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Telephone: (415) 926-2585
INTERNET: beamline@slac.stanford.edu
BITNET: beamline@slacvm
FAX: (415) 926-4500
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Cover: A beam's-eye view of the SLAC Large Detector, or SLD, being readied for installation in 1990. (Photo by Joe Faust).

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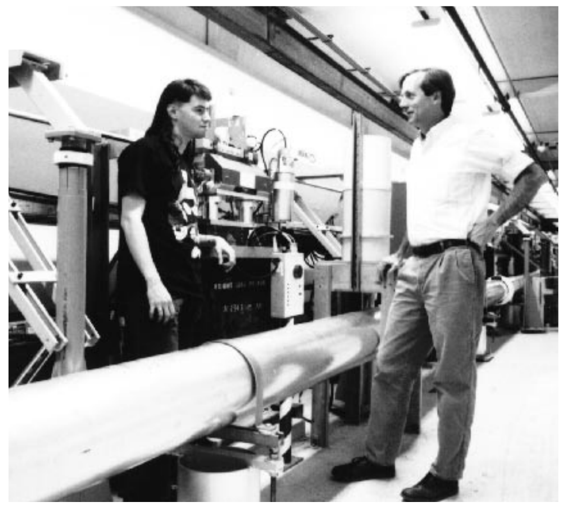

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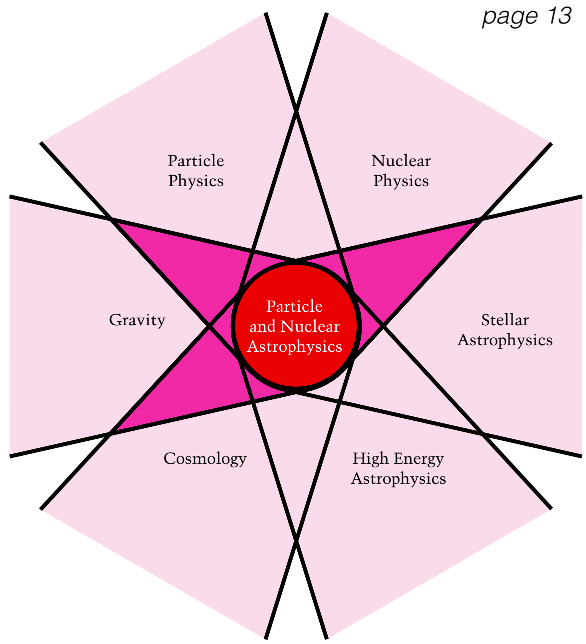

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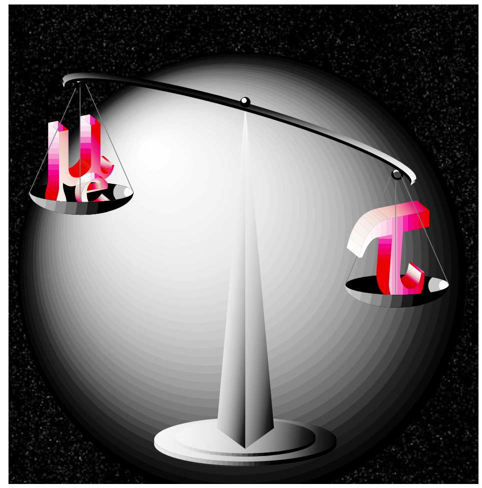

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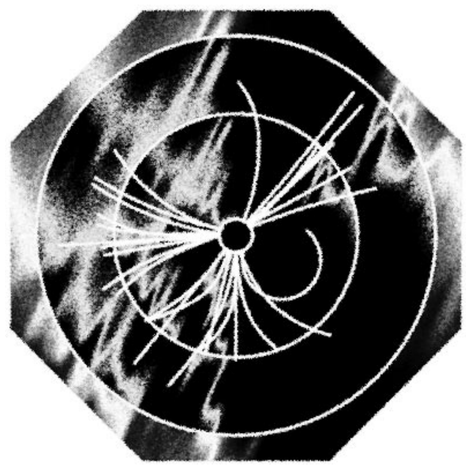

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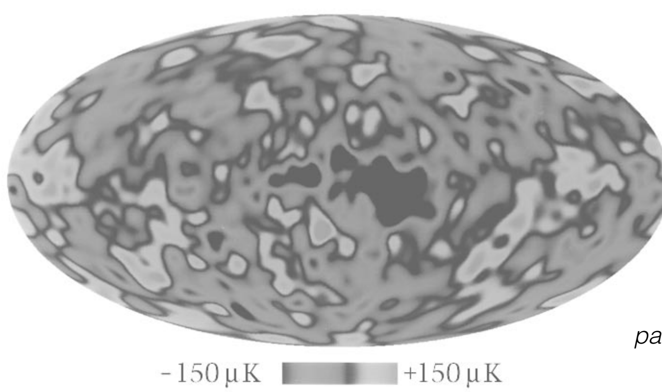

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THE FINAL FOCUS TEST BEAM

Encouraging results on the path towards a future Linear Collider

by
PETER G. TENENBAUM

SINCE THE SUMMER of 1993, accelerator physicists from around the world have been performing a series of experiments on a challenging new beam line at SLAC. The Final Focus Test Beam (FFTB) is the product of an international collaboration to design and build a prototype for a future linear collider final focus system. The goal of the experiments: to focus the SLAC electron beam to a vertical size of 60 nanometers—one tenth the wavelength of visible light, and about one-tenth the smallest spot yet produced by the present SLC final focus system.

The FFTB's construction was completed in the summer of 1993. At that time, a series of shakedown tests were performed of the behavior of the hardware under running conditions. Spring of 1994 saw the FFTB commissioning begin in earnest. These runs accumulated a total of three weeks of beam time, during which the lion's share of hardware and software was fully utilized and commissioned. The beam was ultimately focused down to a vertical size of 70 nanometers and maintained for several hours through dozens of measurements. During a two-week run in September 1994, the 70 nanometer size was quickly recovered, the beam-size measuring devices were more completely optimized, and measurements with the beam energy and energy spread indicated that the chromatic (energy-dependent) aberrations of the beam line were quite small. A quick two-day run in January 1995 was used to resolve minor mysteries which had previously appeared and to perform early tests on a new super-high resolution beam-position monitor.

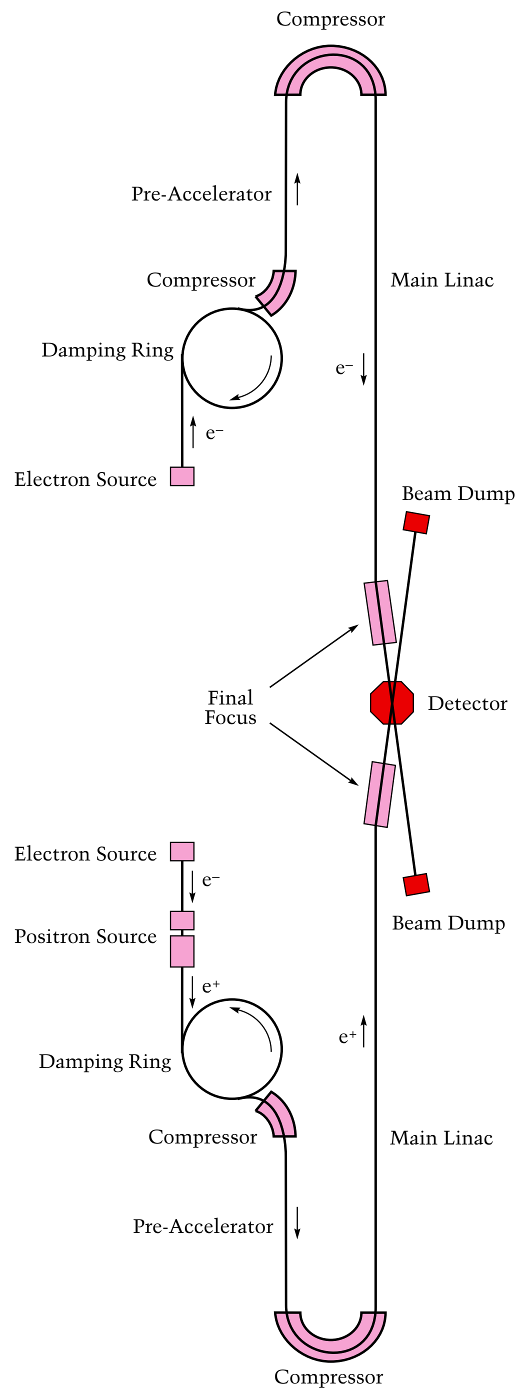
Future FFTB experiments will use the results of the previous experiments to attempt to reduce the beam size further, to below the design goal of 60 nanometers. The new beam-position monitor (BPM) will be fully commissioned and then used to control the beam position to a few nanometers, which is the level required for a high-luminosity machine such as the Next Linear Collider.

THE NEXT LINEAR COLLIDER

Currently, only one linear collider exists: the Stanford Linear Collider (SLC), which collides 50 GeV positrons and electrons. In order to study higher energy realms of physics with great precision, it is necessary to build an accelerator which can collide electrons and positrons at much higher energies—500 to 1,500 GeV. Because of the way in which circular and linear colliders scale with beam energy, only a linear collider is feasible for electrons and positrons at this energy.

In order to produce large numbers of interesting events in a reasonable time, the Next Linear Collider (NLC) must produce luminosities from 10^{33} to 10^{34} cm^{-2} sec^{-1}. Because a linear collider is limited in its collision frequency and in the charge that can be carried in a single bunch, the beam sizes at the collision point will need to be extremely small—around 300 nanometers in the horizontal and as small as 3 nanometers in the vertical! This means that the final focus of the NLC will have to demagnify the beam coming in from the linear accelerator by a factor of about 400 in the vertical. Because the beam will be 100 times as large in the horizontal, it will also be necessary to carefully adjust the beam so that it is not "rolled" at the interaction point—even 1 degree of roll will cause the focused spot to double its vertical size. Such requirements place very tight constraints on the final focus system's alignment, stability, and tunability.

For many years, physicists around the world have collaborated on the design of such a collider. Several experimental facilities have been built to determine the best technologies and techniques to use for various of the collider's subsystems. The Final



Schematic diagram of a future linear collider. Beams of electrons and positrons are accelerated separately in the two linacs, focused in the final focus systems, and brought into collision in the center of the detector. In order to provide the necessary energy to the particles, the accelerator needs to be about 20 kilometers long.

Worldwide R&D for a Future Linear Collider

THE FINAL FOCUS TEST BEAM is one experiment in a worldwide research and development effort directed towards a TeV-scale linear collider. The goal is to fully understand all the sub-systems of such a collider.

One of the most important components of a future linear collider is a pair of linear accelerators—one for electrons, one for positrons. Several different schemes for the accelerators have been proposed, and these form the basis for four of the experiments. Scientists at DESY (in Hamburg, Germany) have proposed a design called TESLA—TeV Electron Superconducting Linear Accelerator—which uses superconducting RF cavities for the necessary acceleration. Their system is being prototyped and tested at the TESLA Test Facility (TTF) at DESY. Also at DESY is the S-Band Test Facility, which is developing an extremely advanced form of the SLAC acceleration scheme, suitable for the demands of a future linear collider. Another scheme, proposed at CERN (in Geneva, Switzerland), uses a low-power, high-current "drive" beam in one accelerator to provide power for a high-power, lower-current beam in a second accelerator running alongside it. The machine which uses this scheme is called CLIC, for Cern LInear Collider. The CLIC two-beam accelerating technique is being developed at the CLIC Test Facility (CTF) at CERN. A fourth acceleration system, using a room-temperature rf system at a much higher frequency than the SLAC linac, is being developed at SLAC in the form of the Next Linear Collider Test Accelerator (NLCTA). The wakefield properties of this system were tested last year in the ASSET (Accelerating Structure SETup) experiment, also at SLAC.

A crucial element of a TeV-scale linear collider is a beam injector and damping ring system which can produce the small emittance, high-intensity bunch trains which will be accelerated by the linac. At KEK (in Tsukuba, Japan), construction has begun on the Accelerator Test Facility (ATF), a prototype for the injector-damping ring complex of a high-luminosity linear collider.

A new generation of beam instrumentation will be required to commission and tune a future linear collider. Prototypes for much of this instrumentation have been developed already for the FFTB. These include the beam position monitors and precision wire scanners (SLAC), the stretched-wire alignment system (DESY), the magnet movers (Max Planck Institute), and advanced beam size monitors (KEK and LAL Orsay). New developments include a beam position monitor of even higher resolution developed at KEK, and a "laser-wire" beam size monitor being developed at SLAC for the SLC.

Focus Test Beam is such a facility: components and ideas for the FFTB have come from KEK in Japan, Max Planck Institute and DESY in Germany, the Budker Institute in Russia, LAL in France, and Fermilab and SLAC in the United States.

DESIGN OF THE FFTB

The FFTB is designed to use the 47 GeV electron beam which is usually deflected into the SLC collider arc and sent to the SLC Interaction Point (see figure at top of next page). During FFTB experiments, the electron beam is reduced in intensity to the NLC design current of 0.7–1.0×10^{10} electrons per pulse, from the SLC's current of about 3.5×10^{10} per pulse. Instead of being deflected to the north, the electron beam is allowed to travel straight ahead from the linac into the FFTB itself.

The use of linear focusing magnets (quadrupoles) to reduce the size of a beam of charged particles is well understood, and in principle can be used to reduce any electron beam to any desired size. This problem is similar to creating a good image of a scene through the optical lenses of a camera. Simple focusing can only work for monoenergetic bunches, because electrons of different energies are focused by different amounts in a given quadrupole magnet. Since all real accelerators will produce electron beams with some energy spread within a bunch, and some energy jitter between bunches, it is necessary to correct this energy-dependent focusing. This is done with nonlinear focusing magnets, called sextupoles. By using a pair of sextupole magnets, with carefully tuned dipole and quadrupole magnets between them, the energy-dependent characteristics of the main focusing magnets can be corrected, without introducing additional effects which would enlarge the focused spot. The smaller the desired spot, however, the more carefully the magnets performing this correction need to be tuned. The FFTB has two such pairs of sextupole magnets: one for correcting horizontal focusing, one for correcting vertical.

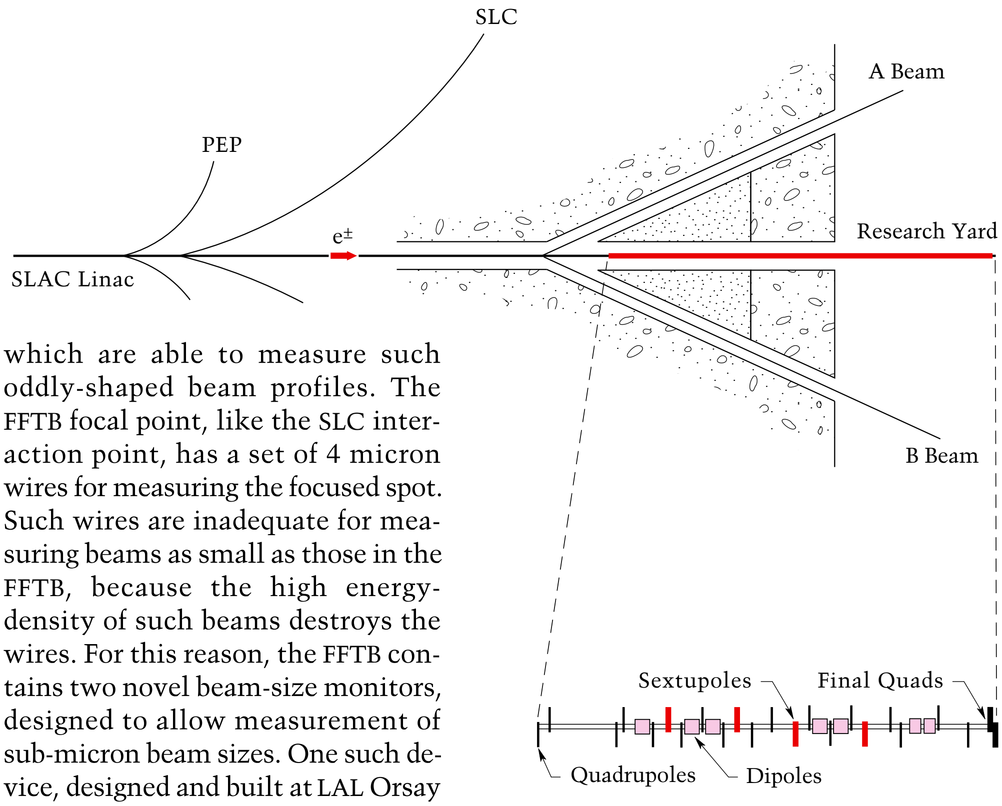
Once the nonlinear tuning described above is properly completed, the expected beam size at the focal point of the FFTB is 2 microns horizontally by 60 nanometers vertically. This represents a demagnification of the incoming beam by a factor of 380, which is the design demagnification for the NLC. While the focused spot has an aspect ratio of 32 to 1, and not 100 to 1, this still introduces all the tuning difficulties due to rolled spots. In short, virtually all of the expected challenges of the NLC Final Focus are also present in the FFTB. In order to meet these challenges, the FFTB has been built with state-of-the-art hardware, including tightly machined quadrupole and sextupole magnets on individual power supplies; a new generation of remote-controlled magnet movers with submicron step sizes; a large number of beam position monitors (BPMs) capable of resolving pulse-to-pulse beam motions of 1 micron; and an external alignment-monitoring system with similar resolutions.

A particular problem for the FFTB and NLC is measuring the beam size. At several points in the FFTB, the beam size is under 10 microns in one dimension and much larger in the other. At these points, a special set of wire scanners has been installed which are able to measure such oddly-shaped beam profiles. The FFTB focal point, like the SLC interaction point, has a set of 4 micron wires for measuring the focused spot. Such wires are inadequate for measuring beams as small as those in the FFTB, because the high energy-density of such beams destroys the wires. For this reason, the FFTB contains two novel beam-size monitors, designed to allow measurement of sub-micron beam sizes. One such device, designed and built at LAL Orsay in France, measures the interaction between the electron beam and a sample of argon or helium gas, injected at the Focal Point. The other, built at KEK in Japan, uses the interaction between the beam and a laser beam interference pattern. Both devices are capable of measuring the beam size down to the goal of 60 nanometers, with a resolution of 10 percent.

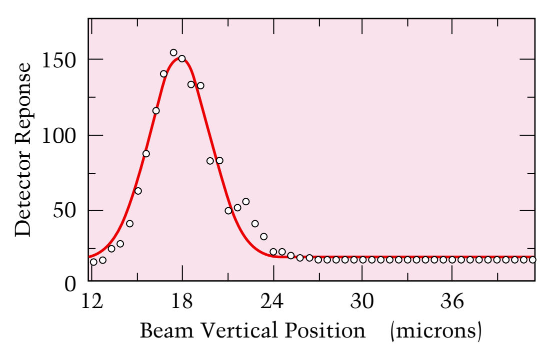
RESULTS FROM BEAM TIME

Once the beam line construction and installation was complete in the summer of 1993, several short runs were made to test the performance of the hardware and instrumentation under running conditions. The sextupole magnets were not used, so extremely small beam sizes were not possible. However, using only the quadrupole magnets, the expected vertical beam size of 1.4 microns was achieved and measured using the focal point wire scanners. This also confirmed that basic control of the beam line—the ability to achieve a given focused size, at a given location—had been accomplished.

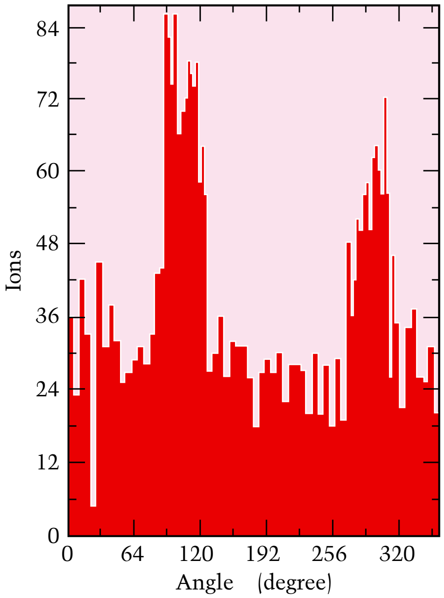
During the spring of 1994, the FFTB ran experiments for a total of



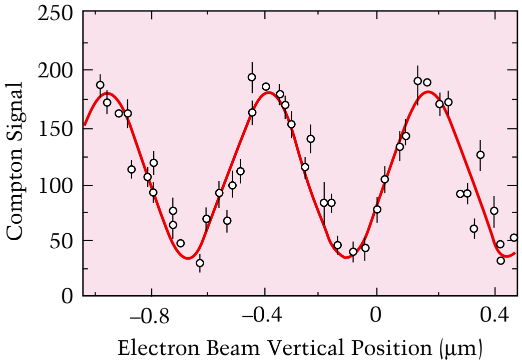
Overview of the end of the SLAC linac, showing the location of the FFTB in relation to the SLC arcs and end station beam lines. Also shown is the arrangement of dipoles, quadrupoles, and sextupoles that make up the FFTB.



Measurement of the focused beam by a 4 micron carbon wire at the focal point of the FFTB. This measurement indicates a 3 micron vertical size. These data were taken in August 1993.



Measurement of the beam in the Gas-Jet Beam Size Monitor. The height of the two peaks relative to the rest of the signal indicates the presence of trapped ions, from which the beam size can be determined. This measurement corresponds to a size of under 100 nanometers.



Measurement of the beam in the Laser-Compton Beam Size Monitor. The electron beam interacts with an interference pattern at the focal point, causing the sinusoidal oscillation in the signal as the beam is scanned across the pattern. The beam size is determined by the height of the sine wave. This measurement corresponds to a 70 nanometer beam size.

The author and Dave Burke in the FFTB tunnel.

three weeks. This time the sextupoles were used at their design strengths, and the focused beam was gradually reduced in size at the focal point. During this time, the Gas-Jet Beam Size Monitor was able to measure focused beam sizes as small as 250 nanometers. Even more exciting, the Laser-Compton BSM succeeded in measuring beam sizes of 70 nanometers. This size was maintained for several hours, during which it was measured repeatedly and consistently found to be within 10 percent of the aforementioned 70 nanometers, with only minor adjustments needed to maintain it.

An additional three week experiment was then performed during September 1994. At this time, the beam size monitors were more fully optimized and adjusted, and an extremely vigorous program of tuning and commissioning was completed. The 70 nanometer spot was quickly restored, and measurements of the energy-dependent properties of the beam line commenced. It was found that increasing the energy spread by a factor of 5, to the NLC design value of 0.3 percent rms, only increased the focal point size by a few percent, demonstrating that the energy-dependent effects were well controlled in the FFTB. During this period of intense operation, several oddities of the beam line turned up for the first time. These issues were addressed during a two-day run of the FFTB in the beginning of January of 1995. During this time an additional piece of hardware was added: a beam position monitor capable of resolving motions of a few nanometers. First beam-based checkout of the new device was also accomplished during the January 1995 run.

FUTURE EXPERIMENTS

At this time, two additional FFTB experiments are planned, for March and December 1995. There are three main goals of these experiments. The first goal is to use the knowledge gleaned from the preceding runs to reduce the spot size to the design size or even smaller. The second goal is to fully commission the high-resolution BPM, and to use it to stabilize the position of the focused spot at the nanometer level. This is crucial to the correct functioning of the NLC, which must collide two beams which are only 3 nanometers tall! Finally, there will be a series of experiments to determine the stability of the beam line with the passage of time, and to improve this stability.

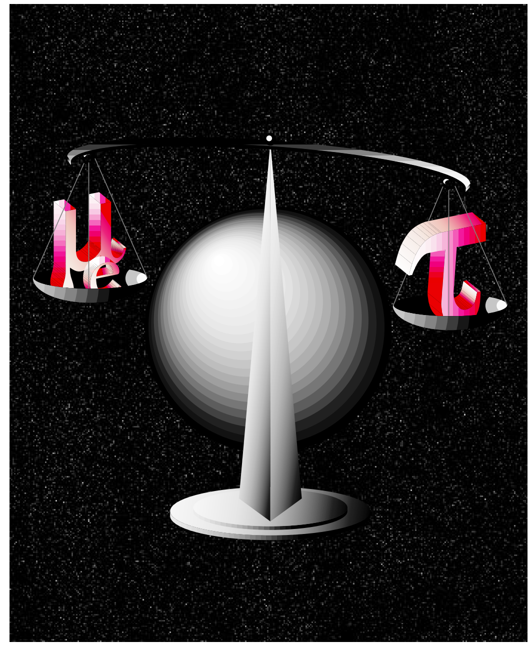
The success of the FFTB in 1994 experiments demonstrates that linear collider final focus systems with large vertical demagnifications and large aspect ratios can be constructed and tuned in a reasonable fashion. This is a major step towards the realization of a higher-energy linear collider.

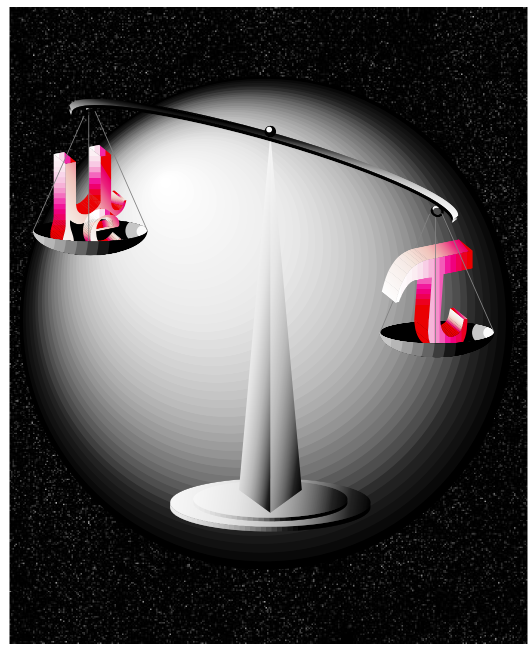
LEPTON UNIVERSALITY

by J. RITCHIE PATTERSON

"You know, it would be sufficient to really understand the electron."

—Albert Einstein





ALL OF US ARE FAMILIAR with the electron as the small companion of the atomic nucleus. It is the atomic nucleus that gives ordinary matter its weight, but the electron is responsible for the space that matter fills, for while it is small, the electron rules vast territories. The electron was first discovered thanks to the electric charge that it carries, and we rediscover the electron whenever we happen to get an electrical shock.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Indeed, the root "electro-" comes from the Greek word meaning amber, so named because amber tends to accumulate electric charge when rubbed, just as we do when we shuffle across a wool rug.

While the electron is unique in the role that it plays in ordinary matter, it is actually part of a trio. The electron's partners, called the muon and the tau, have the same electric charge and seem to share its other properties as well. All its properties, that is, except one: their masses are very different. The muon is heavier than the electron by a factor of about 200, while the tau is heavier by the whopping factor of 3500. These three particles are three of twelve known fundamental particles of nature.

The muon, which we write as μ, was discovered in 1947 in cosmic rays. At the time of its discovery, physicists had untangled quantum mechanics and understood atomic structure and the nucleus. The puzzles of nature had apparently been solved, and many physicists were ready to declare victory and retire. The appearance of a new particle came as a surprise, and not an entirely welcome one. As I. I. Rabi said at the time, "Who ordered this?"

The tau (τ) is a much more recent discovery. It was found in 1975 by a group led by Martin Perl at the SPEAR particle accelerator at SLAC. This group observed that the collision of an electron with an anti-electron (or "positron") sometimes produced particles in a configuration inconsistent with all known processes. Instead, it was exactly what one would expect if new particles were being produced that were similar to electrons, but much heavier.

As far as we know, the electron, muon and tau are fundamental particles, and unlike molecules or atoms, they cannot be broken down into smaller components. This is not the first time that we have thought we have found the fundamental building blocks of nature, and in the past we have often been wrong. Ordinary matter turned out to be made of molecules, molecules of atoms, atoms of nuclei and electrons, nuclei of protons and neutrons, and, most recently, protons and neutrons of quarks. But the electron, muon and tau appear to be indivisible: we see no sign of constituents and they are minuscule in size. In fact, surprising as it may seem, they may be pointlike, with no spatial extent at all.

How do we measure the size of the electron? Just as the electron has electric charge, it also has an intrinsic angular momentum that is constant in time. We call this angular momentum "spin" and measure it in units of Planck's constant $\hbar$, which, like the speed of light, is a fundamental constant of nature. The spin of the electron (and the muon and tau) is $\hbar/2$. Like all circulating electric charges, the electron's spin generates a magnetic field similar to the one around the earth, the strength of which depends on the spatial distribution of its charge. Calculations of this magnetic field have been carried out for the electron using the theory of quantum electrodynamics (QED) with the assumption that the electron is pointlike. The results agree with the experimental value within one part in one billion. This is the most precise test of theory and experiment in physics, and the agreement is a triumph for QED. It tells us that the electron is small indeed: the agreement would be spoiled if the radius of the electron were greater than about 10^{-14} centimeters.

Colliders provide an even more powerful microscope into the electron's structure. By studying the deflections of electrons and anti-electrons when they collide with one another, experimenters in Japan and Europe have probed the electron on a scale as small as 10^{-17} cm, but they see no sign of substructure. Equally precise studies of the muon also yield null results. We know much less about the tau, but so far, it too appears to be free of smaller constituents.

THE ELECTRON, MUON and tau are not alone. Each has a partner called a neutrino, written as ν_e, ν_μ and ν_τ respectively. The neutrinos are massless or nearly so, are electrically neutral, and are insensitive to the strong force that binds atomic nuclei. As a result they are rarely detected. When they were first proposed by Wolfgang Pauli in order to explain the apparent loss of energy and momentum in radioactive decays, he apologized, "I have done a terrible thing, I have postulated a particle that cannot be detected."

Neutrinos may be hard to detect, but they are not rare. In fact, they are produced abundantly in the sun, and more than 10^{13} pass through your body each second, and then continue though the earth and out the other side. Of these, only one per year interacts in your body, leaving a brief ripple in its wake. Like the electron, muon and tau, the neutrinos are believed to be carbon copies of one another. All have the same spin and the same weak charge, and like the electron, muon and tau, they are believed to be fundamental particles.

What links the e and ν_e as partners? In radioactive decays, we see that the e is always accompanied by a ν_e, but never, say, by a ν_μ or a ν_τ. That the neutrino species are distinct was first demonstrated in 1962 by Leon Lederman, Mel Schwartz, Jack Steinberger and their collaborators in an experiment which earned them the Nobel prize.

THESE SIX PARTICLES, the electron, muon and tau plus their three neutrinos are known as "leptons," a name derived from the Greek word *λεπτοσ* meaning small or light. (Had early particle physicists known about the weighty τ, they might have chosen a different name!) High energy physicists like to arrange the leptons in a special way (see figure on right), and refer to each lepton and its neutrino as a generation. The generations are ordered by the masses of the charged leptons.

In addition to the leptons, there is another set of particles called quarks. Quarks are similar to leptons, but unlike leptons, can interact via the strong force. We know of six kinds (or "flavors") of quark: "down," "up," "strange," "charm," "bottom," and "top." All of these are produced prolifically at accelerators except the "top" quark, for which the first direct evidence was reported last year by particle physicists at the Fermi National Accelerator Laboratory located outside Chicago. Quarks are the building blocks of protons and neutrons (a proton is made of two "up" quarks and one "down" quark while a neutron is made of one "up" quark and two "down" quarks). All other particles that we have observed (other than the leptons), such as the π meson, are bound states of the quarks.

Like the leptons, the six quarks seem to come in pairs, and their masses range from very small in the first generation to very large in the third generation. In fact, the top quark weighs about as much as a gold nucleus. Why there should be three generations, and the relationship between the lepton and quark generations, are mysteries.

Could there be a fourth generation of quarks or leptons waiting to be discovered? Current evidence suggests not. Data from the LEP accelerator at CERN in Geneva, Switzerland have shown that there are only three species of light (or massless) neutrinos: these are the ν_e, ν_μ, and ν_τ. Thus, if an additional generation exists, its neutrino must be very massive—a marked departure from the generations that we now know.

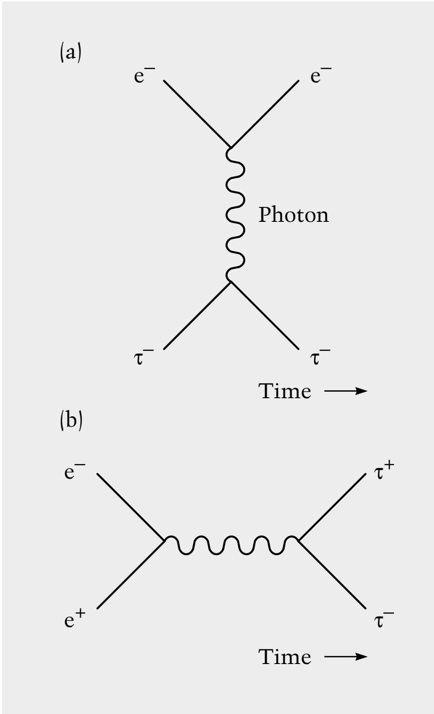
FORCES THAT CONTROL the interactions between particles are as essential to nature as the particles themselves. We know of four forces: gravity; electromagnetism; the "strong" force, which binds together quarks into protons, neutrons, π mesons or other, less common, particles; and the "weak" force, which is responsible for the decay of radioactive nuclei and for much of the activity in the sun.

All of the forces operate in about the same way. Associated with each one is a charge: electric charge for electromagnetism, mass for gravity,

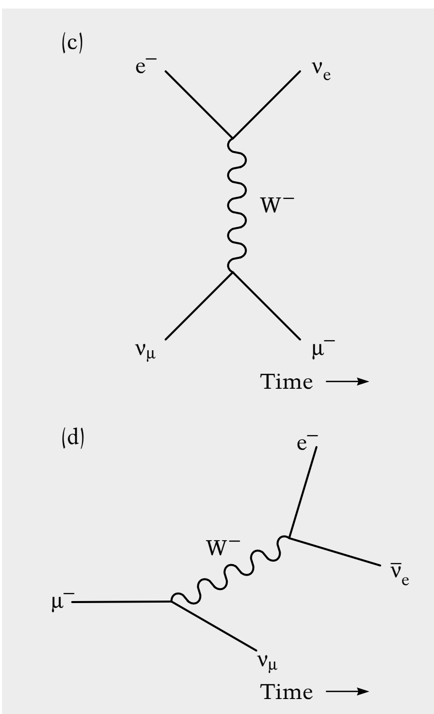
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

The known fundamental particles of nature. The upper six particles are the leptons and the lower six are the quarks. Both the leptons and the quarks are arranged into three generations of two particles each (shown in brackets).



A particle physicist's view of electromagnetic interactions. In the upper figure (a) two charged particles, each represented by a solid line, scatter. A photon carrying energy and momentum is emitted by one and absorbed by the other. The lower figure (b) shows the less familiar annihilation of an electron and anti-electron. Their energy goes into the photon which then materializes into two new particles—in this case a tau and anti-tau.



A particle physicist's view of the weak interactions. In the upper figure (c) an electron and muon neutrino exchange a W-boson, and a muon and electron neutrino emerge. In the lower figure (d) a muon decays by emitting a W-boson and neutrino, and the W then materializes as an electron and electron anti-neutrino. This process is very similar to radioactive decay as well as much of the activity in the sun.

and something called "color" for the strong force (this "color" has nothing to do with the usual meaning of the word). Similarly, there is a "weak charge" associated with the weak force. Electrons, muons, and taus carry this charge as do the neutrinos and quarks.

When Newton developed the concept of force, he viewed it as "action at a distance." We now know that special particles travel between the interacting objects, deflecting them with the momentum and energy which they carry. In the case of gravity, this special particle is the graviton, while for electromagnetic interactions it is the photon.

It is handy to diagram these processes as shown in the adjacent figures. In these diagrams, each particle is represented by a line, and time increases from the left hand side of the diagram to the right. In diagram (a), the electrical repulsion of two charged particles, the particles are well-separated at the left-hand side of the diagram, they approach each other, and exchange a photon, which is represented by the wiggly line, and recoil. These diagrams are convenient for high energy physicists because they can be translated into mathematical formulae for the probability that the scattering will occur: using a method first introduced by Richard Feynman, one simply writes down a mathematical factor for each line and intersection point.

The repulsion or attraction of two charged particles is the most familiar electromagnetic interaction, but it is not the only possibility. As shown in diagram (b), a particle and its anti-particle can meet and annihilate one another to produce a photon which then materializes as a new particle and anti-particle pair. This is how particles such as taus were produced at the SPEAR and PEP storage rings at SLAC and are currently produced at the CESR electron-anti-electron collider at Cornell University. Note that this diagram is identical to figure (a) rotated by 90 degrees except that some particles have been changed from particle into anti-particle and vice versa. As the similarity of the diagrams suggests, the same physics is responsible for both processes.

Weak interactions work in the same fashion as the electromagnetic and gravitational interactions. When two particles carrying the weak charge approach one another, they can exchange a particle, in this case either a "*W*-boson" or "*Z*-boson." The *W*-boson was first observed directly in 1983 by two groups at CERN, one led by Carlo Rubbia, and is now produced routinely at the proton collider at Fermilab, and the *Z*-boson is produced and studied in detail at the LEP collider at CERN and at the SLC at SLAC.

Just as the photon materializes into a pair of particles, so does the *W*. For the *W*, this can be either a pair of leptons or a pair of quarks. Whenever the *W* decays into leptons, it always chooses two leptons from the same generation: an e and ν_e, a μ and ν_μ, or a τ and ν_τ. In fact, experiments have searched for decays in which the W (or some unexpected exotic particle) produces leptons from two different generations, and none have been observed, even though some of these experiments, such as one known as SINDRUM at the Paul Scherrer Institute in Switzerland and another at the Los Alamos National Lab in New Mexico known as MEGA, have searched among nearly 1 trillion decays. Interestingly, when the W decays into quarks, it disregards the ban on cross-generational mixing. This cross-generational quark mixing has some fascinating consequences, some of which motivate the construction of the new accelerators known as B-factories.

We can now explain why we find electrons rather than muons inside atoms. The weak interaction allows a muon to decay into an electron plus two neutrinos, as shown in diagram (d), in a process that is very similar to the radioactive decay of an atomic nucleus. Muons typically survive 2×10^{-6} seconds before decaying in this way. The reverse process, the decay of the electron into a muon plus neutrinos, is forbidden by energy conservation because the muon is heavier than the electron.

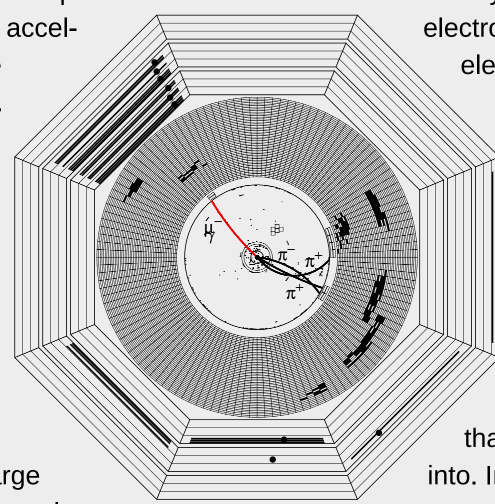
The mass of the lightest lepton has a major impact on our day to day lives. What would happen if the electron were as heavy as a muon? For starters, atoms would be much more compact because the large centrifugal force of these heavy electrons could be overcome only if they hugged the atomic nucleus. As a result, an apple would weigh about what it does now, but it would be the size of a grain of sand. Similarly, a typical person, if she or he could survive at all, which is doubtful given the consequences of heavy electrons for chemistry, would stand only one third of an inch tall.

Like the muon, the tau can decay into an electron plus neutrinos, but its large mass gives it a multitude of other possibilities. For example, it

Modern Particle Detectors

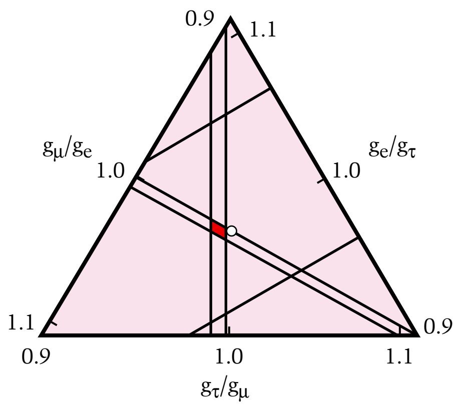
A **TYPICAL MODERN** particle detector is really a collection of many devices each with its own capabilities. These devices are layered around one another like the peels of an onion, all centered on the point where the two accelerated particle beams collide. In most detectors, the innermost layers display the trajectories of charged particles. By placing these devices in a large magnetic field, we learn not only the particle's direction of travel, but also its momentum, which is inversely proportional to its curvature in the magnetic field. Other devices measure the particle's velocity, which combined with the momentum measurement reveal its mass and therefore its identity. Yet other devices detect photons and other electrically neutral particles.

Each of these devices produces electrical signals which are digitized and recorded for later analysis whenever something interesting happens in the detector.



The figure shows the signals in the CLEO detector at Cornell University when an electron and anti-electron annihilate to produce a pair of taus. The taus decay before reaching the detector, so we see only the particles that they decay into. In this event, one tau traveling up and to the left decays into a muon and two neutrinos, while the other, traveling down and to the right, decays into three pions plus a neutrino. We recognize the muon by the signal that it leaves in the outermost layers of the detector—it is the only particle that penetrates that far. The neutrinos escape undetected.

Events like this one can be used to measure the tau lifetime.



This "Universality Triangle" helps physicists assess the weak charges of the leptons. The two vertical lines indicate the band of values of g_τ/g_μ compatible with recent measurements. The bands of allowed values of the other two ratios of weak charges are indicated by lines perpendicular to the other two sides of the triangle. If g_e, g_μ, and g_τ are identical, then the bands will overlap at the center of the triangle. On the other hand, if one charge differs from the other two, then the overlap region (which is shaded) will march toward one corner of the triangle.

may decay into a muon plus neutrinos in an analogous process or even into quark pairs plus a neutrino.

Because it has so many decay options, the tau is very shortlived. The average lifetime of the tau is 0.3 trillionths of a second. This has been measured at accelerators where taus are produced. At the SLC collider at SLAC and the LEP collider in Europe, taus travel about 2 cm in their lifetime, which is easily measurable with modern particle detectors.

What evidence do we have that the electron, muon and tau are identical apart from their masses? This is a topic of current research. Currently, physicists test whether the weak charges of the muon and tau are identical by comparing their decay rates into an electron plus neutrinos. Calculations of the Feynman diagrams indicate that the ratio of the tau to muon decay rates should be proportional to $(m_\tau/m_\mu)^5\,(g_\tau/g_\mu)^2$, where g_μ and g_τ are the weak charges of the τ and μ and m_τ and m_μ are their masses. Recent measurements of the tau mass done at BEPC in Beijing, China, and decay rate done most precisely at LEP (the muon has been around for years and its mass and decay rate are very precisely known) show that the ratio of weak charges is $g_\tau/g_\mu = 0.994 \pm 0.004$, where $\pm$ 0.004 indicates the experimental uncertainty. We see that the ratio of the muon and tau weak charges is nearly unity, and that if they differ, it is only by a tiny fraction. In fact, the ratio of weak charges differs by an amount slightly larger than the experimental error. Future, more precise, experiments will reveal whether this discrepancy is significant.

The ratios of weak charges g_μ/g_e and g_e/g_τ have also been measured at TRIUMF in Vancouver and at Fermilab and CERN respectively, and the results are summarized in the adjacent figure. If the weak charge of one of the leptons were larger than the others, the overlap band shown in the figure would move from the center of the triangle toward one of the corners. In fact, as far as we can tell now, their weak charges are identical. Even a minute difference, however, would signal a profound discovery, so future research will attempt to determine these charges even more precisely.

It may seem surprising that particles whose properties and interactions seem to be identical should have such different behavior: the electron, a principal player in everyday matter; the muon, found primarily in cosmic rays; and the tau, confined to particle accelerators. But as far as we know, the tau and the muon are simply heavy replicas of the electron—only their vastly different masses are responsible for the very different roles that they play in our universe.

Many questions remain. Why are there three generations? Where do they get their masses, and why do they differ so drastically from one another? Why do the weak interactions always produce leptons within a single generation? Is it a coincidence that there are also three generations of quarks? Someday we may know the answers to these questions.

PARTICLE & NUCLEAR ASTROPHYSICS

by BERNARD SADOULET

The author discusses demographics and funding of an emerging field

BY ITS VERY NATURE, science is constantly evolving, and new research fields continuously emerge, in part out of the convergence of fundamental questions of several established fields, the combination of their technologies, and the fertile interaction of scientists of different training. The relatively new field of particle and nuclear astrophysics provides an interesting example of such vitality.

OVER THE LAST TEN TO FIFTEEN YEARS, we have witnessed its birth at the borders between particle and nuclear physics, cosmology, stellar astrophysics, high energy astrophysics, and gravitation. With an attendance of 450 physicists, a recent meeting organized by three divisions of the American Physical Society in Snowmass, Colorado ("Particle and Nuclear Astrophysics and Cosmology in the Next Millennium") testified to the vibrant nature of the current inquiries. This article presents data on the demographics and funding of this emerging field, gathered with the help of several colleagues engaged in the field and of many funding-agency officials. Even with their efforts, however, the funding numbers I shall show are only approximate. Particle astrophysics has a distant past in cosmic-ray studies, which have played an important role in the birth of particle physics as a field. With the development of man-made accelerators during the last 50 years, the quest to understand the structure of matter has increasingly relied on accelerators of growing power and size. Recently, however, this movement has been reversed. A new stream of research is now emerging in which the cosmos is used not only as a natural source of high energy particles but also as a laboratory where we can explore temperatures, energies, mass densities, distance, and time scales that cannot be obtained directly on earth. Obvious examples include the early universe, which probes fundamental physics at very high energy; nuclear reactions in the sun; neutron stars and their equation of state; the physics around very compact objects such as black holes; and so on. In this work a dialogue is established between particle and nuclear physics that provides critical information for the understanding of fundamental astrophysics phenomena, and astrophysics which may challenge our current models of particle physics and provide constraints on unification schemes and hint at necessary transformations.

A new stream of research is now emerging in which the cosmos is used not only as a natural source of high energy particles but also as a laboratory where we can explore temperatures, energies, mass densities, distance, and time scales that cannot be obtained directly on earth.

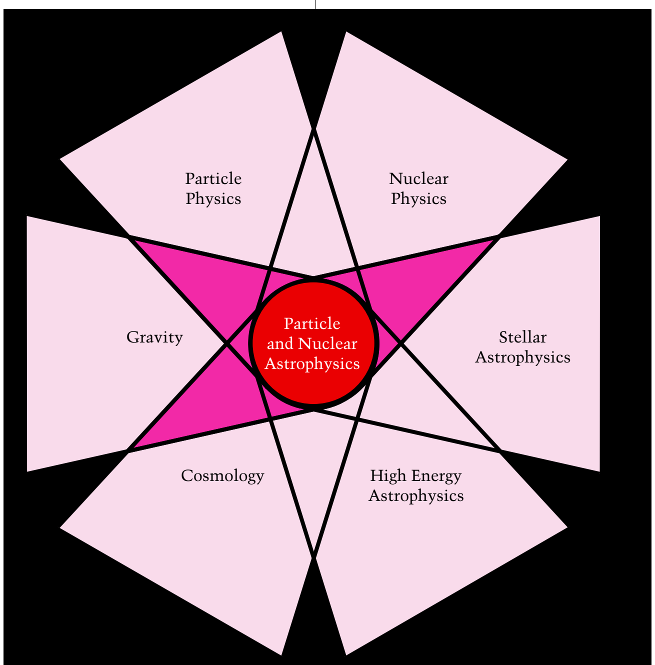
This reverse movement started about 25 years ago with the attempt to detect neutrinos emerging from the sun. Until about a decade ago, however, much of the work in this new field was theoretical in nature, attempting to apply the knowledge gained from nuclear and particle physics research to stellar physics and cosmology in order to widen the range of conditions we understand. This began to change in the early 1980s, when a growing number of experimental particle and nuclear physicists started again to use non-accelerator-based methods and, in many cases, to focus their research on astrophysics. There are at least two major reasons for this recent development: (i) the mismatch between our present accelerator capabilities and the increasingly ambitious theoretical questions we are asking, and (ii) the sociological issue of larger and larger groups (hundreds of physicists) in accelerator-based experiments. The recent work has led to wonderful results, perhaps the most spectacular of which was the detection of neutrinos from the 1987A supernova in two underground detectors that were initially built to search for the decay of the proton. The new detector technologies these experimentalists introduced in astronomy, the powerful computer-reconstruction methods they transposed, and the fertile interaction of their style with that of more traditional astronomers have indeed been a successful combination. An extraordinary amount of new data has been gathered which, combined with vibrant theoretical work, appears to stress our conventional understanding so much that something may have to give!

It is of course difficult to draw a classification of the research activities in such a rapidly evolving field, but we can recognize at least four overlapping categories:

• *Particle cosmology* and the tantalizing questions it tackles: What is the nature of the ubiquitous dark matter and the origin of the predominance of matter over antimatter? What is the explanation for the smoothness of the universe and for the primeval inhomogeneities that triggered the formation of structure and, eventually, galaxies?

• *Neutrino astronomy*. After the pioneering chlorine solar neutrino experiment and the detection of neutrinos from supernova 1987A, neutrino astronomy is coming of age with a new generation of solar neutrino experiments and exploration of ambitious schemes to detect high-energy neutrinos from compact astrophysical sources.

• *Ultra-high-energy astrophysics*. The acceleration mechanisms associated with such compact objects as stellar black holes and active galactic nuclei are poorly understood; the relative role of electromagnetic and hadronic processes is not very well mapped; and the origin of ultra-high-energy cosmic rays and their composition remains a central mystery.



• *Gravitational astrophysics*. There is a continuing challenge to unify gravitation with the other interactions and to make progress in its experimental investigation. The coming generation of gravitational-wave detectors promises to open a new window on violent phenomena in the universe and to provide a complementary source of information on compact objects.

Demographics and Funding

These exciting directions have attracted a number of scientists, primarily but not uniquely from particle and nuclear physics, and with them an already sizable budget. I will try here to provide some quantitative information on these trends. In order to be conservative in summarizing the demographics and budgetary data, I have chosen to restrict the definition of the field to *astrophysics activities explicitly linked by the investigators to particle and nuclear physics*. I have, for instance, only included the studies of the Cosmic Background Radiation at the Center for Particle Astrophysics and at LBL, where connection with particle physics is a primary motivation, and not similar efforts at Princeton, Chicago, and the Goddard Space Flight Center. For similar reasons, only the Large Scale Structure observations at the Center for Particle Astrophysics and at Fermilab enter our data set. An arbitrary energy threshold of 1 GeV has been imposed on cosmic-ray experiments, and only gamma-ray observations from the ground are considered. Even with this very restricted definition, I estimate the number of experimentalists involved in the United States to be about 300 and the fraction of the theory effort devoted to these problems to be at least 10 percent. These numbers are evolving quickly, and as noted above, the last ten years have witnessed a pronounced shift from pioneering theoretical studies to a large number of experimental investigations. We should also note a growing involvement of the national laboratories: LBL, Fermilab, SLAC, Argonne, Livermore, and Los Alamos.

The total funding of this field by American federal agencies (see table) has also become substantial. The Department of Energy supports such activities at a total level of roughly \$26M/yr, with approximately 75 percent spent at universities and 25 percent in national laboratories. The National Science Foundation contributes some \$13M, and NASA contributes \$2M (restricted to cosmic rays above 1 GeV). Gravitation represents another \$11M in the NSF budget, plus the current construction money of LIGO (a \$290M project) and GP-B (a \$250M satellite). Overall, without counting these major construction projects, this amounts to more than \$52M per year that is being channeled to this interdisciplinary field.

I have not systematically gathered any data for the rest of the world. But with active programs in Europe, Japan, and the former Soviet Union, the above numbers would probably have to be doubled.

These numbers are getting impressive, and they testify to the fascination of the subject, the enthusiasm of the scientists, and the ingenuity of the funding officials who have found ways to allow the field to grow. It would, however, be unfair to my colleagues not to report at the same time the present uneasiness of the community, which feels that this emerging field still tends to "fall into the cracks." It does not fit readily within the traditional NSF and NASA astronomy funding categories. Although there is a widening recognition in the Department of Energy that particle and nuclear astrophysics is closely related to its mission

Approximate United States Funding for Particle and Nuclear Astrophysics for Fiscal Year 1994
(thousands of dollars)

Department of Energy	
High Energy Physics	11300
Nuclear Physics	5000
Theory (10 %)	2300
High Energy Laboratories	4400
Weapons Laboratories	3000
Total	*26000*
National Science Foundation	
High Energy Physics	3000
H.E. Theory	1000
Nuclear Physics (incl. 10% theory)	4500
Astronomy	3500
Polar Programs	1000
Gravity (does not include LIGO)	11000
Total	*24000*
NASA	
Cosmic Rays	1500
Theory	500
Total	*2000*

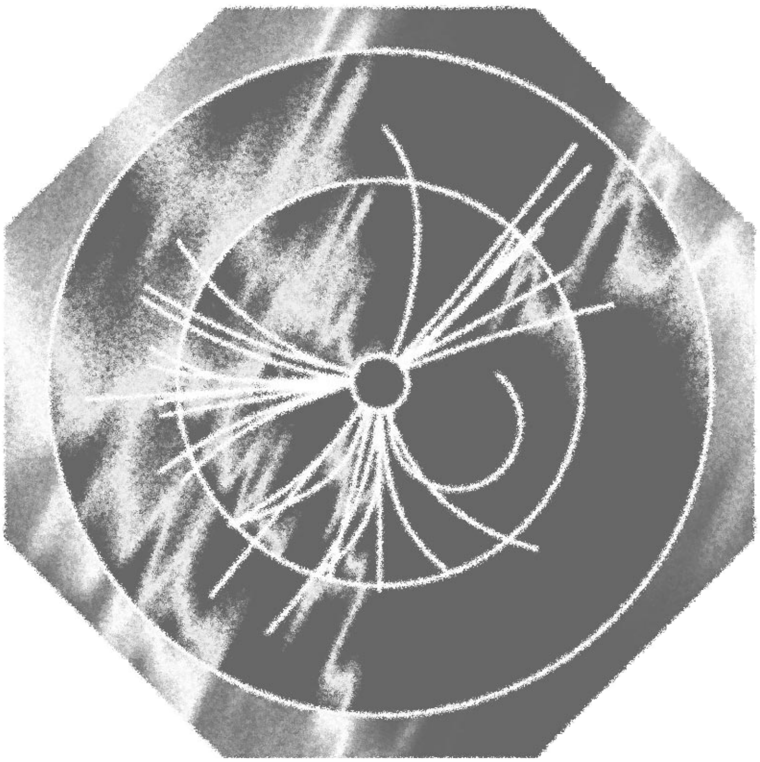
of understanding the forces in nature, DOE officials have historically worried that such activities may appear to conflict with its traditional mandate. There is a general perception that the review process could be improved and that there could be tighter collaboration among the various divisions within the funding agencies and between the different agencies. Frustration is also often expressed about the lack of mechanisms to establish a long-term strategy and priorities across the field, as we have no screening mechanism equivalent to the program advisory committees associated with large particle accelerators, and no suitable standing committee advising the agencies, as HEPAP, NSAC, and SSAC do in their respective fields of High Energy Physics, Nuclear Science, and Space Sciences. Finally, there is the worry that in any budgetary arbitration the more traditional fields may enjoy some historical advantage.

In spite of the efforts of agency officials to remedy these problems, from the studies organized, for instance, by the American Physical Society and the reports of the National Research Council, it is clear that we do not yet have in place the reviewing structure nor the advisory process necessary to address in a coherent fashion the large international projects on the drawing boards. Their price tags, which are often between \$15M and \$100M, are sizable. Our community is actively studying several cosmic microwave background satellites, specialized cosmology telescopes, a new generation of solar neutrino detectors, an air Čerenkov farm to extend the measurement of gamma spectra of active galactic nuclei and black hole candidates, giant extensive air shower arrays to explore the highest energy cosmic rays, and km^3 neutrino detectors to look for high energy neutrino sources, not to mention even more ambitious projects such as a space-based gravitational wave interferometer.

The science is clearly exciting, and the scientific community is voting with its feet. The challenge remains to find the resources and the institutional mechanisms to further decrease the potential barriers encountered by excellent proposals, to welcome young investigators into the field, to optimize the scientific output on a very restricted budget, and more actively to develop the necessary international partnership.

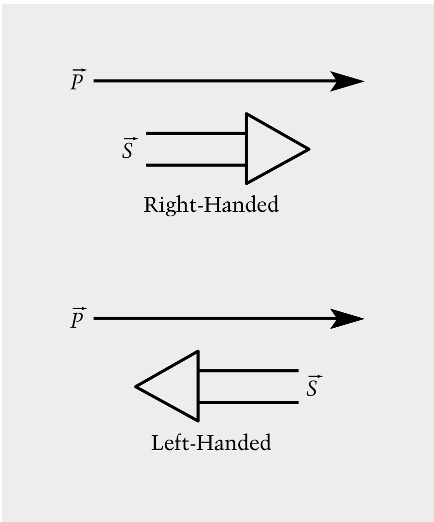
PUTTING A NEW SPIN ON PARTICLE PHYSICS

by MORRIS SWARTZ



Polarized electron beams allow a precision measurement of a key Standard Model parameter.

IN 1991 A HUGE NEW state-of-the-art detector replaced the older and smaller Mark II detector at the interaction point of the Stanford Linear Collider. This detector—named the SLD for SLAC Large Detector—together with the accelerator forms a unique facility for doing experiments in high energy physics. The world's only linear collider, the Stanford Linear Collider or SLC, is also the only $e^+ e^-$ machine to operate routinely with a spin-polarized electron beam.



Left- and right-handed helicity states of a particle with spin $\vec{S}$ traveling with momentum $\vec{P}$.

The SLD was specifically designed to make optimal use of the unique features of a linear collider. Recently the SLC has begun to achieve its goal of producing large numbers of Z particles using highly polarized electron beams; in fact, this collider has substantially exceeded its design goal for beam polarization.

Largely because of these advances, the SLC Collaboration has begun to produce interesting and world-class physics results. The most prominent of these is the world's best single measurement of a key parameter of the Standard Model—the dominant theory of particle physics today. Called the weak mixing angle, this parameter determines the degree of mixing between the weak and electromagnetic forces in this theory. Precise measurements of this parameter are used to search for subtle effects due to physical entities and processes that may lie *beyond* the Standard Model.

MUCH OF THE SLD physics program involves the spin of elementary particles. In 1925, George Uhlenbeck and Samuel Goudschmidt postulated that electrons must have intrinsic angular momenta or *spin*. In order to explain the spectrum of photons emitted by hot hydrogen atoms, they suggested that electrons behave like spinning tops carrying an angular momentum of $\hbar/2$, where $\hbar$ is Planck's constant h divided by 2π. We now believe that all the matter in the Universe is composed of particles (generically called *fermions*) that carry half a Planck unit of intrinsic angular momentum, or spin-1/2. The protons and neutrons inside atomic nuclei are themselves composed of spin-1/2 particles called quarks.

When such matter particles interact with each other, they exchange force-carrying particles called *gauge bosons* which always carry one Planck unit of angular momentum (particles with whole-number values of angular momenta are called bosons). In the Standard Model, the different forces or interactions—weak, electromagnmetic, and strong—are mediated by different gauge bosons. The familiar electromagnetic force is mediated by a gauge boson called the photon. The strong interaction that binds the quarks into protons and neutrons (and protons and neutrons into atomic nuclei) is mediated by a family of eight gluons. The part of the weak interaction responsible for radioactive beta decay and for many of the nuclear processes that occur in solar (and stellar) fusion is mediated by massive W bosons. Last but not least, the weak "neutral-current" interaction, which was not discovered until the mid-1970s, is mediated by the Z boson. The SLD physics program is based principally upon the study of the Z and its interactions with quarks and leptons.

The Standard Model describing elementary particle interactions is actually composed of two conjoined theories. The strong interactions of quarks (mediated by gluons) are described by a theory known as quantum chromodynamics. The electromagnetic and weak interactions are unified in an electroweak theory also known as the Weinberg-Salam or Glashow-Weinberg-Salam theory. In the electroweak theory, the spins of the elementary particles play a fundamental role. In general, the spin axis of a spin-1/2 particle such as an electron can be oriented in any direction in space. However, the two cases for which the spin axis lies parallel to the particle's direction of motion are particularly interesting. If the angular momentum vector is parallel to this direction (the sense of the spin would drive a right-handed screw along this direction), the particle is said to have right-handed helicity. If the angular momentum vector is antiparallel to the direction of travel, the particle is said to have left-handed helicity (see figure at left).

What is interesting about the two helicity states is that they are regarded as *distinct particles* in the electroweak portion of the Standard Model. They have *different* quantum numbers, weak charges, and interactions! This difference is the consequence of the 1958 discovery that the weak "charged-current" interaction—that part mediated by W bosons—involves only left-handed

THE ELECTROWEAK THEORY

THE ELECTROWEAK THEORY is constructed by assigning each fermion two weak charges: the third component of weak isospin I_3, and the weak hypercharge Y_W. The electric charge of each particle (in units of the electron charge) is related to the weak charges by the expression, $Q = I_3 + Y_W/2$. The weak charges of each particle in the first generation of fermions in the Standard Model are listed below along with the gauge bosons that they are coupled to.

THE WEAK CHARGES AND INTERACTIONS OF THE FIRST GENERATION OF FERMIONS

Fermion	I_3	Y_w	Gauge Bosons
ν_L	+1/2	–1	W_1, W_2, W_3, B
e_L	–1/2	–1	W_1, W_2, W_3, B
u_L	+1/2	+1/3	W_1, W_2, W_3, B
d_L	–1/2	+1/3	W_1, W_2, W_3, B
ν_R	0	0	—
e_R	0	–2	B
u_R	0	+4/3	B
d_R	0	–2/3	B

The symbols ν, e, u, and d refer to the neutrino, electron, up quark, and down quark, while the subscripts L and R refer to left- and right-handed helicity. Note that all of the left-handed particles come in doublets of weak isospin and couple to three W bosons. Both left- and right-handed particles couple to the hypercharge-sensitive boson B. The physical gauge bosons are linear combinations of the W_i and B states:

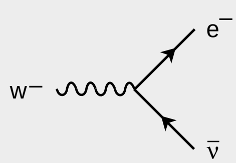
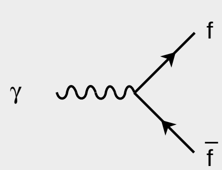
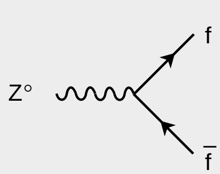
$$W^{\pm} = 1/\sqrt{2}\left[W_1 \mp iW_2^{-}\right]$$
$$Z = W_3 \cos\theta_W - B\sin\theta_W$$
$$A = W_3 \sin\theta_W + B\cos\theta_W$$

where $W^{\pm}$ are the charged gauge bosons that mediate ordinary weak processes such as beta decay, Z is the carrier of the neutral weak interaction, A is the ordinary photon that mediates electromagnetic force, and θ_W is the weak mixing angle. The weak mixing angle is also related to the strengths g' and g of the interactions that depend on hypercharge and weak isospin,

$$\tan\theta_w = \frac{g'}{g}.$$

Numerically, the size of the weak mixing angle is approximately 0.5 radian.

The asymmetry between left- and right-handed particles survives the mixing of the gauge bosons. The coupling strengths of the left- and right-handed fermions to the physical gauge bosons are given below. The W bosons couple to left-handed fermions only. The photon couples to both left- and right-handed fermions with equal strengths proportional to $e = g \sin\theta_W$. The Z boson also couples to both left- and right-handed fermions but with *different* strengths g_L^f and g_R^f.

	LH Coupling	RH Coupling
	$g/\sqrt{2}$	0
	$Q^f g \sin\theta_w$	$Q^f g \sin\theta_w$
	$\underbrace{(g^2+g'^2)^{1/2}\,(I_3^f - Q^f \sin^2\theta_w)}_{g_L^f}$	$\underbrace{(g^2+g'^2)^{1/2}\,(-Q^f \sin^2\theta_w)}_{g_R^f}$

The Left-Right Asymmetry

An important parameter measured by SLD physicists, called "the left-right asymmetry" or A_{LR}, is equal to the difference in Z boson production rates when left- and right-handed polarized electrons collide with unpolarized positrons, divided by the sum of these two rates:

$$A_{LR} \equiv \frac{R(e_L^- e^+ \to Z) - R(e_R^- e^+ \to Z)}{R(e_L^- e^+ \to Z) + R(e_R^- e^+ \to Z)}$$

$$= \frac{(g_L^e)^2 - (g_R^e)^2}{(g_L^e)^2 + (g_R^e)^2} = \frac{2(1-4\sin^2\theta_W)}{1+(1-4\sin^2\theta_W)^2}$$

The second step follows from the fact that the individual production rates are proportional to the squares of the respective *Zee* couplings. Note that the value of A_{LR} must lie between 1 (only left-handed electrons produce Z bosons) and –1 (only right-handed electrons produce Z bosons). The Standard Model predicts that A_{LR} should be somewhat positive; more Z's are produced by left-handed electrons than by right-handed electrons.

The left-right asymmetry is a particularly simple quantity to measure. Since exactly half of the SLC pulses have left-handed helicity and the other half have right-handed helicity, we need only form the asymmetry in the number of Z events detected with left- and right-handed beams, N_L and N_R, respectively. This "raw" asymmetry must be corrected to account for incomplete beam polarization,

$$A_{LR} = \frac{1}{P_e} \times \frac{N_L - N_R}{N_L + N_R},$$

where P_e is the beam polarization, which is the fraction of the beam that is spin polarized (the unpolarized fraction $1 - P_e$ is equally divided between the two helicity states).

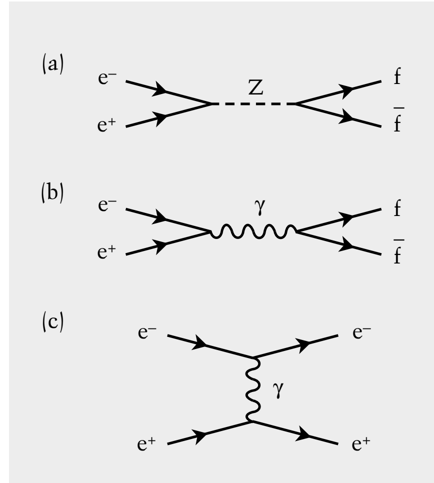
particles; right-handed particles do *not* participate. The architects of the unified electroweak theory therefore had to treat left- and right-handed particles differently. Thus left- and right-handed fermions couple to the Z boson with different strengths, a fact that has crucial implications for experiments with the polarized SLC electron beam.

THE ELECTRON BEAM of the SLC is produced by illuminating a strained gallium arsenide crystal with a circularly polarized laser beam. Depending upon the sign of the laser polarization, mostly right- or left-handed longitudinally polarized electrons are emitted from the crystal and accelerated by the linear accelerator (in 1994–95, about 90% of the beam has the selected helicity and about 10% has the wrong-sign helicity). A number of steps are taken to preserve the beam polarization and to orient it correctly when it collides with the unpolarized positron beam at the SLC interaction point.

The ability of the SLC to collide a polarized electron beam with unpolarized positrons at a center-of-mass energy that is sufficient to produce real Z bosons gives the SLD experiment a unique capability. By changing the dominant beam composition from left-handed to right-handed electrons and back, the SLD experimenter can effectively change the *types* of particles in the beam and compare the rates at which they interact with positrons to produce Z bosons. The electron beam is changed from a dominantly left-handed beam (with one set of weak charges) to a dominantly right-handed beam (with a different set) simply by changing the sign of the voltage on an electro-optical cell (called a Pockels cell) in the polarized electron source. To excellent precision, only the helicity of the beam is changed; all other parameters are insensitive to the sign of the Pockels cell voltage. It is therefore possible to compare very precisely the production rates of Z bosons with left- and right-handed electron beams and extract the so-called left-right asymmetry A_{LR} (see box at left).

SLD physicists search for events in which a Z boson has been produced by recording extensive information about those collisions in which a large amount of energy has been deposited in the detector. They then subject these data to a series of tests in order to distinguish the actual production of a Z boson from the spurious background events that can mimic this process. Incident electrons and positrons can annihilate to produce real Z bosons or virtual photons [see diagrams (a) and (b) on page 23]. Because the SLC energy is tuned to the Z mass, the Z production rate is resonantly enhanced; it is approximately a thousand times larger than the virtual photon production rate. After about 10^{-26} sec, the Z bosons decay into fermion-antifermion ($f\bar{f}$) pairs. About 70% of the time, the final state consists of a quark and antiquark, which appear in the SLD as a back-to-back pair jets of strongly interacting particles. Each charged lepton species (electrons, muons, and taus) is produced about 3% of the time. Electron-positron final states can also be produced by another process [see diagram (c) on page 23] in which the incident electron and

The dominant physical processes that produce large-energy events in the SLD. Initial states are on the left, and time flows as indicated by the arrow.

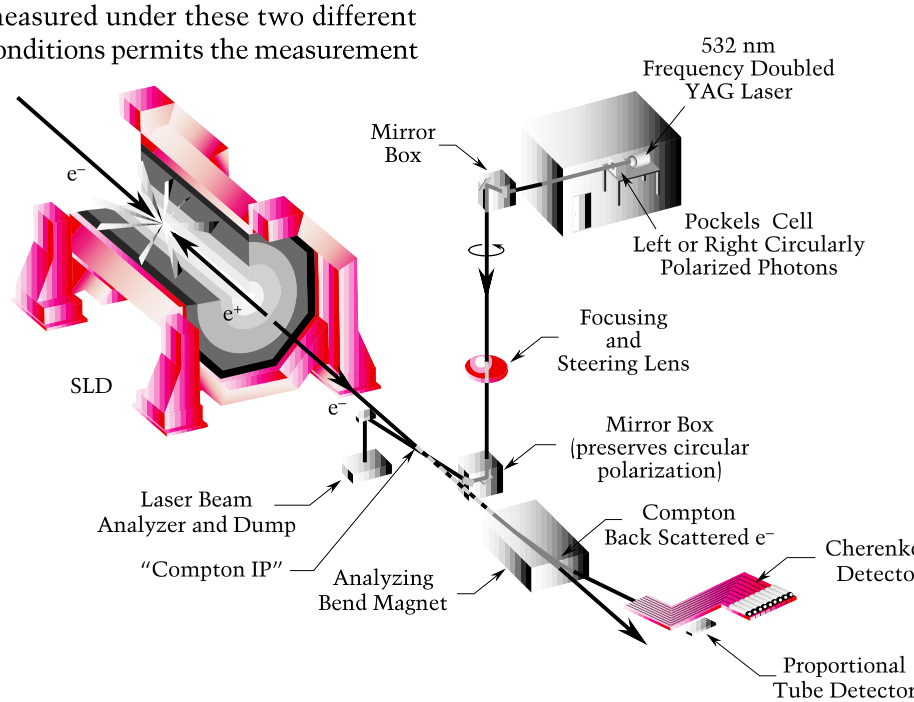


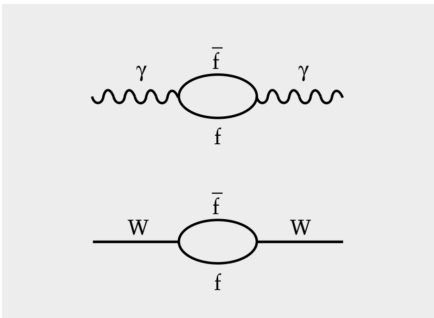
positron exchange a virtual photon as they pass each other; they do not annihilate but deflect each other to large angles. This so-called "t-channel" process leads to about twice as many electron-positron events in the SLD as does the Z decay process alone. Finally, about 20% of all the Z bosons produced decay into neutrino-antineutrino pairs. Since neutrinos interact only very weakly with other matter, they are not detected by the SLD.

All of the observed Z final states can be used to measure A_{LR} except for the e^+e^- final state (which cannot be separated from the unwanted t-channel contribution). A very simple event selection procedure based upon the liquid-argon calorimeter of the SLD is sufficient to identify Z events with very small backgrounds (less than 0.2%) from beam halo, cosmic rays, and unwanted e^+e^- events. Unlike many of the precise electroweak measurements performed at other high energy accelerators, this measurement does not require any knowledge of the efficiency of the detector and the event selection criteria (because it appears in both the numerator and denominator of the asymmetry and therefore cancels out in the ratio). Systematic uncertainties associated with efficiency corrections are therefore not present.

It is, however, important to measure accurately the average polarization of the electron beam, which is accomplished by performing a second colliding-beam experiment 30 m downstream of the first. After interacting with the positron beam at the center of the SLD, the 45.65 GeV electron beam collides with a beam of 2.33 eV circularly-polarized photons from a frequency-doubled Nd-YAG laser (see drawing below). About 1 electron in 10^7 interacts with a laser photon (this process is called Compton scattering). The scattered electrons emerge at tiny angles with respect to their incident direction (the maximum scattering angle is 9.6 microradians). However, the energies of the scattered electrons are significantly degraded; those that ricochet backwards in the electron-photon center-of-mass frame emerge with energies of only 17.36 GeV as viewed in the laboratory. These backscattered electrons are separated from the rest of the beam by a dipole bending magnet; they produce a signal in a Cerenkov detector downstream of this magnet. The number of backscattered electrons is roughly seven times larger when the helicities of the laser photon and electron are opposite (spins parallel) than when they are the same (spins antiparallel). A comparison of the counting rates measured under these two different conditions permits the measurement

A schematic diagram of the Compton polarimeter used to measure the polarization of the SLC electron beam.





Feynman diagrams for vacuum polarizaton corrections.

of the electron beam polarization with a precision of about 1%.

IN 1993, THE SLD experiment logged a total of more than 50,000 Z events with an average beam polarization of 63%. After applying a small correction for the photon exchange backgrounds, the SLD experimenters found the left-right asymmetry to be

$$A_{LR} = 0.1637 \pm 0.0075$$

This value of A_{LR} translates directly into an effective value of the all-important weak mixing angle (see box on page 21) $\sin^2\theta_W$,

$$\sin^2\theta_W = 0.2294 \pm 0.0010$$

This result constitutes the single most precise determination of this key Standard Model parameter yet performed. This quantity has also been extracted from 30 measurements performed by the four LEP experiments at CERN. The average value of this compilation is $\sin^2\theta_W = 0.2321 \pm 0.0004$, which differs from the SLD value by more than two standard deviations.

Why are these results interesting? What are the consequences of one value or the other?

Both A_{LR} and $\sin^2\theta_W$ are sensitive to a number of virtual electroweak processes. The dominant corrections come from the so-called vacuum-polarization effects (see above figure). Gauge bosons can change (briefly) into virtual particle-antiparticle pairs, especially at high energies. These processes alter the electroweak coupling strengths and in turn affect the measured value of these parameters. New particles that are too heavy to be produced directly at the SLC or LEP can still signal their existence by their effect on precisely measured quantities such as A_{LR} and $\sin^2\theta_W$. Unfortunately, these higher-order corrections depend upon all of the particle charges and masses in the Standard Model, including those of the unobserved Higgs boson and the recently observed top quark. They could also hint at the existence of other particles not included in the Standard Model. The measurement of a single electroweak observable does not, in general, test this theory. Measurements of several different observables that depend differently on the top quark and Higgs boson masses are required to carry out detailed tests. The SLD measurement of A_{LR} and $\sin^2\theta_W$ is therefore part of a world-wide program of electroweak testing.

The SLD and LEP values of $\sin^2\theta_W$ are both compatible with Standard Model expectations and other precise electroweak measurements. The SLD value is consistent with heavier top quark masses and lighter Higgs boson masses, while the combined LEP result prefers a lighter top quark and a heavier Higgs boson. We hope that the recent 1994–1995 run of the SLC and SLD will resolve this issue. The SLD Collaboration acquired a sample of more than 100,000 new Z events with an average electron beam polarization of nearly 80%. The uncertainty on the SLD measurement of $\sin^2\theta_W$ should improve by a factor of 2, to the point where it is competitive with the combined LEP uncertainty. A persistent discrepancy with the LEP measurements of this key Standard Model parameter would have interesting implications for particle physics.

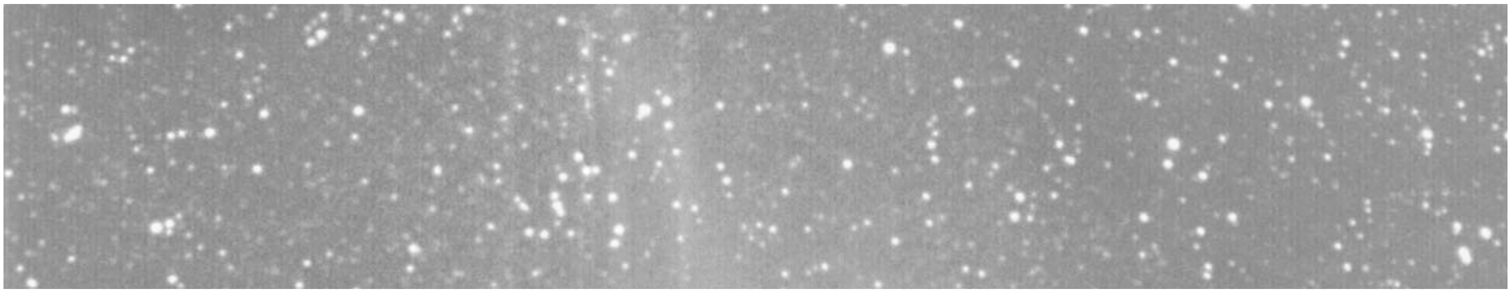
by VIRGINIA TRIMBLE

And How We Know That. . . Part III

COBE & How We Know that the Universe Went through a Hot, Dense Phase

It was a dark and stormy night at the center of the Universe. But this need not concern us, as our story does not take place at the center of the Universe. In fact, the Universe hasn't really got a center, and coming to terms with this is an important part of what is and is not meant by Big Bang.

THE CURRENT "STANDARD MODEL" of cosmology, or hot big bang, is naive and rather proud of it. We find that general relativity is a good description of all the deviations from Newtonian behavior that we see? OK, then the correct (non-quantum) theory of gravity is GR or something very much like it. The observations of wavelength shifts in the spectra of distant galaxies suggest homogeneous, isotropic expansion?



Fine, then the universe is expanding, cooling, and becoming more tenuous. The rate of that expansion, the oldest stars we see, and radioactive elements all suggest time scales of 10–20 billion years? Great! Then we know an approximate age for the expanding universe. Running the expansion backwards implies a past hot, dense state in which an isotropic sea of electromagnetic radiation would naturally be produced and about a quarter of the matter turned into helium? Even better. The radiation and helium we see are then relics from that past and can tell us about its details.

The vast majority of astronomers, including the present author, work happily within this framework, whether we focus on better determinations of the parameters of the standard model and trying to form structure within it or on phenomena like nova explosions, comets, and peculiar A stars, for which the large scale structure of the universe is a sort of Muzak. This is not quite the same as saying we all find standard, general relativistic cosmology intuitively obvious. Everybody is occasionally tempted to think in terms of matter expanding from a point or small region into previously existing space. This is the wrong image. The space itself is expanding and carrying the matter with it. The redshifts we see are not Doppler shifts, caused by relative motion through space, but are rather the stretching out of wavelengths with the metric they propagate on. Thus, whether the universe is finite or infinite, it has no edges and no center, and the only unique point is the time $t = 0$, when the expansion started. This instant is sometimes called the Big Bang, but I think this is a bit misleading.

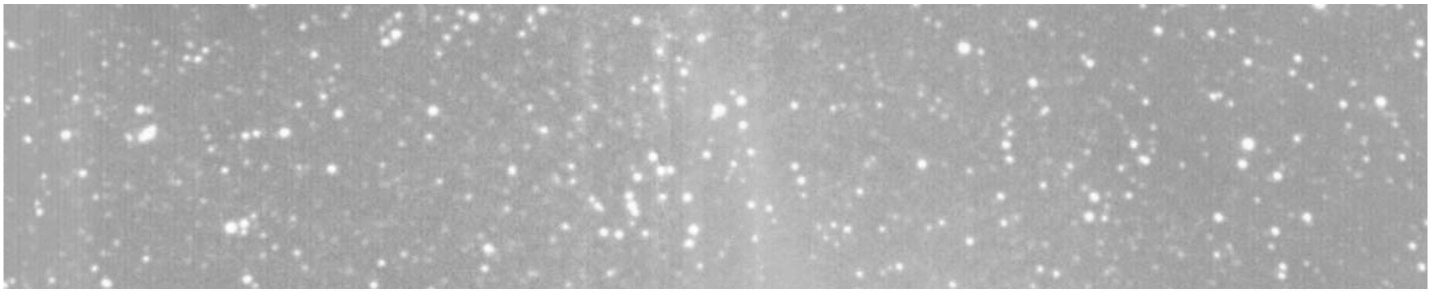
"Big Bang" was once an insult, thrown out over the airwaves of BBC by Fred Hoyle, then (1950) as now a propounder and advocate of the most robust of the alternative pictures, called Steady State. In it, GR is not the right theory of gravity, the universe is not becoming more tenuous, nothing is a fossil of a hot, dense past state, because there never was one, and the universe is infinitely old. In accordance with common, though not universal, usage, I shall take Big Bang to mean simply the four naive conclusions of the first paragraph. Evolutionary cosmology is a less inflamatory, but also less vivid synonym, and a recent contest to find an alternative name produced nothing better than Calvin and Hobbes' "tremendous space kablooie."

Carl Wilhelm Wirtz (1876–1939), one of several astronomers who preceded Hubble in attempting to correlate redshifts of spiral nebulae with their apparent brightnesses or angular diameters (both, in principle, distance indicators). Wirtz seems to have been the first to recognize that the correlation would be cleaner if some non-distance-dependent way could be found to identify classes of physically similar objects. He also contributed to the measurements of surface brightnesses of galaxies, of the galaxy luminosity function, and of the correlation between galaxy brightnesses and their location in clusters. (Courtesy of Helmar Duerbeck, Astronomical Institute, University of Muenster and Astronomische Gesellschaft.)

My remaining pages in this issue are devoted to outlining how the community came to agree on the standard model, why the alternatives are rejected, how the results from COBE on the spectrum and fluctuations of the leftover radiation strengthen the case for a hot big bang and help with pinning down some of the remaining uncertainties, and what came before the Big Bang.

ONCE UPON A TIME

Theory and observation got off to a false start together. Einstein published his first, erroneous theory of gravitation in the same year (1912) that Vesto Melvin Slipher exposed the first spectrogram on which the velocity of a spiral nebula could be measured. Slipher found a blue shift of about 300 km/sec. This is actually the right value, but it is the vector sum of the rotation of our own galaxy and the mutual orbital motion of the Milky Way



and the galaxy he looked at, our nearest large neighbor, the Andromeda galaxy. This large blue shift has very little to do with cosmology, except that it implies a sizable dark matter component associated with the two galaxies.

During the next decade, Einstein put forward the equations of GR as we now know them (in 1916) and his static solution, including the infamous cosmological constant, in 1917. That same year, Willem de Sitter proposed a different solution of Einstein's equations, in which space is static (and empty), but test particles and photons will show a preponderance of red shifts over blue shifts, with roughly a quadratic relation between distance and redshift. The first decade of cosmology closed in 1922 with Alexander Friedmann's imperfectly derived, but correct and complete, set of solutions to the GR equations (in which the universe could expand or contract uniformly, or oscillate, and have either finite or infinite total volume), and with Slipher's accumulation of enough spectrograms of spiral nebulae to show that redshifts were much commoner than blue shifts and that some were as large as 1000 km/sec. The expanding Friedmann solutions, in contrast to the de Sitter one, predicted a linear correlation of redshift with distance, at least locally.

The community was then still bitterly divided over whether the spiral nebulae were merely gaseous structures within our own galaxy or separate, roughly comparable, structures. The arguments (laid out in the Curtis-Shapley debate just 75 years ago) were tangled intimately with the question of distance scales inside the Milky Way and are too numerous to do justice to here. Edwin Hubble forced the "separate but equal" solution in 1924 by finding Cepheid variable stars and other reliable distance indicators in Andromeda and other nearby galaxies.

He did not immediately plot a Hubble diagram. Rather, between 1922 and 1926, attempts to correlate measured wavelength shifts with apparent sizes or brightnesses of spirals were made by (at least) the Swede Knut Lundmark, Germans Gustaf Strömberg and Carl Wirtz, Polish-American Ludwik Silberstein, and American

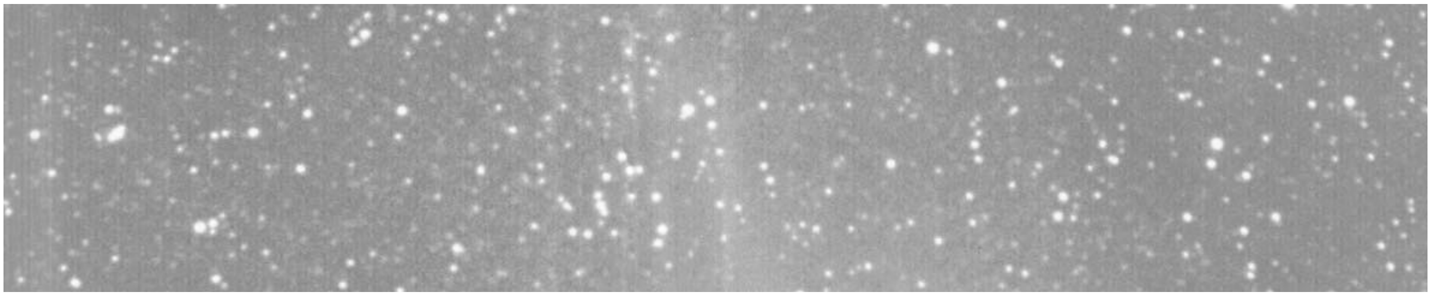
Radial Velocities of 25 Spiral Nebulae

Nebula	Velocity km (sec^{-1})	Nebula	Velocity km (sec^{-1})
N.G.C. 221	-300	N.G.C. 4526	+580
224	-300	4565	+1,100
598	-260	4594	+1,100
1023	+300	4649	+1,090
1068	+1,100	4736	+290
2683	+400	4826	+150
3031	-30	5005	+900
3115	+600	5055	+450
3379	+780	5194	+270
3521	+730	5236	+500
3623	+800	5866	+650
3627	+650	7331	+500
4258	+500		

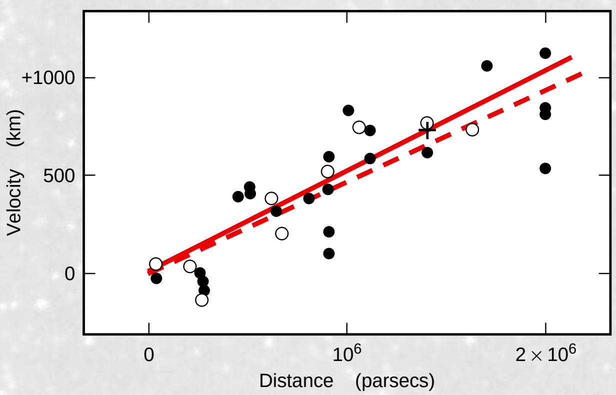
Velocities for the 25 spiral nebulae thus far observed. In the first column is the New General Catalogue number of the nebula and in the second the velocity. The plus sign denotes the nebula is receding, the minus sign that it is approaching. (From "A Spectrographic Investigation of Spiral Nebulae," by Vesto M. Slipher, Proceedings of the American Philosophical Society **56**, 403-409 [1917], reprinted in A Source Book in Astronomy and Astrophysics, 1900–1975, ed. Kenneth R. Lang and Owen Gingerich, Harvard University Press, 1979.)

"....It has for a long time been suggested that the spiral nebulae are stellar systems seen at great distances. This is the so-called 'island universe' theory, which regards our stellar system and the Milky Way as a great spiral nebula which we see from within. This theory, it seems to me, gains favor in the present observations...."

—Op. Cit.



The Hubble Diagram



The Hubble diagram as first plotted by Hubble. He used apparent brightnesses of whole galaxies as his primary distance indicators (and his distance scale differed by a factor of 5–10 from the present one, in the sense of being too small). Notice that the vertical coordinate is incorrectly labeled as kilometers, when it should be km/sec. His fit to the data yielded H = 536 km/sec/mpc with error bars of less than 10% (a mistake being made right down to the present time). [Figure adapted from "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae," Edwin P. Hubble, Proceedings of the National Academy of Sciences **15**, 168–173 (1929)].

"....The results establish a roughly linear relation between velocities and distances among nebulae for which velocities have been previously published, and the relation appears to dominate the distribution of velocities...."

—Op. Cit.

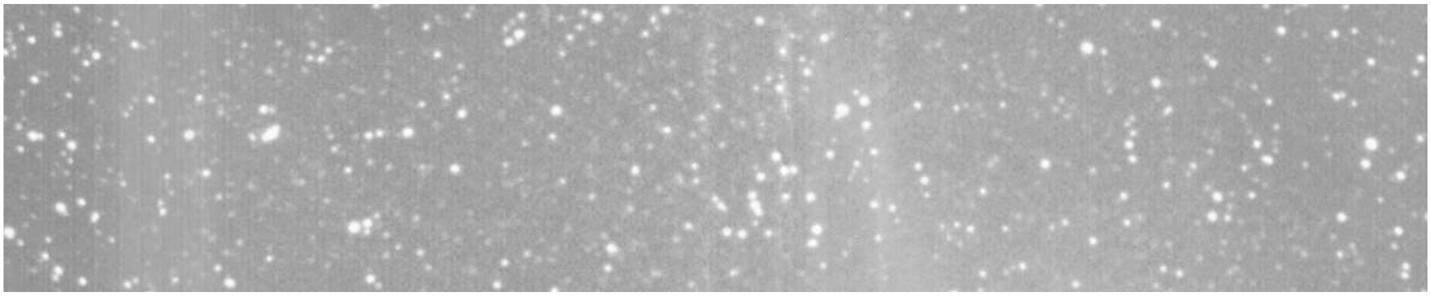
Howard P. Robertson. The motivation was typically the de Sitter solution, and the results fell somewhere between a scatter diagram and the expected quadratic, which has still at least one living defender.

The winning diagram, presented by Hubble in 1929, was linear enough to persuade most who saw it. Slipher's redshifts had been augmented by the first few to be measured by Hubble and Milton Humason with the new 100-in. telescope at Mt. Wilson, but the main improvement was better distance indicators and more careful selection of a sample of galaxies of uniform type for study. Hubble himself oscillated several times in the following years between universal expansion and tired light as his preferred explanation of what was soon dubbed Hubble's Law.* His value for the proportionality constant implied a time scale for the universe, $1/H \approx 2$ Gyr, at any rate comparable with the age of the earth as then understood.

Secondary literature leaves the impression that respectable scientists did not take any of this very seriously for some time. In this context, the latter sections of Richard C. Tolman's **Relativity, Thermodynamics, and Cosmology** (published in 1934 by Oxford University Press) repay study. He is ready to prefer Friedmann models to static or de Sitter ones and to compare the measured mass density of our region of space (extending only to 10^8 light years) with the unique ones of some models. And he is already worried about the discrepancy between $1/H$ and the longer time scales of stellar evolution. But he does not consider extrapolating back in time or farther away than the observed volume of space.

The first great extrapolater was George Gamow, beginning with a 1935 paper in the *Ohio Journal of Science*, addressing the role of neutrons in nucleosynthesis. His

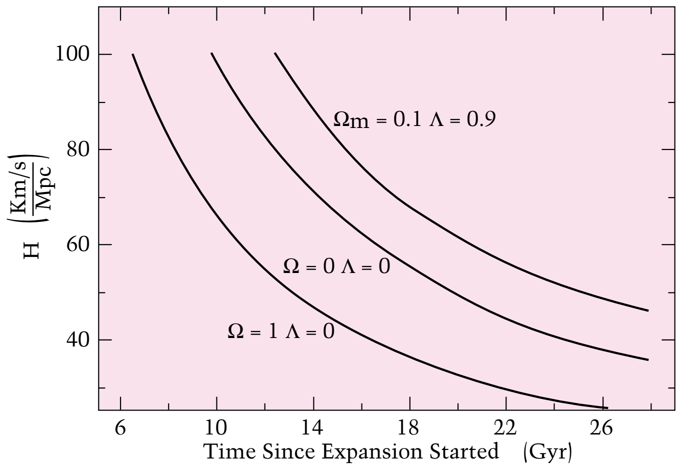
**The linear relation is best written as $(\Delta\lambda/\lambda)\,c = Hd$, where the left side has units of velocity, but can exceed the speed of light, d is distance, and H is the Hubble constant. H has units of velocity/distance, or reciprocal time. In a Friedmann model, expansion has been going on for 1/H in an empty universe, less than that with matter present (e.g., 2/3H for the density that would just stop expansion in infinite time) and longer than 1/H for positive values of the cosmological constant.*



collaboration (1948–53) with Ralph Alpher and Robert Herman produced the first quantitative estimates of the current cosmic temperature and of cosmological nucleosynthesis. They are justly regarded as heroic pioneers. They began, however, from a false premise, with a pure neutron "ylem" at $t = 0$. Neutron decay was then blamed for additional heating as well as for protons and electrons. They had also a hopeless goal—the production of the full range of elements and nuclides in the early universe. Such progression from A = 1 (hydrogen) to A = 238 (uranium) is, of course, interrupted by the extreme instability of all possible A = 5 and 8 nuclides (and the gaps can be bridged only at higher density, by three-particle interactions, such as occur in evolved stars).

The first correct calculation of cosmological nucleosynthesis, starting with thermal equilibrium at early times, came from C. Hayashi in 1950. He also hoped one might still hop across the A = 5 and 8 holes with some suitable mix of protons, deuterons, tritons, helium nuclei, and so forth. Actually one does, a bit. Traces of lithium-7 are among the products of modern standard model calculations (and even a bit of beryllium and boron if one considers sufficiently inhomogeneous initial conditions). That you get about 25 percent helium out of either a Gamovian or a thermal equilibrium sort of hot big bang continues to strike me as slightly mysterious. Perhaps it says nothing more profound than that all nuclear energies are around 1 MeV per amu, but I would be interested in alternative perspectives from those who have thought about the issue.

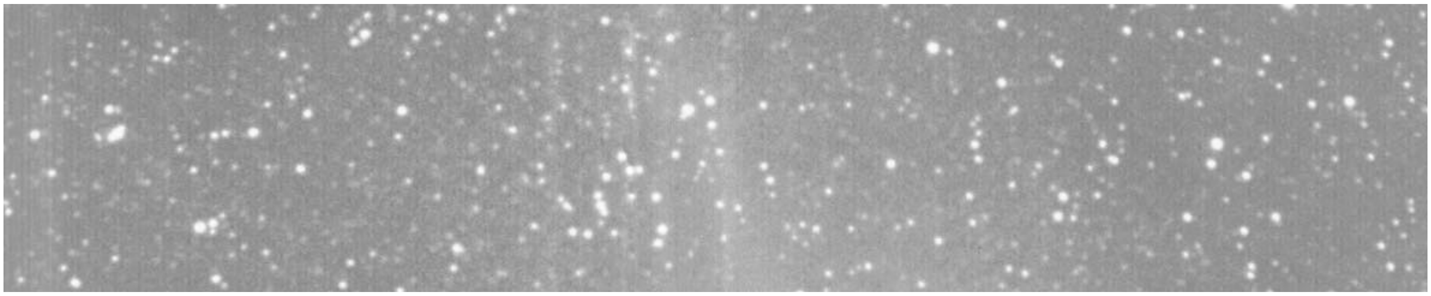
The same 1948–53 period saw the flowering, largely in England, of the Steady State alternative model, in which new matter is continuously created to keep the density of an expanding universe constant. That American students of the time took it much more seriously than did their senior, professional mentors is perhaps mostly a tribute to the writing skills of its propounders, Hermann Bondi, Thomas Gold, and Fred Hoyle and early supporters, including Dennis Sciama, William H. McCrea, and Raymond A. Lyttleton. Apart from philosophical considerations, the primary motivation for



Time since the universe began expanding ("age of the universe") as a function of the correct, global Hubble constant, H, and other parameters whose values are also uncertain. The far left curve is for total density in matter (baryonic plus dark etc.) equal to the critical density and zero cosmological constant. The middle one is for density and cosmological constant both zero (or anyhow small), and the right one for flat space-time geometry with contributions from a matter density (10% of the critical density) and cosmological constant (90%).

steady state was the time-scale problem noted already by Tolman. This became acute when stellar evolution, based on nuclear energy sources, was put on a firm footing, but it quickly ameliorated after the 200-in. telescope was turned to cosmological problems (also starting in 1948) and began to provide evidence for larger distances in the universe and so longer expansion times.

Quite early on, Bondi asked a paleontological question—if the universe was different in the past, where are the fossils? Helium is clearly one such (if and only if there is no other way to account for its ubiquity). Radio galaxies and, soon after, quasars (much commoner at redshifts of 1–2 than here and now) were increasingly accepted as such fossils through the period 1955–65. And the definitive fossil, "A measurement of Excess Antenna Temperature at 4080 Mc/s," was announced in 1965 by Arno Penzias and Robert Wilson (as if you didn't



The Microwave Background Radiation

....Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4,080 Mc/s have yielded a value about 3.5K° higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July 1964–April, 1965). A possible explanation for the observed excess noise temperature is one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter this issue....

—Arno A. Penzias and Robert W. Wilson, *Astrophysical Journal* **142**, 419-421 (1965).

already know). George Gamow's reaction, expressed at the 1967 "Texas" symposium on relativistic astrophysics was, "Well, I lost a nickel, and you found one. Who is to say it's the same nickel?"

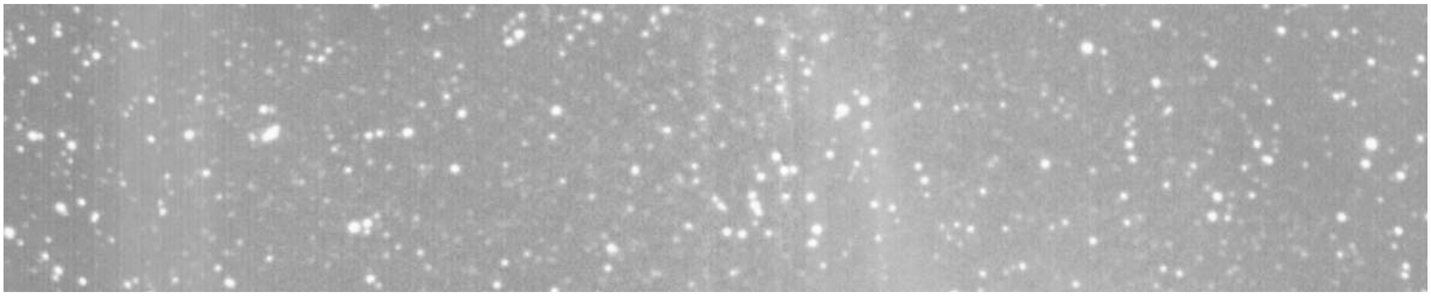
For what it is worth, we are now as far away in time from the Penzias and Wilson measurement as they were from the first nucleosynthesis paper by Gamow. And, despite periodic alarums and excursions, the status of big bang nucleosynthesis calculations remains that the observed amounts of ordinary hydrogen, deuterium, helium-3 and -4, and lithium-7 can be simultaneously produced in the standard model provided that the nuclear and particle physics is taken to be what we see in the laboratory and that the density of baryonic material is between 1 and 10 percent of the total density that would just halt expansion in infinite time ($\rho_c = 3H^2/8\pi G$).

RULING OUT THE ALTERNATIVES

Disciples of Sherlock Holmes (and perhaps Karl Popper, but of this I am not sure) require both that their explanations take care of all the facts and that all conceivable alternatives be ruled out. The previous section addressed the positive side of the hot big bang. Here we look briefly at the flaws of some counter-proposals, though not all of them, as it is already getting on for tea time.

Tired light is the idea that photons lose energy and so are shifted to longer wavelengths simply by traveling long distances. Admittedly, the Feynman graphs for this sum to zero. But it is remarkably difficult to rule out on purely observational grounds. We are still a few orders of magnitude away from being able to see the expected redshift over laboratory distances. (Mössbauer spectroscopy seems to come closest.) The surface brightnesses of distant galaxies as a function of redshift are different in expanding and tired-light cosmologies, but the difference is easily lost in observational uncertainties. The cleanest test comes from the behavior of time intervals. In relativistic expansion, all of them are stretched out, just like the time between wave crests of radiation. In tired light, time intervals are the same for all observers. A couple of supernovae have now been seen at sufficiently large redshifts (0.3 and 0.5) that the time dilation of their light curves should show up. It probably does, though some of the data remain unpublished.

What about a sort of Newtonian or Galilean universe, in which matter explodes outward from a point or small region into previously existing space? Such a universe has a hot, dense phase in its past to make helium and the microwave background radiation. And, of course, after a while velocities and distances will be linearly related. But we must be remarkably close to that central point or region to see as nearly an isotropic universe as we do. This was a sort of 99 percent conclusion even when all we had to go on was the Hubble diagram in different directions. It becomes more powerful with the inclusion of 3K radiation measurements. Even if you blame off-center location for the dipole anisotropy (normally attributed to ordinary motion of our galaxy), we are still restricted to the central 0.1 percent or so.



Friedmann's original set of solutions to Einstein's equations included some that oscillate between expanding and contracting phases. Such a universe could contain objects (very sturdy ones, anyhow) older than $1/H$. Whole conferences have worried about whether there are thermodynamic objections to this. But it doesn't matter. If you accept the general relativity that suggested these solutions in the first place, then they are impossible.

Theorems dating from the 1960s, due to Stephen W. Hawking, G.F.R. Ellis, Roger W. Penrose, W. Israel, B. Carter, and others, establish that, first, if a system once gets into a singular state from non-singular conditions (goes through a collapse phase), it can never get out again, and, second, that we have a singular state (or at least a trapped surface, which is closely related) in our past, and also in our future if the density of the universe exceeds the critical density. Thus a closed universe can expand and contract once, but only once. This conclusion is about the same age as the 3K radiation, but it has taken much longer to find its way into textbooks.

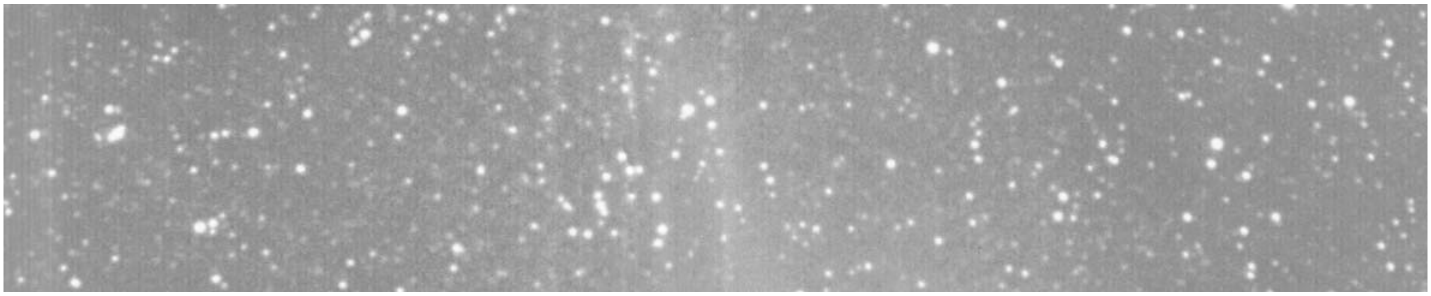
Finally, let us deal collectively with steady state, its modifications, and any other scenarios that do not provide a hot, dense phase 10 or 20 billion years ago. First, unless matter is somehow created as 3/4 hydrogen and 1/4 helium you must fuse protons (or protons and neutrons) into alpha particles. This happens in stars—and a good thing, too, since it keeps them shining. The ratio of helium production to shine is a laboratory number. The density of starlight in the present universe (including that absorbed and reradiated by dust as infrared) is reasonably well measured. And, putting the numbers together, you discover that real galaxies can turn only about 2 percent of their baryonic mass into helium in a Hubble time. Or, looking at it the other way around, if you want to start with pure hydrogen and no hot, dense stage, galaxies have to be 10 times as bright as the ones we see to reach 23 percent helium now.

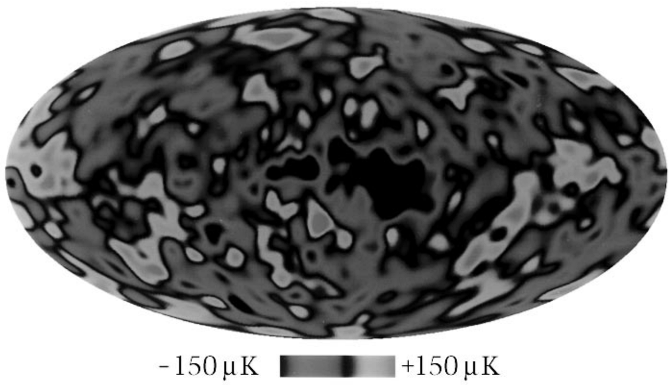
Second, you must come up with the microwave background radiation and make it both very accurately a black body and very accurately the same in all directions in space. A perfectly homogeneous, isotropic, isothermal big bang makes perfectly isotropic, thermal radiation; and we then have only to worry about not messing it up later (next section). But if you produce the radiation in sources distributed through time and space, you must isotropize and thermalize it. The energy requirements are not beyond possibility, being comparable with what you would get by turning another 25 percent of the hydrogen to helium instantaneously [though fusion spread over time won't quite do, since you lose energy density with redshift, z, in proportion as $(1 + z)^{-4}$]. But the energy from the hypothetical sources must be continuously absorbed and reradiated by something that is at 2.7K and blankets the sky. We have no independent evidence for such absorbing material, and strong evidence against it. Radio sources with redshifts of two and more are seen as bright points against the background at centimeter and millimeter wavelengths. The universe is not optically thick at the present time and cannot be continuously isotropizing and reradiating energy, whatever class of sources you care to postulate.

COBE AND THE PROBLEM OF STRUCTURE FORMATION

Can cosmologists close up shop and go home? Not quite. While our standard model does a great job with things (expansion, nucleosynthesis, background radiation) that are homogeneous and isotropic, it has no galaxies, clusters, or other structure. Such a universe has only individual atoms for observers, and we would not be here to talk about it. Structure must form early enough to account for the quasars we see back nearly to a redshift of five, and it must form without ruffling up the passing $2.7(1 + z)$K radiation.

Structure formation is arguably the single most important outstanding problem in modern astrophysics. It is genuinely insoluable with the most obvious choice of initial conditions—baryonic material (only) at the density implied by nucleosynthesis, growing its structures from adiabatic perturbations (ones in which matter





Residual fluctuations in the nearly-isotropic microwave background, after contributions from the solar system, galaxy, and ordinary Doppler shifts have been subtracted. The data are now accurate enough that the experiment group can say with confidence that particular bits of the sky are warmer or cooler than average, based on looking separately at two years of data. (Courtesy George Smoot, LBL.)

and radiation remain coupled until the universe is too cool to keep hydrogen ionized and becomes transparent).

To get density perturbations of order unity now (so they grow non-linearly into galaxies), you must have at least $\Delta p/p = 10^{-3}$ at $z = 1000$, when baryons and photons part company. In an adiabatic lump (where photon number density goes as T^3, and $3^2 = 10$ in astronomical convention), the associated temperature lumps must be close to $\Delta T/T = 3 \times 10^{-4}$. And these will still be with us. But limits in data obtained from the ground were already below 10^{-4} and shrinking when COBE took off. Measured values, at several wavelengths and on several angular scales, are now all in the ball park of $1–2 \times 10^{-5}$.

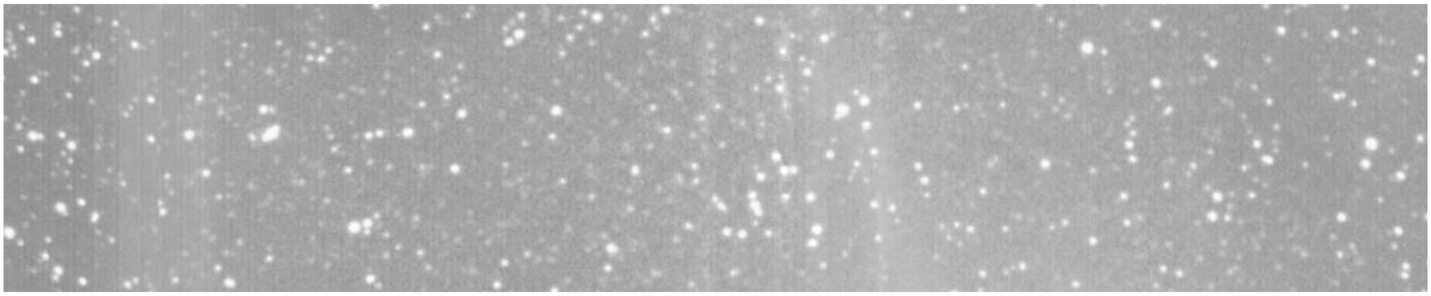
This conflict has driven most studies of large-scale structure formation for the last decade and more. Fruits of the struggle include models with many different kinds of non-baryonic dark matter, non-adiabatic (plus non-Gaussian, and non-scale-invariant) perturbations as starting conditions, and cosmic strings and other seeds for galaxies to condense around. The point of non-baryonic dark matter is that it stops speaking to photons electromagnetically long before $z = 1000$, so lumps can form without dragging radiation with them. But gravitational communication remains between radiation and any kind of matter. Thus you can buy only about one additional order of magnitude between the necessary $\Delta p/p$ and the minimum resulting $\Delta T/T$.

This is, however, all we need, since two years of data from the Diffuse Microwave Radiometer on the COsmic Background Explorer, as well as data sets coming from ground-based observatories from California to the South Pole, now show brightness fluctuations in the background radiation at the "predicted" lower level. COBE and one ground-based observation even find the same warm and cool patches on the sky.

A couple of other happy conclusions have transpired. The relative amplitudes of the fluctuations on different angular scales are, at least, not inconsistent with most people's favorite guess (equal power on all scales, otherwise known as a Harrison-Zeldovich spectrum). The shape of the radiation spectrum is as precisely a black body as anything ever measured, and severely limits any stray energy inputs from, e.g., helium synthesis in pre-galactic stars.

Third, the same fluctuations are seen at several wavelengths, with relative amplitudes that are just the derivatives of a black body spectrum that you expect from "colorless" Doppler shifts and gravitational redshifts due to small variations around isotropic expansion of a big bang universe. In contrast, a "sum of sources" model has fluctuations due to slightly different source numbers and reradiation temperatures in different parts of the sky, and the thermal nature of the fluctuations would be a complete coincidence. This last point seems to have been widely appreciated only within the last six months or so. I first heard it in a talk by Martin Rees at the August 1994 general assembly of the International Astronomical Union. It is a specific objection to recent, quasi-steady-state revivals.

All careful readers of the New York *Times* will remember a recent flurry of responses to a Hubble Space



Telescope measurement of H = 80 km/sec/Mpc, based on the period-luminosity relation of Cepheid variable stars in one galaxy in the Virgo cluster (12–22 Mpc away). If you accept this as the correct global value, are sure that the cosmological constant is zero, and have confidence that the mass density of the universe is closer to the critical density than to zero, then the expansion time scale is necessarily rather less than 10 Gyr. Pushing along the evolution of galaxies and stars so that they look like the ones we see after so short a time presents certain difficulties. It is, however, probably obvious from my tone of ink that I have doubts about the need to accept the triple assumption that leads to the contradiction.

WHAT CAME BEFORE THE BIG BANG?

If you mean by Big Bang a state of exact thermal equilibrium, then all evidence of what come before that state will, by definition, have been wiped out, and this is a silly question. It would then deserve only a silly answer, along the lines of the response to "What was God doing before he created heaven and Earth?" "He was creating hell for people who ask questions like that."*

But we have just persuaded ourselves that the real universe was not precisely in such equilibrium. Rather, there were fluctuations in the density (of something) that have grown into the galaxies, clusters, and voids that we see.

Candidates for non-equilibrium entities which might, therefore, carry traces of what came before the hot, dense phase include many kinds of non-baryonic dark matter and assorted topological and non-topological singularities and solitons, left behind by symmetry breakings and phase transitions, including, of course, the particles and fields responsible for a possible pre-nucleosynthetic epoch of inflationary (exponential in time) expansion. I am not sufficiently knowledgeable to cherish any strong opinions about the existence or nature of these entities. Probably no one would claim that the evidence for and about them is anywhere near as strong as that for the hot, dense phase, of which helium and the thermal background radiation are fossils.

Further work is needed, as the old saying goes. But, meanwhile, us non-experts can respond to questions from the even less expert by saying, firmly, "Yes, there was a big bang! The evidence is overwhelming that the universe was very hot and very dense 10–20 billion years ago, and has been expanding and cooling every since."

**This exchange is widely attributed to St. Augustine. But more careful reading indicates that he really quoted it as an example of the kind of nonsense up with which he would not put. Bohr probably didn't really have a horse shoe over his barn, either.*

What To Read Next

A good introduction to historical materials is N.S. Hetherington, Ed., **Encyclopedia of Cosmology**, Garland Publishing, NY, 1993.

A great place to start if you want to learn to do real calculations and evaluate real observations is P.J.E. Peebles, **Physical Cosmology**, 2nd edition, 1993.

Ralph Alpher and Robert Herman have told their story in *Phys. Today* **41**, 24 (1988).

Some recent words on nucleosynthesis and COBE results are, respectively, C.J. Copi et al., *Science* **267**, 192 (1995), and G. Smoot et al., *Astrophys. J.* **437**, 1 (1994).

The very latest word at any given instance must be sought at conferences and on your preprint shelves.

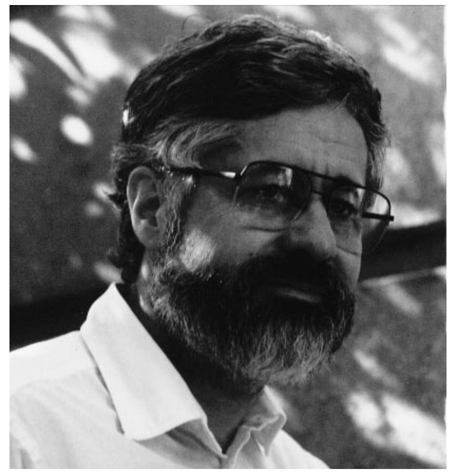
One view of what came before the Big Bang is expressed by A. Linde, "The Self Reproducing Universe," *Scientific American*, November 1994, p. 32.

CONTRIBUTORS

PETER G. TENENBAUM is a graduate student in accelerator physics at the University of California at Santa Cruz. Born and raised in New York City, he came to California in 1985 to pursue a B.S. in physics at Harvey Mudd College. After much pursuit, the degree was captured, and P. T. graduated to Santa Cruz, where he's been ever since.

In addition to the Final Focus Test Beam, P. T. has a general interest in operational issues of advanced accelerators and colliders and is involved in the Next Linear Collider design effort at SLAC. He is also known to dabble in guitar-playing, to the dismay of many.

J. RITCHIE PATTERSON is currently at Cornell, where she is studying the decays of the b quark using data from the CESR accelerator. Recently she and two colleagues have searched for the weak decay of the B meson (an "atom" consisting of a b and $\bar{u}$ quark) into a lepton and neutrino. This decay probes of the structure of the meson and is a possible window into new phenomena.



Valerie MacLean

BERNARD SADOULET is a Professor of Physics at UC Berkeley and the Director of the Center for Particle Astrophysics. Trained in particle physics, he had the chance to participate in the Mark I experiment at SLAC which stumbled onto the J/ψ and charm, and also in the CERN UA1 experiment which discovered the W and Z vector bosons. In 1984, he turned his interest to particle cosmology and since then focused on the dark matter problem. He is currently coordinating an experiment using novel cryogenic detectors to look for Weakly Interactive Massive Particles (WIMPs), which may constitute this dominant component of the universe. In winter 1994, he was a member of the HEPAP subpanel on the "Vision of Particle Physics," headed by Sidney Drell, and data presented here have been mostly gathered at this occasion.

MORRIS SWARTZ did his research at Fermilab and CERN before coming to SLAC in 1986. Since then, he has experienced the downs and the ups of the SLC program as a member of the Mark II and SLD collaborations, respectively. Presently, he is a leader of SLD's Electroweak Working Group, which is busy producing a more precise measurement of the left-right asymmetry.

VIRGINIA TRIMBLE is past chair of the High Energy Astrophysics Division of the American Astronomical Society, the Astronomy section of AAAS, the nominating committee of the Astronomical Society of the Pacific, and a number of other small entities. She is now invited to conferences largely for the purpose of giving historical introductions, concluding remarks, and after-dinner talks.

FROM THE EDITORS' DESK

WITH THIS ISSUE of the *Beam Line*, a milestone of sorts has been achieved. The *Beam Line* can now be read online in Portable Document Format (PDF) via the World Wide Web (WWW). Readers wishing to do this will need a Macintosh, PC, or Sun computer with a WWW browser configured to launch the Adobe Acrobat Reader.

To get to the *Beam Line* WWW page, start at the SLAC Home Page (http://www.slac.stanford.edu). Scroll all the way down the page to SLAC WWW Support and click on "What's New," then *Beam Line*.

The *Beam Line* is prepared using Quark XPress on the Macintosh. Photographs are added conventionally (rather than electronically) because we have found that when the printer makes his own screens the resolution is better. Accordingly, we have optimized the photos in the electronic file in order to reduce the file size as much as possible. The file is then printed to disk to create a PostScript file and processed with the Adobe Acrobat Distiller.

One noticeable bug in this process (and we have let Adobe know about it) is that items given a spot color in Quark XPress (sidebars, figure captions, etc.) become grayscale in the final PDF document. Thus the printed magazine is more colorful than the online version. Since much of what makes the *Beam Line* pleasing to the eye is the page layout, and because we know readers will want articles they print to be readable, we decided to use Adobe Acrobat rather than HTML to produce the online version.

We say a "milestone *of sorts*" because we recognize that *Beam Line* readers working on other platforms will not be able to view the document online. While Sun is currently the only flavor of UNIX with a Reader, others are planned. Of course, with the recent merger of Adobe and Netscape Communications Corporation, viewing PDF files on WWW will get easier and more transparent.

The Adobe Acrobat Reader can be downloaded from Adobe's WWW pages at http://www.adobe.com. They also have written excellent instructions on how to configure nearly any Web browser to launch the Reader as a helper application.

The *Beam Line* will continue to be published conventionally, as well as online, for the foreseeable future. If you have questions or comments, we are eager to hear from you.

Rene Donaldson

Bill Kirk

DATES TO REMEMBER

Jun 19–30	1995 U.S. Particle Accelerator School (PAS 95), Seattle, WA (c/o Fermilab, MS-125: PO Box 500, Batavia, IL 60510 or uspas@fnalv.fnal.gov).
Jul 10–14	6th International Conference on Hadron Spectroscopy (Hadron 95), Manchester, UK (Dept. of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK or hadron95@v2.ph.man.ac.uk).
Jul 10–21	XXIII SLAC Summer Institute on Particle Physics: The Top Quark and the Electroweak Interaction, Stanford, CA (L. DePorcel, SLAC, PO Box 4349, Stanford, CA 94309 or ssi@slac.stanford.edu).
Jul 17–Aug 4	30th Latin American School of Physics (ELAF): Group Theory and Its Applications, Mexico City, Mexico (Secretariat XXX ELAF '95, CIFMA A.C., Apdo. Postal 139-b, 62191 Cuernavaca, Morelos, Mexico or elaf95@ce.ifiscam.unam.mx).
Jul 24–28	16th Annual Meeting, TeX Users Group: TUG '95: TeX Goes to Florida, St. Petersburg Beach, FL (TeX Users Group, PO Box 869, Santa Barbara, CA 93102 or tug95c@scri.fsu.edu).
July 27–29	Workshop on the Search for New Elementary Particles, Trieste, Italy (F. Hussain, ICTP Workshop on the Search for New Elementary Particles, PO Box 586, I-34100, Trieste, Italy or smr864@ictp.trieste.it).
Aug 5–Aug 9	1st International Conference on Frontiers of Physics: Looking to the 21st Century (Limited to 250 Participants), Shantou, P. R. China (95 Shantou Conference, c/o Department of Physics and Astronomy, City College of New York, New York, NY 10031 or 95ocpa@isuhep.hep.ameslab.gov or xylin%stumis@hkucnt.hku.hk).
Aug 20–Sep 2	1995 CERN School of Computing (CSC 95), Arles, France (Miss Jacqueline Turner, CERN School of Computing, CERN, CN Division, CH-1211 Geneva 23, Switzerland).
Oct 16	APS X-ray Centennial Symposium, Argonne National Laboratory, Argonne, IL.
Oct 17	APS Users Organization and SRI '95 Workshops, Argonne National Laboratory, Argonne, IL.
Oct 18	Seventh Users Meeting for the APS, Argonne National Laboratory, Argonne, IL.
Oct 18–20	Synchrotron Radiation Instrumentation '95, Argonne National Laboratory, Argonne, IL.