

*The Magazine of the Society of Physics Students*

## THE NUCLEAR NON-PROLIFERATION BARGAIN UNDER SIEGE

— by *W. K. H. Panofsky, Professor and Director Emeritus, Stanford Linear Accelerator Center, Stanford University; and US Delegate for treaties on the international control of nuclear weapons.*

The U.S. government officially agrees with the worldwide consensus that stopping the spread of nuclear weapons is an urgent task, but doing so is a difficult one indeed. Proliferation of new technology has never been stopped in human history. The discovery of man-made fire, metals, gun powder, explosives and electronics was always followed by the spread of those technologies all over the globe. Each of these new technolo-

gies served a dual purpose: they could serve to improve the human condition or they could support violence. But in respect to nuclear weapons the non-proliferation efforts must succeed or otherwise the very future of civilization will be in danger.

After the first nuclear explosions sixty years ago in Alamogordo, followed by the American nuclear attacks on Hiroshima and Nagasaki, many efforts were made to bring these new destructive weapons, which increase the destructive energy carried by munitions of a given size by a factor of a million, under control. Some of these efforts failed, and some were successful but limited in scope.

A dramatic effort was made through President Eisenhower's "Atoms for Peace" address in 1953; Eisenhower idealistically proclaimed that we could have it both ways: exploit nuclear energy for peace but at the same time pre-

*(continued on page 2)*

## MEDICAL PHYSICS INTERVIEW

— Contributed by *Kenny Homann, University of Texas-Houston*

*Medical physics is an applied field in the physics community that has been practiced since the discovery of X-rays by Wilhelm*



*Roentgen in 1895. A medical physicist applies physics concepts and methods to the diagnosis and treatment of human disease. There are three main fields in medical physics: radiation therapy, diagnostic imaging, and nuclear medicine. Recently, SPS Observer reporter Kenny Homann interviewed two medical physics graduate students from the University of Texas-Houston MD Anderson Cancer Center, Pai-Chun "Melinda" Chi and Earl Gates, and asked them about their experiences with medical physics.*

**KH:** What was your undergraduate background and what degrees are you currently pursuing?

**Melinda:** I have a BS degree in physics (with a "medical and health physics" option) from McMaster University in Canada. I'm currently working on my PhD degree.

**Earl:** I obtained my BS in General Physics from the University of Louisiana

*(continued on page 4)*



L-R (back row) Frank Press, Anthony Turkevich, Hans Bethe, John Tukey, (front row) Wolfgang Panofsky, James Fisk, Carl Romney. The American delegation signs an agreement at the 1959 Geneva Conference on the Discontinuance of Nuclear Weapons Tests.

### AMONG THIS ISSUE'S HIGHLIGHTS ARE THE FOLLOWING:

- Medical Physics Interview (pg. 1)
- 2005 SPS Outstanding Chapters (pg. 6)
- Physics News Update (pg. 8)
- Elegant Connections in Physics (pg. 10)
- AAPT Conference Summer 2005 Report (pg. 20)

## THE NUCLEAR NON-PROLIFERATION BARGAIN UNDER SIEGE

(continued from page 1)

vent the spread of nuclear weapons. Eisenhower's ideas became the basis of the nuclear non-proliferation regime whose cornerstone is the Nuclear Non-proliferation Treaty (NPT). It was signed after long negotiations in 1968 and came into force in 1970. That treaty, together with additional initiatives, has slowed the spread of nuclear weapons beyond what most observers had predicted, as shown in Fig. 1.

I also note that several countries, including Australia, Switzerland, South Korea, Argentina, had nuclear weapon programs, and South Africa actually produced six nuclear weapons. But all these states discontinued their program after having been persuaded that their national security is served better without these weapons. When the Soviet Union broke up, the three countries (Belarus, Kazakhstan and Ukraine) which inherited nuclear weapons released them to the Russian Federation.

The NPT, still the backbone of today's nuclear non-proliferation efforts, seals a complex bargain. Those states, the Nuclear Weapon States or the NWS, which had acquired nuclear weapons before 1968 (the United States, Soviet Union, UK, France, and China) promised not to transfer these weapons, their materials or knowledge of how to make them, to the other signatories. In turn, those others (the Non-Nuclear Weapon States or NNWS) agreed not to acquire nuclear weapons.

To compensate for this blatantly discriminatory nature of this division of the world's nations, the treaty encourages the NNWS to develop nuclear energy for peaceful purposes and the NWS are committed to assist them in this respect. In fact, the treaty guarantees an "inalienable right" to the non-nuclear weapon states to enjoy the fruits of peaceful nuclear energy. The treaty obligates the NNWS in their pursuit of the "peaceful atom" to submit their nuclear facilities to agreed "Safeguards" to be administered by the International Atomic Energy Agency (IAEA) to prevent diversion of materials to nuclear weapons use. Furthermore, Article VI of the NPT obligates the NWS to work in good faith towards reductions of nuclear armaments

with the goal of their eventual prohibition, if not elimination. The components of this bargain are designed to be inseparable. In exchange for foregoing any nuclear weapons ambitions, the NNWS are entitled to the benefits of nuclear energy: at the same time the discriminatory nature of the bargain is to diminish over time by de-emphasis of nuclear weapons in international affairs, accompanied by gradual elimination of nuclear weapons world wide.

The treaty establishes Review Conferences to be held every five years to assess progress and problems. The 1995 con-

Today, the NPT bargain between the NWS and NNWS is justly considered to be under siege from both directions. Today some countries in their pursuit of "peaceful" nuclear power are with some merit suspected of abusing that pursuit to shorten the lead time needed to acquire nuclear weapons. Historically, the NPT non-signatories Israel and India chose this path to become "de facto" nuclear weapon states: their acquisition of nuclear weapons grew from ostensibly "peaceful programs." On the other hand, the nuclear weapon states built up their inventories to a cold war peak of about 70,000 nuclear weapons. Even today, well over a decade after the end of the Cold War, these inventories still contain nearly 30,000 weapons, an inexcusable number. Their average explosive power is about twenty times that of the devices which killed 250,000 Japanese in 1945. The policies of all NWS, in particular those of the U.S., imply indefinite dependence of their military strength on nuclear weapons. Thus today's pressures on the non-proliferation regime derive both from those NNWS suspected of aiming to acquire nuclear weapons and from the NWS retaining inexcusably large arsenals of such weapons and searching for new missions for them.

Let me cite a few technical facts relevant to the nuclear weapon proliferation issue. No nuclear weapons can be fabricated without "a significant quantity"<sup>1</sup> to use the IAEA term, of the 235 isotope of uranium or almost any isotope of plutonium. In turn, U235 is made by "enriching" natural uranium (0.7 percent U235) to Highly Enriched Uranium (generally assumed to contain greater than 90 percent U235). Plutonium is made by "reprocessing" spent fuel from nuclear reactors fed with either natural uranium or Low Enriched Uranium containing 3-4 percent U235. The plutonium is "grown in the fuel," U238 as it captures a neutron and then beta-decays to neptunium and then plutonium.

Thus a proliferating state or a sub-national group intent on acquiring nuclear weapons must either:

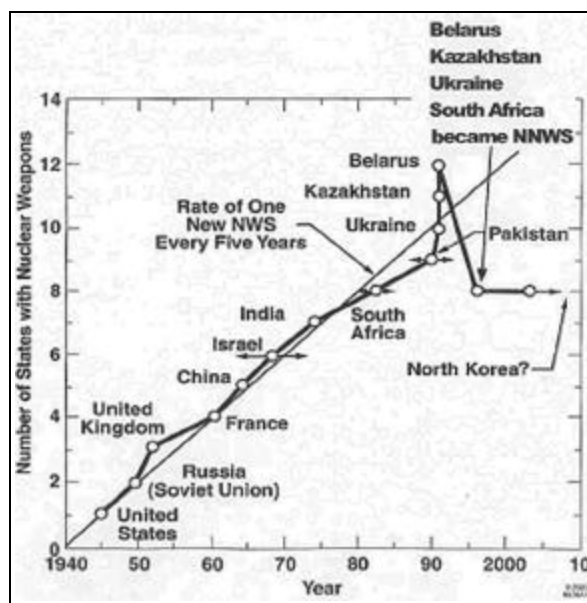


Figure 1

ference extended the NPT indefinitely. A subsequent meeting in 2000 was contentious and the most recent meeting in 2005 ended in failure.

That failure is a symptom of the pressure under which the NPT now finds itself. This discord in part derives from deficiencies of the NPT itself which are being exploited by some of its signatories. Nevertheless, the NPT must be considered to be an unprecedented achievement; today it is signed by all the world's nations with the exception of India, Pakistan, and Israel and, after its recent withdrawal, North Korea. The NPT has demonstrably slowed the spread of nuclear weapons but has not succeeded in stopping that spread entirely.

(continued on page 3)

## THE NUCLEAR NON-PROLIFERATION BARGAIN UNDER SIEGE

(continued from page 2)

- Acquire complete nuclear weapons from a NWS,
- Acquire quantities of HEU or Plutonium sufficient to make a weapon or weapons,
- Construct or acquire enrichment or reprocessing plants.

Peaceful nuclear power overlaps in part with these requirements; the next figure outlines the major components of such a program. But that overlap can be reduced if:

- Enrichment plants are safeguarded by IAEA inspectors and monitoring instruments to assure that enrichment is not carried out beyond a few percent of U235.
- The fuel cycle remains “open,” i.e., the spent fuel is not reprocessed to recover plutonium.
- The IEAE has authority to search for, and inspect if necessary, suspected sites of nuclear weapons activity.

There is however strong pressure in some countries to reprocess spent fuel to recover plutonium and reuse it in so called mixed oxide (MOX) form or to essentially use it as feed material for “breeder” plants which generate even more plutonium. Economic analysis indicates that reprocessing and use in MOX or breeding can not now be justified and will remain so until uranium is in much shorter supply than it is expected to be for many decades. But reprocessing and, in particular, breeding does extend the energy that can be extracted from a given amount of uranium.

In view of the above a NNWS can claim to exercise its “inalienable right” under the NPT to pursue an indigenous nuclear power program which includes its own enrichment and even reprocessing facilities. But doing so will also shorten its lead-time toward a bomb, should it choose to withdraw from the NPT, expel the IAEA inspectors and remove their instruments. This is what North Korea has done and what the U.S. is accusing Iran of planning to do; a path however which Iran has denied that it is intending to pursue.

What can be done to reduce these risks and inherent threats of proliferation? The world will increasingly need nuclear power; therefore we must find means to have it both ways: expand nuclear power but reduce the opportunities for proliferation of nuclear weapons. I will give here only the briefest of outline of possible steps toward that goal:

- Limit the right of withdrawal from the NPT. Currently the NPT incorporates a clause permitting a party to withdraw after giving three months notice with little explanation. This could be changed by requiring United Nations Security Council approval after accepting the stated reasons for withdrawal.
- Eliminate “enrichment” and “reprocessing” as an inalienable right under the NPT and replace it by a guarantee of assured supply of reactor fuel from a Nuclear Weapon State, or even better, from an international entity managing the production of such fuel.
- Strengthen the IAEA by:
  1. Increased funding, which currently is inadequate in view of the expanded responsibilities of the Agency,
  2. Requiring all parties to the NPT to accept the “Additional Protocol.” This document gives the IAEA expanded access to inspect essentially all suspected facilities and expanded authority in other respects. Currently only about a quarter of the NPT parties have accepted this “Additional Protocol.”
- Expand the use of binding positive and negative “security assurances” by NWS to NNWS. A “negative” assurance provides a guarantee by the NWS not to use nuclear weapons against non-nuclear weapons states under any circumstances, unless they were allied with a nuclear weapons state. A “positive” assurance is a commitment to defend a NNWS with nuclear weapons if necessary, if they were attacked by a nuclear weapon state.

Article VI of the NPT is an inseparable part of the non-proliferation bargain. It specifies that each of the parties shall pursue, in good faith, negotiation to end the nuclear arms races “at an early date,” and to proceed toward nuclear disarmament and to a Treaty on general disarmament. Not surprisingly, during the original negotiation leading to the NPT, the NWS made an effort to strengthen the non-transfer provisions of the Treaty

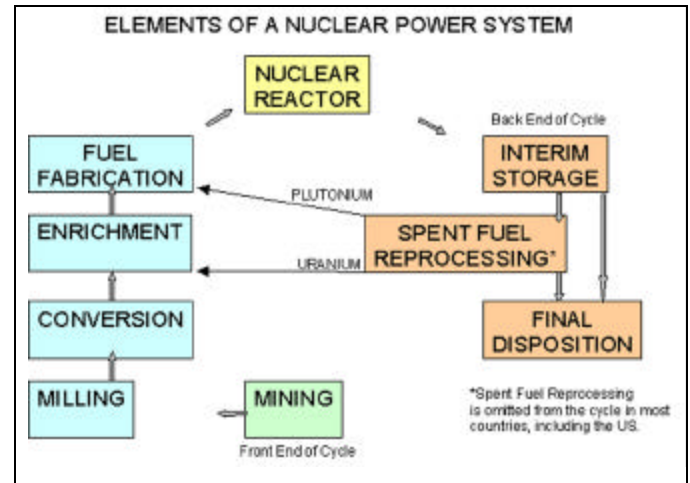


Figure 2

designed to prevent NNWS from acquiring nuclear weapons while the NNWS promoted Article VI in its function to deemphasize the role of nuclear weapons in international affairs. However, the NNWS failed to persuade the NWS to accept any specific timetable for nuclear arms reductions and prohibitions.

Today the nuclear activities criticized by the U.S. Administrations are highly selective.

In the more acrimonious public discourse and during the recent Review Conferences, the “Rogue States” or “Axis of Evil” so designated by the U.S. (North Korea, Iran, and Pre-war Iraq and formerly Libya), were accused of clandestine nuclear weapons programs. At the same time, Israel’s well known acquisition of nuclear weapons, hidden under Israel’s “neither confirm nor deny” policy, was never publicly denounced by any U.S. Administration. Similarly, Pakistan’s nuclear weapons activities were not publicly resisted by the U.S. since we “needed” Pakistan’s assistance in resisting the Soviet Union’s expansion into Afghanistan and today, Pakistan’s help in the “War on Terror.” Similarly, the U.S. reaction to India’s nuclear weapons developments has been essentially mute. Today the U.S. is strongly resisting Iran’s plans for uranium enrichment, while similar activities in Brazil are not criticized publicly.

The much heralded “Proliferation Security Initiative (PSI)” is an agreement among a limited group of states cooperating

(continued on page 23)

## MEDICAL PHYSICS INTERVIEW

(continued from page 1)

at Lafayette, and am finishing up my Masters degree. Go Cajuns!!

KH: Do you think an undergraduate degree in physics is necessary to become a successful medical physicist?

**Melinda: Yes, I think having a degree in physics makes the learning of medical physics easier.**

**Earl: I think it helps. At the very least, one should have a basic understanding of atomic and subatomic interactions, as well as a solid base in mathematics. I know that other people have entered this field with backgrounds in electrical and chemical engineering, so a physics degree is certainly not a must.**

KH: As we found out earlier, you don't have to have Doctor in front of your name to be a medical physicist. Is there any difference in the job description between a PhD and a Masters level physicist?

**Melinda: Generally, having a PhD degree generally means more research and teaching duties (less clinical), and vice versa for MS level. It depends on where you work; however, because in a large institution, MS level physicists are given more opportunity to participate in research projects, whereas, in a small institution, a PhD physicist's responsibility is mostly clinical. It is worth noting that PhD's make about 10 percent more than Master's level medical physicists.**

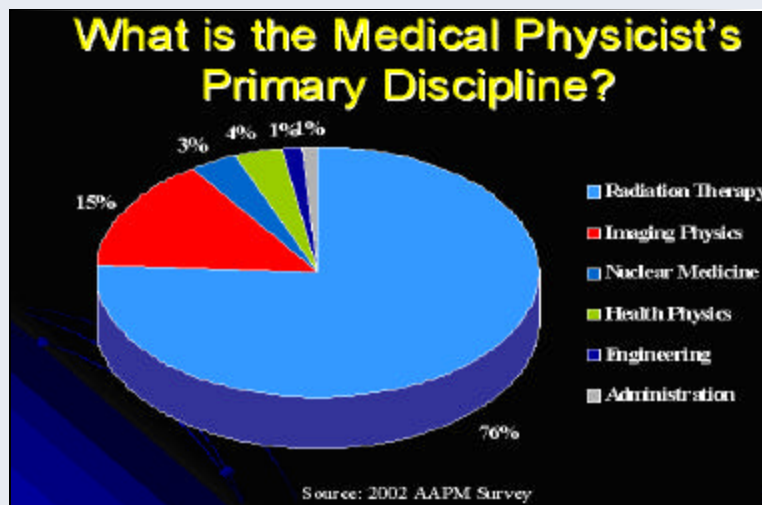
KH: To what extent do you feel that you are doing physics in your current work? What standard topics in the physics curriculum play a part in your research?

**Melinda: I don't feel like I am doing physics most of the time...until I have a problem that is not easy to solve. Usually it helps by going back to basic physics principles.**

**Earl: It's really not that I use advanced E&M in my work, or will ever have to write a formula in Dirac notation again, but I do feel that the things I learned in my undergraduate studies prepared me for this. Mostly, the problem-solving skills, as well as the scientific intuition you develop have been the most powerful tools.**

KH: Do you remember how it is that you first decided to go into medical physics? What reasons would you give for someone else in physics to choose this path?

**Melinda: I like physics and biology, but more physics than biology. This combination made me choose the "medical and health physics option" back in undergrad. Then I found a job working**



Graph courtesy of AAPM.

with several medical physicists, and learned more about pursuing a career in the field.

**Earl: I first learned about the field from a seminar delivered by Dr. John Sunderland, an imaging medical physicist. Years later, when contemplating what to do with this BS in physics, I stumbled upon a couple of graduate schools offering degrees in the field. The idea that I could apply my physics background in an applied field that would do something as significant as treat and possibly cure cancer appealed to me greatly. It's this reason that I would really give to a student considering this path.**

KH: What do you like about the medical physics field? Dislike?

**Earl: It's an applied field that really has a lot of options as far as research and career emphases. Mostly, I like that you do a lot of different things, and are expected to know a wide range of stuff. That keeps me on my feet. Also, I like that the industry is a really close-knit group of physicists. The pay is pretty good, too, by the way. The thing I probably dislike the most is the bureaucracy inherent in most hospital atmospheres, but that is something usually inherent in most workplaces anyway.**

KH: What do you expect to be the most gratifying work experiences in your future? What have you heard about the downsides of your future job path?

**Melinda: Just going into work everyday, knowing that anything I'm doing, whether it be exciting or tedious, has the potential to improve the quality of life of patients. For medical physicists in radiation therapy: a cure for cancer will mean that we don't**

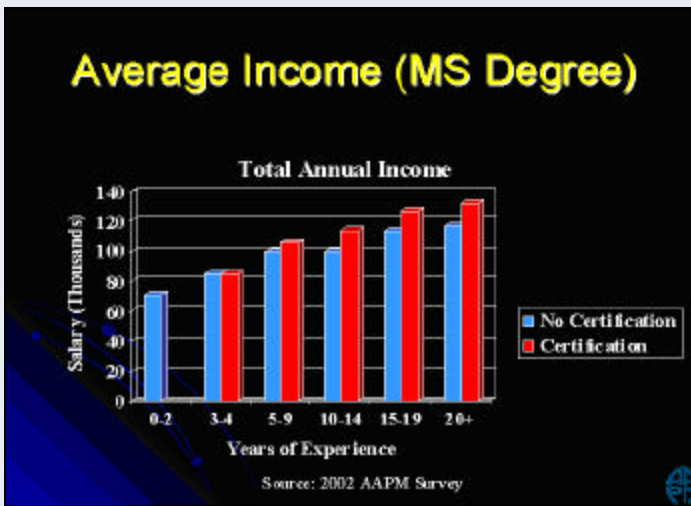
(continued on page 5)

The **SPS Observer** (formerly *The SPS Newsletter*) is published four times per year by the American Institute of Physics, One Physics Ellipse, College Park, MD 20740; telephone: (301) 209-3007; fax: (301) 209-0839; E-mail: [sps@aip.org](mailto:sps@aip.org). Printed in the USA. Postage paid at College Park, MD, and at additional mailing offices.

The **SPS Observer** is edited by Dwight E. Neuenschwander, Southern Nazarene University, Bethany, OK. Assistant Editor and Desktop Publisher is Stephanie P. Campbell, American Institute of Physics, College Park, MD.

## MEDICAL PHYSICS INTERVIEW

(continued from page 4)



Graph courtesy of AAPM.

need radiation therapy anymore, so we will be out of jobs, but there's obviously not a downside to finding a cure for cancer. Physicists in imaging modalities will be needed as long as doctors need pictures of people's insides. For all physicists, the responsibility of caring for a patient's well-being can be pretty daunting as well.

KH: Aside from the graduate degree, are there any other requirements that need to be obtained to be a professional medical physicist and what are the time requirements for those things?

**Earl:** There's a certification process that, to complete, takes roughly 3-4 years after graduation. This opens doors for more jobs and higher pay. You work during the years before certification under the title 'junior medical physicist.'

KH: If someone asked you what they needed to do to become a medical physicist, to what resources would you direct them and what undergrad classes would you recommend for them to take?

**Melinda and Earl:** The best place to start is to go to [www.aapm.org](http://www.aapm.org), which is the scientific society for medical physicists. There's a lot of introductory information there to let you know about the profession. There is also a link for SPS students interested in pursuing medical physics at <http://www.aapm.org/sps/>. If you're still interested, I'd recommend contacting a local medical physicist. They are usually accommodating people, and would be glad to answer any questions you have. The only undergraduate classes that I'd recommend outside of normal physics curriculum would be a statistics class, centering on error analysis, as well as a basic electronics and circuitry class. Without question, we both feel that medical physics is a rewarding field with lots of upsides that is definitely worth checking out. Thanks for your time and best of luck with your future endeavors.

*Kenny Homann will graduate this fall with his Masters degree in medical physics from the University of Texas-Houston Graduate School of Biomedical Sciences. In 2001, he received his BS in physics from Northwestern State University in Natchitoches, LA; the same institution where National SPS Director Dr. Gary White was a professor of physics at the time. Kenny is a member of both the SPS and Sigma Pi Sigma.*



### FOR YOUR INFORMATION

#### PHYSICS SPEAKERS AVAILABLE FOR SPS CHAPTERS AND THEIR DEPARTMENTS

The World Year of Physics has wound down, but the WYP speakers bureau, invented by parts of the American Physical Society, will continue through 2006, thanks to a donation by Las Cumbres Observatory. The target audience is BS/BA physics degree recipients and 4-year colleges, which may very well be you, though we have also been able to fulfill requests from a number of community groups, K-12 schools, and even PhD-granting institutions. The primary goal is to encourage bachelors' recipients to remain in science, preferably physics. What is offered is good speakers on topics like general relativity, related astrophysics (black holes, quasars, cosmology, and all), Einstein, and history of physics in general. Speakers will normally be found at institutions close to the host organization, but we do have some money (thanks to another donor, Warren Smith of Corning Community College) to support travel to truly impoverished institutions.

To request a speaker, go to: <http://www.phys.utb/WYPspeakers/REQUESTS/howto.html>

If by any chance you would be willing to speak to a K-12, 2-year college, or even 4-year college audience on one of these topics, please contact [vtrimble@astro.umd.edu](mailto:vtrimble@astro.umd.edu).

*Virginia Trimble (for APS Forum on History of Physics) and Richard Price (for APS Topical Group on Gravitation and General Relativity)*

# OUTSTANDING SPS CHAPTERS FOR 2005

*Please join us in congratulating all of the SPS chapters that attained outstanding chapter status for the past year. These are chapters active in SPS social activities, in presenting talks at local and national meetings, and whose members engage in physics outreach programs, as well as other activities. The Outstanding SPS Chapters for 2005 (with notes provided by Zone Councilors) are as follows (and away we go!):*

## ZONE 1

### SOUTHERN CONNECTICUT STATE UNIVERSITY

"Lots of outreach activities. Great aspirations. Many activities to support physics on campus, and lots of communication about research."

### UNIVERSITY OF VERMONT

"Lots of work to encourage research among students. Several outreach activities. Great aspirations. Lots of energy. Wide variety of events. Great work!"

## ZONE 3

### DREW UNIVERSITY

"Co-sponsored Zone meeting. President elected as AZC, and SPS intern. Seems like close knit group and open environment (social events). Good recruitment efforts, and involvement in department events and decision-making as well. Six students received internships."

### JUNIATA COLLEGE

"Good participation in local events. Participation in enrollment and other campus events gives chapter visibility. Eight students participated in sectional AAPT meeting and presented research results of experiments carried out in academic lab courses. Good seminar series, interaction with alumni and record of student summer research at off-campus sites. Annually hosts State Science Olympiad—SPS was a main supporter of these events. Six students landed summer internships."

### THE COLLEGE OF NEW JERSEY

"Hosted Zone meeting. Good involvement with alumni, and brought in ~8 speakers."

### ROWAN UNIVERSITY

"Members made many (18!) presentations; four published papers. Chapter involved with local schools, and provides tutors for introductory physics courses. Plan to host 2007 Zone meeting. Good record of research and publication among chapter members."

## ZONE 4

### BRIDGEWATER COLLEGE

"Exhibits numerous qualities for a fully-functioning SPS chapter. Hosted the Zone 4 SPS meeting; conducted outreach demonstrations at several elementary schools and the Children's Museum in Harrisonburg; as well as hosted social gatherings."

### RANDOLPH MACON WOMAN'S COLLEGE

"Hosted a successful and massive outreach event to elementary school students, held shirt design competitions, and promoted the relevancy of physics throughout the college campus. Members were also involved in conferences, one being outside of SPS (NCUR)."

## ZONE 7

### EASTERN MICHIGAN UNIVERSITY

"Lots of activity, great outreach as well as service and plenty of fun physics activities as well as socializing."

### DENISON UNIVERSITY

"Lots of social activities, some outreach and alumni activities as well."

### UNIVERSITY OF MICHIGAN-ANN ARBOR

"Socializing, professional participation, outreach and service as well as activities to get students involved."

## ZONE 8

### AUSTIN PEAY STATE UNIVERSITY

"Students in this chapter have created a very active group. They fielded a good turnout at the Sigma Pi Sigma Congress meeting in Albuquerque, NM, and have been very active in outreach in the community. They nominated a candidate for AZC, Michael Gaither, who is currently serving in that position."

### UNIVERSITY OF LOUISVILLE

"This is also a very active chapter with a Marsh White application/award, an AZC and National Leadership Scholarship recipient (Alyssa Cramer), and lots of outreach and fundraising activities. They also had good representation at Albuquerque, NM."

### PRINCIPIA COLLEGE

"Principia has a large number of members, particularly for a small school. It sent a large representative group to the Albuquerque, NM, meeting."

## ZONE 9

### MARQUETTE UNIVERSITY

"Well rounded chapter; great example for other SPS chapters."

### UNIVERSITY OF WISCONSIN-PLATTEVILLE

"Continues their great record of activity on campus and outreach to the community."

### UNIVERSITY OF WISCONSIN-RIVER FALLS

"Excellent campus involvement, and great spread of physics interest to non-physics students."

*(continued on page 7)*



**SPS Outreach in Zone 18.** California State University Sacramento, CA, Bringing Physics to the Homeless and Less Fortunate, Advisor: Dr. William DeGraffenreid

# Outstanding SPS Chapters for 2005

(continued from page 6)

## ZONE 10

### UNIVERSITY OF LOUISIANA-LAFAYETTE

"Zone meeting host, AZC and AZC nominee (only two in Zone), multiple outreach efforts, Congress participation."

### RHODES COLLEGE

"Zone meeting participation, Marsh White, great outreach programs."

### UNION UNIVERSITY

"Revitalized chapter, local outreach and activities, Einstein/Pi Day celebrations."

## ZONE 11

### AUGSBURG COLLEGE

"Your outstanding membership total is exemplary. Your incredible variety of activities is noted."

### COE COLLEGE

"We note the high level of presentation at professional meetings. The research opportunities are exceptional. The 'Coe Playground of Physics' is an amazing outreach event."

### GUSTAVUS ADOLPHUS COLLEGE

We note the large number of students making presentations at SPS meetings. Your 'Science Saturday' program is a great community activity. Finally, we take special note of your work with 'Habitat for Humanity'."

### MINNESOTA STATE UNIVERSITY-MOORHEAD

"We applaud your community service and outreach programs. The interaction with alumni is laudable and the fact that they give out two scholarships per year is great."

## ZONE 12

### EAST CENTRAL UNIVERSITY

"Large number of trips to professional meetings and presentations. Impressive chapter challenge with video production 'Twin Paradox'. Involvement with community and recruitment."

### TRUMAN STATE UNIVERSITY

"Great outreach and chapter activities."

## ZONE 13

### ABILENE CHRISTIAN UNIVERSITY

"Students active: research/publication. Attended Zone meetings. Provided opportunities for faculty-student interactions beyond classroom."

### ANGELO STATE UNIVERSITY

"Active in outreach. World Year of Physics award. Good opportunities for faculty-student interaction."

### ST. MARY'S UNIVERSITY

"Great job in outreach activities (strong community service). Strong student-faculty support. Students active in Research/publication."

### STEPHEN F. AUSTIN STATE UNIVERSITY

"Hosted Zone meeting, spring 2005. Outreach: community involvement, community service. Attended (one student) 2004 Sigma Pi Sigma Congress. Active in recruitment of new members."

## ZONE 15

### WESTMINSTER COLLEGE

"We would like to welcome Westminster College to the national organization and commend them for involving a large number of students at their small school."

## ZONE 16

### EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

"Very active participation in local, zone, and national SPS activities. To be especially congratulated for becoming such a strong chapter very quickly after being formed (2003). Membership of 100+ after only two years incredible, and the list of activities presented is commendable."

### UNIVERSITY OF TEXAS-EL PASO

"Commitment to outreach and community service in particular, and to their record of active involvement in SPS local, Zone, and national activities. Gives evidence of a chapter that continues to do great things for UTEP and for your community, and that seems to have fun doing it. UTEP-SPS was incremental in reviving Sigma Pi Sigma chapter activities and induction this year."

## ZONE 17

### UNIVERSITY OF ALASKA-FAIRBANKS

"Commendations: school outreach and community involvement; celebration of WYP2005; SPS social events; and field trips."

### CENTRAL WASHINGTON UNIVERSITY

"Commendations: school outreach and community involvement; Sigma Pi Sigma induction; SPS social events; and involvement with the national organization."

### GREEN RIVER COMMUNITY COLLEGE

"Commendations: school outreach and community involvement; SPS social activities; and involvement with the national organization."

### LEWIS & CLARK COLLEGE

"Commendations: hosting a Zone meeting; participation in professional meetings; participation in the national organization; applications to and winning of SPS award and grants; celebration of WYP2005; and school outreach and community involvement."

## ZONE 18

### UNIVERSITY OF CALIFORNIA-SANTA BARBARA

"Hosted Zone meeting. Participated in numerous SPS National activities. Community service ('Shadow a Mad Scientist')."

### CALIFORNIA STATE UNIVERSITY-CHICO

"Attendance at numerous National meetings. Marsh White and Blake Lilly Award winner. Series of well-planned chapter meetings."

### HARTNELL COMMUNITY COLLEGE

"Good outreach activities. Submitted Marsh White proposal. Community Service."



# PHYSICS NEWS UPDATE

The American Institute of Physics Bulletin of Physics News

by Phillip F. Schewe, Ben Stein, and Davide Castelvecchi

Number 755

## OPTICAL VORTEX—TRYING TO LOOK AT EXTRASOLAR PLANETS DIRECTLY.

A new optical device might allow astronomers to view extrasolar planets directly without the annoying glare of the parent star. It would do this by “nulling” out the light of the parent star by exploiting its wave nature, leaving the reflected light from the nearby planet to be observed in space-based detectors. About ten years ago the presence of planets around stars other than our sun was first deduced by the very tiny wobble in the star’s spectrum of light imposed by the mutual tug between the star and its satellite. Since then more than 100 extrasolar planets have been detected in this way. Also, in a few cases the slight diminution in the star’s radiation caused by the transit of the planet across in front of the star has been observed. Many astronomers would, however, like to view the planet directly, a difficult thing to do. Seeing the planet next to its bright star has been compared to trying to discern, from a hundred meters away, the light of a match held up next to the glare of an automobile’s headlight. The approach taken by Grover Swartzlander and his colleagues at the University of Arizona is to eliminate the star’s light by sending it through a special helical-shaped mask, a sort of lens whose geometry resembles that of a spiral staircase turned on its side. The process works in the following way: light passing through the thicker and central part of the mask is slowed down. Because of the graduated shape of the glass, an “optical vortex” is created: the light coming along the axis of the mask is, in effect, spun out of the image. It is nulled, as if an opaque mask had been placed across the image of the star, but leaving the light from the nearby planet unaffected. The idea of an optical vortex has been around for many years, but it has never been applied to astronomy before. In lab trials of the optical vortex mask, light from mock stars has been reduced by factors of 100 to 1000, while light from a nearby “planet” was unaffected (see figure at right). Attaching their device to a telescope on Mt. Lemon outside Tucson, AR, the researchers took pictures of Saturn and its nearby rings to demonstrate the ease of integrating the mask into telescopic imaging system. This is, according to Swartzlander, a more practical technique than merely attempting to cover the star’s image, as

is done in coronagraphs, devices for observing our sun’s corona by masking out the disk of the sun. It could fully come into its own on a project like the Terrestrial Planet Finder, or TPF, a proposed orbiting telescope to be developed over the coming decade and designed to image exoplanets. (Foo et al., *Optics Letters*, 15 December 2005; summary of articles related to optical vortex at:

<http://www.u.arizona.edu/~grovers>)

## FIRST STEPS TOWARD FUSION AT NIF.

Laser pulses shot into a cavity can produce the conditions required to trigger nuclear fusion reactions, scientists at Lawrence Livermore National Laboratory in California report. The finding was a crucial test of principle for Livermore’s National Ignition Facility (NIF, <http://www.llnl.gov/nif/project/index.html>), the \$3.5 billion machine now under construction and expected to start full operations in 2009. NIF will produce fusion reactions by focusing 192 powerful ultraviolet laser beams through small holes into the hollow interior of a gold cavity called a hohlraum. The laser light quickly heats up the cavity’s inner walls, which generate x rays, in a few nanosecond-long bursts of energy more than 60 billion times as bright as the surface of the sun. The outer shell of a small capsule containing frozen deuterium and tritium placed inside this mini-oven will be heated by these x rays and rapidly expand, resulting in heating and compression of its core (to 1000 times its initial density) which will become as dense as the sun’s center, triggering nuclear fusion. During the first hohlraum experiments at NIF, a large team of physicists, engineers and technicians used the four existing NIF laser beams to prove NIF’s x-ray production capability. NIF was operating at just 1 percent of its full design energy, and the cavity contained no fusion materials. However, the x-ray flux inside the cavity—the amount of energy per unit area and per unit time—has been shown to agree with expectations, and is similar to those required for future fusion experiments. (Dewald et al., *Physical Review Letters*, 18 November 2005). Uncertainties over the continued funding of NIF seemed to be resolved in a recent House-Senate conference agreement over the 2006 energy bill. (See *FYI* No. 162, November 11, 2005

<http://www.aip.org/fyi/2005/162.html>.)

## HYPER-ENTANGLED PHOTON PAIRS.

Physicists at the University of Illinois have demonstrated for the first time the entanglement of two objects not merely in one aspect of their quantum natures, such as spin, but in a multitude of ways. Entanglement is the quantum affinity between or among particles (such as atoms or photons) in which the measurement of some property for one particle automatically and instantaneously determines the corresponding property of the other particle. Take the case of two photons entangled with respect to polarization, the orientation of the electric field associated with the photon. The photons, until detected, have no spin orientation; this is the principle of quantum indeterminacy. Indeed, both photons are said to be in a superposition of arbitrary—but parallel—polarization states. Consequently, each photon has a 50 percent likelihood of being measured to have any polarization state—e.g., +45 or -45 degrees. If now one photon’s polarization is measured to be +45, then its entangled twin will surely also be polarized along +45 owing to the way the photons are made in this setup. One of the chief hopes of entanglement research is to exploit the superposition idea and the entanglement idea for performing unusually fast quantum computation. In the Illinois experiment, two photons, produced in a “down-

(continued on next page)



These laboratory images demonstrate how the optical vortex coronagraph works. They were obtained with a green “star” and red “planet” (point light sources). (a) shows how the green light is “spun out,” while the red light remains unaffected. Images of the point sources are shown when large (b) and small (c) apertures are used to limit the transmission of light from (a).

Reported by: Foo et al. in *Optics Letters* for 1 December 2005

Figure courtesy of:  
<http://www.aip.org/png/2005/241.htm>

## PHYSICS NEWS UPDATE (continued from page 8)

conversion" process whereby one photon enters an optical crystal and sunders into two lesser-energy correlated daughter photons, are entangled not just in terms of polarization, but also in a number of other ways: energy, momentum, and orbital angular momentum. (See [www.aip.org/pnu/2005/split/721-3.html](http://www.aip.org/pnu/2005/split/721-3.html).)

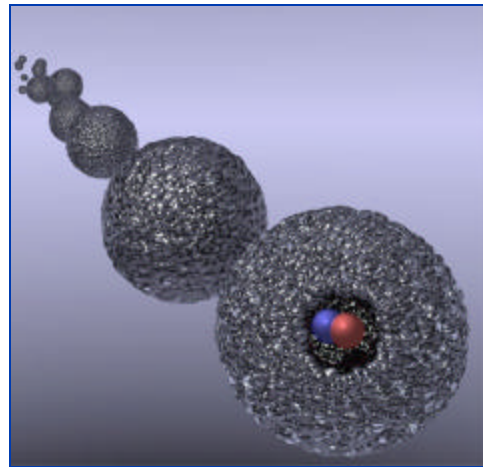
Actually, the photon pair can be produced in either of two crystals, and the uncertainty in the production details of the individual photons is what provides the ability to attain entanglement in all degrees of freedom. Is it better to entangle two particles in ten ways or ten particles in two ways? They're probably equivalent, says, Paul Kwiat, leader of the Illinois group, but for the purpose of quantum computing or communication it might be of some advantage if multiple quantum bits (or qubits) of information can be encoded in a single pair of entangled particles. Kwiat says that his lab detects a record two million entangled photon pairs per second with ample determination of numerous properties, allowing a complete characterization of the entanglement produced. (Barreiro et al., *Physical Review Letters*, upcoming article)

### NORTH PACIFIC "BOING" ATTRIBUTED TO MINKE WHALES.

Human singers send their voice into the supporting medium of air. Whales send their songs into ocean water. One particular song, a sort of fluttering echo, or "boing" sound first heard by human listeners in the North Pacific Ocean in the 1950s (and recorded by US Navy submarines) baffled scientists. Where was it coming from? Only now have the sounds been identified as coming from minke whales. Shannon Rankin and Jay Barlow, scientists at the National Marine Fisheries Service in La Jolla, California, have gathered hydrophone data in the body of ocean between Mexico and Hawaii and combined this with visual sightings of the marine mammals. Not only has the source been traced to minke whales, but the songs seem to be somewhat different on either side of a certain longitude. To the east, the boing sound is issued at a frequency of about 92 Hz and an average duration of 3.6 seconds. The west boing, by contrast, consists of a 135-Hz vocalization with a duration of about 2.6 seconds. The acoustic trace is both frequency modulated (FM) and amplitude modulated (AM). (*Journal of the Acoustical Society*, November 2005; numerous whale sounds, including the boing, can be accessed at <http://swfsc.nmfs.noaa.gov/PRD/PROGRAMS/CMMP/acccsurv.html>)

**QUANTUM SOLVENT.** Scientists at the Ruhr-Universität Bochum in Germany have performed high-precision, ultracold chemical studies of nitrogen oxide (NO) molecules by inserting them into droplets of liquid helium (see figure at right). NO, *Science* magazine's "molecule of the year" for 1992, is important because of its role in atmospheric chemistry and in signal transduction in biology. A radical is a molecular entity (sometimes charged and sometimes neutral) which enters into chemical reactions as a unit. To sharpen our understanding of this important molecule and its reactions, it would be desirable to cool it down, the better to observe its complex spectra of quantum levels corresponding to various vibrational and rotational states. In the new experiment, liquid helium is shot from a cold nozzle into vacuum. The resultant balls, each containing about 3000 atoms, are allowed to fall into a pipe where NO molecules are lurking. The NO is totally enveloped and, within its superfluid-helium cocoon at a temperature of about 0.4 K, it spins freely. The helium acts provides a cold environment but does not interact chemically with the NO molecules. Because of this a high-resolution infrared spectrum of NO in fluids could be recorded for the first time. NO has been observed before in the gas phase, but never before has such a high resolution spectrum been seen in the helium environment. (Haeften et al., *Physical Review Letters*, 18 November 2005; contact Martina Havenith, lab website at: [http://www.ruhr-uni-bochum.de/pc2/helium\\_short\\_en.html](http://www.ruhr-uni-bochum.de/pc2/helium_short_en.html))

**A NANOSCALE GALVANI EXPERIMENT** provides a new way to obtain images of biological tissue. Applying state-of-the-art technology to a seldom-exploited electromechanical property in biomolecules, Sergei Kalinin of Oak Ridge National Laboratory and his colleagues have demonstrated a nanometer-scale version of Galvani's experiment, in which 18th-century Italian physician Luigi Galvani caused a frog's muscle to contract when he touched it with an electrically charged metal scalpel. Described at the AVS Science & Technology meeting in Boston, the new, 21st-century demonstration promises to yield a host of previously unknown information in a variety of biological structures including cartilage, teeth, and even butterfly wings. Employing a technique named Piezoresponse Force Microscopy (PFM), Kalinin and colleagues sent an electrical voltage through a tiny, nanometer-sized tip to induce mechanical motion along various points in a biological



Droplets of helium containing about 3000 atoms can be used to chill molecules of nitrogen oxide to 1-kelvin temperatures but without imposing any complicating chemical reactions. The result: the best infrared spectra of the NO molecule.

Reported by: von Haeften et al., in *Physical Review Letters*

Figure courtesy of:  
<http://aip.org/png/2005/240.htm>

sample, such as a single fibril of the protein collagen. The electromechanical response at various points of the sample, as measured by the probe tip, enabled the researchers to build up images of the collagen fibrils, with details less than 10 nanometers in size. This resolution surpasses the level of detail that can be gleaned on those biostructures by ordinary scanning-probe and electron microscopes. The PFM technique exploits the well-known but infrequently used fact that many biomolecules, especially those that are made of groups of proteins, are piezoelectric, or undergo mechanical deformations in the presence of an external electric field. The researchers have used the PFM technique to produce images of cartilage as well as enamel and dentin (found inside teeth). Besides providing images of biostructures on a nanometer scale, the new technique yields information about the electromechanical properties and molecular orientation of biological tissue. In recent work, the researchers even found unexpected piezoelectric properties in butterfly wings which enabled them to yield molecular-level images of wing structures. (Kalinin, Rodriguez and Gruverman, meeting paper NS-WeM3) (Get a lengthier description at <http://www2.avs.org/symposium/boston/press-room/papers.html>.)



# ELEGANT CONNECTIONS IN PHYSICS

## On the Electrodynamics of Moving Bodies (Part B:

## Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

— by Dwight E. Neuenschwander

This article continues the annotation of one of Einstein’s great papers of 1905, “On the Electrodynamics of Moving Bodies.”[1] For best results, read these notes with Einstein’s paper also before you,[2,3] as together we enter the mind of Einstein.[4] Because his famous “ $E = mc^2$ ” paper came about as a logical consequence of the longer electrodynamics paper, I have merged the two papers in this article.

I encourage you to read Einstein’s papers, if done alongside this article, as follows:

- (2) Read a section of Einstein’s paper first.
- (b) Try to fill in his omitted steps on your own.
- (c) If you get stuck, or when you want to check your work against another student, resume reading this article.

Are you ready? Here we go...

\*\*\*\*\*

In Part B of his great paper Einstein turns to the electrodynamics part of “On the Electrodynamics of Moving Bodies.”[1] He began this paper, as he began so many of his papers, by drawing our attention to an under-appreciated equivalence, this one found in electric and magnetic forces:

*It is well known that Maxwell’s electrodynamics— as usually understood at present—when applied to moving bodies, lead to asymmetries that do not seem to be inherent in the phenomena.*

Einstein illustrated the “asymmetry” with a magnet and a conducting loop. A magnet gliding through a conducting loop at rest drives a current thanks to Faraday’s law. But to an observer riding on the magnet, the current arises in the moving loop because the charges on it move in a magnetic field. In the first case the changing B induces an electric field E, and the electric force  $qE$  acts on particles of charge  $q$ . In the second case, the force is identified as  $qv \times B$  where charge  $q$  is carried with velocity  $v$  past the magnet. Why would the same result arise from apparently different mechanisms? This equivalence could not be a coincidence, reasoned Einstein.

Since all measurements involve the exchange of information limited by the speed of electromagnetic signals, to resolve the “asymmetry” Einstein first had to get to the source of a conceptual confusion. No one had ever asked how, in fact, one actually measures the time interval between separated events, or measures the length of a moving object. This formed Part A of his paper, the “Kinematic Part.” Here we follow him, with annotations, through Part B, the electromagnetic part, of “The Electrodynamics of Moving Bodies.”

### SECTION 6: TRANSFORMATION OF MAXWELL’S EQUATIONS

Einstein begins Section 6 with Maxwell’s equations for electric and magnetic fields in vacuum. In modern vector notation and SI

units, these “Maxwell-Hertz equations” are

$$\nabla \times E = -\partial B / \partial t \tag{1a}$$

$$\nabla \times B = (1/c^2) \partial E / \partial t \tag{1b}$$

$$\nabla \cdot E = 0 \tag{1c}$$

$$\nabla \cdot B = 0 \tag{1d}$$

The curl equations say that a changing electric (magnetic) field produces locally a magnetic (electric) field with a whirlpool. The divergence equations say that, away from point sources, the electric field and magnetic fields have streamlines that do not diverge. Let these four Equations (1) refer to Lab Frame coordinates,[5] where the E and B fields are assumed known. In his paper Einstein writes out the curl equations for E and B, component by component, six equations in all. For instance, the  $x$ -component of the Ampere-Maxwell law, Eq. (1b) reads

$$(1/c^2) \partial E_x / \partial t = \partial B_z / \partial y - \partial B_y / \partial z \tag{2}$$

All six equations have first derivatives of field components, evaluated with respect to position and time coordinates in the Lab Frame. Einstein transforms these derivatives to the Rocket Frame, through the Lorentz transformation derived in Part A. He leaves out the intermediate details. We provide them here.[5]

The Lorentz transformation says

$$t' = \mathbf{g}(t - v_R x / c^2), \tag{3a}$$

$$x' = \mathbf{g}(x - v_R t), \tag{3b}$$

$$y' = y, \tag{3c}$$

$$z' = z \tag{3d}$$

where

$$\mathbf{g} \equiv (1 - v_R^2 / c^2)^{-1/2}. \tag{4}$$

From these it follows that[6]

$$\partial_t = \mathbf{g}[\partial_t - v_R \partial_x], \tag{5a}$$

$$\partial_x = \mathbf{g}[\partial_x - (v_R / c^2) \partial_t], \tag{5b}$$

$$\partial_y = \partial_y, \tag{5c}$$

$$\partial_z = \partial_z. \tag{5d}$$

where to avoid an avalanche of partial derivative symbols I use subscript notation  $\partial_t \equiv \partial / \partial t$ ,  $\partial_x \equiv \partial / \partial x$ . With Eqs. (5) readily at hand, Eq. (2) transforms into Rocket Frame coordinates to become:

$$\mathbf{g}(1/c^2)[\partial_t \cdot E_x - v_R \partial_x \cdot E_x] = \partial_y \cdot B_z - \partial_z \cdot B_y. \tag{6}$$

The “new” term  $\partial_x \cdot E_x$  also appears in Gauss’ law for E, which in Lab Frame coordinates may be written

$$\partial_x E_x + \partial_y E_y + \partial_z E_z = 0. \tag{7}$$

(continued on next page)

# On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

With the Lorentz transformation Eq. (7) becomes

$$\mathbf{g}[\partial_x E_x - (v_R/c^2)\partial_t E_x] + \partial_y E_y + \partial_z E_z = 0. \quad (8)$$

From Eq. (8) let us isolate  $\mathbf{g}\partial_x E_x$ :

$$\mathbf{g}\partial_x E_x = \mathbf{g}(v_R/c^2)\partial_t E_x - \partial_y E_y - \partial_z E_z. \quad (9)$$

In Eq. (6) replace  $\mathbf{g}\partial_x E_x$  using Eq. (9), and do some rearranging to turn the latter into

$$(1/c^2)\partial_t E_x = \mathbf{g}\partial_y [B_z - (v_R/c^2)E_y] - \mathbf{g}\partial_z [B_y + (v_R/c^2)E_z]. \quad (10)$$

This equation merely Eq. (2), the Ampere-Maxwell law for the electric and magnetic fields as measured in the Lab Frame. But the derivatives have been mapped to the Rocket Frame coordinates via the Lorentz transformation. By virtue of the Principle of Relativity, Maxwell's equations in empty-space must say in the Rocket Frame that

$$(1/c^2)\partial E'/\partial t' = \tilde{\mathbf{N}}' \times \mathbf{B}' \quad (11a)$$

$$-\partial \mathbf{B}'/\partial t' = \tilde{\mathbf{N}}' \times \mathbf{E}' \quad (11b)$$

$$\tilde{\mathbf{N}}' \cdot \mathbf{E}' = 0 \quad (11c)$$

$$\tilde{\mathbf{N}}' \cdot \mathbf{B}' = 0 \quad (11d)$$

Therefore, the  $x'$ -component of the Maxwell-Ampere equation, Eq. (11a), for instance, says

$$(1/c^2)\partial_t E'_{x'} = \partial_y B'_{z'} - \partial_z B'_{y'} \quad (12)$$

Now Einstein compares Eqs. (10) and (12). The Relativity Principle requires

$$E'_{x'} = \mathcal{Y}(v_R) E_x \quad (13a)$$

$$B'_{y'} = \mathcal{Y}(v_R) \mathbf{g}[B_y + (v_R/c^2)E_z] \quad (13b)$$

$$B'_{z'} = \mathcal{Y}(v_R) \mathbf{g}[B_z - (v_R/c^2)E_y] \quad (13c)$$

where  $\mathcal{Y}(v_R)$  denotes an overall proportionality factor that may depend on the relative velocity of the two frames. Through similar steps with the curl B and div B equations, Einstein also finds

$$B'_{x'} = \mathcal{Y}(v_R) B_x \quad (14a)$$

$$E'_{y'} = \mathcal{Y}(v_R) \mathbf{g}(E_y - v_R B_z) \quad (14b)$$

$$E'_{z'} = \mathcal{Y}(v_R) \mathbf{g}(E_z + v_R B_y) \quad (14c)$$

To determine  $\mathcal{Y}(v_R)$ , Einstein inverts the transformation two ways, then compares them. In the first way, he inverts the equations algebraically; for example  $E' = E_x/\mathcal{Y}(v_R)$ . But one can also derive the transformation by starting with the Rocket Frame Maxwell's equations and transforming the derivatives of  $E'$  and  $B'$  into derivatives with respect to the unprimed Lab Frame fields and coordinates. Here we must keep in mind that the Lab Frame moves with velocity  $-v_R$  relative to the Rocket Frame. In this way one finds, for example, that  $E_x = \mathcal{Y}(-v_R)E'_{x'}$ . Comparing the two results gives  $\mathcal{Y}(v_R)\mathcal{Y}(-v_R) = 1$ . Einstein notes that, "For reasons of symmetry"  $\mathcal{Y}(v_R) = \mathcal{Y}(-v_R)$ ; therefore  $\mathcal{Y}(v_R) = 1$ .

To sum up Einstein's first "electrodynamics of moving bodies"

result: the fields  $E'$  and  $B'$  observed by the Rocket Observer are, in terms of the Lab Frame fields  $E$  and  $B$ , given as components according to [7]

$$E_{x'} = E_x \quad (15a)$$

$$E_{y'} = \mathbf{g}(E_y - v_R B_z) \quad (15b)$$

$$E_{z'} = \mathbf{g}(E_z + v_R B_y) \quad (15c)$$

and

$$B_{x'} = B_x \quad (15d)$$

$$B_{y'} = \mathbf{g}(B_y + v_R E_z/c^2) \quad (15e)$$

$$B_{z'} = \mathbf{g}(B_z - v_R E_y/c^2) \quad (15f)$$

Einstein summarizes his results of this section with these remarks:

*The above equations can be expressed in words in the following two ways:*

1. *If a point charge  $q$  moves in an electromagnetic field, in addition to the force  $q\mathbf{E}$  acting on it there is also the force  $qv \times \mathbf{B}$  (Old mode of expression).*

2. *If a point charge moves in an electromagnetic field, the force on it equals the electric force  $q\mathbf{E}'$  where the  $E'$  is obtained by transforming the field to a coordinate system at rest relative to the charge (New mode of expression).*

*Analogous remarks hold for magnetic forces. We can see that in the theory developed here,...electric and magnetic forces do not have an existence independent of the state of motion of the coordinate system.*

*It is further clear that the asymmetry in the treatment of currents produced by the relative motion of a magnet and a conductor, mentioned in the introduction, disappears.*

In the remainder of the paper, Einstein pursues further applications of the relativity of electrodynamics.

## SECTION 7: DOPPLER PRINCIPLE AND ABERRATION

Consider a harmonic wave in the electromagnetic field. The Lab Frame observer observes the oscillatory electric field  $E$  and magnetic field  $B$ ,

$$E = E_0 \sin \Phi \quad (16)$$

$$B = B_0 \sin \Phi \quad (17)$$

with phase

$$\Phi \equiv \mathbf{w}t - \mathbf{k} \cdot \mathbf{r}. \quad (18)$$

Here  $\mathbf{w}$  and  $\mathbf{k}$  denote the wave's angular frequency and wavenumber vector respectively ( $\mathbf{k}$  is normal to the wave front, and points in the direction of propagation), so that

$$c = \mathbf{w} / |\mathbf{k}|. \quad (19)$$

on in terms of the Hertzian frequency  $f$  and wavelength  $\lambda$ ,

(continued on next page)

# On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

$$c = fl \tag{20}$$

where

$$w = 2pf \tag{21}$$

and

$$|k| = 2p/l \tag{22}$$

Let us figure out the frequency  $f'$  that will be measured in the Rocket Frame, if we know the frequency  $f$  of the signal as measured in the Lab Frame. The frequency lies buried in the phase. So we start with  $\Phi$ , given in Lab Frame coordinates, and execute the Lorentz transformation to write the phase in terms of Rocket Frame coordinates. To prepare the way, let's write  $\Phi$ , Eq. (18), in the form

$$\Phi = w[t - (Kx + Ly + Mz)/c] \tag{23}$$

where  $K$ ,  $L$ , and  $M$  are the cosines of the angle that the wavevector  $k$  makes with the  $x$ ,  $y$ , and  $z$  axes, respectively. From the inverse Lorentz transformations from Eqs. (3) we find

$$x = g(x' + v_R t') \tag{24a}$$

$$y = y' \tag{24b}$$

$$z = z' \tag{24c}$$

$$t = g(t' + v_R x'/c^2) \tag{24d}$$

Substituting these into Eq. (23) gives, after much algebra which requires the consumption of a large pot of coffee,

$$\Phi = w' [ t' - (K'x' + L'y' + M'z')/c ] \tag{25}$$

where

$$w' \equiv wg(1 - Kv_R/c), \tag{26}$$

and

$$K' \equiv (K - v_R/c)(1 - Kv_R/c)^{-1} \tag{27a}$$

$$L' \equiv (L/g)(1 - Kv_R/c)^{-1} \tag{27b}$$

$$M' \equiv (M/g)(1 - Kv_R/c)^{-1} \tag{27c}$$

We notice that, numerically,  $\Phi = \Phi'$  thanks to the transitive property of the equality relation. But we have the phase given explicitly as functions of the respective Lab and Rocket Frame coordinates, by Eqs. (23) and (25) respectively.[8]

As seen in the Lab Frame, let the light ray (perpendicular to plane wave fronts) move at angle  $\mathbf{j}$  relative to the velocity vector  $v_R$  made by the moving rocket. A sketch of this situation, showing the ray and wave fronts, appears in Fig. 1.

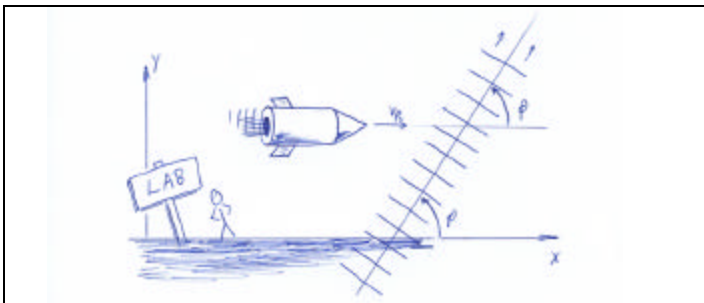


Fig. 1. Motion of a set of wave fronts and their ray. As seen by the Lab Observer, the ray makes the angle  $\mathbf{j}$  with respect to the Rocket's velocity  $v_R$ .

Recall that the light has frequency  $f$  as measured in the Lab Frame. So as measured from the Rocket Frame the frequency  $f'$  is given by Eq. (26),

$$f' = f g [1 - (v_R/c) \cos \mathbf{j}]. \tag{28}$$

If  $\mathbf{j} = 0$ , so that the light ray's direction and velocity of the Rocket relative to the Lab are co-linear, then

$$f' = f [(1 - v_R/c)/(1 + v_R/c)]^{1/2}, \tag{29}$$

the Doppler shift as it is commonly presented in textbooks.

By virtue of Eq. (27a), the direction traveled by the light ray, as seen from the Rocket Frame, makes angle  $\mathbf{j}'$  with respect to the  $x'$ -axis, where

$$\cos \mathbf{j}' = (\cos \mathbf{j} - v_R/c)(1 - \cos \mathbf{j} v_R/c)^{-1}, \tag{30}$$

which Einstein notes is the "law of aberration in its most general form." If the light ray comes in perpendicular to the  $x$ -axis, and thus perpendicular to the velocity of the rocket relative to the lab, then it comes across the  $x'$ -axis of the Rocket Frame at the angle  $\mathbf{j}'$  given by

$$\cos \mathbf{j}' \equiv -v_R/c. \tag{31}$$

"Aberration" was well known to astronomers. It's the same effect as having to tip your umbrella when you run fast in a vertical rain. Because the Earth moves relative to the Sun, and if the speed of light is finite, then one must tip one's telescope in the direction of motion so that a pulse of light entering the top of the moving telescope also hits the mirror at the bottom.

Einstein completes this section by turning his attention to the relativity of the amplitudes of the electromagnetic wave. He needs the amplitudes because the energy carried by radiation goes as the amplitude squared, and electromagnetic energy comes up in Section 8. In Section 7 he is quite terse with the amplitudes, saying

*We still need to find the amplitude of the waves as it appears in the [Rocket frame]. If  $A$  and  $A'$  denote the amplitudes of [the] electric or magnetic [field] in the [Lab Frame] and [Rocket Frame] respectively, we get*

$$A'^2 = A^2 g^2 [1 - (v_R/c) \cos \mathbf{j}]^2.$$

Perhaps this is obvious by inspection to you, but I had to do some scratch work here. So here goes. Take the amplitude squared of, say, the electric field in the Rocket Frame:

$$E'^2 = E_x'^2 + E_y'^2 + E_z'^2 \tag{32}$$

Use now the transformations of Eqs. (15a-c). After a load of algebra you will come up with

$$E'^2 = E_x^2 + g^2(E_y^2 + E_z^2) - 2v_R g^2(E_y B_z - E_z B_y) + v_R^2 g^2(B_z^2 + B_y^2). \tag{33a}$$

To go farther with this, we might recall that the magnitude of a vector, and thus its square, is independent of the spatial coordinates. We can therefore choose the *components* of  $E$  in the Lab Frame to simplify the right-hand-side of Eq. (33) as follows: consider  $E_x = 0 = E_y$ , so that  $E$  has only a  $z$ -component. Since  $B$  points perpendicular to  $E$ ,

(continued on next page)

# On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

and  $E \times B$  points in the direction the wave travels,  $B$  lies in the  $xy$  plane of the Lab Frame. See Fig. 2.

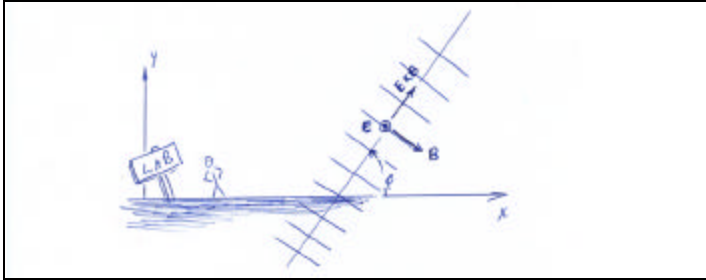


Fig. 2. We consider  $E$  perpendicular to the plane of the figure and  $B$  in the plane.

This arrangement turns Eq. (33) into

$$E'^2 = g^2(E^2 - 2v_R EB \cos \mathbf{j} + v_R^2 B^2 \cos^2 \mathbf{j}). \quad (33b)$$

Finally we recall that, for radiation fields,  $|E| = c|B|$ , which turns Eq. (33b) into

$$E'^2 = E^2 g^2 [1 - (v_R/c) \cos \mathbf{j}]^2. \quad (34)$$

and Einstein's result. For  $\mathbf{j} = 0$ , Eq. (34) gives

$$E'^2 = E^2 (1 - v_R/c) (1 + v_R/c)^{-1}. \quad (35)$$

With Einstein we note that, if the rocket approaches the light source at the speed of light (so that  $v_R = -c$ ), then it follows that to the Rocket Observer, "this source would have to appear infinitely intense."

## 8. TRANSFORMATION OF THE ENERGY OF LIGHT RAYS, THEORY OF RADIATION PRESSURE EXERTED ON PERFECT MIRRORS

In this section Einstein examines the relativity of electromagnetic energy. The energy density of the electric and magnetic fields are given by  $\frac{1}{2} \mathbf{I}_0 E^2$  and  $\frac{1}{2} B^2 / \mathbf{m}_0$ , respectively, where  $\mathbf{I}_0$  and  $\mathbf{m}_0$  denote the permittivity and permeability of empty space. Also, for radiations fields  $E = cB$ . Therefore the total energy density of the electromagnetic field is proportional to  $E^2$ . One might suppose that  $E'^2/E^2$  would be the ratio of energies of electromagnetic radiation in the Rocket and Lab Frames, but that conclusion presupposes that the energy occupies equal volumes. Because of length contraction, "this is not the case."

Therefore Einstein had to work out the relativity of volumes enclosing a fixed quantity light, a pulse emitted isotopically in all directions from a source at rest in the Lab Frame. In terms of the direction cosines introduced above, the  $(x, y, z)$  coordinates of a point on the spherical surface of this light pulse are given by  $(Kct, Lct, Mct)$ , so the equation of this surface would be

$$(x - Kct)^2 + (y - Lct)^2 + (z - Mct)^2 = R^2 \quad (36)$$

This surface is not traversed by any electromagnetic energy, always enclosing the same complex of radiant energy. The equation of this surface describes a sphere in the Lab Frame. Transforming it to the Rocket Frame with the Lorentz transformation of Eqs. (24), Einstein

finds for the equation of the surface an ellipsoid, expressed in Rocket Frame coordinates at time  $t' = 0$ ,

$$(g'x' - Kg'_R x'/c)^2 + (y' - Lg'_R x'/c)^2 + (z' - Mg'_R x'/c)^2 = R^2 \quad (37)$$

Einstein then says, "If  $S$  denotes the volume of the sphere and  $S'$  that of the ellipsoid, then a simple calculation shows that

$$S'/S = g^{-1} [1 - (v_R/c) \cos \mathbf{j}]. \quad (38)$$

Einstein's "simple calculation" requires some scratch work. For an ellipse with symmetry axes of length  $A, B$ , and  $C$ , we know that the volume is  $4\pi ABC/3$ . It's not obvious to me (perhaps it is to you) just for the mere looking, how Einstein gets from Eqs. (36) and (37) to Eq. (38). So, like Einstein, we have to think how to show it ourselves. He pays us the respect of assuming we can do it. Here's how I think about it.

The source of light, it will be recalled, lies at rest in the Lab Frame. Let it emit waves of frequency  $f$  and wavelength  $\lambda$ , as measured in that frame, and let these waves be emitted isotopically in all directions. Consider the spherical surface in this frame that has a radius of one wavelength. See Fig. 3a. The volume  $S$  enclosed by this sphere equals

$$S = 4\pi l^3 / 3. \quad (39)$$

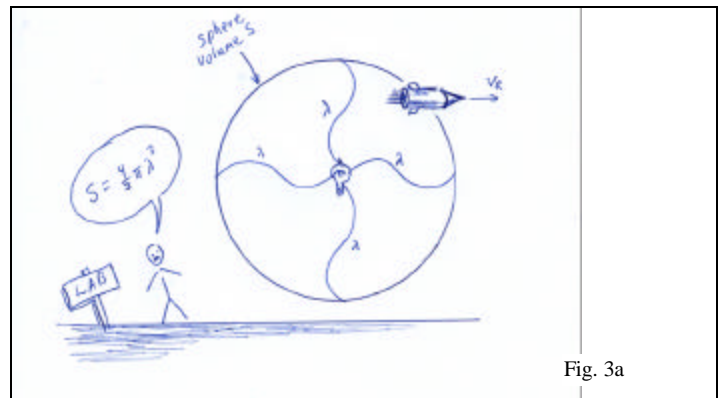


Fig. 3a

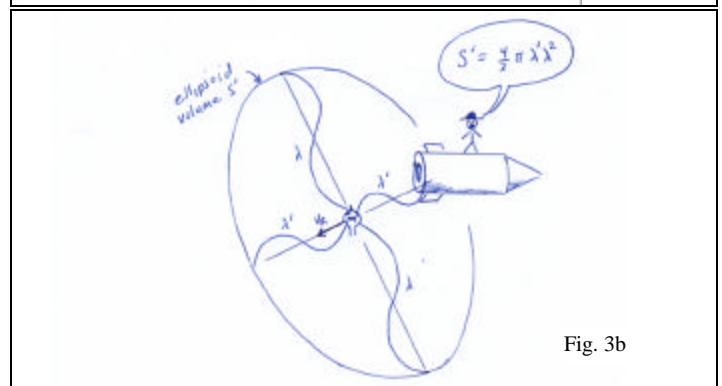


Fig. 3b

Fig. 3. Emission of a wave in all directions. (a) Spherical wave, of radius one wavelength as seen in Lab Frame, where the source is at rest. Note the motion and location of the Rocket Observer relative to the Lab. (b) Same wave seen in the frame of the Rocket Observer.

(continued on page 14)

## On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

Now let's look at the "one-wavelength surface" in the Rocket Frame, which, as Einstein has shown forms an ellipsoid. Consider the Rocket Frame observer for whom (as was seen back in the Lab Frame) the wavefront travels at angle  $\mathbf{j}$  with respect to the Rocket's velocity. This Rocket Frame observer measures frequency  $f'$  given by Eq. (28), and thus the wavelength

$$l' = \frac{l}{g[1 - v_R/c] \cos \mathbf{j}} \quad (40)$$

As seen by this particular Rocket Frame observer, the axes of the ellipsoid *perpendicular* to the relative motion between observer and source will *not* be Lorentz-contracted; and the wavelength *along* the line joining the observer and source will be contracted to  $l'$ . Therefore

$$S' = 4\pi l' I^{2/3}. \quad (41)$$

With Eq. (40) this leads to Einstein's result, Eq. (38).

Now we can move on with Einstein to a discussion of the relativity of electromagnetic energy. If  $U'$  denotes the energy of this light enclosed by the ellipsoid in the Rocket Frame, and  $U$  the energy of the *same* light enclosed by the sphere in the Lab Frame, then

$$\begin{aligned} U'/U &= \frac{E'^2 S'}{E^2 S} \\ &= g[1 - (v_R/c) \cos \mathbf{j}] \end{aligned} \quad (42)$$

which simplifies for  $\mathbf{j} = 0$  to

$$U'/U = [(1 - v_R/c)/(1 + v_R/c)]^{1/2}. \quad (43)$$

This result, Eq. (42), would serve as the starting-point for the world's first derivation of  $E = mc^2$ . But that was a few weeks in the future.

Here Einstein makes a side comment that echoes the light quantum paper that came a few weeks earlier:

*"It is noteworthy that the energy and the frequency of a light complex vary with the observer's state of motion according to the same law."*

Next Einstein considers the reflection of radiation. Let the  $x' = 0$  plane in the Rocket Frame be a perfectly reflecting mirror from which the plane waves of Section 7 are reflected. Relative to the Lab Frame, the incident radiation has amplitude  $A$ , frequency  $f$ , and its ray makes angle  $\mathbf{j}$  with respect to the  $x$ -axis. These quantities as measured in the Rocket Frame before reflection will be denoted  $A'$ ,  $f'$ , and  $\mathbf{j}'$ . They are given in terms of their Lab Frame counterparts by Eqs. (28), (30), and (34). Let these quantities, as measured in the Rocket Frame *after* reflection, be denoted with double primes. According to the laws of reflection, in this frame the post-reflection quantities are related to their pre-reflection values by

$$A'' = A' \quad (44a)$$

$$\cos \mathbf{j}'' = -\cos \mathbf{j}' \quad (44b)$$

$$f'' = f'. \quad (44c)$$

With Einstein let us now transform these post-reflection quantities

back to the Lab Frame, and denote them, as measured in the Lab Frame, with unprimed symbols and "refl" subscripts (Einstein uses triple primes). By reversing the relative velocity between frames in the reverse transformations of Eqs. (28), (30), and (34) we obtain

$$\begin{aligned} A_{\text{refl}} &= A'' g [1 + (v_R/c) \cos \mathbf{j}'' ] \\ &= A' g [1 - (v_R/c) \cos \mathbf{j}' ] \\ &= A g^2 [1 - 2(v_R/c) \cos \mathbf{j} + (v_R/c)^2 ]; \end{aligned} \quad (45a)$$

$$\begin{aligned} \cos \mathbf{j}_{\text{refl}} &= [\cos \mathbf{j}'' + (v_R/c)] / [1 + (v_R/c) \cos \mathbf{j}'' ] \\ &= [-\cos \mathbf{j}' + (v_R/c)] / [1 - (v_R/c) \cos \mathbf{j}' ] \\ &= \frac{2(v_R/c) - [1 + (v_R/c) 2 \cos \mathbf{j}]}{1 - 2(v_R/c) \cos \mathbf{j} + (v_R/c)^2} \end{aligned} \quad (45b)$$

and

$$\begin{aligned} f_{\text{refl}} &= f'' g [1 + (v_R/c) \cos \mathbf{j}'' ] \\ &= f' g [1 - (v_R/c) \cos \mathbf{j}' ] \\ &= f g^2 [1 - 2(v_R/c) \cos \mathbf{j} + (v_R/c)^2 ]. \end{aligned} \quad (45c)$$

Now Einstein uses these results to calculate the light pressure exerted on the mirror. The energy per unit time and per unit area incident on a surface may be written

$$\text{Power/area} = (\text{energy density})(\text{relative velocity})$$

where the relative velocity denotes the normal component of that between the signal and mirror. For radiation fields, the electric and magnetic energy densities are equal, so that the energy density of the electromagnetic wave equals  $E^2/4\pi k_e$  where  $k_e = 9 \times 10^9 \text{ Nm}^2/\text{C}^2$  denotes the Coulomb constant. When the light ray, moving at the angle  $\mathbf{j}$ , overtakes the mirror and reflects, the relative velocity for the incoming ray is

$$c \cos \mathbf{j} - v_R$$

and for the reflected ray the relative velocity is

$$-c \cos \mathbf{j}_{\text{refl}} + v_R.$$

Therefore the difference in power per unit area,  $\Delta I$ , imparted to the mirror by the incident and reflected waves, equals

$$(1/4\pi k_e)[E^2(c \cos \mathbf{j} - v_R) - E_{\text{refl}}^2(-c \cos \mathbf{j}_{\text{refl}} + v_R)]. \quad (46)$$

With the help of Eqs. (45b,c) this becomes, after some algebra,

$$\Delta I = 2 v_R (E^2/4\pi k_e) g^2 (\cos \mathbf{j} - v_R/c)^2. \quad (47)$$

This rate of change of energy per unit area equals the rate at which work is done by radiation pressure  $P$ . By the definitions of work and pressure, this rate of doing work equals  $Pv_R$ . Consequently the light exerts on the moving mirror the pressure

$$P = 2 (E^2/4\pi k_e) g^2 (\cos \mathbf{j} - v_R/c)^2. \quad (48)$$

For small velocities, to first order in  $v_R/c$ , "in agreement with experiment and with other theories, we get"

(continued on page 15)

## On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

$$P = 2 (E^2/4\pi k_e) \cos^2 \mathbf{j} . \quad (49)$$

Here Einstein articulates a strategy for studying the electrodynamics of moving bodies:

*All problems in the optics of moving bodies can be solved by the method employed here. The essential point is that the electric and magnetic fields of light that is influenced by a moving body are transformed to a coordinate system that is at rest relative to that body. By this means, all problems in the optics of moving bodies are reduced to a series of problems in the optics of bodies at rest.*

Einstein will employ this strategy in Section 10, on the dynamics of an electron moving in response to an electromagnetic field.

### 9. TRANSFORMATION OF THE MAXWELL-HERTZ EQUATIONS WHEN CONVECTION CURRENTS ARE TAKEN INTO ACCOUNT

Einstein writes Maxwell's equations for the fields in the vicinity of charged particles present with density  $\mathbf{r}$  and moving with velocity  $\mathbf{v}$ . In SI units, the curl equations say

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t \quad (50a)$$

$$\nabla \times \mathbf{B} = (1/c^2) \partial \mathbf{E} / \partial t + 4\pi k_m \mathbf{r} \mathbf{v} \quad (50b)$$

where  $k_m = k_e/c^2$  denotes the Biot-Savart constant. The divergence equations are

$$\nabla \cdot \mathbf{E} = 4\pi k_e \mathbf{r} \quad (50c)$$

$$\nabla \cdot \mathbf{B} = 0. \quad (50d)$$

*If the electric charges are conceived as permanently bound to small, rigid bodies (ions, electrons), then these equations constitute the electromagnetic foundation of Lorentz's electrodynamics and optics of moving bodies.*

As in Section 6, here Einstein performs a Lorentz transformation on the space and time coordinates in the derivatives (recall the steps from Eqs. (2) through (12)). The new feature here, not present in the homogeneous case, is the transformation of the charge density  $\mathbf{r}$  and current density  $\mathbf{r} \mathbf{v}$ . Here Einstein states his procedure and cites the result; let's walk through it in more detail. Start with, say, the  $x$ -component of the Amperé-Maxwell law, written for Lab Frame observables:

$$4\pi k_m \mathbf{r} v_x + (1/c^2) \partial_t E_x = \partial_y B_z - \partial_z B_y . \quad (51)$$

Use the Lorentz transformation of Eqs. (5) to shift the derivatives to Rocket Frame coordinates. Eq. (51) becomes

$$4\pi k_m \mathbf{r} v_x + (1/c^2) \partial_t' E_x = \gamma \partial_y' [B_z - (v_R/c^2) E_y] - \gamma \partial_z' [B_y + (v_R/c^2) E_z]. \quad (52)$$

To write  $\partial_z E_z$  in terms of time derivatives we use Gauss' law for  $\mathbf{E}$ , Eq. (50c), which says

$$\partial_x E_x + \partial_y E_y + \partial_z E_z = 4\pi k_e \mathbf{r} . \quad (53)$$

Writing these derivatives in terms of Rocket Frame coordinates using Eqs. (5), Eq. (53) gives

$$\gamma \partial_z' E_z = 4\pi k_e \mathbf{r} + \gamma (v_R/c^2) \partial_t' E_x - \partial_y' E_y - \partial_z' E_z . \quad (54)$$

Replacing the  $\gamma \partial_z' E_z$  in Eq. (52) with the right-hand-side of Eq. (54), noting that  $k_e = k_m c^2$ , and doing some re-arranging yields

$$4\pi k_m \gamma \mathbf{r} (v_x - v_R) + (1/c^2) \partial_t' E_x = \gamma \partial_y' [B_z - (v_R/c^2) E_y] - \gamma \partial_z' [B_y + (v_R/c^2) E_z]. \quad (55)$$

According to the Principle of Relativity, Eq. (55) must be identical to the Amperé-Maxwell law for Rocket Frame observables,

$$4\pi k_m \mathbf{r}' v' + (1/c^2) \partial E' / \partial t' = \tilde{\mathbf{N}}' \times \mathbf{B}' \quad (56)$$

Equating the fields of Eqs. (55) and (56) the previous result (*cf.* Eqs. (15)); to reconcile the current density terms between the Lab and Rocket Frames we require

$$\gamma \mathbf{r} (v_x - v_R) = \mathbf{r}' v_x' \quad (57)$$

From the kinematic section, Part A of the paper, Einstein showed the relativity of velocity, which for the  $x$ -component says

$$v_x' = \frac{v_x - v_R}{1 - v_x v_R / c^2} \quad (58)$$

Therefore, Eq. (57) yields

$$\mathbf{r}' = \gamma (1 - v_x v_R / c^2) \mathbf{r} . \quad (59)$$

*Since  $\mathbf{v}'$  is actually the velocity of the electric charges measured in the [Rocket Frame], we have thus shown that, on the basis of our kinematic principles, the electrodynamic foundations of Lorentz's theory of electrodynamics of moving bodies agrees with the principles of relativity.*

*Let me also briefly add that the following important proposition can easily be deduced from the equations we have derived: If an electrically charged body moves arbitrarily in space without altering its charge when observed from a coordinate system moving with the body, then its charge also remains constant when observed from the [Lab Frame].*

### 10. DYNAMICS OF THE (SLOWLY ACCELERATED) ELECTRON

In this section Einstein considers an electrically charged particle with charge  $e$  and mass  $m$  ("called an 'electron' in what follows"). The electron accelerates so slowly that its radiation can be ignored. He begins by asking us to consider the situation when the electron sits instantaneously at rest in the Lab Frame. It will feel, at least instantaneously, no magnetic force even if a  $\mathbf{B}$  field exists in this frame. Einstein applies Newton's Second Law to determine the electron's motion "during the next instant of time." The force equals  $q\mathbf{E}$ , so component by component, cause and effect of the electron's motion are related by

(continued on page 16)

# On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

$$eE_x = md^2x/dt^2 \tag{60a}$$

$$eE_y = md^2y/dt^2 \tag{60b}$$

$$eE_z = md^2z/dt^2 \tag{60c}$$

Now Einstein imagines the electron to be moving through the Lab Frame. In the “old way” of thinking, the force on the electron equals  $q(E + v \times B)$ . But Einstein uses his strategy described earlier, to examine the electron from *another* frame where it does *not* move at the instant in question. He follows his own advice, made at the end of Section 8. Physics is simple when the particles are (at least instantaneously) at rest! Analyze the problem in *that* frame, and afterwards Lorentz-transform the motion to whatever frame you want! So here in Section 10 Einstein confronts an electron moving in the Lab Frame, by first writing the equations of motion in the Rocket Frame chosen to be the frame where the electron is instantaneously at rest. The results can be transformed back to the Lab Frame afterwards, to tell the observer there the laws of the electron’s motion there.

To pull this off Einstein imagines the instant when the electron moves through the Lab Frame at the *same* velocity the Rocket flies through the Lab Frame. This means of course, that in the Rocket Frame the electron appears instantaneously at rest. *This important stipulation leads to a subtle technical point in following Einstein’s next steps.* To illustrate what I mean, let’s go outside Einstein’s deliberations and consider the motion of the particle with generic velocity vector  $(u_x, u_y, u_z)$  as measured in the Lab Frame, and  $(u'_x, u'_y, u'_z)$  (where  $u_x$  denotes  $dx/dt$ ,  $u'_y$  denotes  $dy'/dt'$ , and so forth). As usual, let the relative velocity between the frames be  $v_R$ , parallel to the  $x$  and  $x'$  axes. The subtle point will arise in the existence of three distinct gamma factors, as we shall see. Einstein does not comment on the *conceptual* distinction between them, but makes use of their *numerical* relations in the special case  $u = v_R$ . Note that here in this digression I do not, at first, require  $u = v_R$ ; when we impose  $u = v_R$  then we will have Einstein’s result of the first part of Section 10.

With Einstein, we *will* suppose, at a given instant, that  $u' = 0$ ; the particle experiences for this instant no magnetic force in the Rocket Frame. In describing the physics of this instant, the Rocket Frame observer writes Newton’s Second Law as it applies to the electron:

$$eE'_{x'} = md^2x'/dt'^2 \tag{60a}$$

$$eE'_{y'} = md^2y'/dt'^2 \tag{60b}$$

$$eE'_{z'} = md^2z'/dt'^2 \tag{60c}$$

We now transform the Rocket Frame observables to the Lab Frame, using the Lorentz transformation for the spacetime coordinates (Eqs. 3) and the transformations of the fields from Eqs. (15). Let’s start with  $du'_{x'}/dt'$ , the acceleration in the  $x'$ -direction. We recall the relativity of velocity, which follows from Eqs. (3), and for the  $x$ -velocities gives

$$u'_x = dx'/dt'$$

$$\begin{aligned} &= (dx - v_R dt)/(dt - v_R dx/c^2) \\ &= (u_x - v_R)/h \end{aligned} \tag{61}$$

For brevity I have defined

$$h \equiv 1 - v_R u_x / c^2 \tag{62}$$

To calculate the acceleration in the Rocket Frame we must evaluate

$$du'_{x'}/dt' = d[(u_x - v_R)/h]/dt' \tag{63}$$

For any quantity  $F$ , notice that

$$dF/dt' = (dF/dt)(dt'/dt)^{-1} \tag{64}$$

Here comes the technical point that one can easily overlook in trying to re-create Einstein’s derivation. Recall the time dilation formula: any particle carries its own proper time, its “wristwatch time”[4\*], denoted  $ds$ . For a tick of the wristwatch of duration  $ds$ , the clocks of observers in the Lab Frame record the time interval

$$dt = \gamma(u) ds \tag{65a}$$

and observers in the Rocket Frame record

$$dt' = \gamma(u') ds \tag{65b}$$

where

$$\gamma(u) \equiv (1 - u^2/c^2)^{-1/2} \tag{66a}$$

and

$$\gamma(u') \equiv (1 - u'^2/c^2)^{-1/2} \tag{66b}$$

The  $\gamma$  factor we have been using with the relative velocity *between frames* will henceforth be distinguished by the notation  $\gamma_R$ ,

$$\gamma_R \equiv (1 - v_R^2/c^2)^{-1/2} \tag{67}$$

OK, so on the one hand we have

$$dt'/dt = \gamma(u')/\gamma(u) \tag{68}$$

while on the other hand, from the Lorentz transformation of Eq. (3a) we also have

$$dt'/dt = \gamma_R h \tag{69}$$

We now have a statement about the relativity of the gamma-factors:

$$\gamma(u')/\gamma(u) = \gamma_R h \tag{70}$$

If (as I did) you don’t make this distinction between them in your first run-through of re-creating Einstein’s derivation, you will have a gamma cubed in the “wrong” place, and an “extra”  $h$ . The use of Eq. (70) clarifies the situation and gives Einstein’s result.

Returning to the task at hand, which was to evaluate  $dF/dt'$ , we see we can write it two ways:

$$dF/dt' = (dF/dt) \gamma(u')/\gamma(u) = (dF/dt)(\gamma_R h)^{-1} \tag{71}$$

With this, I originally found

$$du'_{x'}/dt' = (du'_{x'}/dt) (\gamma_R h)^{-3} \tag{72}$$

But using Eq. (70), this may also be written

$$du'_{x'}/dt' = (du'_{x'}/dt) [\gamma(u)/\gamma(u')]^3 \tag{73}$$

We return now to Einstein’s narrative. He said explicitly that,

(continued on page 17)

## On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

“Without loss of generality, we may and shall assume that the electron is at the coordinate origin and moves with velocity  $[v_R]$  along the  $x$ -axis of the [Lab Frame] at the moment with which we are concerned. It is then obvious that at the given moment ( $t = 0$ ), the electron is at rest relative to [the Rocket Frame].” This means  $\gamma(u) = 1$ , and  $h = 1/\gamma_R^2$ , and  $\gamma(u) = \gamma_R$ . With these results, and using the field transformations of Eqs. (15), we find that Eq. (60a), the  $x'$ -component of  $eE' = ma'_x$ , transforms to the Lab Frame as

$$eE_x = m\gamma^3(u) d^2x/dt^2. \quad (74)$$

This was the result as Einstein presented it, using the same symbol for  $\gamma(u)$  and  $\gamma_R$ . As we have seen, in general they are not equal, but in the instant considered by Einstein, they are equal.

We find in a similar manner the transforms for the accelerations of the  $y'$  and  $z'$  components, noting that, at the instant in question, Einstein puts  $dy/dt = 0$  and  $dz/dt = 0$ . We obtain

$$e\gamma_R(E_y - v_R B_z) = m\gamma^2(u) d^2y/dt^2 \quad (75a)$$

If we now invoke where  $\gamma_R = \gamma(u)$ , then with Einstein we obtain

$$e(E_y - v_R B_z) = m\gamma(u) d^2y/dt^2. \quad (75b)$$

Similarly, the  $z'$  equation transforms to

$$e(E_z + v_R B_y) = m\gamma(u) d^2z/dt^2. \quad (76)$$

We have written physics in the Rocket Frame, where the particle, for an instant, experienced electric force  $qE'$  and zero magnetic force. We then transformed the physics to the Lab Frame, to behold the equations of motion for the electrodynamics of the moving body.

Einstein next makes a comment about “longitudinal mass” and “transverse mass.” He notices that Newton’s Second Law when transformed to the Lab Frame, gives a different coefficient than plain old  $m$  on the  $ma$  side of  $F = ma$ . Einstein says we can “preserve the equation

$$\text{Mass} \times \text{Acceleration} = \text{Force}''$$

if we stipulate a re-definition of mass: for forces in the direction of the velocity, we define the “longitudinal mass,”

$$m_{\text{long}} \equiv m\gamma^3(u)$$

whereas for forces perpendicular to the particle’s velocity we define the “transverse mass,”

$$m_{\text{tran}} \equiv m\gamma^2(u).$$

“Longitudinal” and “transverse” masses are not concepts often taught today; they came out of pre-relativity discussions of the electrodynamics of moving bodies. Einstein tips his hat to that contemporary discussion by saying “Following the usual approach,...” when mentioning these “masses.” Einstein concludes this comment with an insightful caution about definitions:

*Of course, with a different definition of force and acceleration we would obtain different values for these masses; this shows that we*

*must proceed very cautiously when comparing various theories of electron motion.*

As Einstein’s work shows, the gamma factors come from the relativity of space and time between the Lab and Rocket Frames; they have nothing to do with mass itself. It’s interesting that he writes the same  $m$  for the electron in both the Lab and the Rocket Frames. There’s nothing to be gained by attaching gamma factors to the  $m$  and calling the result some kind of other mass. Leaving semantics and returning to physics, Einstein continues by noting that his equations of motion do not depend on the particle being literally an electron:

*It should be noted that these results about mass are also valid for ponderable material points, because a ponderable material point can be made into an electron (in our sense of the word) by adding to it an arbitrarily small electric charge. [original emphasis]*

For his last derivation in this famous paper, Einstein will “now determine the kinetic energy of an electron.” Let the electron start from the origin of the Rocket Frame, with zero velocity, and move along the  $x$ -axis by an electrostatic force  $eE$  which also points along the  $x$ -axis. The work done by this force will be

$$\int eE dx.$$

Einstein will equate this work to the increase in kinetic energy, using the work-energy theorem. In a step to follow Einstein will consider motion only along the  $x$ -axis, and write acceleration  $du/dt$  as  $udu/dx$ .

*Since the electron is supposed to accelerate slowly, and consequently cannot emit any energy in the form of radiation, the energy taken from the electrostatic field must be equated to the kinetic energy  $K$  [Einstein used  $W$ ] of the electron. Bearing in mind that [Eq. (74)] holds throughout the entire process of motion, we obtain*

$$\begin{aligned} K &= \int eE dx \\ &= \int m\gamma^3(u) (u du/dx) dx \\ &= m \int_0^v \gamma^2(u) u du \\ &= mc^2 [\gamma(v) - 1]. \end{aligned} \quad (77)$$

*“Thus,  $K$  becomes infinitely large when  $v = c$ . As is the case for our previous results, superluminal velocities are not possible.”*

By reasoning similar to Einstein’s statement above, this expression for kinetic energy must hold for ponderable bodies.

He wraps up the paper by summarizing his results:

*Let us now enumerate the properties of the electron’s motion resulting from the system of equations [Eqs. (74-76)] that are accessible to experiment.*

First, from Eq. (75) (the  $y$ -component) it is possible to determine the velocity of an electron in crossed  $E$  and  $B$  fields, where the forces

(continued on page 18)

## On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

cancel out, in which case  $v = E/B$ . Einstein notes, “This relation can be tested experimentally since the velocity of the electron can also be measured directly, e.g., using rapidly oscillating electric and magnetic fields.”

Second, from the derivation of the kinetic energy, the change in electric potential  $\Delta\phi$  must be related to the electron’s velocity by

$$\Delta\phi = (m/e)c^2 [\gamma(v) - 1]. \quad (78)$$

Third, the radius of curvature  $R$  of an electron moving through a magnetic field  $B$  acting perpendicular to the electron’s velocity will be given from Eq. (75) by

$$v^2/R = (e/m) v B_z [1 - v^2/c^2]^{1/2} \quad (79)$$

giving the predicted radius of curvature

$$R = (mv/eB_z) [1 - v^2/c^2]^{-1/2} \quad (80)$$

*These three relations are a complete expression of the laws by which, according to the theory presented here, the electron must move.*

*In conclusion, let me note that my friend and colleague M. Besso steadfastly stood by me in my work on the problem discussed here, and that I am indebted to him for several valuable suggestions.*

“On the Electrodynamics of Moving Bodies” was published in *Annalen der Physik* in June 1905. By September, Einstein had thought of another observable consequence of the theory: the equivalence of mass and energy. In a letter to Conrad Habicht that summer, Einstein wrote[2]

*One more consequence of the paper on electrodynamics has also occurred to me. The principle of relativity, in conjunction with Maxwell’s equations, requires that mass be a direct measure of the energy contained in a body; light carries mass with it. A noticeable decrease of mass should occur in the case of radium. The argument is amusing and seductive; but for all I know the Lord might be laughing over it and leading me around by the nose.*

The  $E = mc^2$  paper was published in *Annalen der Physik* in September 1905. It was very short, a kind of afterthought to the long electrodynamics paper earlier that spring. The short note was titled

Does the Inertia of a Body  
Depend on Its Energy Content?  
*Annalen der Physik* 18, 639-641 (1905)

*The results of an electrodynamic investigation recently published by me in this journal lead to a very interesting conclusion, which will be derived here.*

This “interesting conclusion” was “ $E = mc^2$ .”

Einstein recalls the discussion of his Section 8 of his “Electrodynamics of Moving Bodies” paper, where the ray of a system of plane light waves carries energy  $\varepsilon$  relative to the Lab Frame makes the angle  $\phi$  with Lab Frame  $x$ -axis. The Rocket Frame moves

parallel to the Lab  $x$ -axis, with velocity  $v_R$ . Recalling what for us here is Eq. (42),

$$\varepsilon' = \varepsilon \gamma [1 - (v_R/c)\cos \phi], \quad (81)$$

Einstein now lays out the following scenario:

Let a body at rest in the Lab Frame have energy  $E_0$  relative to the Lab Frame, and energy  $E_0'$  relative to the Rocket Frame. Of course, Rocket Observers see this body moving with velocity  $-v_R$  relative to them.

Suppose this body emits plane light waves with energy  $\varepsilon$  as measured relative to the Lab Frame. Let half the energy carried by these waves move in the direction that makes angle  $\phi$  with respect to the  $x$ -axis, and the other half of the energy be carried in the opposite direction. Let  $E_1$  and  $E_1'$  denote the energy of the body after emission of light, as measured in the Lab and Rocket Frame respectively. The body remains at rest with respect to the Lab Frame, and continues moving with its original velocity relative to the Rocket Frame, because the light waves emitted in opposite directions conserve momentum.

According the Principle of Relativity, conservation of energy must be true in both reference frames. Energy conservation gives, in the Lab Frame,

$$E_0 = E_1 + [\frac{1}{2}\varepsilon + \frac{1}{2}\varepsilon], \quad (82)$$

and in the Rocket Frame,

$$\begin{aligned} E_0' &= E_1' + \{\frac{1}{2}\varepsilon \gamma[1 - (v/c)\cos \phi] \\ &\quad + \frac{1}{2} \varepsilon \gamma[1 + (v/c)\cos \phi]\} \\ &= E_1' + \varepsilon \gamma. \end{aligned} \quad (83)$$

By subtraction we have

$$(E_0' - E_0) - (E_1' - E_1) = \varepsilon(\gamma - 1). \quad (84)$$

Einstein says, “Both differences of the form  $E' - E$  occurring in this expression have simple physical meanings.” The term  $(E_0' - E_0)$ , for instance, compares the energy values of the body before emission between the Rocket and Lab Frames. Within an additive constant  $C$ , this energy difference will be the body’s kinetic energy as measured in the Rocket Frame, before the light was emitted:

$$E_0' - E_0 = K_0' + C \quad (85)$$

where  $K$  denotes kinetic energy. Likewise, after emission we may write

$$E_1' - E_1 = K_1' + C. \quad (86)$$

since  $C$  does not change during the emission of light. Eq. (84) becomes

$$K_0' - K_1' = \varepsilon(\gamma - 1). \quad (87)$$

*The kinetic energy of the body with respect to the [Rocket Frame] decreases as a result of emission of the light by an amount that is*

*(continued on page 19)*

# On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and its Corollary, $E=mc^2$ , by Albert Einstein

(continued from previous page)

independent of the properties of the body. Furthermore, the difference  $K_0 - K_1$  depends on the velocity in the same way as does the kinetic energy of an electron.

In this last sentence Einstein refers to his derivation, in Section 10 of the *Electrodynamics* paper (and our Eq. 77), that the kinetic energy of a moving electron is  $mc^2(\gamma - 1)$ .

Recalling that  $\gamma = (1 - v^2/c^2)^{-1/2}$ , upon expanding the binomial, to leading order in  $v/c$ , we can get

$$K_0 - K_1 = \frac{1}{2} (\epsilon/c^2) v^2. \tag{88}$$

From this equation one immediately concludes:

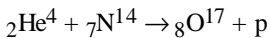
If a body emits the energy  $\epsilon$  in the form of radiation, its mass decreases by  $\epsilon/c^2$ . Here is it obviously inessential that the energy taken from the body turns into radiant energy, so we are led to the more general conclusion:

the mass of a body is a measure of its energy content; if the energy changes by  $E$ , the mass changes in the same sense by  $E/9 \times 10^{20}$  if the energy is measured in ergs and the mass in grams.

It is not excluded that it will prove possible to test this theory using bodies whose energy content is variable to a high degree (e.g., radium salts).

If the theory agrees with the facts, then radiation carries inertia between emitting and absorbing bodies.

In 1905 the strongly radioactive element radium was an energetic enigma, having been discovered in 1898 by Marie and Pierre Curie. The mechanism for its enormous energy release could not be understood until after the atomic nucleus was discovered by Rutherford in 1911. By comparing the masses of products to reactants in the first known produced nuclear reaction done in 1919,



using alpha particles from a radioactive source, the experiment dramatically confirmed  $E = mc^2$ .

[1] Albert Einstein, "Zur Elektrodynamik Bewegter Körper," *Annalen der Physik* 17, 891-921 (1905).

[2] Einstein quotes in this annotation are from the translation by John Stachel (Ed. and trans.) and Roger Penrose, *Einstein's Miraculous Year: Five Papers that Changed the Face of Physics* (Princeton Univ. Press, 1998). This excellent translation includes a chapter of background and history of each of the five 1905 papers.

[3] An earlier translation of Einstein's 1905 relativity papers is W. Perrett and G.B. Jefferey (trans.), *The Principle of Relativity* (Methuen, 1923; reprinted by Dover, 1952).

[4] In 1912 Einstein wrote a summary of Special Relativity in which some of his 1905 calculations re-appear. This was recently published with translation as *Einstein's 1912 Manuscript on the Special Theory of Relativity* (Braziller, 2003).

[5] I can only assume in this article that the reader is familiar with Part A of this annotation, 'On the Electrodynamics of Moving Bodies (Part A: Kinematics) by Albert Einstein,' *SPS Observer* (Fall 2005), pp. 10-15. Translation dictionary for notation between this annotation and Einstein:

This annotation	Einstein
Lab frame*	Rest system $K$
Rocket frame*	Moving system $k$
speed of light: $c$	$V$
Relative velocity between reference frames:	
$v_R$	$v$
$(1 - v_R^2/c^2)^{-1/2}: \gamma$	$\beta$
Lab coordinates $(x, y, z, t)$	$(x, y, z, t)$
Rocket coordinates $(x', y', z', t')$	$(\mathbf{x}, \mathbf{h}, \mathbf{z}, t)$
Electric field: $(E_x, E_y, E_z)$	$(X, Y, Z)$
Magnetic field: $(B_x, B_y, B_z)$	$(L, M, N)$
frequency: $f$	$\nu$
Direction cosines: $(K, L, M)$	$(a, b, c)$
Energy of light: $U$	$E$
Fundamental charge: $e$	$\epsilon$
Electron mass: $m$	$\mu$

\* The "Lab frame" and "Rocket frame" were introduced by E. Taylor and J. A. Wheeler, *Spacetime Physics* (Freeman, 1966, 1992). The Lab frame records events in space and time with unprimed coordinates  $(t, x, y, z)$ ; the Rocket frame employs primed coordinates  $(t', x', y', z')$ . The respective axes such as  $x$  and  $x'$  are parallel; the clocks throughout both frames read zero when the two origins coincide; and the Rocket moves with uniform velocity  $v_R$  relative to the Lab parallel to the  $x$  axis. In the Rocket frame the Lab moves parallel to the  $x'$  axis with velocity  $-v_R$ .

[6] To see this, consider any  $f(x, t)$ , where  $x$  and  $t$  are functions of  $x'$  and  $t'$ , so that  $f(x, t) = f[x(x', t'), t(x', t')]$ .

Then

$$\partial_t f = (\partial_{x'} f)(\partial_t x') + (\partial_{t'} f)(\partial_t t')$$

and similarly for  $\partial_{x'} f$ . Use the Lorentz transformation to find  $\partial_t x'$  and  $\partial_t t'$ . Einstein writes these derivative relations explicitly in Ref. 4.

[7] In Einstein's versions of these equations, some of his terms and ours here differ by a factor of  $1/c$  because he uses different units. Using Einstein's original approach we have derived the same results but in SI units. Results similar to ours are displayed in the intermediate electrodynamics text of P. Lorrain, D. Corson, and F. Lorrain, *Fundamentals of Electromagnetic Phenomena* (Freeman, 2000), p. 234; and D. Griffiths, *Introduction to Electrodynamics*, 3rd Ed. (Prentice-Hall, 1999), p. 531.

[8] Einstein's transformation of the phase, showing  $\Phi' = \Phi$ , anticipates the "invariance of the scalar product in spacetime," with the case

$$\omega t' - \mathbf{k}' \cdot \mathbf{r}' = \omega t - \mathbf{k} \cdot \mathbf{r}.$$

The quantum postulates  $E = h\nu$  and  $p = h/\lambda$  for electromagnetic radiation came shortly after the 1905 electrodynamics paper, but if we use them in the above we find the invariance of the scalar product of the energy-momentum four-vector with the spacetime four-vector,  $\langle p' | x' \rangle = \langle p | x \rangle$

[9] Quoted in Stachel, Ref. 2, p. 117. ◆

(continued on page 20)

# AAPT Conference Summer 2005

Parallel Coverage by

Ron Proctor & Michael Malmrose

## SIDE A

Ron Proctor, Weber State University, SPS

I first became interested in physics while taking an introductory astronomy course. The course deepened my love of astronomy and exposed me to some physical problem solving tools. I was hooked and soon switched my major. After some adjustment, I found a niche for my skill set and I now work as the production Director for Ott Planetarium at Weber State University. My undergraduate work will eventually boil down to a Bachelor of Integrated Studies (BIS) degree; incorporating physics, art, and communication. This course of study will (hopefully) lead to a career in scientific visualization or graduate work in science journalism.

As an undergraduate about to begin my (first) senior year, I was excited for this opportunity to report on the AAPT Summer 2005 Conference for SPS. This being my first large academic conference, I expected the proceedings to be somewhat dry. In retrospect I cannot justify this expectation, as most of the physics teachers I know are lively, fun, engaging people. The AAPT participants I met did not disappoint.

My colleague and I enjoyed two days at the conference, taking in poster sessions, exhibits and presentations. My favorite part was a little block of three paper presentations. The first, by J. Ronald Galli, involved "Time Dilation and Length Contraction," illustrated with only a light clock. Galli's presentation conveyed these concepts in a very effective and condensed fashion.

The second presentation of the series was by D. J. Wagner of Grove City College. She discussed her research, "Filling the Void: Teaching about Semiconductors and Semiconductor Devices." I did not expect her talk to be especially important to me, as I have little to do with semiconductors, but I was surprised at the relevance of her presentation to my upcoming research project, "The Effectiveness of Scientific Visualization Techniques: Teaching the Lunar Cycle." I found the discussion of her research methods to be quite useful. In particular, I was impressed with her characterization and organization of the student responses both in the pre- and post-introduction phases. Her presentation encouraged me and got me thinking

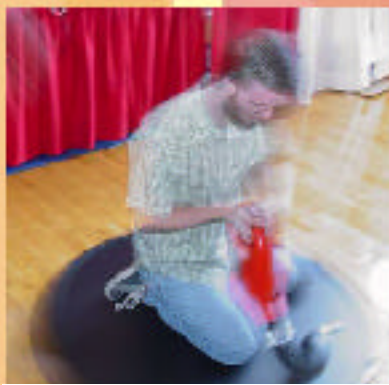
## SIDE B

Michael Malmrose, Weber State University, SPS

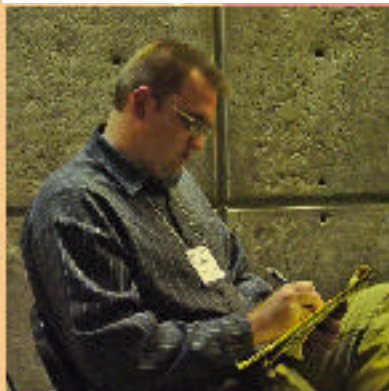
In the seventh grade, my science teacher Mr. Jenkins, a biologist, assigned each of his students to watch at least one hour of science-related programming a week and write a list of ten things that we learned from the program. It was while completing the assignment that I discovered an ancient set of videocassettes at my local library named *Cosmos* narrated by the late Carl Sagan. I had always been interested in space and checked out a couple of the tapes and went about my assignment. After viewing the first episode, I devoured the other 12 over the next couple of weeks. Sagan's enthusiasm was contagious and I soon read every book of his that I could get my hands on. Later on in high school, I was reading Stephen Hawking when I should have been paying attention to my English teacher. This early exposure, and my success in a general education physics course my first semester in college, guided my decision to major in physics.

Like my colleague, I am an undergraduate about to embark on the first of two "senior" years at Weber State University in Ogden, UT. I was thrilled when asked to report on the AAPT summer conference. Unlike Ron, this is my second conference. I was fortunate enough to present a poster (as a group of five students) at the June 2004 AAS meeting in Denver, CO. However, since I did not present anything at this conference, I was free to wander and try out various demos, instead of standing by my poster, begging people to ask me a question. I even was able to ride a makeshift hovercraft made from a leaf-blower and a couple of sewn together pieces of fabric. Ron and I were also quite impressed at the soda and ice cream kept cold in our dreadfully hot Utah summer by dry ice pellets. We also met fellow SPS members at the University of Utah who were in charge of selling T-Shirts and laser pens commemorating the event.

Like Ron I also very much enjoyed a three-talk session given Tuesday afternoon. Weber State's own J. Ronald Galli spoke on the topic of "Time Dilation and Length Contraction" using only one horizontally oriented, moving clock. It was cool to see somebody I have taken a



Mike riding a leaf-blower powered hovercraft.



Ron takes notes during a presentation.



J. Ronald Galli demonstrates Light Clock models.

## SIDE A

about how I will present my own research when the time comes.

The third presentation was by Harry Manos of Los Angeles City College. He discussed “Auroral

Photography.” The presenter was a first time aurora photographer who, with the help of a young man in Alaska, developed some considerable skill and technique. The images he displayed were brilliant and beautiful. Since seeing the aurora myself in 2001, I have felt drawn toward its mystery. This enigmatic light in the sky can tell us much about the Earth’s upper atmosphere, magnetosphere, and the Sun-Earth environment. (One of my favorite demonstrations at our planetarium is the Classroom Aurora built by John Sohl. Our apparatus simulates the aurora by evacuating a cylindrical chamber and running 5,000 volts across the expanse. The result is a beautiful red glow that can be manipulated with a magnet). Manos’ presentation inspired me to develop my photography skills and to always keep a camera and tripod in my vehicle, just in case.

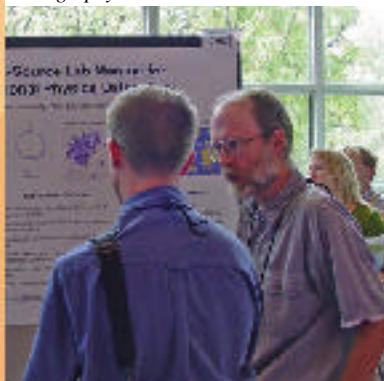
During our visit to the conference, Mike and I had the opportunity to speak with many exhibitors and presenters. I really appreciated the opportunity to review and evaluate so many different ideas.

The diversity of the conference was a pleasant surprise. Even knowing that physics is such a broad subject, I could not

have imagined so much variety. There really was something for everybody. I thoroughly enjoyed the time I spent at this conference and I look forward to my next.



*Harry Manos discusses Auroral Photography.*



*Dan Schroeder presented one of the many excellent posters.*

## SIDE B

class from come up with the same ideas of special relativity, without using trains and firecrackers. It really helps to have another thought experiment to think about when I wrestle with the difficult concepts of space and time. After his talk,

Dr. Galli was kind enough to show these two blooming young physicists his patented “Galli Cat,” a wire model that seeks to explain why cats always land on their feet. The Galli Cat has a series of springs along its spine that when flexed create a small torque so that when released, the cat simply rolls over and lands on its feet naturally. This explanation is much simpler and elegant than the explanation given by many physics books.

We were also treated to a talk discussing the finer points of photographing the Aurora Borealis. You cannot take exposures for much more than about 30 seconds, because the aurora is in constant motion and you will not get a very good picture. This was a fitting talk because the next AAPT meeting takes place in Alaska in January, 2006.

I am very grateful to have been able to attend a conference where actual scientific research was presented. It was a great reminder of what I am dedicating so much time and effort to, learning abstract concepts and very difficult math. One of my teachers has compared science to a giant house of which each of us are responsible for laying our own individual bricks. At these confer-

ences, we proudly display our bricks to the world for anybody to take their best shot at. Many times our bricks do not fit and need modification before they are usable, other times they need to be discarded completely. Regardless, we have made an important contribution to the advancement of human knowledge. I will end with the words of another of my childhood discoveries, Bill Nye the Science guy, “Science Rules!”

## THE NUCLEAR NON-PROLIFERATION BARGAIN UNDER SIEGE

(continued from page 3)

with the U.S. to intercept nuclear weapon related shipments by and to “rogue” states. Thus a major challenge to the non-proliferation “bargain” is the lack of an even-handed enforcement policy by the United States. The IAEA as an organ of the United Nations does a significantly more equitable job, but has limited authority and resources.

During the NPT Review Conference the NNWS attempted to flag the alleged non-compliance of the NWS, in particular Russia and the U.S., with Article VI charging these states with insufficient progress in Nuclear Arms Control. But this is a difficult case to make since the NPT does not provide quantitative language which specifies a time-table for nuclear arms reductions by agreed amounts. Indeed after the end of the Cold War the United States and the Soviet Union combined still retain about 30,000 nuclear weapons, over 95 percent of the world’s total. These numbers include long-range (strategic), short range (tactical) weapons and nuclear weapons held in reserve. While the U.S. and Russia agreed in 2002 under the Moscow Treaty to reduce “operationally deployed strategic weapons” to about 2200 by the year 2012, that category is only a minor fraction of their total inventory. The Moscow Treaty expires in the year 2012 and contains no provisions for monitoring or control and specifies no stages through which its goal should be reached. So the U.S. and Russia continue to maintain that they are “in compliance” with Article VI, while the NNWS take the position that these vast numbers, and the policies of using these weapons, contradict the spirit, if not the legal text, of Article VI. Both sides are technically correct, but this inherent conflict undermines the Treaty.

These are the overt conflicts putting the NPT “under siege.” But the basic causes for this tension are fundamental: they are rooted in the nature of nuclear weapons and the historical difficulty of preventing the proliferation of any new technology.

Indeed, the NPT has greatly slowed the spread of nuclear weapons beyond expectations. But nuclear weapons in a fundamental sense are the “great equalizer” between the great powers and the lesser states. Since even a single nuclear weapon detonated in a city can kill about a million people and can dwarf the damage of the September 11 attacks, a small state, once having acquired a very small number of such weapons, becomes a very serious factor in the affairs of nations. In turn, the military policies of the U.S. drive nuclear proliferation. As long as the United States, as the remaining “super power,” flaunts its nuclear and conventional military power and its willingness to use that power, other countries, unable to match that power, will be induced to acquire nuclear weapons. In the words of a former Deputy Defense Minister of India: “Never negotiate with the United States unless you have a nuclear weapon.”

But above all, in the long run, states must be persuaded that their National Security is served better if they do not acquire nuclear weapons than if they do. In other words, we must consider the motivation for nuclear weapons proliferation.

Thus I conclude that the siege now confronting the non-proliferation treaty will not be totally lifted unless the use of violence in resolving international conflicts is drastically diminished. Many of the measures cited here in summary can make this siege less oppressive, but true long range relief must await the emergence of a less violent world.

<sup>1</sup> A significant quantity of plutonium is 8kg and of U235 is 25kg.



### Welcome to the Nucleus!

This website is designed for physics and astronomy undergrads. There are all sorts of resources for research and learning, plus cool links and discussion forums for talking with fellow students.

**Summer Research Opportunities on The Nucleus**  
<http://www.compadre.org/student/research/main.cfm>

Last year, our database provided students with access to roughly 1000 summer science opportunities at more than 140 research sites! We plan to have even more submissions this year. Employers began posting their positions for Summer 2006 in late fall, so stay tuned.

Our summer opportunity database is searchable by state or keyword—just type in what you’re looking for and let our search engine do the rest!

The Nucleus is a collaboration between [AAPT](#) and the [SPS](#), funded in part by the [NSF/NSDL](#) as part of the [ComPADRE Digital Library](#).  
 ©2006, All Rights Reserved

**the nucleus**   
 resources for physics and astronomy undergraduates

<http://www.compadre.org/student/>



**SPS Featured Chapter**  
**Hampton University**  
**Hampton, Virginia**

INSIDE THIS ISSUE

- 1** The Nuclear Non-Proliferation Bargain Under Siege  
— by *W. K. H. Panofsky*
- 1** Medical Physics Interview  
— by *Kenny Homann, University of Texas-Houston*
- 5** **FOR YOUR INFORMATION:** Physics Speakers Available for SPS Chapters and Their Departments
- 6** Outstanding SPS Chapters for 2005

- 8** Physics News Update
- 10** **ELEGANT CONNECTIONS IN PHYSICS:** On the Electrodynamics of Moving Bodies (Part B: Electrodynamics), and Its Corollary,  $E=mc^2$ , by Albert Einstein  
— by *Dwight E. Neuenschwander*
- 20** AAPT Conference Summer 2005 Report  
— by *Ron Proctor and Michael Malmrose, Weber State University SPS Chapter*
- 23** Welcome to the Nucleus!

INSIDE THIS ISSUE



National Office  
Society of Physics Students—Sigma Pi Sigma  
One Physics Ellipse  
College Park, MD 20740

Non-Profit Org.  
U.S. Postage  
**PAID**  
Bowie, MD  
Permit No. 4434