acts like a brake applied to Earth's spin and slightly displaces the bulges from the Earth–Moon axis. This offset allows Earth and the Moon to exert torques on one another. The consequences include Earth's day gradually getting longer as the Moon slowly recedes from Earth.

Geological and paleontological evidence has long supported the hypothesis that the days were shorter in the distant past. To clinch the the torque-coupling hypothesis, confirmation was needed that the Moon's orbit is receding. This became possible in 1969, when the Apollo 12 astronauts left reflectors on the lunar surface, enabling the distance between Earth and the Moon to be measured to millimeter precision with pulsed lasers.

A Simple Model of Tidal Forces and Bulges

Let us start with an isolated, smooth, spherically symmetric, nonrotating Earth with a rocky core covered by a global ocean. Such an Earth is necessarily spherical because gravity is an inverse-square central force.[5]

Now bring the Moon into the game. Assume it to be a spherically symmetric body. So long as Earth and the Moon can each be modeled as a single particle, tides do not enter into the picture. Each body orbits the system's center of mass, following Kepler's laws; equivalently, the system behaves like a "reduced mass" $mM/(m+M)$ orbiting in a central field.[6]

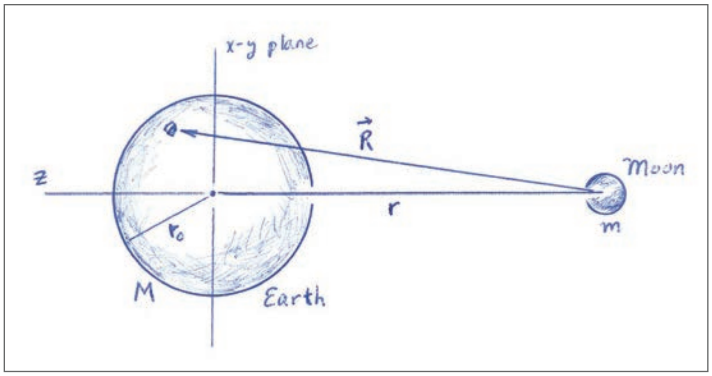

Fig. 1. Coordinate system for calculating tidal forces. The origin lies at Earth's center, with the Moon located distance *r* from it.

For now, let's ignore the effects of the other planets and the Sun. Once we understand how one body produces tides on another, we can include the tidal effects of additional bodies by superposition. We will also pretend for now that the Moon orbits directly over Earth's equator.

The Moon exerts a gravitational force on Earth. To a first approximation the Moon can be considered a point source of a gravitational field **g**. We need to map this **g** across Earth. As observers riding on Earth, let us fix our coordinates to it.

Let the unperturbed spherical Earth have mass M and radius r_o, label the Moon's mass m, and denote the distance between the centers of the bodies r. Place the origin of an xyz coordinate system at the center of Earth. The displacement from the Moon's center to an arbitrary point within Earth's volume is described by vector **R** (Fig. 1) [7]:

$$\mathbf{R} = x\,\mathbf{i} + y\,\mathbf{j} + (z+r)\mathbf{k}. \tag{1}$$

The Moon's gravitational field at that point is $\mathbf{g}(x,y,z) = -Gm\mathbf{R}/R^3$. Since $r \approx 60r_o$, to first order in ratios such as x/r we can use the binomial theorem to write

$$\frac{1}{R^3} \approx \frac{1}{r^3}\left(1 - \frac{3z}{r}\right) \tag{2}$$

so that

$$\mathbf{g}(x,y,z) \approx -\frac{Gm}{r^3}\,[x\mathbf{i} + y\mathbf{j} + (r - 2z)\mathbf{k}]. \tag{3}$$

We must also note that Earth accelerates toward the Earth–Moon system's center of mass. Whenever we do physics in a reference frame that accelerates with acceleration $\mathbf{a}_o$ relative to an inertial frame, we must subtract $\mathbf{a}_o$ from the acceleration **a** that is due to the "real" forces. Without the tides or Earth's rotation, *every* point in the planet would fall freely toward the Moon with an acceleration equal to the Moon's gravitational field at Earth's *center*, $\mathbf{a}_o = (Gm/r^2)(-\mathbf{k})$. Therefore, the *effective* lunar gravitational field acting on Earth, $\mathbf{g}_{\text{eff}} = \mathbf{g} - \mathbf{a}_o$, becomes

$$\mathbf{g}_{\text{eff}}(x,y,z) = \frac{Gm}{r^3}\,[-x\mathbf{i} - y\mathbf{j} + 2z\mathbf{k}]. \tag{4}$$

A map of $\mathbf{g}_{\text{eff}}$ throughout Earth's volume resembles a quadrupole, pushing Earth outward along the Earth–Moon axis (our z axis) and squeezing inward in cross sections perpendicular to the axis (Fig. 2). At a point on Earth's surface along the z axis, $|g_{\text{eff}}| = 1.1\times10^{-6}$ m/s^2, about 10^{-7} of Earth's own gravitational field.[8] This difference and the planet's plasticity allows its material to bend or flow in response to stresses. A bulge forms facing the moon, and another bulge exists on the opposite side.

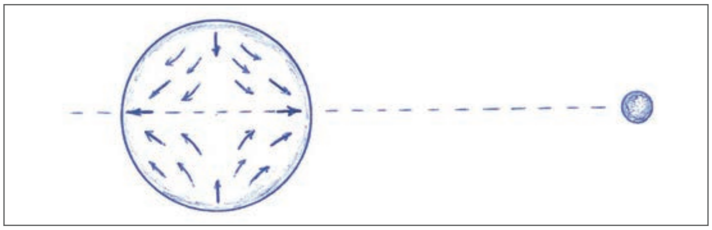

Fig. 2. Tidal stresses on the Earth due to the Moon.

If tidal forces exceed a body's self-gravitation and internal cohesive forces, the tides rip the body apart. The closest orbital radius about which one body can orbit another without disintegrating is called the "Roche limit." I will return to this below.

As Earth spins under the Moon, a wave of flexing a few centimeters in amplitude runs through the lithosphere. We who are on land bob up and down as we are carried along. The oceans have a more noticeable response, exhibiting pronounced tidal bulges. From where we sit on the seashore, we see the tide "come in" until high tide, then "go out" toward low tide. About 12$\frac{1}{2}$ hours later our piece of coastline passes through the second high-tidal bulge (two per day, the "diurnal" tides).[9] Why 12$\frac{1}{2}$ and not 12 hours? Earth spins west to east, so the Moon appears to rise in the east and set in the west. However, it rises about 52 minutes later each day, because it orbits eastward about 12° daily. Following the Moon, the tidal bulges creep eastward across Earth's surface.

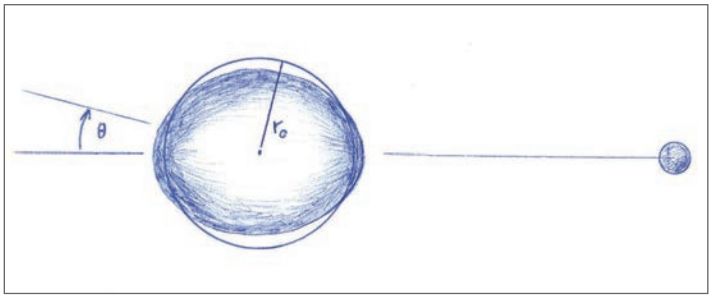

Fig. 3. Tidal bulges.

We can calculate the shape of an idealized ocean surface with tidal bulges (neglecting Earth's rotation, solar tides, and coastline effects). Think of $\mathbf{g}_{\text{eff}}$ as the negative gradient of a potential φ. The potential that yields $\mathbf{g}_{\text{eff}} = -\nabla\varphi$ is

$$\begin{aligned}\varphi &= -\frac{Gm}{r^3}\left(-\frac{x^2}{2} - \frac{y^2}{2} + z^2\right) + const.\\ &= -\frac{Gmr_o^2}{2r^3}\,(3\cos^2\theta - 1) + const.\end{aligned} \tag{5}$$

where, on the surface, $r_o^{\,2} = x^2 + y^2 + z^2$ and $z = r_o\cos\theta$ (Fig. 3). A sailboat of mass m' floating on the ocean surface "feels" not only Earth's own gravitation, but also the potential energy of φ. At an elevation of $h+r_o$ above Earth's center, the sailboat's potential energy, for $h << r_o$, is

$$U = m'g_oh + m'\varphi, \tag{6}$$

with $g_o = GM/r_o^{\,2}$ denoting the magnitude of Earth's own gravitational field at r_o.[8] An ideal ocean in equilibrium has an equipotential surface with an axially symmetric but oblong shape,

$$h = \frac{GMr_o^2}{2g_or^3}\,(3\cos^2\theta - 1) + const. \tag{7}$$

High tides occur at θ = 0° and 180°, along the line connecting the terrestrial and lunar centers. Low tides occur at θ = ± 90°. The maximum and minimum heights differ by

$$\Delta h = \frac{3Gmr_o^2}{2r^3g_o} = \frac{3mr_o^4}{2Mr^3}. \tag{8}$$

For the lunar tides induced on Earth, $\Delta h \approx 53$ cm.

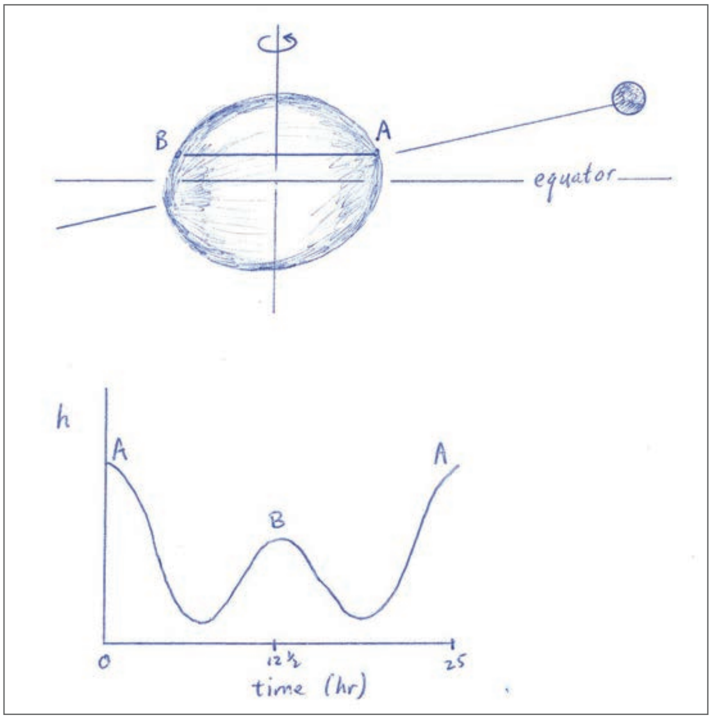

Fig. 4. The diurnal tides. The relative amplitudes of successive high tides depend on the latitudes of the observer and the Moon.

The Sun is about 300 million times more massive than the Moon, but it is also about 400 times more distant. Thus, for solar-induced tides on Earth, Δh is about 24 cm, less than half the lunar tide. Solar tidal bulges lie along the line connecting the centers of Earth and Sun. They add to the lunar tide to produce the net tide. (Tides on Earth due to Jupiter and other planets are negligible.) When the Sun–Earth–Moon system is colinear during a new Moon or a full Moon, the solar and lunar tides add constructively to produce maximum high tides, the "spring tides." During the lunar first- or third-quarter phases, the high tides fall to their minimums, the "neap tides."[10]

The Earth's equator tips about 23° relative to the ecliptic, and the Moon's orbit tips 5° from the ecliptic. Tidal bulge peaks can therefore appear at different latitudes within 28° of the equator. As a result, successive high tides at a given location may have different depths. Depending on the latitude, an observer might pass through a bulge's maximum during one high tide but be off the bulge's peak when passing through the opposite one $12\frac{1}{2}$ hours later (Fig. 4).

Interaction of Tides with Land Masses

So far our calculations have conceptualized a simple model that reveals the essentials of tidal dynamics. But the tide–land interactions introduce significant complications. If your boat can make it into the bay only at high tide, a lot rides on having an accurate prediction! When sailing into Half Moon Bay in Auckland, New Zealand, for instance, the equilibrium tidal bulge model must be supplemented with local statistics. Only then can those who live by the tide reliably predict its timing and depth.

As Earth's rotation carries a coastline into a tidal bulge, the tide appears to advance in a relentless wave. In some locations, the shape and dimensions of a bay may introduce tidal resonances with astonishingly large amplitudes. At the Bay of Fundy between New Brunswick and Nova Scotia, high and low tides can differ by some 12 meters! As with musical instruments, such resonances occur whenever the length of the "tube" closed on one end is $\frac{1}{4}$ the wavelength.[11]

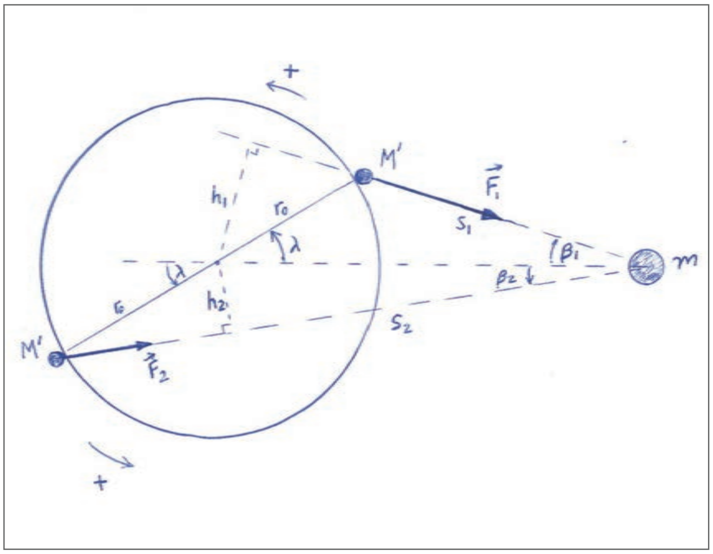

Fig. 5. Model of the Earth–Moon system for studying the torques on the Earth.

Interaction between water and land also has long-term, potentially ominous global effects. Earth's crust rotates about the planet's axis (~400 m/s at the equator) much faster than the speed at which a tidal bulge propagates as a wave.[12] Therefore the rocky bulk of the planet spins beneath the oceans. Since water has a nonzero viscosity, the oceans sliding over the seafloor act like a brake on Earth's crust. This friction pulls on the tidal bulges. Since Earth spins faster than the Moon orbits, the tides lead the Earth-to-Moon axis by a small amount, presently about 10° and denoted λ in the equations to follow. This offset has consequences. The mass M' carried by each bulge gives the Moon's gravitation a "lever arm" by which it torques Earth. Operating in the same direction, tidal friction and lunar gravitational torques slowly decrease Earth's spin.

By Newton's third law, Earth's tidal bulges also exert forces on the Moon. Each of those forces has a component tangent to the lunar orbit that exerts a torque on the Moon, changing its angular momentum and making the Moon recede from Earth. George Darwin articulated this effect in 1897.[13] Let us model it.

Frictional and Lunar Torques on Earth

Here we will lay out the implications of torques on Earth produced by (a) tidal friction as the rotating Earth crust slides beneath its ocean load and (b) the Moon's gravity acting on Earth's tidal bulges. For now we neglect the Sun's torque on the Earth.

The spinning Earth tugs at the water above the ocean floor, while the bulge wants to stay pointed at the Moon. Thus the magnitude of the tidal friction depends on the difference in the angular velocities of Earth's spin and the lunar orbit. Let $\dot{\varepsilon}$ denote the angular velocity of Earth's spin ($\dot{\varepsilon} \approx 2\pi/24$ hr presently), and let the Moon's orbital angular velocity above Earth be denoted $\dot{\theta}$ ($\approx 2\pi/27$ days). The tidal frictional torque will be a function of $(\dot{\varepsilon} - \dot{\theta})$. To first order we may write the frictional torque as $-b(\dot{\varepsilon} - \dot{\theta})$, where b is some constant.

To represent the Moon's gravitational torque on Earth's tidal bulges, we can model Earth as a sphere of radius r_o and treat the bulges as two point masses, each of mass M', lying on the planet's surface along a line inclined at angle λ from the Earth–Moon axis (Fig. 5).

The rotational version of Newton's second law says the net torque acting on Earth equals the rate of change of the planet's angular momentum. When the system is viewed from above

Earth's northern pole, with counterclockwise rotations assigned the positive sign, Newton's second law in terms of torque gives

$$-b(\dot{\varepsilon} - \dot{\theta}) + (F_2h_2 - F_1h_1) = I\ddot{\varepsilon}\ , \tag{9}$$

where the double overdot denotes the second derivative with respect to time, I represents Earth's moment of inertia about its spin axis, and the forces F_1 and F_2 are the lunar gravitational forces on the near and far bulge, respectively, with lever arms of lengths h_1 and h_2. From Fig. 5 the force magnitudes are $F_1 = GM'm/s_1^2$ and $F_2 = GM'm/s_2^2$. A lever arm distance can be written $h_1 = r\sin\beta_1$, and with the law of sines and small angles, $\sin\beta_1 \approx \beta_1 \approx r_o\lambda/s_1$; similar expressions hold for h_2. To a good approximation $s_1 \approx r - r_o$ and $s_2 \approx r + r_o$. Equation (9) then becomes approximation,

$$-b(\dot{\varepsilon} - \dot{\theta}) + (GmM')(r_o r\lambda)\left[\frac{1}{(r+r_o)^3} - \frac{1}{(r-r_o)^3}\right] = I\ddot{\varepsilon}\ , \tag{10}$$

giving a clockwise torque; hence the angular acceleration is negative and $\dot{\varepsilon}$ decreases with time. Earth's day is presently shrinking by about 0.0023 seconds every century, about 2 hours every 300 million years. Assuming this rate to be constant (which it isn't, but the assumption nonetheless offers an order-of-magnitude long-term estimate), 900 million years ago the day would have been about 18 hours long, a conclusion consistent with fossil records from that era.[14]

At this deceleration rate, 3 billion years ago the day would have been about 6 hours long! Prevailing winds of 100 mph or more would have been normal. With the smaller solar-induced tides and violent wind-driven wave action on shores, the transition of life from the sea to the land would have faced extra challenges! Had the Moon never come into existence, life on this planet would be very different.[2] We owe the Moon some profound appreciation. We may live with it and not by it, but our physiology and routines of life have adapted to its rhythms.

As a player in tidal friction, the tidal bulge offset angle λ depends on the difference between Earth's spin frequency and the Moon's orbital frequency. If Earth's spin period were the same as the lunar orbital period (with the Moon in geosynchronous orbit), the Earth–Moon system would rotate as if it were a rigid body, with the tidal bulges aligned along the Earth–Moon axis. Should the Moon somehow orbit faster than Earth spins ($\dot{\varepsilon} < \dot{\theta}$), the tidal bulges would lag the Earth–Moon axis, changing the sign of λ. The Moon would appear from Earth to rise in the west and set in the east. Evidently, λ is a function of ($\dot{\varepsilon} - \dot{\theta}$).

Earth's spin will continue to slow down, with λ decreasing all the while, until $\dot{\varepsilon} \rightarrow \dot{\theta}$ and $\lambda \rightarrow 0$. When $\dot{\varepsilon} = \dot{\theta}$ one of the Earth's hemispheres will face the Moon all the time, an effect called "tidal phase locking." Then $\lambda = 0$ and the lunar torque exerted on Earth will vanish.

Now let's switch perspectives and think about the tidal forces exerted by Earth on the Moon. The Moon is already phase locked to Earth; the satellite's spin period equals its orbital period, so the Moon always presents the same face to us. It was not always this way. Early in the history of the Earth–Moon system, a Moon newly formed by accretion would have been hot and relatively fluid. Using Eq. (8), the max-to-min tides on the Moon (due to Earth) compared to those on Earth (due to the Moon) would have been

$$\frac{(\Delta h)_{Earth\ on\ Moon}}{(\Delta h)_{Moon\ on\ Earth}} = \left(\frac{M}{m}\right)^2 \left(\frac{\rho}{r_o}\right)^4 , \tag{11}$$

where ρ denotes the lunar radius. Because $M \approx 100m$ and $\rho \approx \frac{1}{4}r_o$, Earth would produce tidal bulges about 40 times larger on the Moon than those the Moon produces on Earth. Thanks to large tidal torques [15] and the small lunar moment of inertia, the Moon phase locked to Earth early in its history. Thus the Moon keeps only one face toward Earth today, with its spin and orbital periods equal. The now-frozen lunar tidal bulges, aligned along the Earth–Moon axis, offer no lever arm for Earth to exert torque on the Moon.

However, Earth's tidal bulges are not yet aligned along that axis, so they exert a torque on the Moon relative to Earth's center. To analyze those torques, let's reuse Fig. 5, invoke Newton's third law, and evaluate the torques with respect to Earth's center. The net torque changes the lunar angular momentum, which can be partitioned into the orbital angular momentum *of* the Moon's center of mass revolving about Earth, plus the lunar spin angular momentum *about* the Moon's center of mass.[16] Newton's second law, written in terms of torque, now says

$$F_1h_1 - F_2h_2 = \frac{d}{dt}(mr^2\dot{\theta} + i\dot{\theta}), \tag{12}$$

where we have invoked the equality of the Moon's orbital and spin angular velocities, and i denotes the lunar moment of inertia about its spin axis. The torque computations are similar to our previous case but with a crucial change of sign, leaving

$$(GM'm)(r_o r\lambda)\left[\frac{1}{(r-r_o)^3} - \frac{1}{(r+r_o)^3}\right] = \frac{d}{dt}(mr^2\dot{\theta} + i\dot{\theta}). \tag{13}$$

This time the term in square brackets is positive, which implies

$$2mr\dot{r}\dot{\theta} + (mr^2 + i)\ddot{\theta} > 0. \tag{14}$$

The Moon's orbit about Earth is well described by Kepler's third law, which says that $\dot{\theta}^2 \sim 1/r^3$. Differentiating this with respect to time means that $2\dot{\theta}\ddot{\theta} \sim -3\dot{r}/r^4$. Using Kepler's third law again to substitute r for $\dot{\theta}$, we find that $\dot{\theta} \sim -1/r^{5/2}$. For large r and short times (astronomically speaking), the lunar angular acceleration is very small and the orbital angular velocity approximately constant. Thus it seems safe to say that $2mr\dot{r}\dot{\theta} > 0$, which means that, in our era, $\dot{r}$ cannot be zero or negative. Thus $\dot{r} > 0$, which means the Moon recedes from Earth.

Only after the Apollo 12 astronauts left reflectors on the Moon capable of reversing the direction of a laser beam could the value of $\dot{r}$ be measured. It turns out to be about 3.8 cm/yr.[17]

Long-Term Future

For the foreseeable future the Earth will keep rotating as the Moon revolves around it. As the Moon recedes, its orbital period will slowly lengthen, and Earth's spin will gradually slow down. Those effects will continue, with the phase-locking mechanism making continual adjustments, until Earth's rotation period matches the Moon's orbital period. The Moon and Earth will then be *mutually* phased-locked to each other. The Moon will not be visible from half of Earth's surface! The tidal bulges will still be there, but they will lie along the Earth–Moon axis. At a fixed latitude, high and low tides will no longer occur. Earth's day will be about 50 times longer than it is today, and the Moon's orbital radius will be about 1.4 times its present value.[18] For those on Earth who can see it, the Moon will subtend an angle about 70 percent of its present angular diameter in the sky. Solar eclipses will be annular, not total.

However, the Sun will continue exerting tidal forces on Earth, causing tidal stresses, tidal bulges, and tidal friction, though diminished from the lunar-induced case. With the solar-induced tidal friction operating, Earth's spin will continue to slow after the Moon and Earth become mutually phase locked. If the Moon could be dismissed, Earth and the Sun would eventually become phase locked. With the Moon still in action, the solar-induced torque will slow Earth's spin *below* the value at which the planet phase locked to the Moon. Then the Earth will spin more slowly than the Moon orbits, and the Moon will appear from Earth to rise in the west and set in the east. Lunar tides will reappear with torques opposite from those of our era. Those future lunar-induced tidal bulges will lag instead of lead the Earth–Moon axis. Instead of receding, the Moon will approach the Earth. The closer the satellite gets, the stronger the tides, until the Moon comes within the Roche limit.

To estimate the upper bound for the orbital radius at which tidal forces break the Moon apart, neglect the chemical bonds that hold the rocks together and imagine the Moon is held together only by its self-gravitation.[19] Return to Eq. (4) after interchanging the roles of Earth and the Moon, and look at the stress along the Moon's z axis. When the lunar self-gravitation becomes less than the z component of the tidal force, the Moon will disintegrate; that is, when

$$\frac{Gm}{\rho^2} < \frac{2GM\rho}{r^3} \qquad (15)$$

or $r < (2M/m)^{1/3}\rho$. Since $M \approx 100m$ and $\rho \approx 1.74\times10^6$ m, the Moon would come apart when $r < 10^7$ m ~ $10r_o$. Perhaps Earth will then have a Saturnian ring system! The actual Roche limit is smaller than this crude estimate because the Moon's rocks are held together by internal forces. The Moon presently orbits at about $60r_o$, well outside our pessimistic Roche limit.

All of this would take billions of years, much longer than the lifetime of the Sun.[20] Four to five billion years from now, the Sun will deplete the hydrogen in its core. Nuclear collisions fusing hydrogen to helium today will be quenched. Gravity will squeeze the solar core tighter, raising its temperature. Before the core temperature hits the 100 MK or so necessary to fuse helium to carbon, the layers around the core will reach the 15 MK or so necessary to start hydrogen fusing to helium. Shells of fusion working their way through the star will swell it into a red giant that will engulf the Earth–Moon system.

However, this planet, moonlight walks, sunrises and sunsets, and the starry sky are no less beautiful for their being temporary. Get out there and enjoy them! Appreciate what we have, and be aware of what it means. We are part of nature, not a spectator on the sidelines. Connect with the many worlds around us! ●

Acknowledgments

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[1] Statement by Charles Kuralt in the CBS Documentary "The Moon Above, The Earth Below" (1989), broadcast on the 20th anniversary of the flight of Apollo 11.

[2] Neil F. Comins and William J. Kaufmann III, *Discovering the Universe*, 5th ed. (W.H. Freeman, New York, NY, 2000). See the provocative essay on p. 146, "What if the Moon Didn't Exist?" See also Comins' essay by the same title on a website of the Astronomical Society of the Pacific, http://www.astrosociety.org/education/publications/tnl/33/33.html.

[3] Michael Seeds and Dana Backman, *Horizons: Exploring the Universe*, 12th ed. (Brooks-Cole, Boston, MA, 2012), p. 68.

[4] Comins and Kaufmann (Ref. 2), p. 140.

[5] Because fields from a point source go as inverse distance squared, the point-sphere equivalence theorem for gravitation (Newton's law of universal gravitation) and electrostatics (Coulomb's law) holds. This can be shown with integration or by Gauss' law. See any calculus-based introductory physics text with chapters on gravity, Coulomb's law, and Gauss' law.

[6] See John C. Taylor, *Classical Mechanics* (University Science Books, Sausalito, CA, 2005), p. 296; Jerry B. Marion and Stephen T. Thornton, *Classical Dynamics of Particles and Systems*, 5th ed. (Thornson Brooks/Cole, Belmont, CA, 2004), pp. 287–289.

[7] See Hans C. Ohanian, *Gravitation and Spacetime* (W.W. Norton, New York, 1976), pp. 26–32; Taylor (Ref. 6), pp. 330–336; Marion and Thornton (Ref. 6), pp. 198–204.

[8] Another noninertial acceleration comes from Earth's spin, which carries angular velocity $\omega = 2\pi$ rad/day $= 7.3\times10^{-5}$ rad/s. A point on Earth's equator gets carried around the spin axis with the acceleration $r_o\omega^2 \approx 4\times10^{-8}$ m/s^2 (~25 times smaller than tidal forces), directed toward the local vertical. See "When '**F**' does not Equal 'm**a**,'" *SPS Observer* (Spring/Summer 2001), pp. 10–14.

[9] The word "diurnal" may seem less strange if we compare it to the more familiar "nocturnal."

[10] The "spring" tide's name is not seasonal but comes from the notion of the tide "springing up" higher than usual. According to *Webster's Dictionary*, "neap" comes from the Middle English *neep* or the Anglo-Saxon *nep*, which meant "scarcely touching."

[11] One might ask how a pulse of water, such as an incoming tide, can have "a wavelength." A wave pulse can be built by a superposition of harmonic waves.

[12] Left to itself, the tidal bulge, as a heap of water, would form a wave pulse, a superposition of waves. In deep water the phase velocity of a surface wave is $\sqrt{(g\lambda/2\pi)}$ for wavelength λ. Everyday waves have wavelengths on the order of 100 m or less, giving speeds on the order of 10 m/s or less. In contrast, tsunamis can travel over 500 mph, with wavelengths on the order of 100 km. See, e.g., http://walrus.wr.usgs.gov/tsunami/basics.html.

[13] George Howard Darwin, *The Tides and Kindred Phenomena in the Solar System* (Houghton, Mifflin and Co., Boston, MA, 1898), Chs. XVI and XVII, "Tidal Friction" and "Tidal Friction (continued)." This book was adapted from Darwin's Lowell Lectures at the Lowell Observatory in Boston in 1897. George Darwin (1845–1912) was a highly decorated astronomer, professor at Cambridge University, President of the Royal Society, and (in case you are wondering) the son of Charles Darwin.

[14] Seeds and Backman (Ref. 3), p. 70. 900 million years ago the only life on Earth was algae and bacteria, and they were sparsely distributed; see, e.g., Bill Frio, *Geology of the Great Basin* (University of Nevada-Reno Press, Reno, NV, 1986), p. 32.

[15] The strong tidal torquing of the early Moon would keep its interior hotter for a time longer than otherwise; a similar thermodynamics seems to be operating on Jupiter's moon Europa today, which has a deep-water ocean beneath its frozen crust, despite the intense cold of the Jovian region. Radioactivity also provides a long-lasting heat engine for planetary structures.

[16] See any introductory physics textbook, or "Angular Momentum and 'Spin,'" *SPS Observer* (Fall 2000), pp. 10–14. The theorem follows because angular momentum is additive.

[17] It is an elementary exercise in geometrical optics to design a set of mirrors that will return a light ray back along its incident direction. The arrays of reflectors built into automotive taillights use the same geometry.

[18] Robert B. Gordon, *Physics of the Earth* (Holt, Rinehart, and Winston, New York, 1972), p. 69.

[19] Bradley W. Carroll and Dale A. Astlie, *An Introduction to Modern Astrophysics* (Addison-Wesley, Reading, MA, 1996), pp. 766–767.

[20] Longer than the Sun's lifetime follows from a back-of-the-envelope estimate. For the Earth to become phase locked to the Moon, assuming nothing else changes, the Earth would have to lose about 26 hours. If the spin slow-down rate would stay at 0.0023 s/century for all time, this would take only 280 billion years! Of course, as the Moon recedes, its orbital period changes, so the coupled situation gets rather dynamic. But the point is, for large bodies the phase-locking timescale may be comparable to a star's lifetime. However, many planetary satellites besides our Moon are already phase locked to their planets. Pluto and its satellite Charon are already mutually phase locked.

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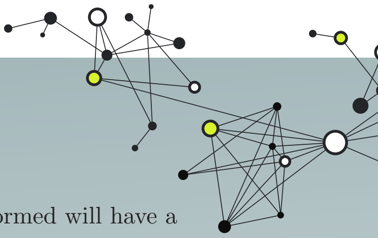

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