The SPS Observer

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The year 2010
marks 50 years since
the laser's invention.
See the related articles
on pages 2 - 5 inside.

The **SPS Observer**

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Photographer Dan Tentler captured this stunning image during the 2009 LA Geeks Dinner at the Laserium. The entire laser light show was set to the album Dark Side of the Moon by Pink Floyd.

Photo by Dan Tentler
http://www.lightbending.net

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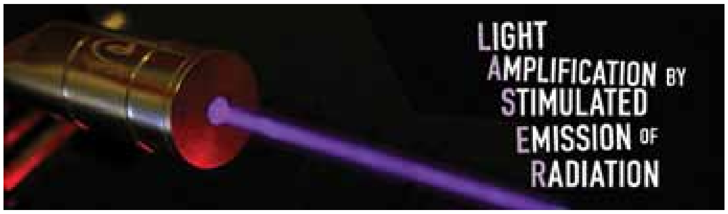
Exciting the Imagination

The SPS council joins in celebrating 50 years of the LASER



In January 2010 we set off on a yearlong celebration – the 50th anniversary of the invention of the laser. It can be truly said that no single invention has had a greater impact on our daily lives than the laser. From the most exotic applications to the simple or mundane, it is the laser that makes possible the many and varied devices of our modern world. It is only fitting that we take this opportunity to pause and reflect on what has been accomplished and to imagine what the future may hold.

The Society of Physics Students (SPS) has joined in this effort by selecting as its 2010 theme "Exciting the Imagination". This theme was chosen by the council members at its 2009 National Council Meeting for its holistic, yet simple message: That while the laser is inarguably the tangible product of human minds, it was the imagination (and dedication) of its creators that brought it into being.

That spark of creativity lies within the imaginations of us all, and we hope that in the coming year we can rekindle that spark, in ourselves and in others. The SPS is proud to lend its voice to those who celebrate our past and look forward to our future. And while we may have been taming photons since 1960, let us not forget that it is the untamed and unfettered imagination of human minds that will produce the exciting new world of tomorrow. Let us then take the opportunity that the new year brings to truly excite our imagination.

—The LaserFest Committee
of the SPS Council

LaserFest is a yearlong celebration of the 50th anniversary of the laser, which was first demonstrated in 1960, and is a collaboration between the American Physical Society, the Optical Society of America, SPIE, and IEEE Photonics Society (IEEE is the Institute for Electronics and Electrical Engineers). From DVD players to eye surgery, the laser is one of the greatest inventions of the 20th century—one that has revolutionized the way we live. Events around the world, LaserFest Celebrations, will showcase how the laser works, the history of the laser and its impact on society, and the laser's potential for the future.

—Taken from www.laserfest.org, where a schedule of planned events, free posters, interviews with scientists, and a list of LaserFest partnering organizations, including SPS and Sigma Pi Sigma, can be found.

What is light?[1]

Credit: Tom Zagwodzki/Goddard Space Flight Center

NASA Goddard's Laser Ranging Facility directing a laser (green beam) toward the Lunar Reconnaissance Orbiter (LRO) spacecraft in orbit around the moon (white disk). The moon has been deliberately over-exposed to show the laser.

By Gary D. White

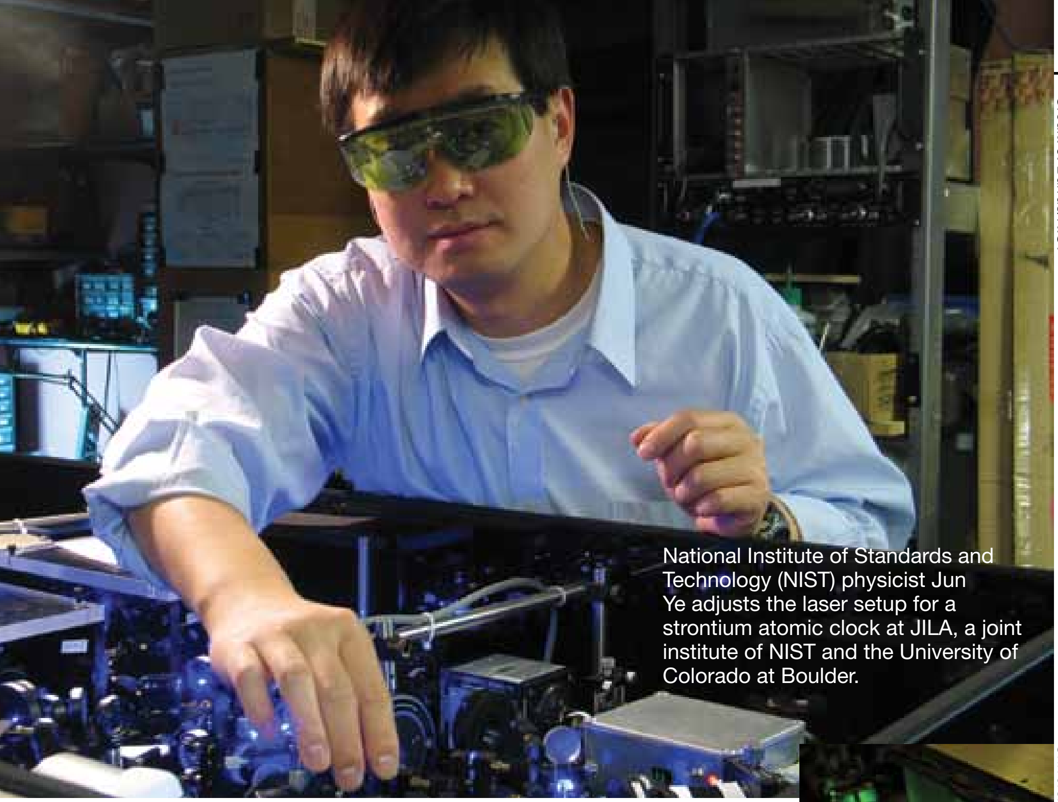
Everything about a laser screams physics—from its humble origins as a “solution looking for a problem,”[2] to its myriad uses today, both practical and in pure research; from its contorted acronym to the convoluted history of its invention—but nothing speaks so loudly as the mere fact that it is light, purified, synchronized, and amplified, yet still light. And yet what, exactly, is light? Is your favorite textbook answer included below?

- Electromagnetic radiation produced when electrons jump from a higher to a lower energy level.
- Transverse waves of oscillating electric and magnetic fields.
- Quanta of energy that propagate at 186,000 miles per second.
- The electromagnetic spectrum!—ROY G. BIV, ultraviolet, infrared, microwaves, X-rays, radio waves, gamma rays, television, etc.
- A massless form of energy that is emitted when charged particles are accelerated.
- The bosonic mediator of the electromagnetic interaction analogous to the gluon and the graviton.

Lately, though, I have begun to think that a better question is, “What is light like?” In my cartoon view[3] of science history, I see the answer as something of a slow-motion serial tennis match. Newton serves up particles first, with compelling arguments about light travelling through empty space. Huygens, Young, and Fresnel, and eventually Maxwell and Hertz, team up constructively to return the serve powerfully with an overwhelming smash of evidence of the wave nature of light. Then a miraculous volley by Planck, Lenard, Einstein, and Millikan save the particle view, with emergent photons as clumpy as, well, tennis balls. Finally, Bohr invokes the principle of complementarity and officially ties the game. As much as I like this historical caricature, it is rather simplistic and unsatisfying. I have never felt that I fully understood what Bohr meant by wave-particle complementarity, and I wonder about his purported admonition, “never express yourself more clearly than you think.”[4]

> “…[F]or several years after the laser’s invention, colleagues used to tease me about it, saying, ‘That’s a great idea, but it’s a solution looking for a problem.’ The truth is, none of us who worked on the first lasers imagined how many uses there might eventually be.”
>
> —Charles Townes, in *How the Laser Happened*

In any case, there is another question that enlightens me: What is light not like? It is clearly not merely a classical tennis-ball-type particle since it exhibits interference phenomena and polarization effects. But neither is it merely a classical wave; after all, it travels through a "vacuum." (I am always struck by the demonstration that begins with an alarm clock ringing inside a glass bell jar that is being evacuated. As the air is removed, will it get dark inside the bell jar or will the ringing sound diminish, or both? The answer



National Institute of Standards and Technology (NIST) physicist Jun Ye adjusts the laser setup for a strontium atomic clock at JILA, a joint institute of NIST and the University of Colorado at Boulder.

Credit: J. Burrus/NIST

> “I spent 10 years of my life testing [the photon concept and] the 1905 equation of Einstein’s [E=hf], and, contrary to all my expectations, I was compelled in 1915 to assert its unambiguous experimental verification in spite of all its unreasonableness since it seemed to violate everything we knew about the interference of light.”
>
> —R. A. Millikan in his autobiography

> “All the years of conscious brooding have brought me no closer to the answer to the question, ‘What are light quanta?’ Of course today every rascal thinks he knows the answer, but he is deluding himself.”
>
> —Albert Einstein, 1951, quoted in Raymond W. Lam, *Seasonal Affective Disorder and Beyond*

The ultra-fast, ultra-intense laser, or UUL, with laser pulse durations of one femtosecond, could change cancer treatments, dentistry procedures, precision metal cutting, and joint implant surgeries.

University of Missouri, College of Engineering

shows that light and sound are distinct phenomena.) If the vacuum demonstration is not convincing, there is the photoelectric effect, wherein very bright beams of red light cannot eject electrons from a metal surface while the dimmest blue beams can. The arguments leading from the photoelectric effect experiment to textbook photons are subtle and, for me, have never completely excluded all competing views. For those who like more concrete, modern evidence, there is a recent report of a simple undergraduate beam-splitting experiment[5] with the primary theme being, “photons exist."

But beyond being convinced that photons exist, what is a photon? I have tended to envision a photon in a variety of ways: usually a transverse slinky pulse, occasionally a localized propagating pulse of crossed electric and magnetic fields, and rarely, an exotic version of a Schrödinger wave packet, modified somehow so that it has no mass, no charge, and boson statistics. But upon reading recently, “Thus, there is no quantity analogous to $|\psi|^2$ giving a probability density for finding a photon in space,”[6] I have decided to reconsider the question.

So, what is a photon like? What is a photon not like? What do you think? Send us your answers and analogies—feel free to exercise your poetic license—and we will publish the most interesting of them. In the meantime, next time you click that laser pointer, watch that DVD, or scan a loaf of bread, remember that 50 years ago the laser was invented, without any inkling of its everyday use.

Footnotes:

1 This article is a slight variation on a piece the author wrote for the Spring 2002 issue of *Radiations* magazine, the official publication of the Physics Honor Society. For more erudite commentary on light and some beautiful imagery, see also the modern and classical “Museum of Light” articles in that issue and in the Fall 2001 issue.

2 Charles Townes, *How the Laser Happened*, 1999, Oxford University Press. For a more recent perspective on the history of the ruby laser, see the article in the January 2010 issue of *Physics Today*, “Bell Labs and the Ruby Laser”.

3 While he should not be blamed for the cartoon mentioned above, I learned much from the treatment of the emergence of the photon idea in Arnold Arons’ classic, *Teaching Introductory Physics*.

4 Felicity Pors of the Neils Bohr Archives in Copenhagen wrote the following to me regarding this quote which I found repeated many times but never with a citation: “I do not know of any published work of Bohr’s with this quote, but on p. 9 of the *Bulletin of Atomic Scientists*, vol. XIX, no. 7, Sept 1963, there is a margin comment by Robert Oppenheimer in which he relates that … Bohr apologized for so much talk and time. ‘You see, he said, my great problem is never to speak more clearly than I think.’ It is not clear to me whether Oppenheimer is describing this quote first- or second-hand.”

5 “Photon quantum mechanics and beam splitters,” *American Journal of Physics*, 70 (3), March 2002, by C. H. Holbrow, E. Galvez, and M. E. Parks.

6 T. Newton and Eugene Wigner showed that photons do not have localized spatial representations in their 1949 *Reviews of Modern Physics* article (vol. 21, p. 400), but I got additional insight from *Optical Coherence and Quantum Optics* by L. Mandel and E. Wolf (Cambridge U.P., 1995, see section 12.11), and especially from “The calculated photon: Visualization of the quantum field,” *American Journal of Physics* 70(1), Jan 2002, by M. Legare and R. Oliveri, from which the quote above is actually taken.

Laser Outreach jumps to the Next Level

By Mike Lucibella, American Physical Society

In June 2009, the American Physical Society (APS) put out a call for “LaserFest on the Road” grant requests. APS offered grants of up to $10,000 to groups who wanted to sponsor laser-themed outreach events throughout the U.S. and internationally under the LaserFest on the Road banner. SPS chapters from across the country responded to the call. Here is what two of the funded chapters are doing with their LaserFest on the Road grants.

Angelo State University: Lasers Hit the Road

One of the awardees, the SPS chapter at Angelo State University in San Angelo, Texas, received a LaserFest grant to bring laser and optical physics to schools throughout rural west Texas. Calling themselves the Peer Pressure Team, or P²T for short, the team already puts on dozens of events each year, culminating in a week-long physics road trip.

Each year after spring finals, the team piles into a rented van and their advisor’s Chevy Suburban to tour across rural west Texas, performing free physics demo shows at schools. Each trip lasts an exhausting five days, with demonstrations at two or three schools each day.

“We’re hoping with the grant to incorporate the laser a lot more into the show,” said Logan Hancock, a senior in the school’s physics program and president of Angelo State University’s SPS chapter. “Our main goal is to show how life-changing the laser is.”

Sure to be one of the most popular additions to the show is their proposed CO_2 laser that can melt bricks and cinderblocks. The team is planning to use their funds to build the laser, which they will compare to green and red lasers. Mirrors, lenses, and fog machines will further show off how light can be reflected and refracted. The team will even hand out a take-home laser scavenger hunt, encouraging students to see where lasers are commonly used.

Credit: Peer Pressure Team

The 2009 Peer Pressure Team with Toni Sauncy (middle row, 2nd from left), SPS advisor for Angelo State University and president of SPS.

Credit: Peer Pressure Team

Students try on diffraction glasses during a 2009 show by the Peer Pressure Team.

The LaserFest on the Road additions will add these to an already healthy arsenal of demonstrations that P²T uses to show off basic principles of physics. As their team name implies, many of these demos center around air and water pressure, including compressing marshmallows with a vacuum pump and trying to pull apart two Magdeburg hemispheres.

The team formed in 2003 but was largely limited to the areas immediately around the school. Then during the World Year of Physics 2005, they got a boost from a Physics on the Road grant, enabling the first road trip. Since then the program has continued to bring physics shows to students ranging from kindergarten to high school across west Texas.

Despite their success, Hancock said that securing funds each year is always an issue. The last two years a retired faculty member generously donated the funds needed to keep the trips going. Getting funding from the university has proved more challenging, but Hancock said that the team is committed to bringing physics to schools.

“It’s fun,” said Hancock. “This program has been really active since before I was here.”

Pennsylvania State University: Lasers and the Arts

A LaserFest on the Road grant will give physics students in Pennsylvania a chance to show off their artistic side. The chapter’s planned event, “The Function and Beauty of Lasers”, will mix science with art in a contest exhibition featuring works themed around light and lasers.

“What we’re trying to do is bring together the science community and the nonscientific community,” said Jason Bartell, a junior in the school’s physics program and vice president of the chapter. “I hope that they see how science, art, and popular culture in general can be compatible.”

The contest exhibition will open in March in one of the big open public spaces in the school before moving to a gallery in the liberal arts building. Judges from the physics department will award the winner of the show a $300 cash prize. After the exhibition formally ends, the pieces will continue to be on display throughout the halls of the campus.

Bartell said that the contest is open to

Photos by Matt Noll

Students wander through the 2009 Universal Art Competition at Penn State.

anyone interested in competing, artist, physicist, or otherwise.

The exhibition will not be all style and no substance. Each piece will have a companion explanation describing the connection between science and the artwork. In addition, the chapter will create a table of demonstrations and information about how lasers work. They plan to include a range of working lasers showing off some of the unexpected places lasers can be found.

"Everybody knows about laser pointers and laser cutting, but not as many know about things like laser cooling," Bartell said.

The chapter hopes to be able use the demonstrations in future outreach opportunities for a range of education levels. "We're hoping to get a demonstration table that is flexible enough that it can be tuned to higher and lower levels," Bartell said. "Once we get together this well-organized demonstration for LaserFest, we will be able to use it in the future."

The chapter already has some experience blending science and the arts. Last year, to coincide with the International Year of Astronomy, the chapter hosted the Universal Art Competition. The exhibition featured twelve artists with astronomy-themed pieces. Bartell said that he and his chapter hope that this year will be just as successful.

"We've been very fortunate to have a good body of officers these last couple of years," Bartell said. "The members of SPS are willing to put in the time and effort."

Randolph College Takes on Pinewood Derby

By Peter Sheldon, SPS Advisor
Randolph College

A long-time tradition for Cub Scout packs across the country is the Pinewood Derby: scouts make small-scale cars and race them along a regulation track. This fall, the Randolph College SPS chapter spent half a Saturday working with a Lynchburg, VA, Cub Scout pack, learning about the physics of Pinewood Derby car racing. Six Randolph College students and I talked with the pack about the concepts of gravity, friction, inertia, and stability, and did demonstrations of these phenomena. We also discussed the scientific method with the intention of then scientifically testing different aspects of the cars. The Cub Scouts will each receive their science belt loop for this activity.

After group discussion and demonstrations, the Cub Scouts broke into four groups, with one or two SPS student leaders per group, and each group tested a different aspect of making Pinewood Derby cars using the scientific method. Two groups tested shape, one group tested weight, and one group tested different ways of reducing friction. Each group made cars, recorded times along the track, made changes, and tested them again.

"This is a great opportunity for our Cub Scouts to learn the physics behind Pinewood Derby car racing," said Michael Glover, one of Pack 48's leaders. "The race is one of the highlights of the year for our scouts, and this workshop will help them learn the science behind it."

The Randolph SPS chapter is very active in the community, working with schools, the local children's museum, and running an annual Science Day on campus. We are well-enough known that we get requests to help out with certain local groups, and that is what happened with the Cub Scouts this year. We hope to make it a tradition. The Cub Scout pack loved the event. At one point, one pack member spontaneously shouted out loud, "I love science!" I am certain that any Cub Scout pack across the country would welcome a similar opportunity to work with SPS groups.

We believe that bringing science to the public is our most important job, and getting the word out about science and what we do is important. To that end, for most of our events, someone in the college relations office on campus calls all the local newspapers and radio stations. It can be tough to get them to come out, but if they can find a different angle, they might come. In this case, they focused on the Cub Scouts rather than SPS, which was fine with us. The news video of the event can be seen at the Randolph College SPS website: http://physics.randolphcollege.edu/sps.

If you would like to know more about this event, please contact Randolph College SPS advisor Peter Sheldon, psheldon@randolphcollege.edu.

Cub Scouts eagerly anticipate a car's arrival at the finish line.

Randolph College SPS member Wenjun Xu helps scouts figure out how to make a faster car.

Photos by Dave Blount (College Relations, Randolph College)

The Accessible Universe

By Noreen Grice, President,
You Can Do Astronomy LLC

SPS remains committed to promoting discussions of diversity in physics with its Future Faces of Physics campaign. This article features a different kind of outreach—one that I first was exposed to as an observer at an astronomy camp for blind students at Yerkes Observatory in Williams Bay, WI. "Astronomy for blind students!?" was my reaction when I first heard about the camp, but Noreen and others like her have taught me that science really is for all, and with some creativity, can be made accessible to all. For resources and suggestions on how to do this, please visit the Future Faces of Physics page on the SPS website, http://www.spsnational.org/programs/futurefaces/ .

–Kendra Rand

Noreen Grice, president of a design and consulting company that focuses on making astronomy and space science accessible to people with disabilities.

Photo courtesy of Noreen Grice

Twenty-four years ago, I was an astronomy student at Boston University entering my senior year. I had just started working part time in the Charles Hayden Planetarium at the Boston Museum of Science when a group of blind students came to one of my shows. The manager told me to help the students to their seats. Back then I presented prerecorded shows, and I recall standing in the console, welcoming everyone to the Planetarium, and then pressing a button on the Apple IIE computer to start the show.

> *I have met amazing people, including several students who aspire to be the first blind astronauts in space and on Mars!*

After the show, I asked the students how they liked the Planetarium program. They told me "it stunk" and walked away. That was quite an eye-opener for me.

It had never occurred to me that the Planetarium was not accessible, but these students made me realize that the shows were not very descriptive and were very visually oriented. Even though I didn't know how to do it, I was determined to make astronomy accessible to people who are blind.

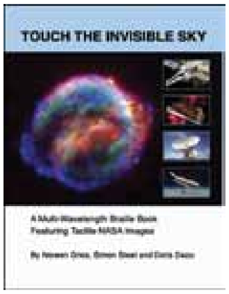
I began making tactile diagrams by hand-etching illustrations on plastic sheets. I learned a lot from blind people reviewing my first tactile images, like never put the title of the diagram at the bottom of the page because people read tactually from top to bottom. Also, never use single dots as symbols without including a tactile key code because a single dot is the letter "A" in Braille….otherwise you have alphabet soup for pictures!

It took a while for me to get the hang of it, but I began making tactile pictures to go along with all of the planetarium shows. Then I got a Braille embosser to mass produce my pictures. Later, I switched to a swell form machine. [Swell form machines make tactile images based on black and white contrast. A user copies a printed image onto special paper and runs it through a swell form machine, which uses heat to make the black areas "swell".] And while I was learning how to make good tactile images, I began writing a manuscript that would be my first book, *Touch the Stars*.

I now have five tactile books under my belt: *Touch the Stars* (1990, now in its 4th edition – 2002), *Touch the Universe: A NASA Braille Book of Astronomy* (2002), *Touch the Sun: A NASA Braille Book* (2005), *The Little Moon Phase Book* (2005), and *Touch the Invisible Sky: A NASA Braille Book Featuring Multi-Wavelength Tactile Images*, coauthored with Simon Steel and Doris Daou (2007).

In addition to writing accessible books, I have worked with the National Federation of the Blind in their youth programs. Through my consulting company, I have also presented teacher workshops and designed tactile images

(Continued on page 8)



For more information on *Touch the Invisible Universe* and Noreen's other books, visit http://www.youcandoastronomy.com/.

for exhibits. I have met amazing people, including several students who aspire to be the first blind astronauts in space and on Mars!

The astronomy-related resources I develop for blind and visually impaired students are also designed for use with sighted students and those with different learning styles. My goal is to bring people of all abilities together as equal peers, using the same materials.

Please check out my website at www.youcandoastronomy.com and my page on Facebook!

If your chapter is interested in obtaining a free copy of Touch the Invisible Sky, *send an email to sps@aip.org and let us know how you plan to use the book in your outreach efforts. Please use the subject line "Touch the Invisible Universe." Copies are limited, so act now!*

Electrifying an Audience

By Hayley Manning, SPS President,
The University of Texas at Austin (UT)

Creators of the original Singing Tesla Coils, the crew of ArcAttack used their high-tech wizardry to generate a truly "electrifying" performance at the University of Texas at Austin this November. Two custom-designed, hand-built Tesla coils shot electrical arcs into the air that reached up to 12 feet long. The band used the coils as musical instruments, emitting a unique sound reminiscent of the early days of the synthesizer.

Guests of the concert ranged from physics undergraduate and graduate students who had been talking about the coming event for weeks, to local high school students brought to the show by one of the university's physics professors. Even students intrigued by the fliers or who just saw lightning and were overcome with curiosity enjoyed an opportunity to see something they had never experienced before. At peak, about 1,000 people stood on UT's main mall and watched as ArcAttack lit up the stage right in front of the campus's signature tower.

Not only was it entertaining to see the electricity arc to any metal within its reach, but the band itself was composed of both typical instruments and some very different and creative ones. Two members of the band played electric guitars, while another member controlled both the Tesla coils and robotic drummers from his keyboard. That's right, robotic drummers. The band used not one but two systems of drums that could be remotely controlled from a computer or keyboard, with previously programmed beats as well as spontaneous ones utilized in the show. Add this to the different pitches produced by the coils and you have a rich, full sound capable of getting the crowd's blood pumping and engaging them in this one of a kind performance.

ArcAttack's six members entertained the crowd with a set of songs ranging from the Mario Bros. theme song to the Imperial March, and even adapted more mainstream songs from artists such as DJ Shadow to entertain all. Music wasn't the only attraction. The crowd was thrilled when one member came out in a full body suit of chain mail and allowed the bolts of electricity to arc to himself. ArcAttack also invited some members of the crowd on stage to take a turn in a Faraday cage the group had specifically built for these shows. It was quite an experience to stand in a metal mesh cage with electricity arcing to a point mere inches from your face, all the while surrounded by the smell of ozone and sound of deafening rock music!

ArcAttack demonstrates the Faraday suit.

Photo courtesy of ArcAttack

This event was cohosted by the UT chapter of SPS, and also by the UT Physics Department. The department's Associate Chairman for Undergraduate Affairs, Dr. Sacha Kopp, has recently been working with the department on an initiative to pick apart and tear down the stereotypes surrounding physics as a course of study, asking students to consider that physics is valuable because it answers the "why" questions that we come across in everyday life. To show the fun side of the subject, they even printed T-shirts that display the famous "Physics is like sex" quote by Richard Feynman and gave them away free to all UT physics undergrads.

This concert was an attempt to reach out to the general student population and show them that not only can physics be aesthetically and musically pleasing, but that the questions raised when observing everyday physical phenomena are important and the answers should always be pursued. The UT chapter of SPS was glad to help promote this initiative and to provide a good time for its members.

There is nothing more encouraging than seeing an entire department share the joys of physics with the community and have a great time while doing it. Now that they have successfully pulled off their first event of this scale, the UT SPS chapter plans to continue such a great tradition of outreach on their campus and in their community. It is often difficult, but the need for physics student groups to break out of the mold and find ways to help inspire their communities is more pressing now than ever before.

"And the Spooky Science Award goes to..."

The SPS National Office knows that SPS chapters like to have a good time, so we sent out a call for your spookiest photos from fall 2009. We received a frighteningly large number of scary entries and turned to the SPS National Council for help determining the top five, shown below. Each of these chapters received an official SPS Spooky Science kit. To see the other chilling entries, visit the SPS website, www.spsnational.org.

Spooky

Photo by Zach Boerner

Monopole, Please!
The Colorado School of Mines tries desperately to prove the existence of the magnetic monopole.

Photo courtesy of Green River Community College

Pumpkin Graveyard
There isn't much left of a pumpkin after being launched some 250 feet by students from Green River Community College.

Spookier

Photo by Annie Wise

Singing Flame
Rhodes College SPS students entertain the crowd with fire before their legendary pumpkin drop.

Photo by Aaron Lemmer

Vanquished! Zombies can't match the University of Wisconsin-River Falls superpowered application of a bed of nails.

Spookiest

Photo by Jordan Keough

Phun with Phluorescence
This scene from the Idaho State University haunted lab will scare the light right out of you.

History of Big Bang Cosmology, Part 8: Initial Conditions and Inflation

Dwight E. Neuenschwander

As you know, the main bodies of evidence affirming the big bang include the dark sky, the Hubble expansion, element abundances, and cosmic microwave background radiation (CMBR), including its microKelvin temperature fluctuations. In Parts 1–7 of this series we briefly introduced these topics.[1–7]

Recall that the universe expands according to Hubble's law. At large scales the relative velocity v between a pair of galaxies is proportional to the distance D between them, $v = HD$, with $H_{\text{now}} = 70.1 \pm 1.3$ (km/s)/Mpc, although it varies with time.[8] In a familiar metaphor, the velocities in Hubble's law are not like *walking across* a rubber sheet, but instead are analogous to *being carried* on a *stretching* rubber sheet. Such "carried-along" motion is called "comoving". If H were constant across cosmic history, then the time elapsed since any pair of points in the universe separated (the time since the big bang itself) would be $\Delta t = v/D = 1/H_{\text{now}} \approx 14$ Gyr. At any epoch, $1/H$ defines the Hubble time, and c/H the Hubble distance that light travels during this time, offering a size scale for the observable universe.

We saw how the existence of the Hubble expansion implied a hot, dense early state, a gas of elementary particles, the "ylem." As the universe expanded and adiabatically cooled, nuclei of light elements precipitated out of the ylem. To match the predicted abundances to observations required a billion-to-one ratio of photons to baryons, which offered a crucial prediction: after the gas of nuclei, electrons, and photons cooled enough to allow matter to become electrically neutral (matter–photon decoupling, about 380,000 years after the beginning), all those photons must still exist to be observable today, an afterglow of the big bang. By now this remnant photon gas would have cooled to a few degrees above absolute zero. The detection of this CMBR at 2.7 K by the mid-1960s ruled out the competing steady state cosmology and affirmed the big bang.

Going into the 1970s, the standard model big bang paradigm faced several new puzzles. One challenge came from the observation that for the big bang to be consistent with theories of galaxy formation, temperature fluctuations in the CMBR *must* exist at the microKelvin level of precision. These fluctuations were measured in the early 1990s, as told in Part 7. Another set of challenges arose in the seeming excess of necessary initial conditions. Both sets of challenges—initial conditions and germinating the seeds of structure formation—found a common solution in a scenario called inflation, when the expansion suddenly and dramatically accelerated. Here in Part 8, and later in Part 9, we examine two epochs of an accelerating universe. The first epoch, discussed here, was incredibly violent and brief, occurred *very* early in cosmic history, and established the seeds of galaxy formation. The second epoch, less violent but longer-lasting than the first, seems to be occurring now and to be connected with the enigmatic dark energy. The second acceleration is the focus of Part 9.

The Unperturbed Standard Model

At the milliKelvin level of precision, the CMBR temperature ($T = 2.726 \pm 0.010$ K[9]) is amazingly uniform across the sky, affirming the cosmological model based on the Friedmann–Lemaître–Robertson–Walker metric that assumes large-scale isotropy and homogeneity. This model allows only a time-dependent rescaling of space. In spherical coordinates and allowing for non-Euclidean geometry, the invariant proper time interval $d\tau$ between events is parameterized as

$$c^2\, d\tau^2 = c^2\, dt^2 - R^2[(1-k\chi^2)^{-1}\, d\chi^2 + \chi^2 d\omega^2] \qquad (1)$$

where t denotes the time since the big bang as measured by the wristwatch strapped to any comoving observer, $d\omega^2 \equiv d\theta^2 + \sin^2\theta\, d\varphi^2$, and c = speed of light. If space is flat (i.e., Euclidean), then $k = 0$; if it is spherical (hyperbolic), then $k = +1(-1)$. $R = R(t)$ is the length-dimensioned "cosmic scale factor" and χ a dimensionless coordinate-grid label that identifies spherical surfaces centered on the origin. $R(t_2)/R(t_1)$ gives the factor by which the universe expands between two times. The distance between two spherical shells is $\int R(1-k\chi^2)^{-1/2}\, d\chi$.

When put into Einstein's field equations with cosmological constant Λ, Eq. (1) yields the Friedmann equation for the evolution of $R(t)$:

$$H^2 + k/R^2 = \kappa\rho + \Lambda/3 \qquad (2)$$

where $\kappa \equiv 8\pi G/3c^2$, G is Newton's gravitation constant, and ρ is the energy density. Hubble's parameter is defined as

$$H = c\dot{R}/R \qquad (3)$$

where $\dot{}$ denotes the time derivative $d/d(ct)$.

Einstein's field equations along with energy conservation give a second relation for R,

$$\ddot{R} = -\tfrac{1}{2}\kappa(\rho + 3P)R + \tfrac{1}{3}\Lambda R \qquad (4)$$

where P denotes the pressure. The energy density and partial pressure of constituent i are related by an equation of state,

$$P_i = w_i\, \rho_i \qquad (5)$$

where i denotes matter, radiation, or anything else we might encounter. For nonrelativistic matter $w_m = 0$, and $w_r = -\tfrac{1}{3}$ for radiation. We can treat Λ as a density by introducing $\rho_\Lambda = \Lambda/3\kappa \geq 0$ with $w_\Lambda = -1$. Λ is too small to dominate physics in the early universe; we know Λ to be small from its negligible influence on classic general relativity effects such as the precession of perihelion.

To see which constituents dominate in different eras, write the first law of thermodynamics for an adiabatic expansion of the universe, noting that volume ~ R^3:

$$d(\rho R^3) = -P\,dR^3. \qquad (6)$$

Insert the equation of state to find $\rho_i \sim R^{-3(1+w_i)}$, which in Eq. (2) (neglecting k) leads to $R \sim t^{1/2}$ for radiation, $R \sim t^{2/3}$ for matter, and $R \sim e^{t\lambda}$ for Λ, where $\lambda \equiv \sqrt{(\Lambda/3)}$. Because $T \sim 1/R$ (with $T^2 t \approx 2\times10^{20}$ K^2 s in the early universe), radiation dominates early on, matter dominates after matter–photon decoupling, and Λ dominates an old universe.

To compare the model to reality we must express these relations in terms of observables. When we ignore Λ, Eq. (2) suggests a critical energy density for which $k = 0$: $\rho_{cr} \equiv H^2/\kappa$. Define $\Omega \equiv \rho/\rho_{cr}$, the ratio of actual to critical energy density, and do likewise for each constituent species, $\Omega_i = \rho_i/\rho_{cr}$. Although it is not a density, disguise the curvature term as a curvature density $\Omega_k \equiv k/R^2H$. These steps allow Eq. (2) to be elegantly written as

$$1 = \Omega_m + \Omega_r + \Omega_\Lambda + \Omega_k \equiv \Omega + \Omega_k . \quad (7)$$

Notice that $\Omega = 1$ in a flat universe, $\Omega < 1$ in an open universe, and $\Omega > 1$ in a closed universe.

If only matter and radiation filled the universe, then the expansion would continuously decelerate. We are thus motivated to define a "deceleration parameter $q \equiv -\ddot{R}/RH^2$, so Eq. (4) can be neatly written

$$q = \tfrac{1}{2}\Omega_m + \Omega_r - \Omega_\Lambda . \quad (8)$$

The evolution of the densities in Eqs. (7) and (8) may be expressed in terms of their present values rescaled by functions of redshift. The fractional change in wavelength between emitter and receiver defines the redshift,

$$z \equiv (\lambda_{rec} - \lambda_{emit})/\lambda_{emit}. \quad (9)$$

The stretching of space follows the same pattern, $R_{now}/R_{then} = 1+z$. Thus, Ω_r (for instance) as a function of redshift can be written $\Omega_r(z) = \Omega_{r,now} H_{now}{}^2 (1+z)^{-4}$, because $\rho_r \sim T^4$ by Stefan's law. Thereby can the present values of H, q, Ω, and the Ω_i observed today be related to specific models of the early universe's composition; the finite speed of light means that when looking into deep space we receive signals from the past. A Taylor series expansion in δ of $R(t) = R(t_{now} - \delta)$, along with Eqs. (2)–(4), allow us to write, for modest z, the time–redshift correlation

$$\delta = z/H_{now} - (B/H_{now})[\,z/H_{now} - (B/H_{now})\delta^2] + \ldots \quad (10)$$

where $\delta \equiv t - t_{now}$, and $B \equiv (H_{now})^2\,(1 + \tfrac{1}{2}\,q_{now})$. For instance, when matter and radiation decoupled almost 14 Gyr ago, the photon temperature was 3000 K. We detect the CMBR today at about 3 K, which puts the last photon–matter scattering at $z \sim 1000$.

The parts-per-thousand uniformity measured in the CMBR gave crucial affirmation to the unperturbed big bang model. But this success, like all successes, allowed other interesting problems to surface.

Horizon, Flatness, and Structure Problems

In 1981, Alan Guth and Paul Steinhardt wrote,

> *In the past few years certain flaws in the standard big-bang theory of cosmology have led to the development of a new model of the very early history of the universe. The model, known as the inflationary universe, agrees precisely with the generally accepted description of the observed universe for all times after the first 10^{-30} second. For this first fraction of a second, however, the story is dramatically different....*
>
> *...When the standard big-bang model is extended to these earlier times, various problems arise. First, it becomes clear that the model requires a number of stringent, unexplained assumptions about the initial conditions of the universe....*
>
> *The inflationary universe was invented to overcome these problems . [It has] a very attractive feature: from almost any initial conditions the universe evolves to precisely the state that had to be assumed as the initial one in the standard model....*[10]

Let us consider some of those problems. With ourselves located at the origin $\chi = 0$, consider the propagation of a ray of light emitted at time T by a comoving source. Let the ray travel radially to us where we receive it at time t. Because $d\tau = 0$ for light, the χ-coordinate of the emission event is, by Eq. (1),

$$\chi_{emm}(t,T) = \int_T^t dt'/R(t'). \quad (11)$$

If χ_{emm} diverges as $T \to 0$, that is good because it means that our "view" of the past universe has no limit; we can in principle receive signals from events arbitrarily close to the big bang itself. But if χ_{emm} is finite as $T \to 0$, then $\chi_{emm}(t,T)$ can never exceed the finite value $\chi_{emm}(t,0)$.[12] Our deep-space view of the past universe gets cut off by this so-called horizon.

The problem manifests itself when we consider that other observers elsewhere in the universe, who place themselves at the origins of *their* respective coordinate systems, would find the same result. We and they would be able to see *some* of each other's sky, but not *all* of it, yet we both measure the *same* CMBR temperature for our *entire* skies. How can two skies have the same temperature but be causally disconnected? A uniform CMBR temperature should preferably emerge as a consequence of the model, and not have to be postulated as an initial condition. This is the "horizon problem." From Eq. (11) the horizon problem arises if $R \sim t^n$ where $n < 1$, i.e., if $\ddot{R} < 0$ unrelentingly throughout cosmic history.

A related problem asks: Why is the universe so flat? The observed value of Ω is very nearly (if not exactly) equal to 1. But if $\Omega = 1+\varepsilon$ where $\varepsilon \neq 0$, then $|\varepsilon|$ grows rapidly with time. For $|\varepsilon|$ to be close to zero today, when $t \sim 10^{18}$ s, seems, again, to require fine-tuning the initial conditions [11].

If an epoch existed in cosmic history when $\ddot{R} > 0$, a loophole opens through these problems. For instance, if R had a sudden burst of enormous growth, then the k/R^2 term in Eq. (2) would quickly become indistinguishable from zero, the universe *driven* to flatness independent of initial conditions.

Only one tiny problem remains: find a mechanism within nature that makes $\ddot{R} > 0$. Clearly a small positive Λ would produce an accelerating universe later in cosmic history, when the energy densities of radiation and matter have thinned out, leaving ρ_Λ to dominate the energy budget. But that does not solve the horizon problem in the early universe. Not only is Λ too small, but it also *repels* (negative pressure!) so matter won't clump to it—not an effective path to galaxy formation! That bring us to the problem of structure formation.

Although we can model the unperturbed universe with a smoothed-out energy density, the real universe shows a hierarchy of structures. Galaxies, clusters of galaxies, and superclusters separated by vast voids exist. The approximately smooth CMBR can be reconciled with lumpy matter by postulating fluctuations in an otherwise smooth primordial density, $\rho = \rho_o (1 + \delta)$, where $|\delta| << 1$ (sub-o denotes "unperturbed background"). Gravity would attract matter into regions where $\delta > 0$, draining matter from regions where $\delta < 0$, offering positive feedback to the fluctuations.

Before photon decoupling liberates the CMBR, what could be efficiently attracted into the overdense regions while baryonic matter was continually kicked around by scattering with photons? Here the necessity of cold dark matter (CDM) seems compelling, even though nobody yet knows the identity of the CDM particles themselves! They must be uncharged so they are not dispersed by all those photons. They must be cold (nonrelativistic) and heavy, so baryonic matter could be attracted to them as early as possible. The CDM must be non-baryonic, because the nucleosynthesis calculations place tight restrictions on baryon abundances, and they are already accounted for.

The inhomogeneities, once formed, must leave their imprint on the CMBR. Before photon decoupling, as matter collects in an overdense region, the photons there get squeezed. Their pressure and temperature shoot above ambient conditions. The overpressure pushes back on the surroundings like a spring, opposing the compression. With a period determined by the size of the region being compressed, these compressions and rebounds drive oscillations—sound waves forming a harmonic series of standing wave modes—until decoupling occurs. As adiabatic compressions and rarefactions, these perturbations must show up in the CMBR temperature field. A glimpse into this story was discussed in Part 7. As described there, temperature fluctuations in the sound waves that existed reveal themselves as peaks and valleys in a graph that plots the CMBR power spectrum against angular resolution on the sky.

When the density fluctuations seeding cosmic structure were first studied, identifying a mechanism to produce them initially, without having to postulate them as yet another set of initial conditions, was a worthy puzzle. James Peebles and J.T. Yu closed a 1970 paper worrying about this point: "It is well to bear in mind that this calculation of the initial density fluctuations are invoked in an *ad hoc* manner because we do not have a believable theory of how they may have originated...."[13]

Happily, quantum mechanics requires fluctuations— however microscopic—in any observable. If you accept quantum physics, you are stuck with fluctuations; they do not have to be postulated. Admittedly, it is a bold leap to suggest that microscopic quantum fluctuations triggered structure formation across the entire universe! To understand the evolution of these fluctuations, we must go back deep into the very early universe, to about $t \sim 10^{-35}$ s. The horizon, flatness, and structure problems share a common solution in the short but violent epoch of accelerating expansion known as inflation. The first step toward inflation was taken by Alan Guth in 1981. He began, "The standard model of hot big-bang cosmology relies on the assumption of initial conditions which are very puzzling in two ways... The purpose of this paper is to suggest a modified scenario which avoids both of these puzzles."[14]

Inflation

Suppose a spatially uniform scalar field $\Phi(t)$ permeates the entire universe.[15] Treated as a relativistic fluid, a scalar field's energy density and pressure are

$$\rho_\Phi = \tfrac{1}{2}\dot{\Phi}^2 + V(\Phi) \qquad (12)$$

and

$$P_\Phi = \tfrac{1}{2}\dot{\Phi}^2 - V(\Phi) \qquad (13)$$

where $V(\Phi)$ denotes a model-dependent potential. The equation of state for such a field would be

$$w_\Phi = \frac{\tfrac{1}{2}\dot{\Phi}^2 - V(\Phi)}{\tfrac{1}{2}\dot{\Phi}^2 + V(\Phi)} \qquad (14)$$

Since the field Φ could vary with time, so could its equation of state. In such a context the field Φ is sometimes whimsically called "quintessence". Notice that if its kinetic energy term grows negligible, then quintessence becomes an effective cosmological constant as $w_\Phi \to -1$. Be that as it may, most models use a potential that looks like Fig. 1.

When the scalar field energy density dominates over all other constituents, Eqs. (2) and (4) become

$$H^2 = \kappa\,[\,\tfrac{1}{2}\dot{\Phi}^2 + V(\Phi)] \qquad (15)$$

$$\ddot{R} = -\kappa R\,[\,\dot{\Phi}^2 - V(\Phi)]. \qquad (16)$$

Eliminate $\ddot{R}$ between Eqs. (15) and (16) to obtain

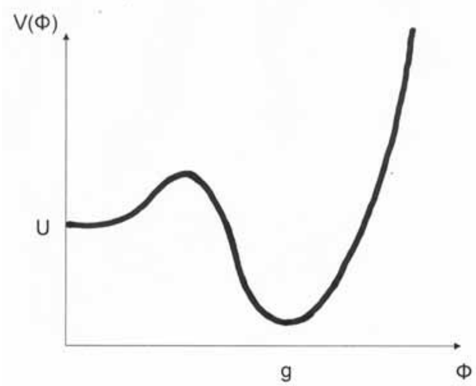


Fig. 1. Schematic potential $\boldsymbol{V}(\Phi)$ for the scalar field Φ. Note that when $\Phi = 0$ then $\boldsymbol{V}(0) = \boldsymbol{U}$, the false vacuum, and that $\boldsymbol{V}$ = min**.** when $\Phi = \boldsymbol{g}$.

$$\ddot{\Phi} + 3H\dot{\Phi} = -dV/d\Phi \qquad (17)$$

which resembles $F = ma$ for a mass sliding down a curve with gravity and friction: $-dV/dx - b\dot{x} = m\ddot{x}$. If we want the scalar field to produce inflation we need $\ddot{R} > 0$, which requires $\dot{\Phi}^2 < V(\Phi)$. Let us push this to an extreme. Suppose that $\dot{\Phi}^2 << V(\Phi)$, or equivalently, $\ddot{\Phi} << \tfrac{1}{2}\, dV/d\Phi$. From the mechanical analogy this assumption bears the name slow roll approximation, made possible if the peak of $V(\Phi)$ is broad and almost flat. Then Eqs. (15) and (17) become

$$H^2 \approx \kappa V \qquad (18)$$

and

$$3H\dot{\Phi} \approx -dV/d\Phi. \qquad (19)$$

During the slow roll (when $V \approx$ const. $\equiv U$), Eq. (18) integrates to $R(t) \sim \exp[t\sqrt{(\kappa U)}]$. This exponential inflation in R, and exponential decline in temperature ($T \sim 1/R$), continues until V drops into its deep well, whereby Eq. (17) oscillations at about $\Phi = g$ damp out because of the friction until Φ reaches its minimum, $V_{\min} \geq 0$. Φ sliding down into the well corresponds to the decay of the scalar field's energy into familiar particles, releasing latent energy $\rho_\Phi R^3 \sim UR^3$, which reheats the universe. When does this happen, and how long does it take?

Inflation models propose temperature-dependent coefficients in the potential of the form

$$V(\Phi, T) = a(T)\Phi^2 + b(T)\Phi^4. \qquad (20)$$

The parameters in a and b may be chosen such that a critical temperature T_c exists (see Fig. 2). For $T > T_c$ the stable state resides at $\Phi = 0$ where $V = U$. When $T \sim T_c$ the "slow roll" begins, and for $T < T_c$ the potential well becomes available, where the

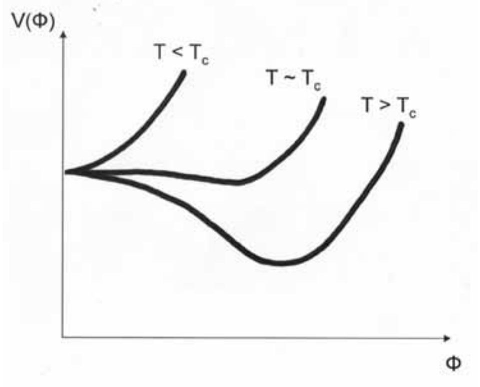


Fig. 2. Temperature-dependent potentials.

stable state resides at $\Phi = g$, with $V(g) = V_{min}$. When $\Phi = g$ the interactions of the Φ field's quanta with other particle species endow the latter with their masses.[16] To give quarks and leptons their masses, the grand unified theories[17] need $T_c \sim 10^{27}$ K, which occurred at around 10^{-35} s. Using these numbers as an illustration, and taking $U \sim T_c^{\,4}$ (all particles are ultra-relativistic, so $\rho \sim T^4$ as in Stefan's law), inflation proceeds with doubling time $\sim (\ln 2)/\sqrt{(\kappa U)} \sim 10^{-34}$ s. Suppose (in a ridiculously extreme illustration) that inflation continues until $T \sim 1$ K. From Eq. (2) and with $R \sim 1/T$, the elapsed time is $\Delta t \sim (\ln 10^{27})/\sqrt{(\kappa U)} \sim 10^{-32}$ s, a hundred doubling times. So during this "supercooling" era the scale factor R increases by $\sim 2^{100} \approx 10^{30}$; a region 10^{-15} m wide inflates to 10^{+15} m, from the size of a proton to 0.1 light-years![18] Regions of quantum fluctuations were exponentially stretched along with space itself, and CDM falling into these regions carried structure formation forward. The rapid expansion also drives the curvature to zero, and because the preinflation microscopic regions were already in thermal equilibrium, the uniform temperature of the sky follows.

All this has been completed when the universe has aged to about $t = 10^{-35}$ s + 10^{-32} s $\approx 10^{-32}$ s. At the end of the "slow" roll, the phase transition occurs, releasing latent energy in an orgy of particle–antiparticle production, reheating the universe to $\sim 10^{27}$ K. After inflation ceases at $t \sim 10^{-32}$ s, the universe expands "normally" as the Friedmann equation describes. Coming out of inflation, the universe enters the radiation-dominated era; three minutes later helium nuclei form, then atoms become neutral at $t \sim 380{,}000$ years as the universe enters the matter-dominated era.

The evidence for these perturbations in the CMBR was on hand by early 1993, in data from the COBE-DMR team, as told in Part 7. Their efforts have since been beautifully extended by other groups working hard to fill in the CMBR power spectrum. These groups include those using the DASI interferometer in Antarctica,[19] the balloon-borne Boomerang [20] and MAXIMA[21] instruments, and the Wilkerson Microwave Anisotropy Probe (WMAP) spacecraft. The shapes, sizes, and placements of the peaks in the power spectrum can be predicted for various models, with their diverse parameters for the early universe's ingredients and properties. These predictions can be compared to measured values extracted from the real spectrum, including the present values of H, q, Ω, Ω_i, Λ, and others. Data from experiments such as DASI, Boomerang, MAXIMA, and WMAP have so far affirmed the "ΛCDM" paradigm, an inflationary, flat universe with CDM and positive Λ (or its equivalent). For instance, WMAP data folded in with other groups' data reports $\Omega = 1.0052 \pm 0.0064$ and $\Omega_\Lambda = 0.721 \pm 0.015$.[22, 23] The power spectrum offers a precision tool for studying the early universe.

One of the most astonishing recent discoveries suggests the expansion is again undergoing positive acceleration, despite matter's gravitational role of trying to throw on the brakes. We seem to be in another inflationary era, milder but longer-lasting than the spectacularly violent one at $t \sim 10^{-32}$ s. Coupled to the accelerating universe is the observation that Ω_Λ now dominates the energy budget ($\Omega_\Lambda \approx 0.72$), raising the astonishing notion that the energy density of empty space—the notorious dark energy–now controls cosmic dynamics! We will discuss dark energy and the accelerating universe in our next and final installment in this series on the history of big bang cosmology.

Acknowledgments

Thanks to Thomas Olsen for many useful suggestions.

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[8] The value of H is usually presented in terms of the astronomer distance unit, the "parsec" (pc): 1 pc ≈ 3.26 light-years, the distance from which the radius of Earth's orbit (1 AU) subtends one arc-second.

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[11] Grand-unified theories of particle physics also predict magnetic monopoles in greater abundances than are observed (none so far). Inflation pushes the boundaries between "domain walls" that lead to monopole production beyond the observable scale.

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The XXIV International Conference of Physics Students (ICPS)

By Josh Fuchs, Rhodes College
Split, Croatia, August 10–18, 2009
To read the entire report, visit http://www.spsnational.org/programs/awards/2009/fuchs_icps.pdf.

ICPS is the annual conference of the International Association of Physics Students. This year's conference was held in Split, Croatia. It was organized entirely by the student section of the Croatian Physical Society. ICPS truly is a conference for physics students run by physics students. There were roughly 480 participants representing 32 different countries. There were 99 student lectures, along with 55 poster presentations and 7 guest lectures. As co-recipients of the Society of Physics Students Outstanding Student Award for Undergraduate Research, Gabe Caceres from Augustana College and I represented SPS and the United States at the conference.

Tuesday, August 11th

Today was the first full day of ICPS. It began with the opening ceremony where we heard welcoming remarks from the president of the Croatian Physical Society, a representative from the Croatian Ministry of Science, Education and Sports, a professor at the University of Split (the venue for the scientific program of ICPS), and the president of the local physics society in Split. All of them were very happy that ICPS was being held in Croatia and talked about the history and current status of physics in Croatia.

As happens at any great physics conference, next we were treated to three demos. The first demo modeled the Croatian Adriatic winds, called Bura winds. It was done by sublimating dry ice and directing it down an enclosed incline, simulating a hydraulic jump. The next demo was the Ruben tube with sound waves and fire, verifying that physicists all over the world enjoy fire. The last demo used an electromagnet to levitate a plate. After a short break we heard a guest lecture by Dr. Silvia Tomić, a physicist at the Institute of Physics in Zagreb, Croatia. She talked about her research in solid-state physics with biopolymers and DNA.


Photo by Josh Fuchs

Josh wading in the Adriatic Sea while in the city of Supetar.

At lunch I met Ole from Germany. I told him about the research I would be presenting and found out that he did a microgravity flight with the European Space Agency (ESA). We swapped stories about our experiences and compared how the ESA and NASA conduct their microgravity programs. I was very excited to meet someone with experiences similar to my own! After lunch was the first section of student lectures. I attended sessions on topics ranging from quantum computing to particle physics to astrophysics. One aspect of ICPS I really enjoyed was the variety of student lecture topics. I loved having so many sub-fields of physics presented.

There was another guest lecture that evening by Dr. Stuart Cunningham of the National Oceanography Centre in the United Kingdom. He talked about large-scale circulation in the Atlantic Ocean and how his research shows evidence of global warming.

That evening was the Croatian party. We were shown a Croatian tourism video and treated to three songs by a local a cappella group. After that, different types of Croatian food were set out on the tables for everyone to taste. I tried a few different things but did not go back for seconds. I went to bed exhausted from the first day of ICPS but loved every moment.

Wednesday the 12th

The student lectures in the morning were interesting and just as diverse as those of the day before. The guest lecture on this day was delivered by Dr. Hendrik Ferdinande from Ghent University in Belgium. He talked about how the Bologna Reforms in 1999 tried to standardize higher education across Europe and the different things that have happened to physics in Europe as a result.

That afternoon we had some free time. I went with four of my friends, Leon (Croatia), Robin (UK), Pao (Thailand and the UK), and Issam (Morocco), to walk around Split. We realized that our group consisted of people from four different continents, which I thought was pretty cool.

The National Party, where participants prepare food and drinks from their home country, was held Wednesday night. The National Party turned out to be my favorite party. Growing up in Texas, I felt obligated to bring some Texas drink coasters and wear my Texas flag t-shirt. I enjoyed walking around to different tables trying as much food as I could. Later in the evening, each country was given the opportunity to make a presentation of some sort. Gabe and I decided to pass and listened as most people sang songs from their countries.

Thursday the 13th

This was the day of my presentation. I got up early so I could look it over one last time. I presented some research I have been working on at Rhodes College for two years, so I felt pretty confident in talking about it. The title of my presentation was, "Binary Orbital Motion of Electrically Charged Spheres in Weightlessness," about a research project conducted with


Photo by Josh Fuchs

Josh (left) at the beach with Konrad (Germany), Jessica (Ireland), and Clemens (UK).

six undergraduate students and two faculty members from Rhodes College. The experiment was conducted through NASA's Reduced Gravity Student Flight Opportunities Program, which allows undergraduate research teams to conduct experiments in a weightless environment. I showed some cool video footage of the experiment, which I always enjoy showing people. About 60 people attended my lecture, and I fielded some good questions at the end. I felt good about the presentation and was glad to have it behind me.

To read about the rest of Josh's trip, and his co-winner Gabriel Caceres' trip as well, visit http://www.spsnational.org/programs/awards/2009/osa.htm.

Three C's at the Four Corners: Communication, Collaboration, Camaraderie

Fall 2009 Meeting of the Four Corners Section of the APS

By Ben Frandsen, Brigham Young University
Golden, CO, October 23–24, 2009


Photos by Zach Boerner

Participants enjoying the poster session on Friday afternoon.


SPS students pose with their equipment after a demo contest.

Early in the morning of Friday, October 23rd, my faithful alarm clock awakened me and I rolled out of bed, ready to start another day at school. Only after several seconds did the almost too-good-to-be-true thought come to mind that school was cancelled for me that day! To be fair, I actually love attending Brigham Young University (BYU) and I find my classes most satisfying, but I was nevertheless thrilled that early Friday morning. Rather than heading to campus for my quantum mechanics class, I would catch a plane for Denver, Colorado, on my way to the Four Corners meeting at the Colorado School of Mines located in picturesque Golden, Colorado.

I'll admit, more than just excitement accompanied me on the plane—I was a bit nervous as well. As a junior at BYU, I had already had ample opportunity to be involved in conducting research with experienced professors, and had even presented some of our research at various events on the BYU campus, but I had never before traveled to a research conference to present in front of a potentially large and certainly very intelligent audience. The Four Corners meeting was my first exposure to this important part of the physics world.

My particular research project, which most recently has involved x-ray diffraction with piezoelectric materials, is absolutely fascinating to me, but it would be tragic if that were the only branch of physics with which I were familiar. While it is impossible to know everything, we can still benefit tremendously from learning about the many different directions of research. That is exactly what happened at the Four Corners meeting. On that Friday morning before the conference, I had never heard of an XUV frequency comb and I had absolutely no familiarity with attosecond laser physics, but by Friday evening, after hearing several talks on the subject, I was pleasantly surprised to realize that I could now conduct a conversation with another scientist about these fascinating branches of physics! This type of communication happened in every session with every speaker, enlarging and enriching my awareness and understanding of current developments in physics.

Communication brings with it the potential for collaboration. During the poster session on Friday afternoon, I took the opportunity to browse the hundreds of interesting and well-designed displays, thereby getting a taste of the dazzling variety of research projects happening at the universities in the Four Corners section of the APS. I was also able to speak in depth with several students who were presenting their posters, and I was surprised at how applicable some of their projects were to mine. I was particularly impressed by the posters of two students—one from the University of Colorado at Boulder, whose work on piezoelectrics gave me new insights into my own investigation of a particular type of piezoelectric material, and the other from Utah State University, whose experiences with x-ray diffraction at a synchrotron dovetailed nicely with my own recent trip and upcoming follow-up trip to the synchrotron at Argonne National Laboratory. It was gratifying and reassuring to realize how effectively research meetings like this one facilitate collaboration between scientists. I hope to take advantage of this tremendous opportunity in the future.

Finally, a remarkable feeling of camaraderie accompanied the entire proceedings. I felt a sense of unity and friendship, not only with my fellow BYU students, but also with students from all across the Four Corners section. Listening to the amazing plenary speakers, including NASA astronaut John Grunsfeld, APS President Cherry Murray, National Ignition Facility Director Richard Boyd, and others, was that much more meaningful and memorable because it was shared with other aspiring scientists. By the time we had our outdoor barbeque Saturday afternoon, a very friendly and comfortable atmosphere had been created, and I think many of us left the meeting impatient for the next chance to associate with so many great young scientists once more.

The Four Corners meeting exceeded my expectations and left me grateful for what I had learned, motivated to get back to the lab and continue working hard, and excited for future opportunities to attend research conferences. Many thanks to the hundreds of people who spent thousands of hours organizing and executing this event—it was well worth it.

Going to a meeting?

The Society of Physics Students (SPS) offers travel support at a level of $200 for SPS chapters or individual students reporting on a national physics meeting for SPS. Interested? See the details at www.spsnational.org/programs/awards/reporter.htm.

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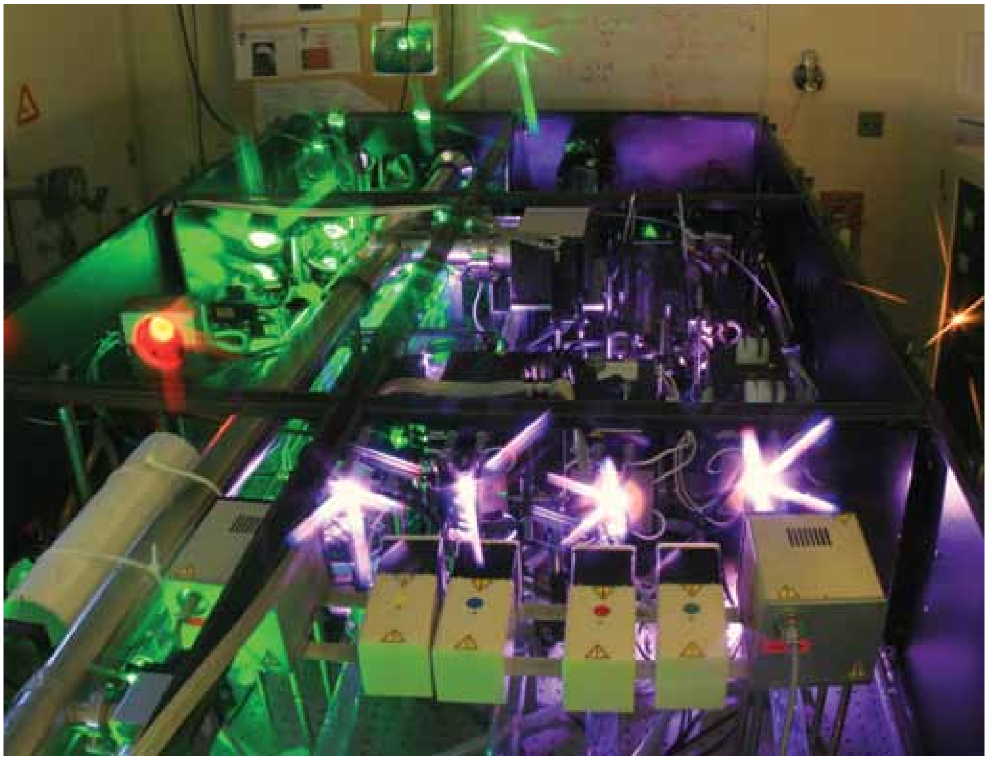

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