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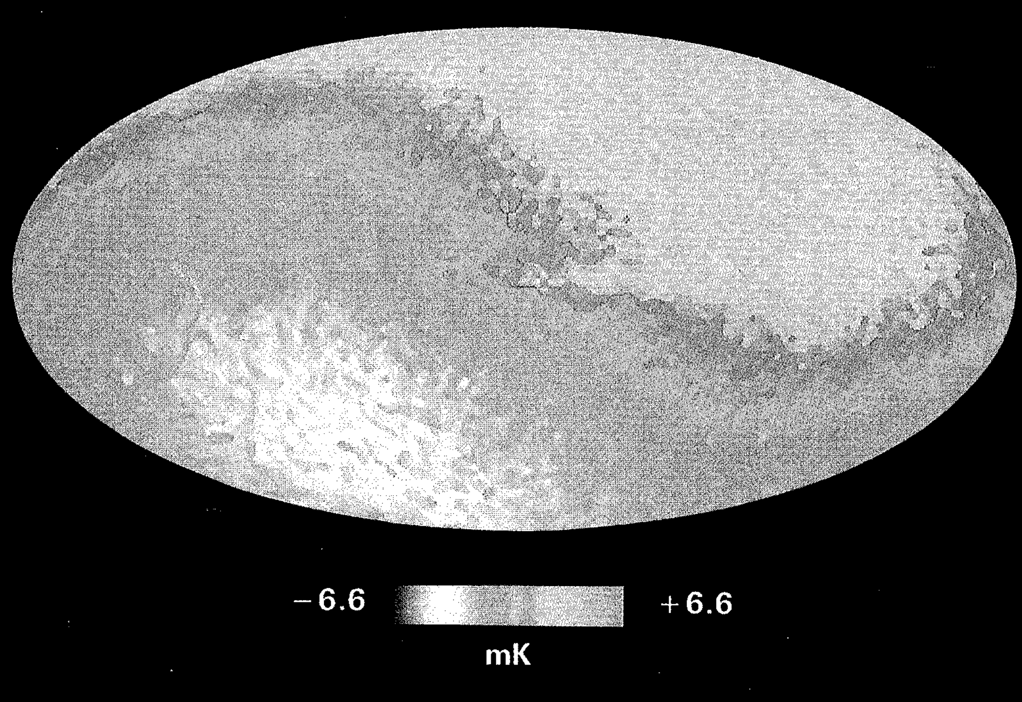

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

FALL/WINTER 1990 VOL. 20, NUMBER 3

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Cover: Fluctuations in the temperature of the cosmic microwave background radiation as reported by the Cosmic Background Explorer satellite. Hot spots are shown in red. The entire sky is projected on the figure, with the plane of the Milky Way as the equator. All temperature anisotropies can be identified as individual sources (mostly in the galactic plane) or as a dipole moment to the radiation pattern caused by the motion of our galaxy through the Universe. (Courtesy of NASA/Goddard Space Flight Center)

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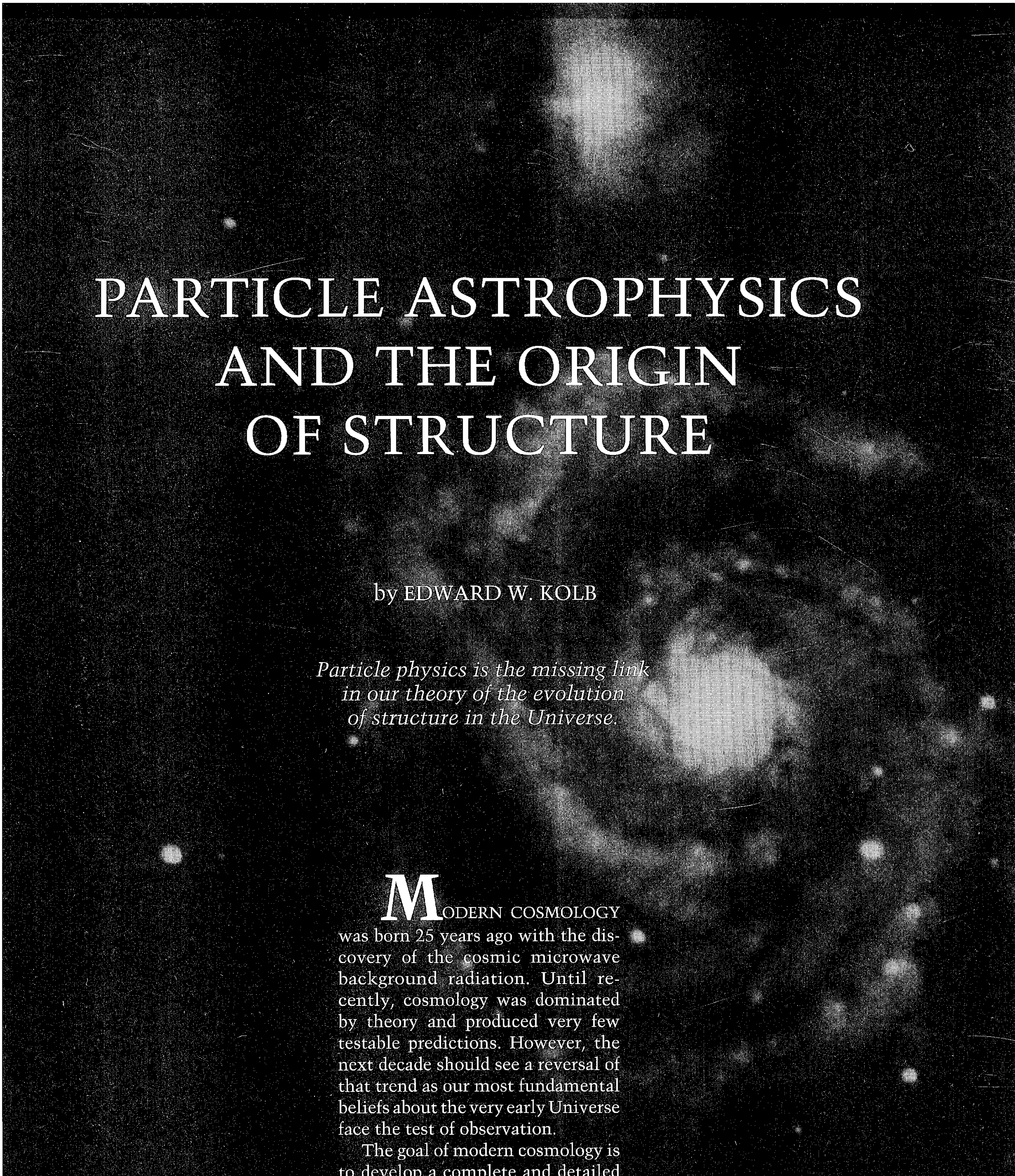


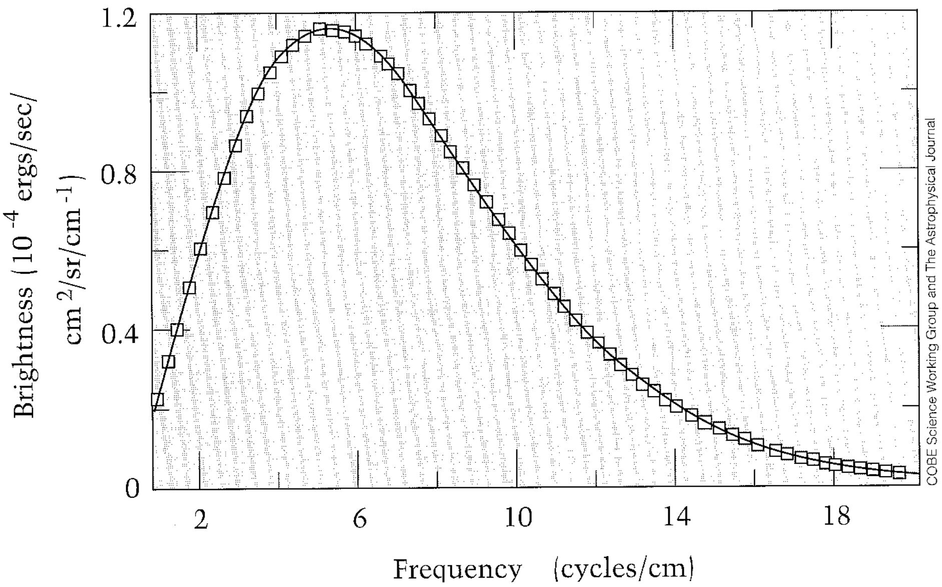
PARTICLE ASTROPHYSICS AND THE ORIGIN OF STRUCTURE

by EDWARD W. KOLB

Particle physics is the missing link in our theory of the evolution of structure in the Universe.

MODERN COSMOLOGY was born 25 years ago with the discovery of the cosmic microwave background radiation. Until recently, cosmology was dominated by theory and produced very few testable predictions. However, the next decade should see a reversal of that trend as our most fundamental beliefs about the very early Universe face the test of observation.

The goal of modern cosmology is to develop a complete and detailed picture of the origin, evolution, and large-scale structure of the Universe based upon the laws of physics. In



The spectrum of the cosmic microwave background radiation as measured by the cosmic background explorer satellite. The solid curve is the spectrum of a blackbody of T=2.735 K.

the past decade it has become clear that it is impossible to achieve this goal without the foundation of high-energy physics. This article will focus on one aspect of the application of high-energy physics to cosmology, namely the origin of large-scale structure.

Just as in particle physics, cosmology has a standard model: the "big bang." Just as there is a fundamental principle as the basis of the standard electroweak theory (the principle of gauge invariance), so there is a corresponding principle at the heart of the big bang, the *Cosmological Principle*, which states that on large scales the Universe is spatially homogeneous and isotropic. Evidence that the Universe obeys the cosmological principle comes from observations of the distribution of radiation and the distribution of matter. Each plays an important role in understanding the emergence of structure in the Universe.

CONSIDER FIRST the radiation in the Universe. Most of this radiation resides in the microwave region of the spectrum as a diffuse cosmic background. The present temperature of this cosmic microwave background radiation (CMBR) is 2.735K. The microwave background is truly a relic of the early Universe. Background photons last scattered about 350,000 years after the big bang, when the temperature of the Universe fell well below the binding energy of hydrogen, allowing protons and electrons to combine and form neutral hydrogen. The present distance to this surface of last scattering of the microwave photons is about $3000h^{-1}$ megaparsecs (see box above right). Thus, the microwave radiation provides information about the Universe on the very largest distance scales we can probe.

In the past year or so there has been significant new information about the microwave background. Perhaps the most spectacular new result is that the spectrum of the radiation is indeed that of a "blackbody" as predicted by big bang theory. This important measurement was made about a year ago by the *Cosmic Background Explorer* (COBE) satellite. The results of the COBE measurements are shown in the graph above. The prediction of a thermal spectrum is spectacularly confirmed by the data.

The second important piece of information that has emerged in recent years is the high degree of *isotropy* of this radiation. If we remove the dipole component to the radiation pattern caused by the motion of the earth about the sun, the sun about the Milky Way, and the Milky Way through the Universe, the temperature of the background radiation seems to be the same in all directions. The temperature differences are quantified in terms of temperature fluctuations, written $\Delta T/T$. Here ΔT is the difference between temperature measured at a certain place on the sky and the average temperature, T. Once the dipole moment is subtracted, there is no detectable ΔT. A map of the temperature of the microwave background temperature made by COBE is shown on the cover. If one removes the obvious dipole component, the radiation temperature is uniform to the limits of the measurement. Although the cosmological principle implies that the background should be isotropic, we know that it can't be exactly smooth. Some small anisotropy must be present, because the microwave background should contain imprints of the primordial wrinkles in the distribution of matter in the early Universe. Most cosmologists believe that these small wrinkles are ultimately responsible for the formation of structure. However these predicted wrinkles have never been detected.

The Language of Astronomy

THE BASIC UNIT OF LENGTH IN ASTRONOMY is the parsec. One parsec (pc) is 3.1×10^{18} cm, or about 3.26 light years. The typical distance between stars in our solar neighborhood is about a parsec. We are roughly 10 kpc from the center of the Milky Way, which represents about a third of the diameter of a spiral galaxy like our own. The nearest large galaxy is the Andromeda galaxy, about 1 Mpc away. This distance between galaxies is representative of the separation of "field" galaxies, which are isolated galaxies not associated with rich clusters of galaxies.

The distance to extragalactic objects beyond our local group of galaxies is usually determined by Hubble's law: $cz = H_0 d_L$, where c is the velocity of light, z is the redshift ($z = \lambda_{OBS}/\lambda_0 - 1$, where λ_{OBS} is the observed wavelength of some spectral feature of laboratory wavelength λ_0), H_0 is the Hubble constant, and d_L is the distance to the object. The quantity cz is the speed at which the object is receding from the local group.

Sixty-one years after the discovery of the expansion of the Universe, the Hubble constant is still uncertain by about a factor of two! The Hubble constant is usually expressed in terms of a dimensionless "reduced" Hubble constant h: $H_0 = 100h$ $\mathrm{kms^{-1}\,Mpc^{-1}}$, and the uncertainty in the Hubble constant translates into the range $0.4 \lesssim h \lesssim 1$. The uncertainty in h generally appears in the estimated distance to extragalactic objects. For instance, the distance to the galaxy LML1924 with redshift $z = 0.1$ is $d_L = 300h^{-1}$ Mpc, or between 300 and 750 Mpc.

The experimental limits on temperature fluctuations depend upon the angular separation of the two regions of the sky studied. The limits vary from $\Delta T/T \lesssim 10^{-5}$ on angular scales of a few minutes, to $\Delta T/T \lesssim 3\times10^{-5}$ on angular scales of 90°. This isotropy of the microwave radiation tells us that on the surface of last scattering, the Universe is very smooth. This regularity is the best proof of the cosmological principle. If the radiation is isotropic about us, and we do not occupy a special point in the Universe, the radiation should be isotropic about every observer. A Universe that is isotropic about every observer must be homogeneous.

NOW CONSIDER THE OTHER component of the Universe: matter. There is evidence that on the largest scales the distribution of matter is homogeneous and isotropic. This evidence comes from the isotropy of counts of the numbers of galaxies in different directions; the isotropy of the x-ray background (which is believed to have a large cosmological component produced by hot gas early in the Universe); the distribution of galaxies found by the InfraRed Astronomical Satellite (IRAS); the distribution of faint radio sources; the quasar distribution; and the random velocities of galaxies that trace the matter distribution.

The Universe is smooth on large scales but clumpy on small scales. It is not clear on what scale the transition from structure to smoothness occurs. Evidence for the homogeneity and isotropy of the matter distribution based upon the distribution of galaxies has been elusive. In the past decade or so there have been several large projects dedicated to producing 3-dimensional maps of the location of bright galaxies. These maps have produced a wealth of information, along with quite a few surprises. In every volume of the Universe ever mapped, there are indications of structures as large as the size of the survey itself. For instance, the largest contiguous volume of the Universe ever mapped in 3 dimensions, the Center for Astrophysics (CfA) redshift survey of about 10,000 galaxies, contains structures that fill the entire survey. The largest structure in this survey is known as the "Great Wall" of galaxies, more than 100 megaparsecs across. This survey also shows evidence that galaxies seem to be aligned on the surface of bubbles about 20 megaparsecs in diameter. Structures of this size fill the entire survey.

In the past few years the size, diversity, and magnitude of structures in the Universe has astonished, and even alarmed, cosmologists. It seems that every time we look on larger scales we manage to find larger objects. Some cosmologists have suggested that rather than a Universe obeying the cosmological principle, the distribution of matter in it more closely resembles a fractal, which would imply that it has no "average" density. Theorists continue to advise observers that the distribution of matter is uniform on large scales, while stubborn observers, ignoring the sage advice of theorists, proceed to dig out from the background larger and larger structures. Guided by the cosmological principle, the theorists say that the reason these structures are so hard to find is because they are but small perturbations on a smooth background.

CAN WE REALLY BELIEVE that we have identified the largest structures in the Universe? How can the cherished cosmological principle be reconciled with the enormous structures seen in the latest observations? It is worthwhile to remark that even the heroic effort involved in the CfA survey pales in comparison to what is actually required. The CfA survey effectively covers about 2×10^5 h^{-3} cubic megaparsecs. While this is an enormous volume to survey, it is only about thirty billionths of the visible Universe, which is about 7×10^{12} h^{-3} cubic megaparsecs. In a very real sense we have only explored our own back yard! A comparison might prove useful here. If we were to stand in the middle of the Fermilab site in summer and survey thirty billionths of the surface of the earth (about 6 square miles), we might come to the conclusion that the surface of the earth is covered by corn!

What we really need is a project dedicated to surveying as large a fraction of the Universe as possible. How large must this survey be? We know that the Universe must be smooth on the scales of $3000h^{-1}$ megaparsecs because of the microwave background. We also know that the Universe is very lumpy on "small" scales, say less than $5h^{-1}$ megaparsecs. What we clearly need is a survey of the Universe large enough to see the transition from bumpy to smooth. It is anticipated that the planned Chicago—Fermilab—Institute for Advanced Study—Princeton Sky Survey Project will, by the year 2000, survey a volume containing 100 times more galaxies than the CfA survey (a million galaxies!). If the cosmological principle is correct, this survey should easily contain the largest structures in the Universe, and finally we would have a "fair sample" of the Universe.

Now consider the nature of the mass in the Universe. The mass of a galaxy can be determined in much the same way as the mass of the sun is measured: through measurement of the rotation velocity of objects orbiting about it, and by use of a generalization of Kepler's third law. When the mass of a galaxy is determined in this manner it is found that only about 10% of the mass of a galaxy can be accounted for in the form of stars or gas. The bulk of the mass of a galaxy is invisible to us, not emitting electromagnetic radiation of any wavelength. The same phenomenon is discovered when larger objects such as galaxy clusters are studied. Perhaps as little as 1% of the total mass of the Universe can be accounted for; most of the rest of its mass is invisible. This hidden component of the matter content of the Universe is called *dark matter*.

Agreement between the predictions of light element production in the big bang and the primordial abundances of these elements inferred from present observations suggests that the dark matter cannot be made of baryons.

Agreement between the predictions of light element production in the big bang and the primordial abundances of these elements inferred from present observations suggests that some of this dark matter cannot be baryonic (i.e., made of baryons). The fact that we don't know what the Universe is made of is not from lack of effort, but perhaps from an incomplete knowledge of all the elementary particles. Many cosmologists believe that the dark matter of the Universe is in the form of a yet to be discovered elementary particle.

IN THE EXCITEMENT of discovering walls, voids, bubbles, great attractors, dark matter, and the like, it is easy to lose sight of the most obvious feature of structure in the Universe: the Universe is very inhomogeneous on small scales, becomes smoother on larger ones, eventually becoming very smooth on the largest observable scales. Why would the Universe be clumpy on small scales and smooth on large ones? Why would the distribution of galaxies show spatial structure while none is seen in the background radiation? It is believed by most cosmologists that the answer lies in the theory of gravitational instability.

According to the gravitational instability theory of structure formation, at the time of the last scattering of the CMBR, fluctuations in the distribution of matter were small, just as the differences in the temperature of the CMBR were small. In the last 12 billion years or so these small fluctuations grew to become galaxies, galaxy clusters, walls, bubbles—all the structures we now see—while the photons did not participate in this process and remained smoothly distributed. Thus we start with a Universe smooth in matter and radiation and end up with the matter clustered but the radiation smooth.

Just as temperature fluctuations may be expressed in terms of a dimensionless contrast, fluctuations in the mass density are expressed in terms of a dimensionless overdensity. If the Universe 350,000 years after the bang was smooth to better than one part in a thousand, the overdense regions were overdense by much less than one tenth of one percent.

However, such small perturbations in the distribution of matter are important because they are "unstable" against gravitational collapse. Regions of the Universe where there is more matter than average accrete surrounding matter, and the density contrast inexorably increases. Eventually the perturbations, which started small (density contrast much smaller than one), become large (density contrast larger than one). Once the density contrast becomes large, the structures become self-bound and no longer participate in the universal expansion of the Universe: structure has formed.

The two key pieces of information needed to quantify this picture of gravitational instability are (i) the nature of the primordial perturbations, including the amplitude of perturbations of various physical sizes; and (ii) the nature of the dark matter content. Particle physics, through its impact in the very early Universe, plays a crucial role in providing these two key ingredients.

THE MOST COMPELLING theory for these two ingredients is that the perturbations were produced in a phase transition at very early times, and that the dominant dark-matter content of the Universe today is a *weakly-interacting massive particle*, or WIMP. If the WIMPs are much more massive than the temperature of the Universe at the time of last scattering of the CMBR, they will have very small thermal velocities at that time, and they will be "cold." The theory of structure formation using primordial density perturbations and WIMPs for dark matter is known as the cold dark matter, or CDM, model.

In principle, the development of structure in the gravitational instability theory is a straightforward initial data problem. If at a given time, say at the time of last scattering of the CMBR, one is given the spectrum and amplitude of the seed perturbations, along with the matter content of the Universe, one may predict how structure emerges from the primordial seeds. Of course this is not a calculation amenable to analytical methods, but depends upon large N-body computer simulations. What are needed to test the CDM hypothesis are the exact initial conditions for such a simulation. These initial conditions must be provided by events that occurred in the very early stages of the evolution of the Universe, when particle physics played a dominant role.

The leading candidate for the origin of the primordial perturbations is a quantum effect during an epoch of rapid expansion of the Universe known as *inflation*. The first concrete model for inflation was proposed in 1980 by Alan H. Guth, then a postdoc in the SLAC theory group. It is interesting to note that inflation was proposed to explain the large-scale smoothness of the Universe. Only later was it realized that inflation not only explained the large-scale smoothness but also provided a mechanism for generation of the seed inhomogeneities necessary for the small-scale structure.

At the heart of the inflationary model is an assumption that at some epoch in the very early Universe the energy density of the Universe was dominated by "vacuum" or

The Expansion of the Universe

AS THE UNIVERSE EXPANDS, it cools. The expansion of the Universe is best expressed in terms of a "scale factor" $R(t)$. The scale factor represents the relative increase in distance between objects co-moving with the expansion. In the expanding Universe the scale factor increases with time. If today the distance to some object is $D(t_0)$, at an earlier epoch the distance to the object was smaller: $D(t) = D(t_0)[R(t)/R(t_0)]$. The fact that $D(t)$ was smaller in the past implies that the density was larger. If today the density of matter in the Universe is $\rho(t_0)$, at some earlier epoch the matter density was $\rho(t) = \rho(t_0)[R(t_0)/R(t)]^3$. The temperature of the Universe is inversely proportional to the scale factor. If t_0 represents the present time, then $T(t) = T(t_0)[R(t_0)/R(t)]$. For a "matter-dominated" Universe (a Universe with matter density exceeding radiation energy density), the age of the Universe is related to the scale factor and the present age: $t = t_0 [R(t)/R(t_0)]^{3/2}$.

It may easily be shown that the change in the scale factor of the Universe in expansion is related to the red shift as $R(t_0)/R(t) = 1 + z$. This means that the light from a galaxy at redshift $z = 0.1$ was emitted when the density of the Universe was a factor of $(1+0.1)^3 \sim 1.33$ times larger than today, the temperature of the Universe was $1 + 0.1 = 1.1$ times larger than today, and the age of the Universe was $1/(1+0.1)^{3/2} \sim 86.7\%$ of the present age.

In the standard big bang model the scale factor was infinitely small at some finite time in the past. This implies that at this time, $t = 0$, the density, temperature, and energy density of the Universe was infinite.

Phase Transitions and Spontaneous Symmetry Breaking

THE PICTURE OF SPONTANEOUS SYMMETRY BREAKING is encoded in a Higgs potential. If a Higgs field (more accurately, some component of a field with many internal degrees of freedom) is represented by ϕ, then the vacuum expectation value of the field (the minimum of the potential) is located away from $\phi = 0$. In the electroweak theory this vacuum expectation value is 246 GeV. For Grand Unified Theories it is much larger, typically 10^{15} GeV. At high temperature, interactions of the Higgs field with the particles of the thermal bath modifies the Higgs potential, causing the minimum of the high-temperature potential to be at $\phi = 0$, restoring the symmetry. As the temperature cools below some critical temperature the minimum of the Higgs potential shifts from $\phi = 0$ to $\phi \neq 0$, breaking the symmetry.

If this picture is correct, the Universe originated in a different state of symmetry than we observe now. As the Universe expanded and cooled, it underwent a series of phase transitions associated with different states of symmetry. These phase transitions may have an important influence on the subsequent evolution of the Universe. They may produce topological defects (monopoles, cosmic strings, domain walls, or textures), non-topological defects (Q-balls, non-topological solitons, etc.), or lead to inflation.

Generally the potential energy of the high-temperature ground state of the system is larger than the energy of the zero-temperature ground state. In inflation the mass-energy density of the Universe is dominated by this potential energy. Since this potential energy permeates all space and is unaffected by the expansion of the Universe, the potential energy density drives the Universe in exponential expansion until the phase transition has completed and the potential energy is zero. Of course why the potential energy of the Universe should be exactly zero remains a mystery (the cosmological constant problem).

"potential" energy. The way Guth originally envisioned this occurring was attributed to a phase transition associated with spontaneous symmetry breaking of a grand unified theory (GUT). In this approach one imagines the vacuum expectation value of the Higgs scalar field responsible for GUT symmetry breaking as the order parameter of the phase transition.

The prediction of high-temperature restoration of spontaneously broken symmetries was made in the early 70s by Soviet physicists Andrei Linde (now at Stanford University) and David Kirzhnits. At high temperature the Higgs field responsible for spontaneous symmetry breaking would have an average value of zero, while below some critical temperature the average value of the Higgs field in the vacuum would be nonzero. Guth assumed that there is some barrier in the Higgs potential separating the high-temperature and low-temperature values of the Higgs field, and this field could be trapped in the high-temperature phase for some time below the phase transition. The potential energy of this configuration would easily dominate the energy density of the Universe.

Cosmologists had recognized that a Universe dominated by vacuum energy expands exponentially in time, rather than as a power law in time as for a Universe dominated by matter or radiation. The rapid increase, or inflation, of the Universe while dominated by vacuum energy would have the effect of smoothing out any wrinkles in the Universe.

The original model of Guth suffered from a fatal flaw: the phase transition was never completed. However the idea that physical processes occurring in the early epochs of the Universe were responsible for its smoothness was too attractive to pass up. Soon after Guth's original proposal, it was realized that inflation was also possible in a weakly first-order, or even second-order, phase transition if the Higgs potential is very flat. In this version of inflation, known as slow-rollover inflation, the Universe is dominated by the Higgs potential energy while the Higgs field classically evolves from the high-temperature minimum to the zero-temperature minimum of the Higgs potential. In fact it was soon realized that although a phase transition was a fundamental part of the original proposal, it wasn't absolutely necessary. All that is required is some scalar field displaced from its minimum.

INFLATION CAN PROVIDE the smooth background, but what about the small wrinkles necessary for structure formation? So far inflation has been described as a purely classical phenomenon in which a classical scalar field evolves to the ground state of its potential. However there are interesting quantum processes occurring during this epoch that will produce small wrinkles in the smooth background.

The physical distance between any two points in a space expanding exponentially increases so rapidly that observers cannot remain in causal contact once their separation is greater than some critical distance known as the "horizon." The horizon distance depends upon the Planck mass (10^{19} GeV) and the mass scale of symmetry breaking (10^{15} GeV).

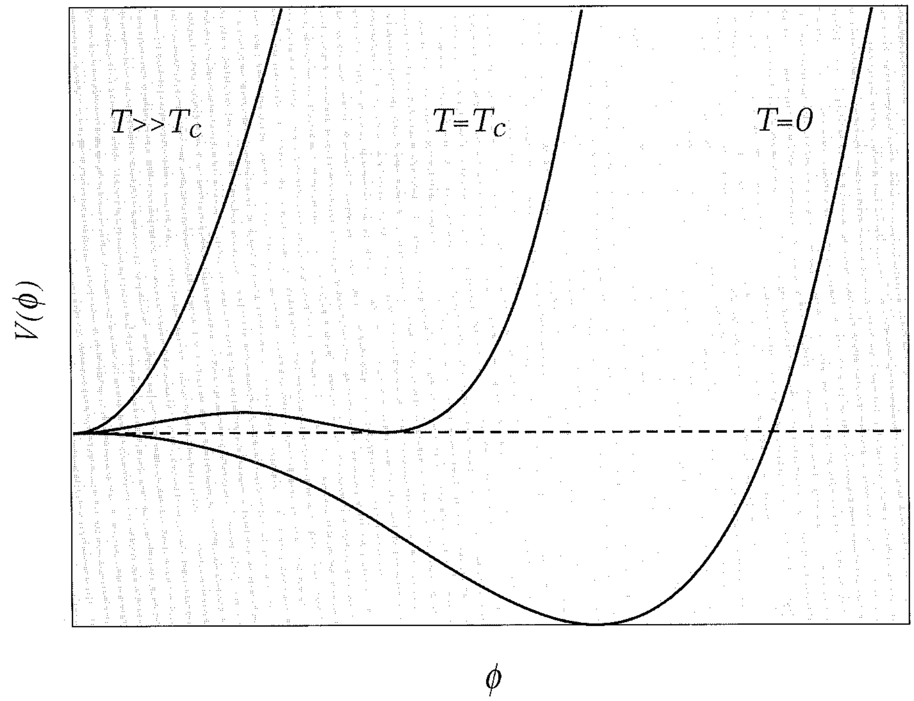
The existence of the strongly curved space-time background has a profound effect on the vacuum of quantum field theory. Just as the vacuum of quantum field theory is perturbed by the presence of the gravitational effects of a black hole, leading to particle creation at the horizon of the black hole (known as Hawking radiation), so the existence of the strongly curved space-time background leads to particle creation at the horizon during inflation.

The effect of particle creation during inflation is to impress small inhomogeneities upon the smooth background. Because of the high degree of symmetry of a space-time dominated by vacuum energy, the inhomogeneities also have a high degree of symmetry: they should be scale-invariant. This is exactly the spectrum that had been assumed by cosmologists for a decade! The magnitude of the perturbations depends upon the coupling constants in the Higgs potential.

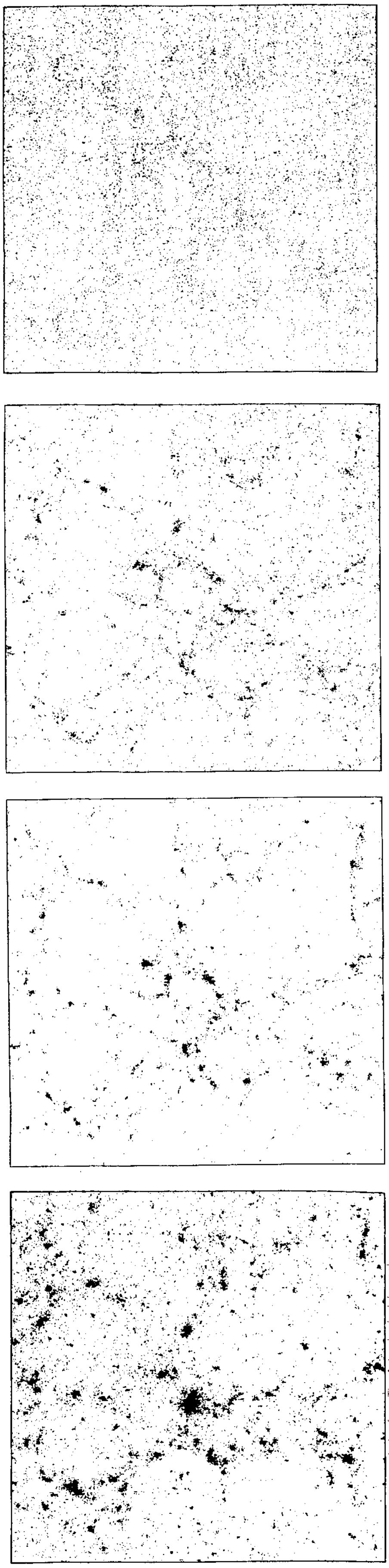
In addition to the seed perturbations, the nature of the dark matter must be specified. Here, particle physicists have been more than generous, providing a veritable zoo of new species of particles as candidates for dark matter. The common picture in the origin of species is that in the very early stages of expansion all particles were in thermal equilibrium. For most particle species, when the temperature drops below the mass of the particle, annihilation of the particle with its antiparticle (or with itself if it carries no conserved quantum numbers) reduces the relative abundance of the particle to insignificant levels. What is needed for dark matter is a particle species that is stable (has a lifetime much longer than the age of the Universe) and interacts weakly enough that it drops out of thermal equilibrium before annihilations have a chance to reduce its relative abundance.

It is most interesting to note that "weakly," as used in the above sentence, means an interaction strength roughly equal to the weak interaction. Any stable particle species with interaction cross sections slightly less than those set by the weak scale will survive primordial annihilations. In fact the first dark matter particle of this ilk was a very massive neutrino proposed in 1974 by Ben Lee of Fermilab and Steven Weinberg of Texas.

Measurements of the width of the Z^0 at SLAC and LEP have ruled out the "Lee-Weinberg" neutrino, and attention has shifted to supersymmetry. If the lightest supersymmetric particle is neutral (the *neutralino*) and stable (as predicted by most supersymmetric models), it would survive primordial annihilation in sufficient numbers to dominate the mass of the Universe today. Optimistic cosmologists anxiously await the discovery of supersymmetry to learn what the Universe is made of.



The Higgs potential is temperature dependent. At temperatures much greater than some critical temperature T_c the minimum of the potential is the origin. Below the critical temperature the minimum of the potential is away from the origin. Inflation can occur while the vacuum is trapped in the high-temperature phase, or while evolving to the low-temperature ground state if the potential near the origin is flat.



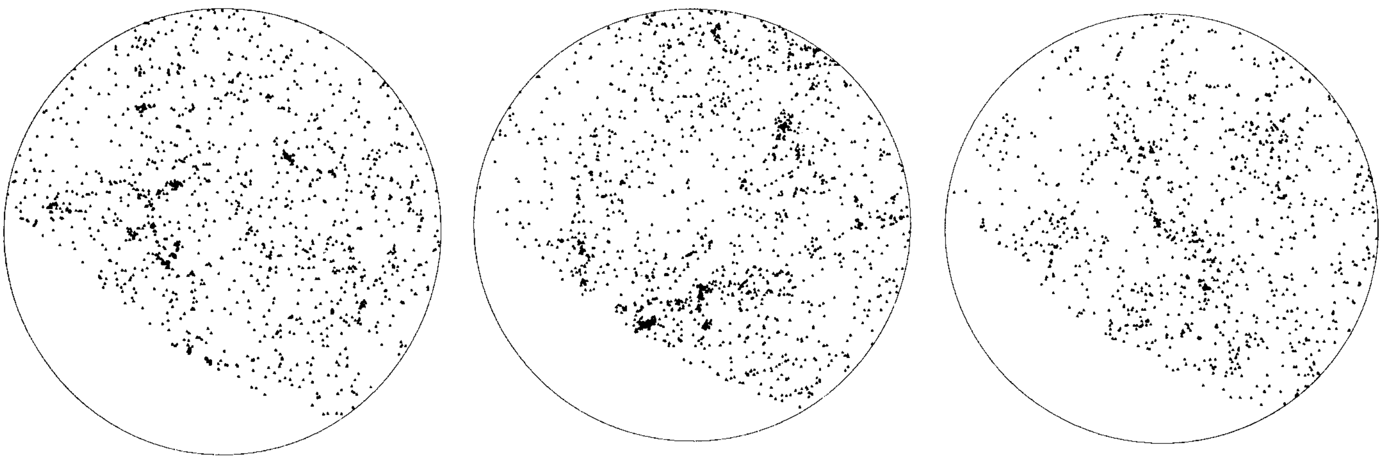
The evolution of structure from smooth initial conditions is demonstrated by these "snapshots" of the computer simulation of a CDM model by Davis, Efstathiou, Frenk, and White. The snapshots show the distribution of matter (indicated by black dots) in the Universe at different times (time runs from top to bottom). In the top panel the distribution of matter is smooth. As the Universe evolves, subsequent panels illustrate the growth of structure in a CDM Universe.

QUANTUM PERTURBATIONS produced during inflation, coupled with a cold dark matter particle species as the dominant matter content of the Universe, specify the initial conditions necessary for gravitational instabilities to lead to structure formation. To be sure, there are many possible variations on this theme. We have learned that very complicated Higgs potentials may lead to different types of perturbation spectra. There are also other mechanisms of generating dark matter. One oft-studied example is the axion that has been proposed to solve the strong CP problem of QCD. Around the time of the QCD transition, when the density of the Universe drops below nuclear matter density and the quarks and gluons become confined, theory predicts that a condensate of axions will be formed. This condensate would act as cold dark matter because a condensate has zero momentum.

In spite of the variety of proposed dark matter candidates, the predictions of the CDM model are remarkably robust for the calculations of structure formation. Structure that develops in a Universe dominated by 10^{-5} eV axions is very similar to the structure in a Universe dominated by 40 GeV neutralinos. This insensitivity of the growth of structure to the identity of the cold dark matter candidate is a double-edged sword. It allows cosmologists to study the growth of structure without regard to the particle physics details, but it means that it is unlikely that hints about the identity of the cold dark matter particle will come from simulations of structure formation.

An example of the growth of structure due to gravitational instability in the CDM model is illustrated by the left panels. Each point in the figure represents dark matter (hence the black dots). The initial configuration of the mass points is very nearly uniform. The key word here is "nearly." There are small perturbations of the spectrum as predicted by inflation. As the Universe evolves in time, the small perturbations grow. Additional simulations on the next page show a possible final state for the clustering compared to the actual observed distribution of galaxies. Although one cannot say simply on the basis of a comparison between the pictures that the CDM model is correct, there is qualitative agreement.

We do learn that small differences in the initial spectrum and amplitude of the perturbations at early times lead to a much different Universe at late times. The Universe is very sensitive to initial conditions. Universes that appear very similar at an early age can appear quite different today. Such an amplification over time of small differences in initial conditions happens to many observables. At the age of one day, Burt Richter in many ways resembled Burt Reynolds. However, small differences in initial conditions have been



To compare the predictions of the CDM model with the actual Universe it is necessary to view the simulations in the same way the distribution of galaxies is viewed. The first two pictures are artificial redshift catalogues constructed by Davis, Efstathiou, Frenk, and White from their numerical simulations, and the picture on the right is an actual galaxy survey from the Center for Astrophysics.

amplified over time, and they are not very similar in appearance today.

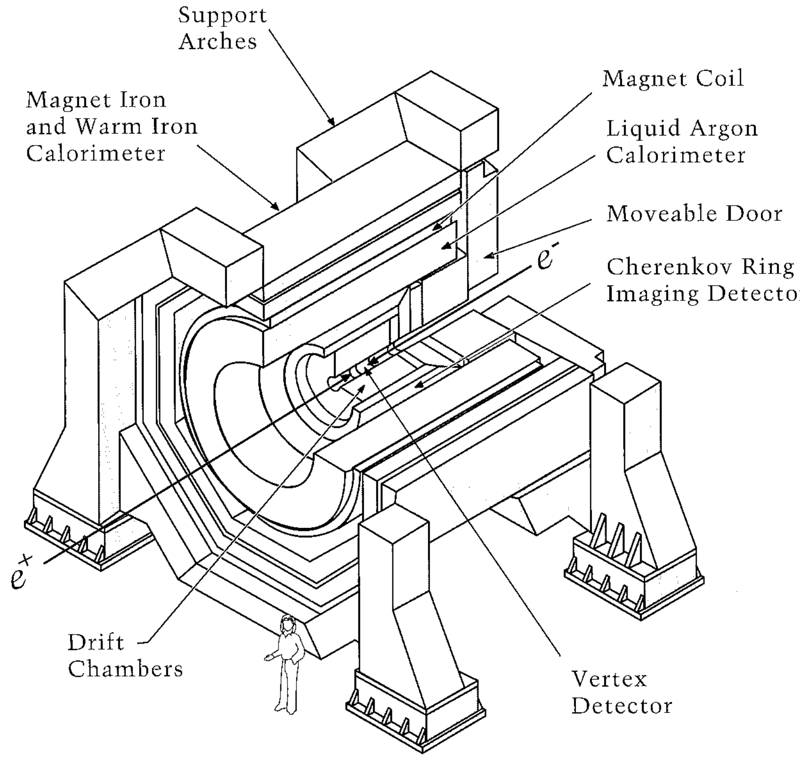
THE CDM MODEL REMAINS the most concrete theory ever proposed for the formation of structure in the Universe. The model is highly specific and predictive. There is a quite lively debate in the astronomical community today about whether CDM can produce the structures that seem to be emerging on the largest scales. Recent determinations of correlations in the distribution of galaxies on very large scales are difficult to reconcile with the CDM model if the spectrum of primordial perturbations is scale free. If these determinations are supported by subsequent work, it would imply that inflation was more complicated than the simple models studied so far.

The formation of large-scale structure is not the only test of the CDM hypothesis. The number and variety of tests of the CDM model are impressive. In the very near future, accurate measurements of fluctuations in the microwave background radiation should find evidence for the spectrum of perturbations produced by inflation, or disprove the simplest (and hence most attractive) inflationary models. If fluctuations in the microwave background are found, it should be easy to check that they are Gaussian as predicted by most inflation models.

In addition to astronomical tests, there are particle physics handles on testing the CDM model. Discovery of supersymmetry at FNAL, SLAC, CERN, or the SSC would make the neutralino possibility for dark matter most appealing. Likewise, much more stringent limits on the scale of supersymmetry breaking would rule out this possibility. If inflation occurs during a phase transition associated with spontaneous symmetry breaking, we expect that there must be a Higgs mechanism operating. The cosmological implications of the phase transition depend upon the details of the Higgs potential. Although the inflationary transition cannot be associated with the electroweak theory, confirmation of such a mechanism by discovery of the electroweak Higgs boson would tell us that the basic picture of spontaneous symmetry breaking is correct. Detection of an axion in the laboratory would have profound implications for cosmology as well as particle physics. Direct detection of WIMPs in dark-matter detectors would not only confirm that the dominant mass component of the Universe is dark, but also point the way for future exploration of the high-energy physics frontier.

ONE OF THE OLDEST GOALS in cosmology is to understand the origin of the structures in the Universe. The interplay of high-energy physics and cosmology is most important in this study. Particle physics, through its effects in the early Universe, can account for the overall smoothness, the small wrinkles, and the dark matter. While the CDM theory might not be correct in all details, might have serious gaps, or might be just plain wrong, it is the most complete and testable model for the origin of structure ever proposed. The possibility that we are on the verge of understanding the very origins of structure—as a result of convergence in the study of the largest structures in the Universe and the elementary constituents of matter—makes this a most exciting time in particle cosmology.

SLAC's newest, and largest, detector brings the latest technology to the study of the Z.



SLD Prepares For Physics

by BILL ASH

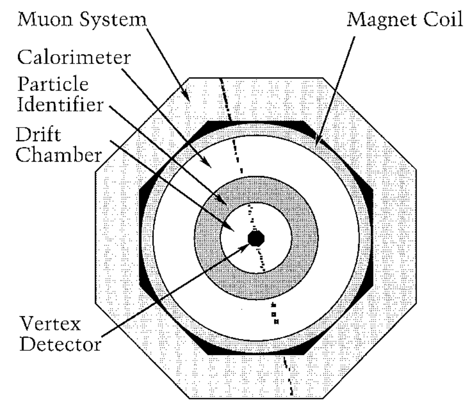
IN EARLY 1991, the first new experimental facility at SLAC in a decade will begin taking data at the Stanford Linear Collider (SLC), combining a new generation in particle detectors with a new generation of accelerators. Aptly named for its 4000-ton, six-story size, the SLC Large Detector adapts new technology in particle detection to the special features of the collider for a more detailed look at the *Z*. The tour of the SLD described in the following pages is thus a look both at what's new in detectors and at what's special about linear colliders.

Exploring the SLD by foot might be good exercise, as the scale of the drawing above shows, but it wouldn't be very informative. A better path is shown in the upper right drawing, one of the first tracks recorded by the detector during cosmic-ray tests in August. The tour starts at the center of the computer-generated display and passes in turn through the regions labeled vertex detector, drift chamber, particle identifier, calorimeter, and muon system. At each step more information is gathered about each of the dozens of particles that will come from the collision of an electron and positron. Finally, a computer program reconstructs this information into a complete picture and description of the event for further study.

THE VERTEX DETECTOR is too small to show up on this display. In fact, the original meaning of SLD is alleged to be "Slick Little Detector," named for this beer can-sized device that can precisely determine the origin of all the charged particles produced in each event.

As shown in the photograph at middle right, the vertex detector is an array of postage-stamp-sized electronic chips layered on two concentric cylinders surrounding the beam pipe. The chips, called Charge-Coupled Devices, are like electronic

Left This cutaway schematic shows all the detector elements installed inside the massive steel barrel and endcaps. The complete detector weighs 4000 tons and stands six stories tall.



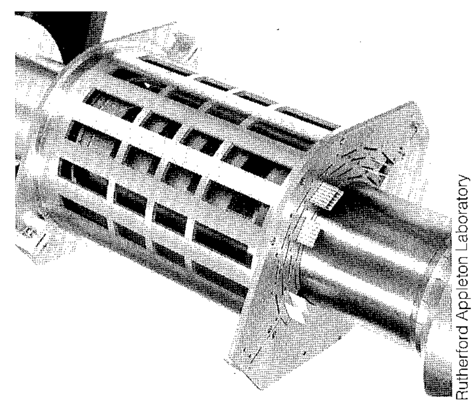
checkerboards, with about 500 squares on a side. They are typically used to convert optical images into electronic signals, as in a video camera, but their application here is easier to explain. Particles traveling through the thin chips leave behind small electric charges in the squares they cross. Drawing lines through these squares indicates the track of the particles.

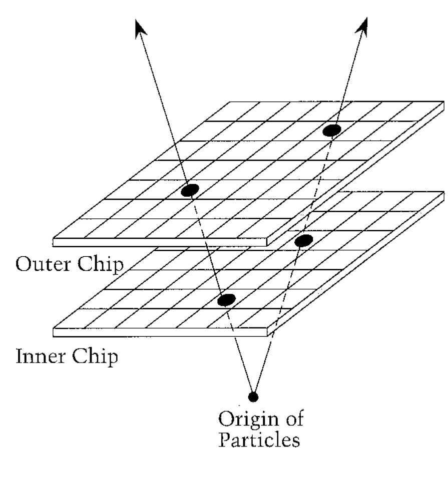
The charges deposited are the equivalent of checkers, and the trick is to find out where the checkers are. When the readout command is given, all the checkers move one square toward the edge. The nearest row dumps its charges into an electronic readout. In the example shown there are no checkers in the nearest row so no charges are collected. One step later, however, the readout notes that there is a checker in the fifth square from the left on the inner board. On the next step, it picks up the checker third from left in the top board and so on. After seven steps, the boards are cleared and the original charges have been sent to the computer in a long line of signals that can be rebuilt into a checkerboard display later on.

This elegant, self-contained package determines where a particle crossed to about one-tenth the diameter of a human hair. Developed by British collaborators in SLD for a small fixed-target experiment at CERN, this technology is even better suited to the linear collider. The beam pipe in SLC is less than two inches in diameter at the collision point, very small by accelerator standards. This allows the two layers of chips to be placed closer to the beams, enhancing the precision with which lines can be traced back to their origins. An added benefit is that many fewer of these very expensive chips are needed to cover the area, making the technique affordable.

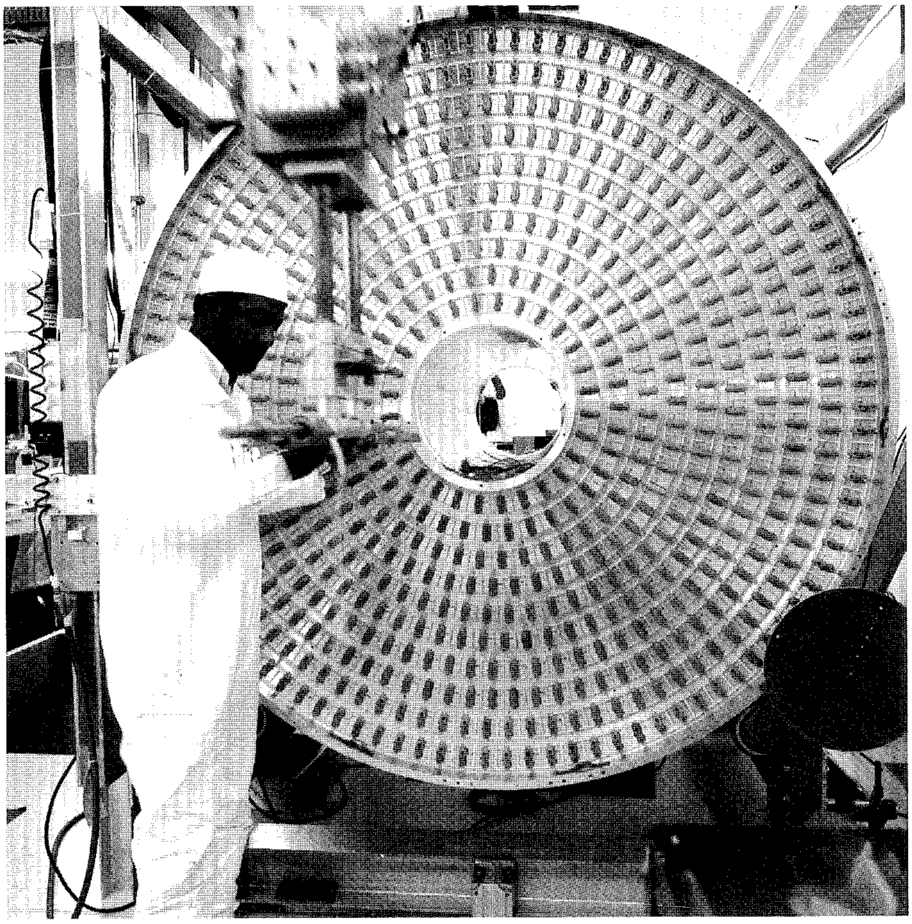
The SLD vertex detector is especially powerful in looking for those particles that quickly decay into others, such as particles containing a charm or bottom quark. With coarse measurements, all the tracks would still appear to come from the same place. With this device, however, the decay particles can be tracked back to a point, or vertex, distinctly separated from the origin of all the others—hence the name.

NEXT OUT FROM THE CENTER is the drift chamber, a horizontal, thin-walled cylinder, six feet long and six feet in diameter, with a small tube through the center to accommodate the beam pipe and vertex detector. Some 35,000 fine wires are strung the length of the cylinder between precisely placed holes in the aluminum ends. When the chamber is filled with a gas mixture and high voltage applied to groups of wires, it becomes a sort of mammoth Geiger counter. Charged particles passing through the chamber temporarily knock a few electrons loose from gas atoms. These electrons are attracted to certain wires, called sense wires, knocking loose more electrons on the way to give a large signal. The "drift" in the name of this chamber refers to the time it takes electrons to drift to the nearest sense wire from its starting point. By measuring this time, the location of the original track can be determined much more precisely than just the spacing between wires.

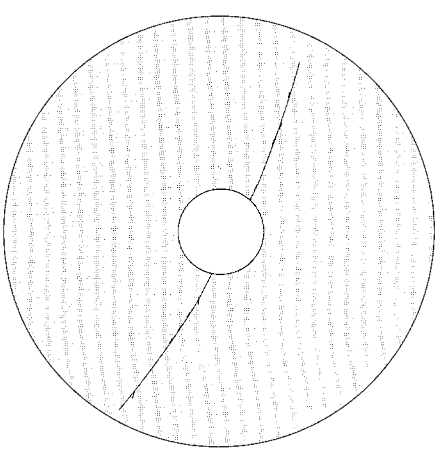




Top: A typical cosmic-ray track passes through the elements of the SLD detector. Middle: Photograph of the six-inch-long vertex detector ready for testing. Bottom: In this checkerboard schematic two particle tracks leave charges in the two layers of the vertex detector.



Left: Photograph of the endplate of the SLD drift chamber.



The SLD's magnetic field causes this cosmic ray to curve in the drift chamber.

Geiger counters are nearly a century old, and the principle of drift chambers has been in use in big detectors for more than a decade. So, what's new here? Part of the novelty came in making the walls and sides of the chamber very thin to reduce the deflection of the particles when they enter and exit the chamber. The aluminum endcaps are less than a quarter-inch thick, and the cylindrical walls are a honeycomb of fiber-reinforced plastic sandwiched between two aluminum sheets less than twenty thousandths of an inch thick. Sealing these lightweight ends and walls together makes a rigid unit that can withstand the 13-ton force exerted by the 35,000 taut wires.

The disadvantage was that all the wires had to be strung from the outside! A kind of high-tech loom was set up in which a long rod was sent through a small opening in one end cap to the corresponding opening in the other. The 25 heavier wires in each group were pulled through one at a time and secured through holes around the edges of the opening. This was followed by a package of 28 wires, some of them only one-thousandth of an inch thick. One stage in this operation is shown in the top left photo; 700 shuttles and 6 months later, the chamber was finished.

The drift chamber measures a particle's position to a few thousandths of an inch at eighty steps along its path from the inner to outer wall. This is good enough to detect the curvature of even very high-energy particles in the magnetic field of the SLD, as shown in the enlarged event display at the left. Knowing this curvature, one can calculate the momentum of a charged particle passing through the chamber, and get a good idea of its energy. Putting this information together with the precise particle locations from the vertex detector is a big step toward a complete description of the event.

THE SLD distinguishes different species of particles, such as electrons, pions, and protons, by the way they radiate ultraviolet light in certain gases and liquids. First observed by the Russian P. A. Cherenkov in 1934, this phenomenon has been used for a long time in small devices looking at well-defined particle beams. Surrounding an active region with such a device, however, is extremely difficult, analogous to making an inside-out eyeball to look at an object from all sides at once. The Cherenkov Ring Imaging Detector (CRID) solves this problem with mirrors and electronics.

Just after entering the CRID, a particle passes through a small container of liquid freon with just the right density and optical properties. The particle radiates ultraviolet light in a cone-shaped pattern, with slower particles making narrower cones. The original particle continues on undisturbed and the light passes into another vessel containing ethane gas with a trace amount of an exotic chemical called TMAE that absorbs the light, leaving a ring of electric charge in its place.

The particle identity is related to the diameter of the ring, which now must be measured. A uniform electric field along the second box pulls the ring of charge toward the end without distorting it—like raising a window shade with a printed pattern on it. After drifting the length of the box, the ring crosses a picket fence of high-voltage wires that produce signals. A computer analysis of when these signals originated on various wires allows one to reconstruct the ring—both its size and where it was in the chamber when formed.

The slower particles in an event are well discriminated by the rings they form in the liquid freon. In order to sort out the faster, more energetic particles, a second stage was added to the CRID. After leaving the converter box, the primary particle passes through a gas, where it again radiates. The resulting cone of light is reflected by an array of large spherical mirrors back into the conversion box giving a ring of different size.

In the analysis of an event, the computer follows the tracks from the drift chamber through the CRID, looks up the size of the rings associated with each track, and figures out what kind of particle it was.

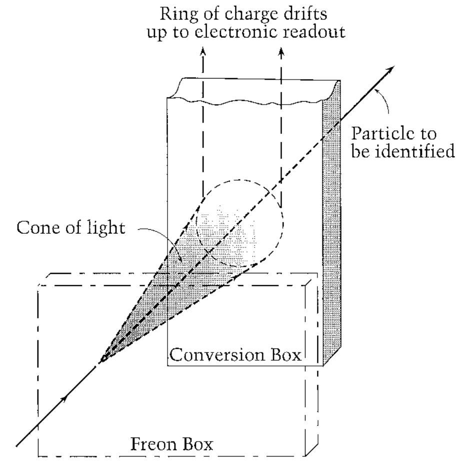
Making all these elements with their special fluids, fields, wires, and electronics is an engineering tour de force that has only been accomplished in SLD and in a detector at CERN called DELPHI, which was commissioned last year.

INFORMATION ON THE charged particles of the event has come from the three inner sections, but the neutral particles, which make up a third or more of the total, are so far invisible. These finally make their mark in the Liquid Argon Calorimeter (LAC), a hollow aluminum spool filled with pure liquid argon and stacks of lead plates.

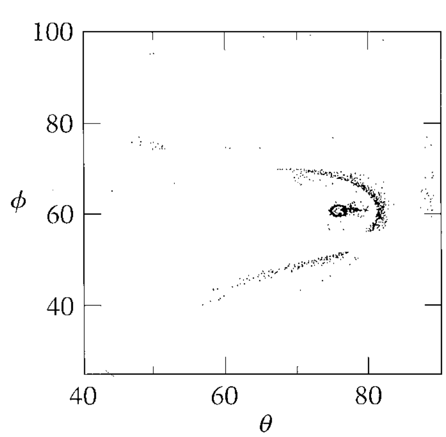
When electrons, photons, and the heavier particles like protons and pions travel through the LAC they interact in the metal plates, producing more particles of lower energy in a cascade called a shower. This happens equally to the charged and uncharged species. Eventually, the shower consists of many "soft" particles that deposit their energy in the argon as a trail of charge that is collected and measured.

The amount of charge deposited in the LAC is proportional to the total energy of the particles that entered it. The process is similar to what occurs in the calorimeters of old physics and chemistry experiments, which measure the total heat of a reaction or process, hence the name.

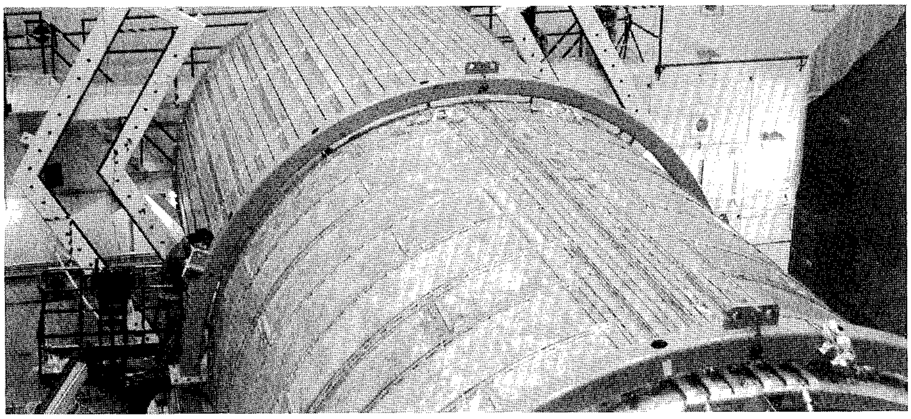
The operating principle here is even older than that of the drift chamber: the ionization left by a charged particle in the argon collects on the metal plates, giving a direct

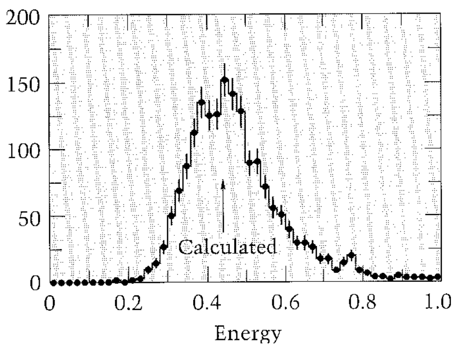


This two-step process converts light emitted by a particle into a ring of charge that can be measured. Different kinds of particles can be identified by the different sizes of ring.



This overlay of test data from about 100, 10-GeV kaons shows the computer reconstruction of a small gas ring and a section of the larger liquid ring.





Top: The 650-ton liquid argon calorimeter was assembled in place using large scaffolds. Bottom: In its first test, the calorimeter measured the energy of cosmic rays.

signal. Without the multiplying effect of the high-voltage wire in a Geiger tube, the signal is smaller, but it is also more stable, so the amount of energy indicated by a certain size signal does not change. The best medium for a particle calorimeter turns out to be liquid argon, which requires vacuum-insulated vessels cooled by liquefied nitrogen gas. This is difficult engineering, but liquid argon has been used since SPEAR days, so again the question is, "What's new?"

Part of the answer is the sheer size of the beast. The main calorimeter weighs 650 tons and is suspended in a vacuum by low-conductivity supports. The cryogenics plant that maintains the 12,000 gallons of liquid argon and liquid nitrogen surrounds the detector with three stories of pipes, valves, pumps, and control panels.

As big as the total device is, however, the small-scale organization is more of a headache. Making a calorimeter of big metal sheets wouldn't be too difficult, and it would do the job of giving the total energy left by particles traveling into it. But the experimenter wants to know the energy of each of the many particles produced in any collision and where in the calorimeter they passed. This task would require about 40,000 little calorimeters packed together and pointed at the center of the detector, and the LAC is essentially just that. About 500,000 sheets of lead, each around two inches on a side and a tenth of an inch thick, were carefully assembled into some 300 stacks, each about one foot wide and six feet long. These were in turn loaded into the outer vessel and wired to the outside. In order to spread the work in this large project, four universities and a SLAC group built stacks and subassemblies separately. The final three-year-long assembly and check out in the collider hall required a 30-foot-high platform with elevator-style scaffolds on the sides, much of it in near clean-room conditions.

Cosmic-ray muons have been used to test the ability of the LAC to measure energy accurately. Muons deposit the least energy of any particle the system will encounter at SLC. The signals due to several thousand cosmic rays are plotted together in the graph at left, producing a very clean peak that matches the expected energies.

AT THE END OF THE TRAIL is the Warm Iron Calorimeter, or WIC, consisting of hundreds of long, thin gas-filled plastic boxes stuffed between the 14 iron plates that make up the body of the detector. When a charged particle passes one of the high-voltage wires strung along these boxes, it acts much the same as in the drift chamber, producing a detectable signal. Metal strips along the plastic boxes pick up signals that show directly which wire a particle passes, and other strips at right angles show how far along the wire it went. The result is a point on the path of the particle through the WIC.

So what's new? Well, scale, for one thing. Placed side by side, these chambers would cover a football field. Each chamber must be coated with conducting film of just the right thickness and strung with wires precisely aligned and held with the correct tension. The idea of particle detectors made from coated plastic and the industrial process to make it possible both come from the Frascati Laboratory in Italy. Acres of these chambers are now used in particle detectors by many different experiments in Europe and the United States.

Most individual particles produced in beam collisions will be stopped by the pieces of the detector closer in and will never get to the WIC. Muons, however, easily get through. Because the iron plates between the chambers are magnetized, the muon tracks will have more or less curvature depending on their energy, much like the charged particles in the drift chamber. Thus the WIC serves to identify muons and to measure their direction and energy.

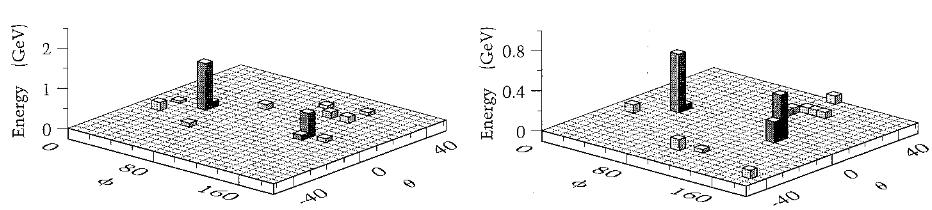
But this system does more. Rectangular metal pads throughout the assembly pick up signals over larger areas corresponding to the individual sections of the LAC. The size of these signals, which is related to the amount of energy that has leaked out the back side of the LAC, is used to improve the overall energy measurement in the SLD.

The computer display below of a cosmic ray muon shows both coordinates of tracks passing two planes of the WIC, with the height of the bin being a measure of the energy. The WIC is almost a detector in itself; because it was finished first, it has been used to help check out other systems.

THE FIVE DETECTOR elements have different purposes and principles but a shared problem. The information is contained in a staggering number of electronic signals in the middle of a closed box with very few openings or channels to bring out cables. The WIC, for example, has 100,000 channels sensing hits on wires. The LAC, the CRID, and the drift chamber total a similar number, and these contain signals whose size and shape are also important. And of course there is the vertex detector with nearly 500 chips, each with a quarter-million potential locations. Running wires directly would present all kinds of problems, quite apart from the space considerations. In some sense it is like a telephone exchange for a large city.

The alternative is to place sophisticated electronic circuits directly on each detector system to simplify the information and hence reduce the wiring. For example, instead of bringing out every wire of the WIC, a small circuit can scan the wires and send out the location of just those wires that have hits.

A second big reduction exploits the pulsed nature of the linear collider. As collisions occur 120 times per second, the time between these pulses can be used for more involved electronic reduction. During this 8-millisecond pause, for example, circuits on the LAC can



In this computer display of cosmic-ray data the warm iron calorimeter chambers that surround the SLD have been "unrolled" into planes. The blocks precisely locate where a particle passed and the height of the block is a measure of its energy.

SLD Collaborating Institutions

INFN Sezione di Bologna

Boston University

University of British Columbia

Brunel, the University of West London

California Institute of Technology

University of California, Santa Barbara

University of California, Santa Cruz

University of Cincinnati

University of Colorado

Columbia University

Universitá di Ferrara & Sez. INFN

Laboratori Nazionali di Frascati, INFN

University of Illinois

KEK National Lab, Japan

Lawrence Berkeley Laboratory

Massachusetts Institute of Technology

University of Massachusetts

Nagoya University

University of Oregon

Universitá di Padova & Sez. INFN

Universitá di Perugia & Sez. INFN

INFN Sezione di Pisa

Rutherford Appleton Laboratory

Rutgers University

SLAC

University of Tennessee

Tohoku University

TRIUMF

Vanderbilt University

University of Victoria

University of Washington

University of Wisconsin

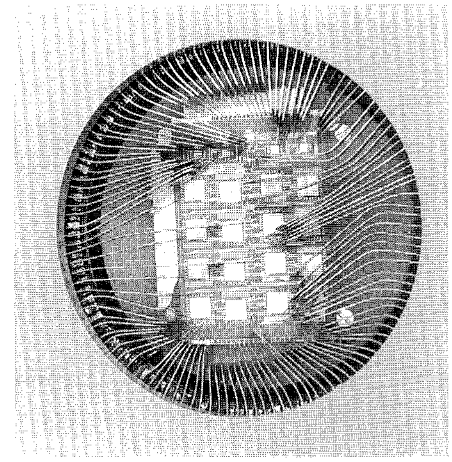
Yale University

measure the size of a signal on a section of the calorimeter, convert it to bits readable by a computer, combine it with up to 800 other signals, and send all this information out on one fiber optic cable to the outside.

Conventional techniques of building the necessary electronics using printed circuit boards would result in packages much too large to fit on the ends of the LAC in the numbers needed. Instead, SLAC worked with the Stanford Electronics Laboratory and local industry to produce "hybrids" that combine some features of printed circuits with the very large scale integration (VLSI) technology used in computer chips. The postage-stamp-sized chip shown above contains 8 channels of circuits. It would have been 1000 times as large had it been fabricated with conventional techniques.

AND STILL THE JOB'S not done. Once all this information is organized enough to get out of the detector in a reasonable way, it enters a computer that must turn it into useful numbers and displays. For every hour spent by physicists and engineers designing, building, and testing the pieces of the detector and electronics, another hour goes into developing the software to deal with the information.

The on-line programming group writes the computer code needed to coordinate and control all the electronics packages distributed throughout the SLD. Calibration circuits must be activated and decisions made on which events to accept for full readout and which to



ignore. All the data from the separate parts of the detector must come together at the same time in a coherent way and be written onto magnetic tape for more detailed analysis later. The on-line group also provides the computer control and monitoring for gas quality and the hundreds of voltages, temperatures, pressures in all the detector systems, each of them a complicated industrial process in itself.

The other side of the software house works backwards. They first construct a computer model of the full detector and run made-up events through it. These Monte Carlo simulations are useful from the first design of the detector through the final analysis of data. For example, how small should the individual elements of the LAC be made? If they are too large, important details of the events will be lost; too small, and money will be wasted. Using general properties of the collisions that are known from other experiments, Monte Carlo simulations helped find the best design. While the detector was coming together, this group developed the computer code that will transform the detector data of wire addresses, pulse heights, and time distributions into the tracks, rings, and energies that give the ultimate picture of each event.

SOLVING THE SPECIAL challenges of each of the individual SLD systems was not enough. All these

Left: In this test station wires run into the postage-stamp-sized electronic circuits that perform the same tasks as conventional electronic circuits a thousand times larger.

pieces had to fit together in a 4000-ton structure that could be easily opened for maintenance and closed to better than a tenth of an inch. This work by a talented team of mechanical engineers was the literal framework of the entire detector. As shown in the cutaway drawing on page 11, the massive arches at each end support the central barrel, and moveable endcaps close in from each end. All the systems nest together to surround the collision point with no gaps.

The structure was much too large and heavy to be built as a single unit and moved to the collider hall. Instead, it was designed so the contractor, Kawasaki Heavy Industries, could build it up from some 100 separate pieces, mark it, and break it down for shipment. The huge puzzle was then put back together in the relatively small collider hall like a ship in a bottle.

The structure also includes a large aluminum coil to produce the magnetic field in the detector. Since the field is only needed in the drift chamber, the coil would normally go between that chamber and the CRID. In this position, however, the material of the coil would interfere with the particles before they reached the CRID and LAC, thereby degrading the performance of these units. So the coil was made large enough to surround the LAC—and to fill the hold of a ship on its delivery to SLAC from Mitsubishi Electric Company.

The very large size and mass of SLD has had one side benefit. Virtually none of the radiation produced by the collider beams can escape. With the addition of concrete around the pipe bringing the beams from the SLC tunnels, the detector becomes "self-shielded." No other walls are required and physicists can literally work on the detector while the machine is running.

Last but not least, the structure must withstand the acceleration of an earthquake, a requirement roughly equivalent to standing it on its side without damage. This was successfully checked in an unscheduled test on October 17, 1989.

THE TRUE TEST of the SLD will follow months of check-out on the SLC, after physicists learn to thread the beams through new superconducting quadrupoles into the ends of the detector and adjust the new beam pipe with its sophisticated masks to block unwanted stray particles in the beam. As this work progresses, the vertex detector, drift chambers, CRID, LAC, and WIC will be further tuned up along with the electronics and readout programs.

Sometime in the next few months, pictures will emerge from the SLD. The vertex detector will give precise origins of particles, including those that decay; the drift chamber will give energies of charged particles and the CRID will identify their types; the LAC will measure energies of the neutral particles; and the WIC will pick up the muons.

The end of ten years of work in detector development and construction will be signaled by the beginning of a productive role in physics.

In Memoriam

The SLD collaboration takes this opportunity to recognize the work and dedication of engineer Dave Chambers, whose untimely death last spring was a sad loss to all his colleagues.


SUSAN BLOOM

1990 Nobel Prize

This year's Laureates lit a torch in the darkness. . . .They did not anticipate anything fundamentally new. . . .the prize was awarded "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

—Cecilia Jarlskog, Nobel Committee

by MICHAEL RIORDAN

A LITTLE OVER TWENTY years ago the high-energy physics community was just waking up to the possibility that the hypothetical "quarks" of Murray Gell-Mann and George Zweig might in fact be real, physical objects after all. Early results from a second series of inelastic electron scattering experiments, done by a collaboration of physicists from MIT and SLAC, had begun to come in favoring this interpretation.

Dubbed "partons" by Richard Feynman, tiny grains deep inside the proton had appeared to be deflecting some of the electrons at large angles

Left: The 1990 Nobel Laureates in Physics and fellow quark hunters, gathered together once again in Stockholm. Front row (left to right): Dick Taylor, Jerry Friedman, and Henry Kendall. Back row (left to right): Arie Bodek, Dave Coward, Michael Riordan, Elliott Bloom, James ("Bj") Bjorken, Les Cottrell, Marty Breidenbach, Guthrie Miller, Jurgen Drees, Pief Panofsky, Luke Mo, and Bill Atwood.

in the first generation of these experiments, run in 1967–68. In the second round, begun in 1970 and continuing through 1973, the MIT-SLAC group fired vast swarms of electrons at both protons *and* neutrons and examined the scattering patterns in much greater detail. Together with other experiments, the new results showed that partons had the properties expected for quarks. A striking new layer of matter had been uncovered at SLAC.

After a lapse of two decades, the Royal Swedish Academy of Sciences finally awarded the Nobel Prize for these pivotal experiments, which fundamentally altered physicists' view of matter. The 1990 physics prize was given to Jerome I. Friedman and Henry W. Kendall of MIT, and Richard E. Taylor of SLAC "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics."

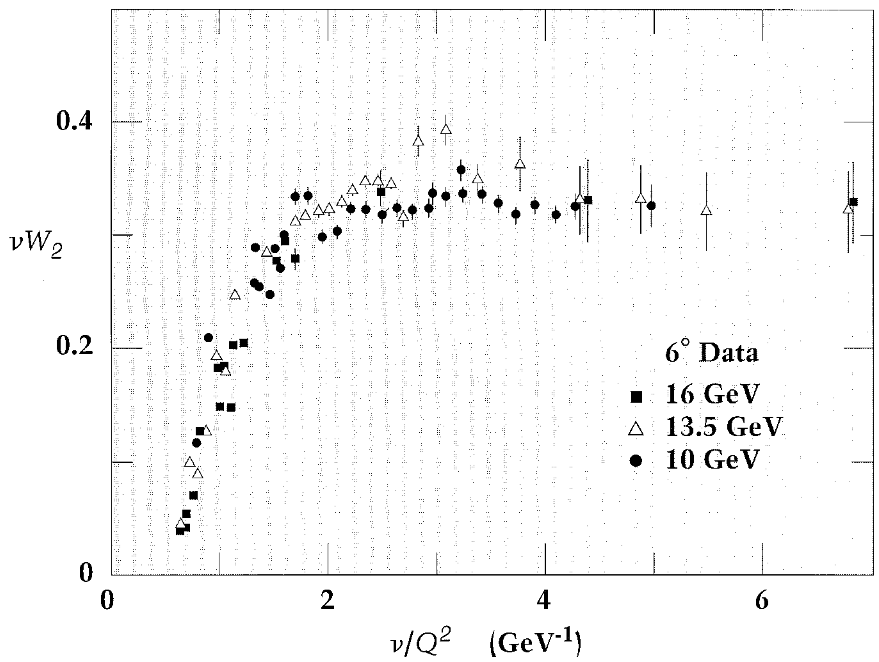
THE FIRST of these inelastic electron scattering experiments, SLAC Experiment 4B, had been proposed in 1966 by Caltech, MIT, and SLAC physicists and quickly approved by Director Wolfgang ("Pief") Panofsky. It was planned as a survey experiment, the kind of work generally done when a new accelerator comes on line and opens up an unexplored energy domain, in this case that between 6 and 20 GeV in electron scattering. When it came time to run this experiment during the autumn of 1967, however, the Caltech contingent had elected not to participate, largely because they thought the necessary corrections for effects of radiation from the electrons would prove too difficult in the inelastic region and the results would be ambiguous.

Quarks are taken for granted today, as if no more problematical than pebbles or stones, inanimate objects at the very base of reality.

Having worked in electron scattering for the previous decade, Friedman and Kendall had developed a computer program that they used to convince the remaining members of the collaboration that these "radiative corrections" would be manageable. Their simulations helped bolster the collaboration's confidence that meaningful cross sections could be extracted from the raw data, both in the resonance region and the "deep inelastic" regime wherein a large energy transfer to the proton occurred. Interest in deep inelastic scattering had grown during 1967, after SLAC theorist James Bjorken began suggesting it might give information about possible proton constituents.

MASSIVE SPECTROMETERS in End Station A (ESA) had been designed and built under Taylor's supervision during the mid-1960s. He also directed construction of a complex beam transport system to guide the powerful electron beam from the linear accelerator to ESA. The MIT group built most of the individual particle detectors for the 8-GeV and 20-GeV spectrometers, the two huge devices used in the experiments, and worked on the fast electronics and data acquisition system, one of the first to rely heavily on a computer for monitoring the equipment and logging data. The members of that first collaboration included Elliott Bloom, Dave Coward, Herbert ("Hobey") DeStaebler, Jurgen Drees (now at the University of Wuppertal) and Luke Mo (now at Virginia Polytechnic Institute) of SLAC Group A and Marty Breidenbach, then an MIT graduate student stationed at SLAC, who wrote his Ph.D. thesis on this experiment.

Experiment 4B ran in September and October of 1967, employing the 20-GeV spectrometer to record the scattering patterns at angles between 4 and 8 degrees. During the data-taking, everybody recalls observing an unexpectedly high counting rate in the deep inelastic region, roughly a factor of 10 higher than expected, but the collaboration was divided over its interpretation. The optimists were hopeful that they had stumbled upon some new phenomenon, but more conservative elements preferred to wait until after the radiative corrections—then a laborious process involving *all* cross sections measured at a given scattering angle—were done.



Above: Graph of the structure function νW_2, as presented by the MIT-SLAC collaboration at the 1968 Vienna Conference.

When the MIT version of these corrections, finished in early 1968, indicated that these high counting rates were *not* due to radiative effects, after all, expectations of new physics swelled. That spring Kendall, at Bjorken's suggestion, made a key plot of the structure function νW_2, which he had extracted from the corrected inelastic cross sections measured at 6 degrees. When plotted versus the variable ν/Q^2 (the energy loss of the electron divided by the square of its momentum transfer to the proton), the data appeared to "scale." They fell along a single universal curve, that is, independent of the primary electron energy at which the measurment had been made.

STILL, DOUBTS about the validity of the radiative corrections persisted until the SLAC version of the analysis (done mainly by Luke Mo with the aid of SLAC theorist Paul Tsai) was completed in July 1968, confirming the scaling behavior first observed in the MIT analysis. This convinced the rest of the group that the scaling behavior was not just an artifact of the data reduction. Based on this concurrence, the collaboration agreed to reveal this scaling result at the 1968 Vienna Conference that August, even though they did not fully understand its physical significance.

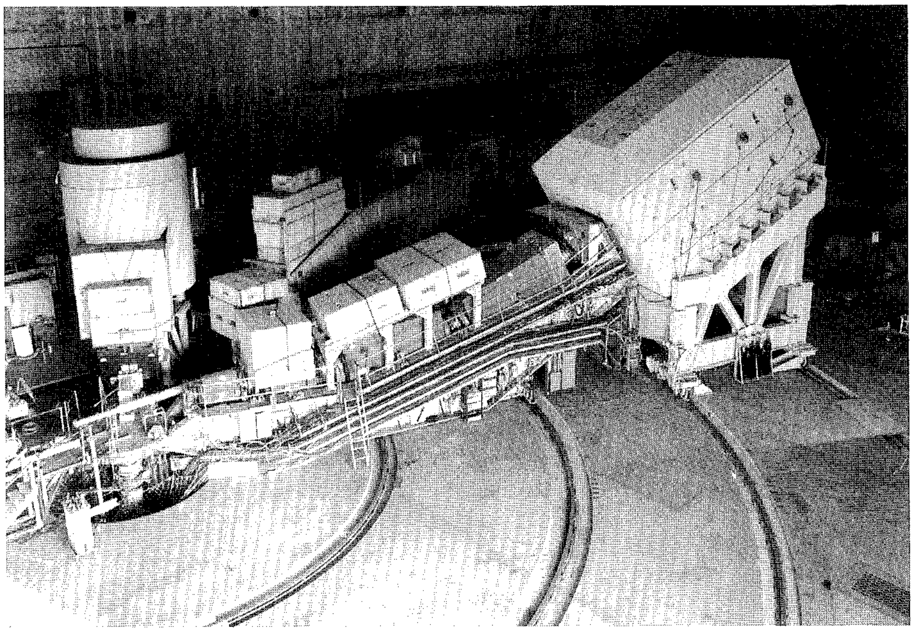
That very same month Feynman happened to visit SLAC and got an early peek at the MIT-SLAC data, which he immediately interpreted as evidence for his parton model of the proton. According to this hypothesis, the universal scaling function originally proposed by Bjorken was essentially the momentum distribution of the partons.

Late that summer the MIT-SLAC group returned to End Station A for further measurements of inelastic electron-proton collisions, first at an angle of 10 degrees using the 20-GeV spectrometer, and then at 18, 26 and 34 degrees with the 8-GeV spectrometer. Joining Group A for the wide-angle measurements were Lesley Cottrell and Guthrie Miller, (now at Los Alamos National Lab).

The structure functions extracted from these deep inelastic cross sections continued to fall upon the same universal curve, bolstering the parton interpretation. The group was also able to extract rough values for an important parameter R (the ratio of cross sections for the absorption of longitudinally and transversely polarized virtual photons), which again bore out parton model predictions.

In 1969 the collaboration published two papers in the same issue of *Physical Review Letters*, summarizing the 6 and 10 degree measurements and comparing these data with theoretical predictions. They were among the ten most-cited papers in high-energy physics that year, indicative of the burgeoning interest in this new research.

Right: End Station A spectrometers used to detect scattered electrons in the MIT-SLAC experiments: 1.6 GeV (left); 20 GeV (background); 8 GeV (right).



Further, more detailed results came from a second generation of deep inelastic experiments, in which electron scattering from the proton and deuteron was measured over a wider range of kinematics—and with much better accuracy. Arie Bodek (now at the University of Rochester), Scott Poucher (now at AT&T), and I joined the MIT group for this second set of experiments, performed in 1970, which again used the 20-GeV spectrometer at 6 and 10 degrees and the 8-GeV spectrometer at 18, 26 and 34 degrees. We performed data analysis and wrote our dissertations on these experiments.

After correcting for the motion of the neutron and proton within the deuteron, we extracted electron-neutron cross sections and compared them with the corresponding proton data. As expected in the quark-parton model, electrons bounced off protons more readily than they did from neutrons. And a detailed study of the Q^2 dependence of the ratio R indicated the partons had spin-1/2, consistent with quark model predictions. By 1973 the evidence for quarks was beginning to get strong.

Two more deep inelastic experiments were done at SLAC through 1973, both designed to study electron scattering from neutrons and protons at large angles and very high Q^2. One was performed in 1971 by the MIT group together with the SLAC Spectrometer Facilities Group, using the 8 GeV spectrometer. In the other, Group A physicists set up the 1.6 GeV spectrometer in ESA to detect electrons deflected at angles of 50 and 60 degrees; Bill Atwood did much of the work and wrote his Ph.D. thesis on that experiment.

MEASUREMENTS of deep inelastic neutrino-nucleon scattering made at CERN by the Gargamelle collaboration helped seal the case for quarks. Scaling behavior was found in these measurements, too, indicating that neutrinos were also encountering small objects inside protons and neutrons. Structure functions extracted from these cross sections fell along a universal curve, similar to the SLAC data; when CERN physicists multiplied their results by 5/18, a ratio predicted by the quark-parton model, the two data sets fell along the very same curve. This was strong evidence that both electrons and neutrinos were striking objects with the *fractional* electric charges, 2/3 and −1/3 times the electron charge, that were expected of quarks.

Complete conversion of the entire particle physics community had to wait a few more years, however, until the aftermath of the famous November Revolution in 1974. There was no way to explain the J and ψ particles without invoking a fourth, charmed quark. And there had always been one nagging problem with the quark-parton interpretation of the deep inelastic scattering results: we seemed to be hitting free, unbound quarks inside the nucleon, but they could never be found shooting out after the collision. Quantum chromodynamics, which supplied a force between quarks that became *stronger* with increasing separation, was an infant theory in 1973 and didn't gain wide acceptance until a few years later. The "gluons" this theory needed as carriers of the interquark force in fact received early support from the MIT-SLAC experiments and from deep inelastic muon-nucleon scattering at Fermilab and CERN.

Quarks are taken for granted today, as if no more problematical than pebbles or stones, inanimate objects at the very base of reality. They are used almost unthinkingly throughout particle physics—and are currently making their way into nuclear physics and cosmology too. But those of us who worked long and hard to understand whatever was happening inside protons and neutrons can never take these fascinating objects so lightly. It was a great pleasure for us to see their discovery awarded science's most prestigious prize.

○

GEORGE CARYOTAKIS AND THEODORE LAVINE

RF Power System Development

THE STANFORD LINEAR COLLIDER (SLC) accelerates both electrons and positrons to 50 GeV in one 3000-meter-long linac with a 17-megavolt-per-meter accelerating gradient. The Next Linear Collider (NLC) is envisioned to consist of two separate linacs, one for electrons, the other for positrons, each 2500 to 5000 meters long, with gradients of 50 to 100 megavolts-per-meter. Initial operation of the NLC will probably be at beam energies of 250 GeV. However, an important design goal is to accommodate increases in beam energy up to at least 500 GeV, probably via upgrades to the radiofrequency (rf) power system.

This article describes the development programs now under way at SLAC to provide rf power for the NLC, the rationale leading to the choice of devices being developed, and the problems that must be solved before the NLC rf power system can be acquired and operated at reasonable cost.

The SLC consumes 16 megawatts of peak rf power per meter of accelerator; the NLC will require as much as 200 megawatts-per-meter to develop the necessary gradients for the initial 250-GeV beam energy. To hold the power bill for running the machine within reasonable limits (*i.e.*, in order to minimize the average power needed), the machine will be operated at a quarter of the wavelength of the SLC: 2.6 cm *vs.* 10.5 cm. This reduces all dimensions by a factor of four and the time necessary to fill the structure with rf energy to one-eighth that of the SLC. As a consequence, the rf pulses can be made much shorter: 0.1 microsecond for the NLC *vs.* 1 microsecond for the SLC. For the same pulse repetition rate, this reduction in the pulse-length reduces by a factor of ten the average power needed, making the power consumption in comparison to the SLC roughly proportional to the ratio of total lengths of accelerator in the two machines. By virtue of its shorter wavelength and increased gradient, the total length of the accelerator structure in each NLC linac can be less than in the SLC, despite a five-fold increase in energy.

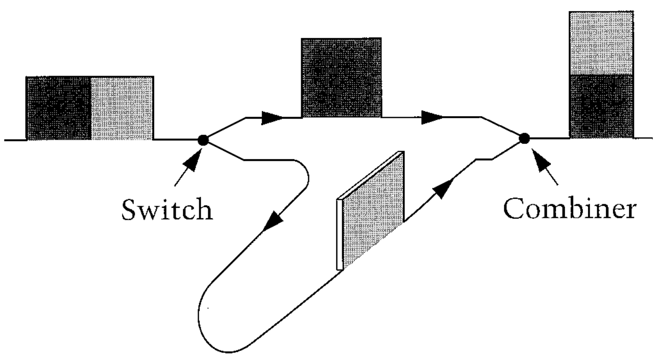
However, there is a price to be paid for this accommodation by Nature. For both the linacs and their power systems the field gradients and power densities are greater in the smaller 2.6-cm-wavelength accelerator structures. In addition, the reduced pulse-length introduces some inefficiencies in the components of the rf power system that have finite risetimes.

There are two ways to provide a 0.1-microsecond-long rf pulse to an NLC linac. The first is to produce it directly from a microwave amplifier, which must then be powered by a modulator capable of forming a 0.1-microsecond-long high-voltage pulse from the ac mains. The second is to operate the rf source at a more conventional output pulse-length, say one microsecond, and to process the rf output energy so that the peak power is increased, with a corresponding decrease in the pulse duration. The second (and the more conservative) approach is being taken for the NLC power system: we are designing and building a 100-megawatt, 1-microsecond klystron, and an rf pulse compressor to increase the peak klystron power by a factor between four and six. This approach is intended to reduce the risk of developing and manufacturing fundamentally novel microwave sources..

RADIOFREQUENCY POWER for the existing SLAC linac is produced by klystrons. A klystron is a narrow-band, high-gain amplifier for microwave signals. A klystron amplifies by using the input microwave signal to modulate the velocity of a nonrelativistic electron beam (pulsed or continuous). As the beam drifts, the velocity modulation is converted into density modulation, which is amplified further as the beam passes through a series of resonant cavities. The rf harmonic content of the bunched beam induces, in the output cavity, an rf field which acts to decelerate the beam. In the process, approximately half of the kinetic energy in the beam is converted to rf power. The remaining energy in the beam is dumped into a water-cooled collector. The electron gun, beam tube, microwave circuit, and beam collector all are integrated into a single vacuum envelope.

Despite extensive experience with klystron design and fabrication at SLAC, several challenges for the klystron designer are posed by the NLC requirement of high power at short wavelength. In order to achieve the desired klystron output power, which is the product of klystron beam power times klystron efficiency, a beam of sufficient intensity must be generated and confined within the klystron tube by magnetic focusing. The dimensions of the klystron beam tube and microwave cavities are proportional to the rf wavelength. To achieve the requisite beam power, a 100-megawatt klystron may require a beam kinetic energy (dc voltage) in excess of 500 kilovolts. For NLC klystron (designated at SLAC as "XC") development, the beam parameters have been chosen to be 440 kilovolts and 520 amperes. Later in the XC development program, assuming that the modulator design is not compromised, we may consider increasing the voltage and decreasing the current. This will simplify the focusing of the klystron beam and reduce electric field gradients in the electron gun. It also will reduce the magnetic field required to focus the beam. Since the power consumption of the electromagnets needed to confine the klystron beam may exceed the average power of the prototype klystron, the klystrons in a practical NLC power system should employ either superconducting electromagnets or permanent magnets to focus the klystron beams.

Another challenge is power extraction from the output cavity of the klystron. The conventional method of extracting rf power from the bunched electron beam is to have the beam traverse a resonant cavity shaped to present a short gap to the beam. The rf voltage developed across the output gap must be approximately equal to the beam dc voltage (kinetic energy) in order for the interaction to be efficient. For the XC klystron



Each stage of a "binary" rf pulse compressor combines the delayed leading half of an rf pulse with the trailing half of the pulse.

this is about 440 kilovolts or more. Since the gap-length must be relatively short (0.5 cm, compared to the 2.6-cm wavelength), the electric fields which develop can cause electrical breakdown. The XC solution is an "extended interaction" output structure which extracts energy from the klystron beam at several gaps,each of which holds only a fraction of the beam voltage. The rf energy extraction circuit then is a structure similar to that of an rf linac, only with lower phase velocity since it must be synchronous with the beam.

As of this writing, two XC klystrons have been constructed and tested, the first with a single output cavity, the second with a double-gap extended interaction output cavity. They produced 60 and 70 megawatts, respectively, at 0.05-microsecond pulse-length, and 20 and 40 megawatts, respectively, at the 0.8-microsecond pulse-length suitable for pulse compression.

SCHEMES UNDER STUDY for rf pulse compression and peak power multiplication fall into two categories: transmissive and reflective. In the transmissive category, time-intervals of the klystron pulse are separately delayed by different amounts, and then recombined into a shorter pulse of greater amplitude. We have built a high-power-capable "binary" rf pulse compressor that has three stages, each of which combines the delayed leading half of an input rf pulse with the trailing half of the pulse (see drawing at left). Delays are implemented using low-loss waveguides. Each stage multiplies peak power by 1.8 while halving the pulse-length. (Without losses, the multiplication factor would be 2.) The net result of all three stages is to multiply peak power by 5.5 for one-eighth the duration of the klystron pulse. This pulse compressor has been tested successfully with up to 25 megawatts of long-pulse power from the first XC klystron and has produced compressed pulses of 120 MW peak power for 0.07 microsecond duration.

In the reflective category of pulse-compression schemes, resonant energy-storage cavities coupled to the klystron are charged-up by the klystron, and then discharged during the time that it takes to fill an accelerator section. This scheme can multiply peak power by a factor up to nine when the input power suddenly is reversed in phase and the rf wave reflected from the storage cavity adds to the phase-reversed wave from the klystron. However, efficiency falls below 70% for multiplication factors greater than five per stage, because of residual energy trapped in the storage cavities.

The SLED scheme that has been used since 1976 to triple the peak power of SLAC klystrons is an example of a reflective scheme. In the original implementation of SLED for the SLAC linac, the power output amplitude is not constant throughout the accelerator filling-time. However, the design for the NLC linacs requires constant rf amplitude for the entire accelerator filling-time. Consequently, a new reflective pulse-compression scheme, called SLED-II, is under development to produce constant amplitude output pulses. In SLED-II pulse compression, the resonant storage cavities are delay-lines made of low-loss waveguide, electrically shorted at the end. The delay-time is the time-period it takes microwave energy to travel to the shorted end, to reflect off the short, and to return to the input end. A resonant buildup of energy takes place in the delay lines during an input pulse lasting several delay periods (typically 4 to 8). Phase-reversal of the input pulse then effectively releases the stored energy to produce a flat-top output pulse lasting one delay period. To achieve the desired 0.1-microsecond-long output pulse-length (equal to the NLC accelerator filling-time), the shorted delay-lines are approximately 50 feet long. A low-power SLED-II has been tested successfully. A high-power version is planned for 1991.

The klystron and rf-pulse-compression programs are proceeding in parallel at SLAC, with the objective of demonstrating a practical rf power system sometime during 1992. The approach being adopted for the total system appears to be conservative enough to allow initial development to be completed in approximately two years.

Suggestions for Further Reading

"The Next Linear Collider," by Ronald Ruth, *SLAC Beam Line*, Summer 1990, pp. 10–17.

"RF Power Sources for Linear Colliders," by M. A. Allen, R. S. Callin, G. Caryotakis, H. Deruyter, K. R. Eppley, K. S. Fant, Z. D. Farkas, W. R. Fowkes, H. A. Hoag, J. Feinstein, K. Ko, R. F. Koontz, N. M. Kroll, T. L. Lavine, T. G. Lee, G. A. Loew, R. H. Miller, E. M. Nelson, R. D. Ruth, A. E. Vlieks, J. W. Wang, P. B. Wilson, J. K. Boyd, T. Houck, R. D. Ryne, G. A. Westenskow, S. S. Yu, D. B. Hopkins, A. M. Sessler, J. Haimson, and B. Mecklenburg, SLAC-PUB-5274 (June 1990), published in Proceedings of the 2nd European Particle Accelerator Conference (Nice, France, 1990), pp. 146–148.

"Binary RF Pulse Compression Experiment at SLAC," by T. L. Lavine, G. Spalek, Z. D. Farkas, A. Menegat, R. H. Miller, C. Nantista, P. B. Wilson, SLAC-PUB-5277 (June 1990), published in Proceedings of the 2nd European Particle Accelerator Conference (Nice, France, 1990), pp. 940–942.

"SLED: A Method of Doubling SLAC's Energy," by Z. D. Farkas, H. A. Hoag, G. A. Loew, and P. B. Wilson, SLAC-PUB-1453 (June 1974), published in proceedings of the 9th International Conference on High Energy Accelerators (SLAC, 1974), pp. 576–583.

"SLED-II: A New Method of RF Pulse Compression," by P. B. Wilson, Z. D. Farkas, and R. D. Ruth, SLAC-PUB-5330 (September 1990), published in proceedings of the 1990 Linear Accelerator Conference (Albuquerque, New Mexico).

History Notes

THE GREAT DEBATE about the nature of spiral nebulae came to a climax in 1925. Early speculation by Immanuel Kant, among others, had envisioned nebulae as independent star systems, separate from our own Milky Way, but so far away from us that their misty, foggy ("nebulous") appearance could not be resolved into individual stars.

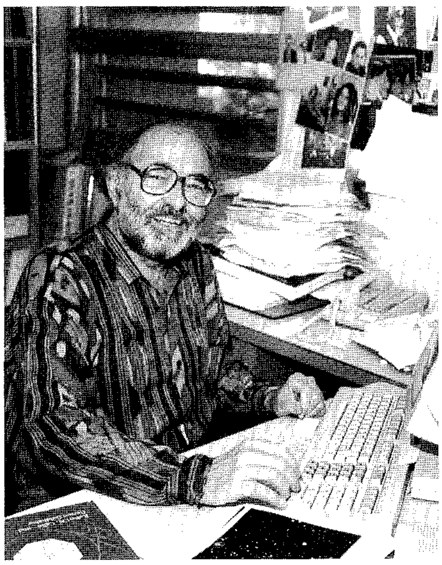
But the evidence was equivocal. Many of the spectroscopically observed nebulae had been shown to be gaseous and thus inconsistent with an assemblage of stars. And even though the spiral nebulae showed star-like spectra, there was still no clear separation in the theories of the time between the two different types of nebulae.

The issue was sharpened in 1920 during the famous debate that occurred between Harlow Shapley and Heber Curtis at the April meeting of the National Academy of Sciences, with Curtis championing the separate "island universe" view of the spiral nebulae.

The definitive proof of this view came in early 1925 with the publication of Edwin Hubble's observation of individual Cepheid variable stars in two nearby galaxies, M31 and M33, the great spirals in Andromeda and Triangulum. Using the established relationship between the period of light variation and absolute luminosity, Hubble was able to establish a distance of a little less than a million light years to both M31 and M33—a distance far beyond the limits of our own Milky Way.* And if M31, whose central region is barely visible to the naked eye, still spans a visual space larger than the moon, then how far away must be the galaxies that appear to be only tiny spirals in even the largest telescopes? Very far indeed. To the eye of man, the universe had become a vastly larger place.

**Later work gives the distance to M31 as closer to two million light years.*

PEOPLE AND EVENTS



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Gerson Goldhaber

Goldhaber and Pierre Win Panofsky Prize

GERSON GOLDHABER, professor of physics at the University of California, Berkeley, and faculty senior scientist at Lawrence Berkeley Laboratory (LBL), shares the 1991 W. K. H. Panofsky Prize of the American Physical Society (APS) with French physicist Francois Pierre of Saclay for the discovery of "charm," a new property of matter, in 1976.

The prize, the APS's highest award for experimental particle physics, was awarded to Goldhaber and Pierre for their discovery of charmed mesons. According to the APS citation, their discovery "furnished dramatic confirmation of the existence of charmed quarks, provided important support for the electroweak theory, and elucidated the nature of the narrow resonances *J*/psi and psi." The prize consists of a certificate and $5000 ($2500 to each recipient).

The discovery of the charmed meson, or D^0 particle, took place at LBL while Pierre was there as a visiting scientist in the mid-70s. Both he and Goldhaber were members of the SLAC-LBL collaboration at the SPEAR accelerator at Stanford Linear Accelerator Center (SLAC), and had participated in the discovery of the *J*/psi, a particle containing "hidden charm," in 1974.

The *J*/psi, discovered independently by the SLAC-LBL group and by an MIT-Brookhaven National Laboratory collaboration, had been widely recognized as belonging to a new family of particles. But because it is composed of a quark and its antiquark, which cancel each other out in certain respects, the *J*/psi did not exhibit the new property dubbed "charm" explicitly. Thus it remained for the discovery of the D^0 (which is made up of a charm quark paired with an antiquark of ordinary matter) to reveal the properties of charm and confirm the nature of the *J*/psi.

In the same week in 1976, Goldhaber and Pierre independently analyzed the data from electron-positron annihilations at SPEAR and found evidence for the creation and decay of the charmed meson. Pierre returned to France in 1976 and is now at the high-energy physics institute in Saclay.

McMillan Receives National Medal of Science

EDWIN MCMILLAN, Nobel laureate and former director of Lawrence Berkeley Laboratory, received the National Medal of Science, the Nation's highest award for scientific achievement. He was cited for identifying neptunium, the first transuranic element, and for his discovery of the "phase stability principle," an idea that led to the invention of the synchrotron.

Schwartz Returns to Physics at BNL

Brookhaven National Laboratory

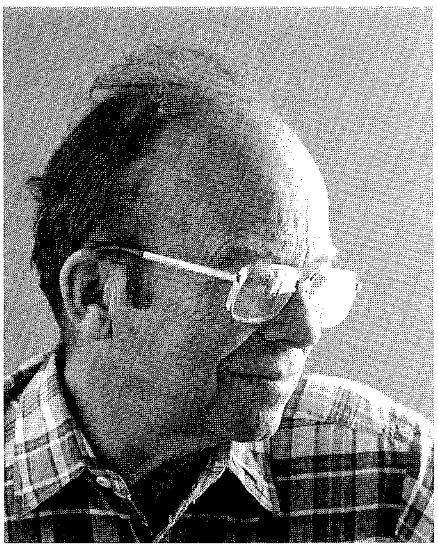
MELVIN SCHWARTZ has recently resumed his distinguished career in physics by assuming the post of Associate Director for High Energy and Nuclear Physics at Brookhaven National Laboratory (BNL) on Long Island. Schwartz is a Nobel Laureate in Physics, having shared the 1988 Prize with Leon Lederman and Jack Steinberger for the classic 1962 experiment conducted at BNL that established the distinction between the electron neutrino and the muon neutrino. In the late 1960s and during the 1970s he was Professor of Physics at Stanford University and the leader of Experimental Group G at SLAC. During that time he and his collaborators carried out experiments at SLAC, BNL, and Fermilab. He replaces Larry Trueman who is returning to research in the Theory Group of the BNL Physics Department.

Schwartz founded the firm Digital Pathways, of Mountain View, California, in 1970, and he has served as the firm's full-time President for the last ten years. Now that he is back in physics again on a full-time basis, we look forward to much more of the wit and wisdom that are his well-respected stock in trade.

Riordan Joins URA for Year

BEAM LINE EDITOR MICHAEL RIORDAN, who has edited this publication and served as Science Information Officer at SLAC since 1988, has accepted a one-year appointment as Staff Scientist and Assistant to President John Toll at Universities Research Association (URA) in Washington, D.C. URA is the consortium of 78 universities in the United States and Canada that manages Fermilab and the SSC Laboratory. Riordan's responsibilities are liaison with Fermilab and the SSC Laboratory, as well as keeping science writers informed about the activities of these laboratories. Toll says, "We are fortunate that Michael Riordan has agreed to contribute his unique combination of scientific expertise and creative talents during a critical stage of development at both laboratories."

Riordan wrote *The Hunting of the Quark* in 1987, based in part on the MIT-SLAC inelastic scattering experiments that discovered quarks (see his article on page 18). His latest book, *The Shadows of Creation*, co-authored with David Schramm of the University of Chicago, has recently been published by W. H. Freeman & Company (see "Contributors," page 31).

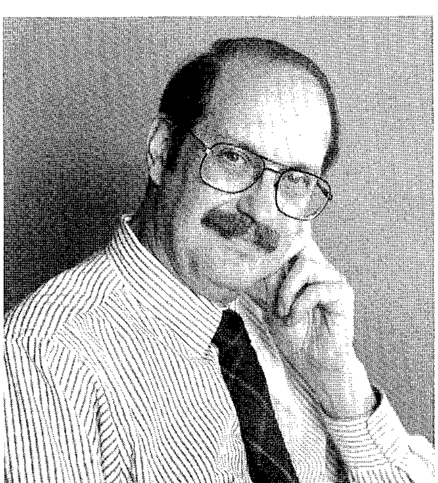


Panofsky Wins AAAS Arms Control Award

WOLFGANG K. H. PANOFSKY, Director Emeritus of Stanford Linear Accelerator Center, has been selected as the first recipient of the AAAS Hilliard Roderick Prize for excellence in the field of Science, Arms Control, and International Security. The award states, "Dr. Panofsky's work in recent years—his writing both for the technical community and for the general public, his testimony before the Congress, and his advisory role with the executive branch of the government—provides the ideal example of the effective use of technical knowledge to clarify policy options related to such important and controversial issues as the Strategic Defense Initiative, the testing of nuclear weapons, and the verification of arms control treaties. . .These exemplary efforts to apply science and technology to critical issues of arms control and international security will set a high standard for future winners of this Award."

Panofsky is chairman of the Committee on International Security and Arms Control of the National Academy of Sciences and has been instrumental in furthering the important and constructive dialogue between U.S. and Soviet scientists on issues of international security.

In accepting the Award, Panofsky said that it was fitting that the AAAS should strengthen its already active program in arms control since science has provided both a dramatic increase in the power of the tools of warfare and the means for their control.



Siemann Joins SLAC Faculty

ROBERT SIEMANN, formerly a professor at Cornell University and well known throughout the world for his expertise in accelerator physics, has joined Stanford Linear Accelerator Center as a Professor in the Accelerator Theory and Special Projects Department. During the past seventeen years at Cornell, he made many contributions to accelerator science through his teaching and research. "I am interested in both the theoretical and practical aspects of linear colliders," he says, "and being at SLAC offers the unique opportunity to study the full range of these problems." Siemann will head the SLC Positron Task Force and help with the coordination of the upcoming SLC run. In addition to his research activities, he plans to teach accelerator physics at Stanford and at the U.S. Particle Accelerator School.

FROM THE EDITORS' DESK

BEAM LINE EDITOR Michael Riordan is presently away from SLAC on a one-year leave of absence. (See "People and Events," page 27.) During this period we will try to keep the ball rolling.

A few words about our continuing intentions and plans. Our ideal is to see the *Beam Line* become a journal that publishes articles of broad general interest to the worldwide particle-physics community. A good example in this issue is Rocky Kolb's "Origin of Structure" article, which qualifies on two key counts: it connects in an obvious and interesting way with particle physics, and it is presented at a level that is accessible not only to colleagues but also to the interested observer of the field.*

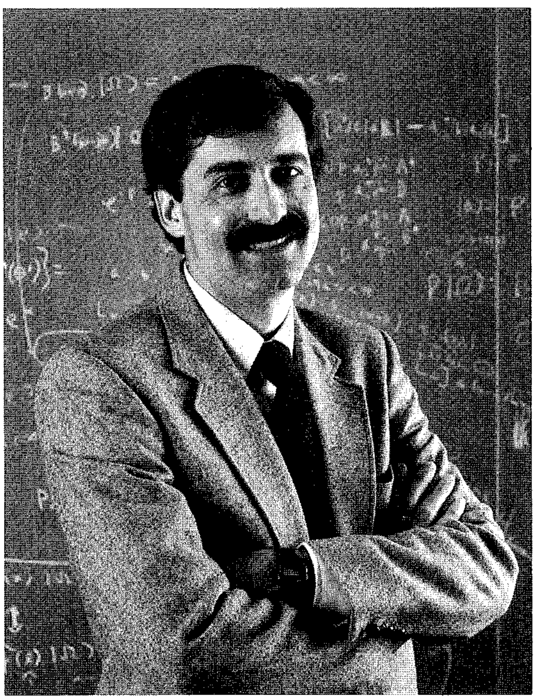
However, the *Beam Line* still has a distance to go before it becomes something more than a SLAC newsletter. We start from a position that is parochial in at least three senses: *(a)* we work at SLAC and not some other lab; *(b)* we are more familiar with electrons than protons; *(c)* we are a lab in the U.S. and not elsewhere. So our SLAC-electron-U.S. orientation has been and continues to be evident in the first several issues of the new *Beam Line.*

But we're working on it, with possible articles in preparation on the HERA turn-on, science education, neutrino mass, computer simulation for radiation therapy, generic B factories. . . .We repeat our earlier invitations to prospective authors: Give us a call, and let's talk about it. We also welcome letters to the Editors.

*In *The First Three Minutes,* Steven Weinberg pictures his reader as "a smart old attorney." We picture our reader as someone with a lively curiosity about, and probably some background in, the physical sciences.

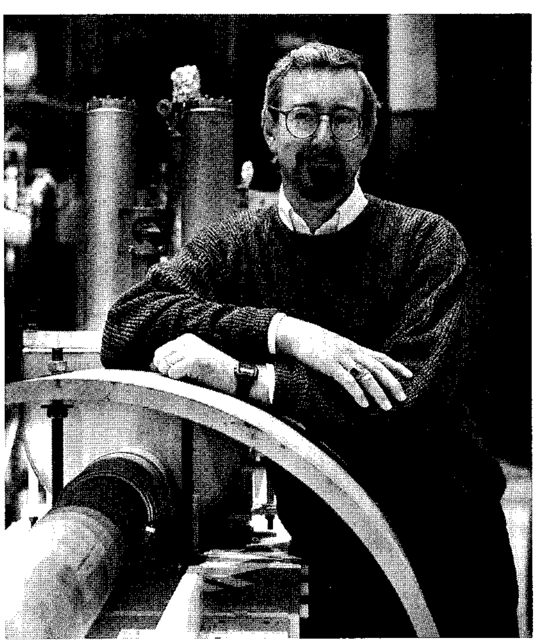
Rene Donaldson   Bill Kirk

CONTRIBUTORS



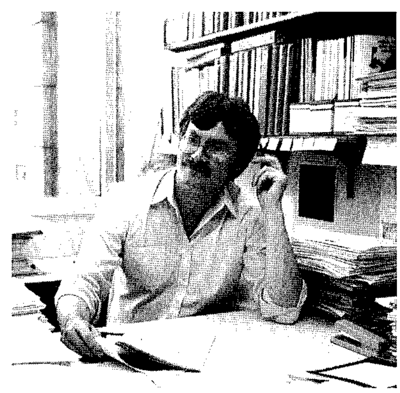
Fermilab Visual Media Services

EDWARD W. KOLB came to Fermilab in 1983 to start the highly successful NASA/Fermilab Theoretical Astrophysics Group in collaboration with Michael S. Turner. Since that time he has been head of the group, as well as a Professor of Astronomy and Astrophysics at The University of Chicago. "Rocky" is also a professor in the Astronomy and Astrophysics Department of the College, and the Enrico Fermi Institute of the University of Chicago. His main scientific interest is the interface between particle physics and cosmology. With Turner, Kolb recently wrote *"The Early Universe,"* a monograph summarizing the present state of the field of particle cosmology. A frequent lecturer at conferences and schools, Kolb is also active in educational activities, giving popular accounts of the big bang to science teachers, students, and the general public.

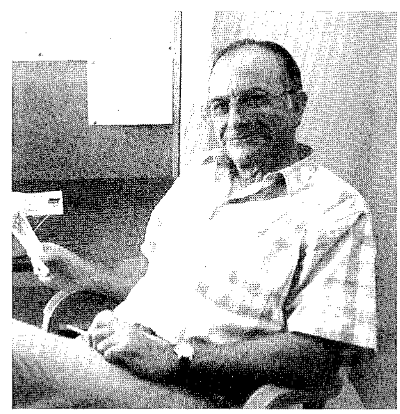


BILL ASH heads the group that built the superconducting final focus for the SLD, having earlier managed the contract with the firm in Japan that built the solenoidal coil for this large detector. Ash came to SLAC in 1972 to work on the polarized target for the spin-structure experiments in End Station A. In 1976 he joined the group that built and ran the SLAC side of the MAC detector at the PEP storage ring. He served as editor of the *Beam Line* from 1982 to 1985; published newsletters for PEP, SLC, and SLD; and has edited several conference proceedings.

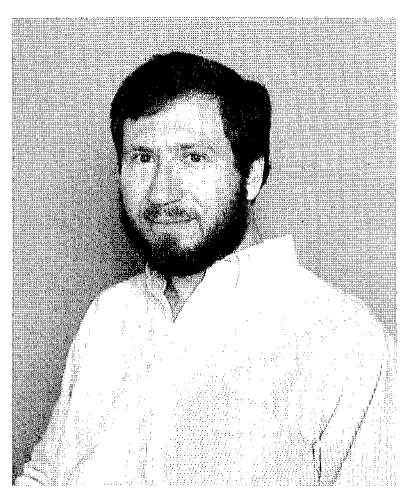
MICHAEL RIORDAN, contributing editor of the *Beam Line*, is on a year's leave of absence to Universities Research Association in Washington, D. C. (see "People and Events," page 27). Prior to his departure, Riordan was SLAC's Science Information Officer. His latest book, *The Shadows of Creation*, co-authored with David Schramm of the University of Chicago, has just been released by W. H. Freeman & Company. It presents an overview of dark matter, current attempts to detect it, and its role in formation of galaxies. Riordan's previous book, *The Hunting of the Quark*, won the 1988 American Institute of Physics Science Writing Award.



GEORGE CARYOTAKIS is completing his first year as head of the Klystron/Microwave Department. He came to SLAC after a 30-year career at Varian Associates, where he was a microwave tube engineer for the first few years and a manager during most of that period. At SLAC he is doing some of both, since he is helping with the development of the X-band klystron intended to be the power source for the Next Linear Collider. Caryotakis has been active in government advisory committees on microwave tube development, and he holds several patents on klystron and traveling wave tube designs.

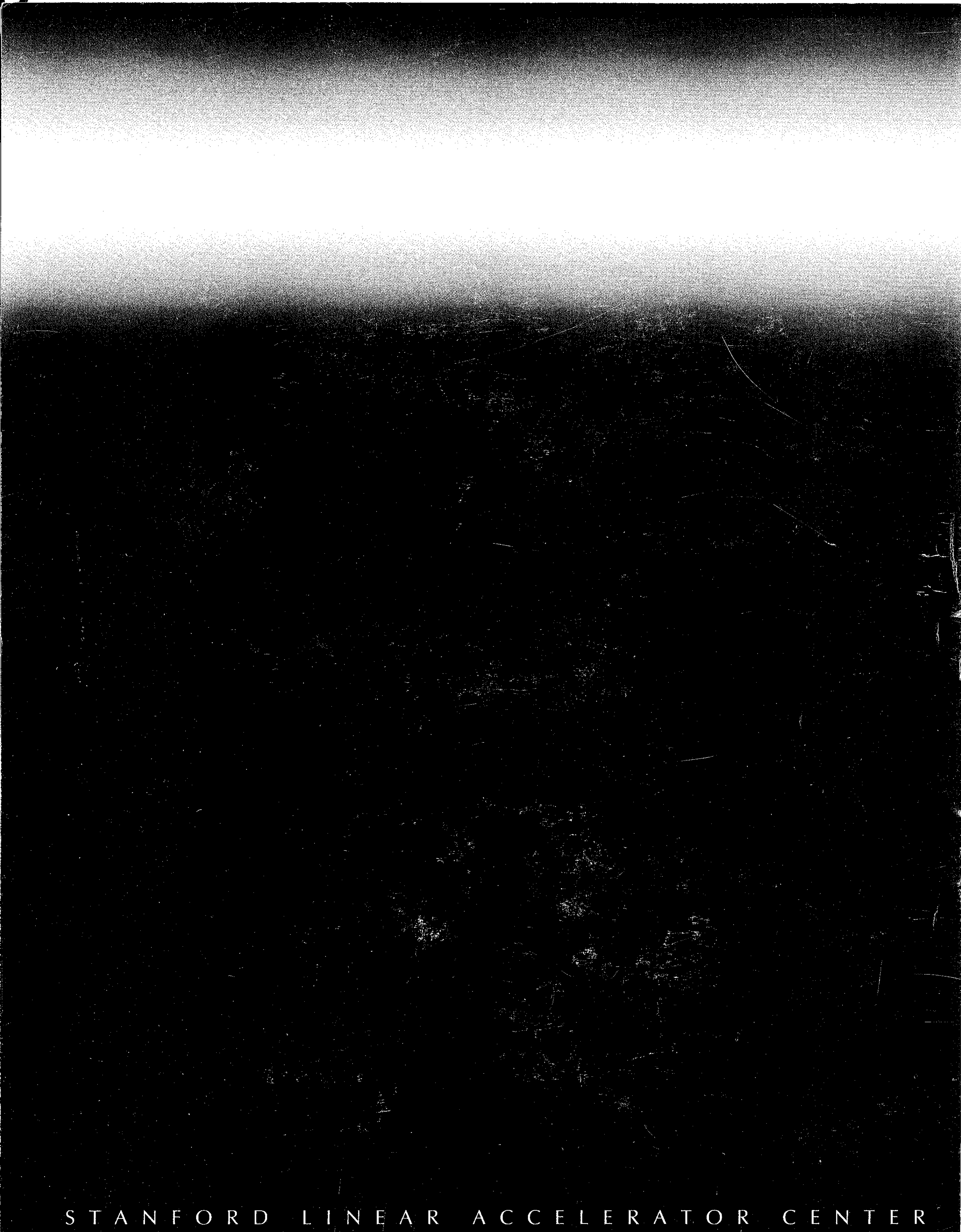


THEODORE LAVINE is a physicist in SLAC's Accelerator Theory and Special Projects Department. Since 1987, his research has been on experimental high-power rf source development for future linear colliders and on experiments in high gradient acceleration. He also works on polarized electron source development for the SLC. Lavine was a SLAC "user" from 1980 to 1987; as an experimental physicist at the University of Wisconsin, he was a member of the MAC Collaboration and worked on electron-positron annihilation experiments at the PEP storage ring, including searches for supersymmetric particles and for additional neutrino species.



DATES TO REMEMBER

Apr 22–25	General Meeting of the American Physical Society, Washington, DC (W. W. Havens, Jr., The American Physical Society, 335 E. 45th St., New York, NY 10017).
May 6–9	Particle Accelerator Conference, Sheraton Palace Hotel, San Francisco, California [for registration information contact Carolyn Beckmann, Los Alamos National Laboratory (505) 667-3118 or BITNET BECKMANN@LAMPF].
May 8–9	2nd Annual REXX Symposium for Developers and Users, Asilomar, CA (G. David, REXX Symposium, 7 Gateview Court, San Francisco, CA 94116-1941).
May 17–18	Fermilab Users Annual Meeting, Batavia, IL (Bert Forester, Users Office, Fermilab, P. O. Box 600, Batavia, IL 60510).
May 20–25	Strings and Symmetries 1991, Stony Brook, NY (Institute for Theoretical Physics, SUNY, Stony Brook, NY 11794-3840, BITNET STRINGS@SUNYSBNP).
May 24–29	4th Conference on the Intersections Between Particle and Nuclear Physics, Tucson, AZ (E. D. Zukowski, Brookhaven National Laboratory, Bldg. 510 F, Upton, NY 11973-5000, BITNET HENP@BNLDAG).
Jun 10–14	Workshop on the Design of a Detector for a High-Luminosity Asymmetric B Factory: Summer Session at SLAC, Palo Alto, CA (Anamaria Pacheco, SLAC, Bin 95, P. O. Box 4349, Stanford, CA 94309, BITNET ANAMARIA@SLACVM).
Jun 17–Aug 9	Summer School in High Energy Physics and Cosmology, Trieste, Italy (ICTP, P. O. Box 586, I-34100 Trieste, Italy, BITNET VARNIER@VX1CP2.INFN.IT).
Jul 25–Aug 1	15th International Lepton Photon Symposium at High Energies, Geneva, Switzerland (by invitation)(L. Griffiths, LP-HEP91 Conference Secretariat, CERN, 1211 Geneva 23, Switzerland).
Aug 5–16	SLAC Summer Institute on Particle Physics, Lepton-Hadron Scattering, Palo Alto, California [Jane Hawthorne, SLAC, Bin 62, P. O. Box 4349, Stanford, CA 94309, BITNET SSI@SLACVM or (415) 926-2877].
Aug 18–22	Particles and Fields '91, American Physical Society Division of Particles and Fields and Division of Particle Physics, Canadian Association of Physicists, Vancouver, Canada [PF91 Secretariat, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3, (604) 222-1047, BITNET PF91@TRIUMFCL].



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