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The COSMIC BACKGROUND EXPLORER
by GEORGE F. SMOOT

A pathbreaking satellite provides important new insights about the origins of the Universe.

The COSMIC BACKGROUND EXPLORER (COBE) satellite is famous around the world for measuring the largest and oldest structures ever discovered in the Universe. Human beings, living on a tiny planet orbiting a small star in an ordinary galaxy, have now reached back in time to try to understand the origin of the Universe. We have launched a little space probe, orbiting not far above the surface of the Earth, to receive the faint whispers of the cosmic explosion, the Big Bang, which started the expansion of our Universe about 15 billion years ago. The new data have greatly strengthened our conviction that the Big Bang picture is valid, and have begun to fill in some of the details. We have measured tiny differences in the brightness of the microwave radiation leftover from the Big Bang, only a few parts per million. These differences reveal the structure of the Universe when it was less than a nanosecond old.

The COBE satellite was built at NASA's Goddard Space Flight Center, located near Washington, DC. A team of hundreds of engineers, scientists, technicians, managers, computer programmers, and many others worked together from 1976 to 1989 to design, build, test, and launch it. The project grew from proposals by three original teams of scientists from the University of California at Berkeley, MIT, Princeton University, Goddard, and the Jet Propulsion Laboratory. Many obstacles were overcome on the way to launch. One of the largest was that the project needed new and difficult technology, such as superfluid liquid helium to cool two of the instruments. An even greater challenge came when the Space Shuttle Challenger exploded in 1986 and launch opportunities on the Shuttle were greatly restricted. The COBE had to be almost completely rebuilt to fit onto an expendable rocket. Nevertheless, this feat was accomplished and COBE was finally launched on a small Delta rocket on November 18, 1989.

How can one possibly measure the distance to something that far away? To measure things farther away than the nearest stars, we have to use the fact that more distant stars look fainter. This can be a reliable, quantitative method if we can convince ourselves that we know how bright each star really is, but achieving that goal has taken generations of astronomers working with the largest telescopes, and it still doesn't work perfectly. One of the big uncertainties is that stars and galaxies may have changed during the long times it takes light to travel these distances. The distant stars and galaxies viewed today were not exactly the same when the light left them as the nearby ones we now observe.

Except for the planets and the nearest stars, astronomers can't see things move across the sky, even with telescopes. Instead, we measure motion using the Doppler effect. We measure the changes in the wavelengths of light to determine whether a luminous object is approaching us or receding. Visible light is shifted towards the blue end of the spectrum when an emitter is approaching us and towards the red end when the object is receding. The amount of blueshift or redshift is proportional to the speed of motion on the line of sight. To determine a light-emitting object's velocity relative to us, we need to know the wavelength of the light waves when they were emitted and to compare it with the wavelength we observe. This is possible because the Universe is composed of atoms, and each kind of atom (at least in the gaseous phase) emits light only at certain specific wavelengths.
In the late 1920s Edwin Hubble made an extraordinary discovery, which overthrew humanity’s prior concept of the Universe. He showed that many nebulae were in fact distant galaxies—clouds of hundreds of millions of stars. Hubble found a very simple relationship, now called Hubble’s Law, between a galaxy’s redshift and its distance from us: redshift is proportional to distance. Hubble’s Law, called at the time “The General Recession of the Galaxies,” shows that the Universe is expanding. All the galaxies are moving apart.

A naive extrapolation back in time leads one to conclude that the galaxies all started their motions from a single spot at a single time in the distant past. The remarkable implication is that the entire observable part of the Universe began in a great explosion! What could have possibly caused such an event? Scientists working on the question have some possible explanations, but it will be many years before they reach an agreement.

One remarkable aspect of this explosion is that we cannot see either a center or an edge to the Universe. It seems to us that everything is rushing away from us, but since Copernicus we are not so proud as to think that we sit in the middle. The Universe is expanding uniformly everywhere, like a loaf of bread that rises as the yeast grows within it. Scientists think that space itself is expanding rather than that galaxies are moving out into previously existing space.

This expansion of space produces a redshift by stretching the wavelength of light. The light from more distant objects takes longer to arrive and thus has more time to be stretched than light from nearby galaxies. A uniformly expanding space automatically yields Hubble’s Law. It gives the same relationship for an observer located anywhere in space. It is not necessary for a galaxy to move relative to its local region of space; the general expansion of space produces a redshift proportional to the distance between an object and its observer. If the galaxy is also moving, then there is an extra Doppler shift added to the cosmological redshift caused by expanding space.

Before Hubble published his findings Albert Einstein, the Belgian cleric Georges Lemaitre, the Russian mathematician Alexander Friedmann and others had considered how the Universe would behave under the influence of its own gravity. They realized that the Universe could not be motionless—it had to expand or contract. Also, it would appear as though we stood at the very center of the expansion, as Hubble observed. Even more astounding, there need not be a center—the Universe could be infinite and still have a cosmic expansion. Einstein himself did not like this idea at first, but Hubble’s experimental data ended the uncertainty. Cosmologists soon understood that there were two possible futures for the Universe: it could expand forever, or it could expand for a while and then collapse back on itself.
cosmic explosion might have done. At first, they guessed that the Big Bang, starting with just a primordial soup of neutrons and protons, might have manufactured all the chemical elements. But they soon found that this idea was wrong. In fact, only the lightest elements—hydrogen, helium, deuterium, and lithium—could have been generated in the Big Bang. All the rest must have been made later, in stars and supernovae. Gamow, Alpher and Herman made one key prediction: about 25 percent of all the matter in the Universe must be helium, and the rest is almost all hydrogen. Their predictions are in extremely good agreement with the data we get from measuring the composition of stars, so the idea of the Big Bang received a strong confirmation. But proponents of opposing theories did not give up.

In 1948 Gamow, Alpher and Herman made another extremely important prediction: the Universe must be filled with the dim remains of the thermal radiation that originated in the Big Bang. They calculated that this radiation should be very cold, corresponding to a temperature of about 5 degrees above absolute zero. The expansion of the Universe would have cooled it from its blazing temperatures of billions of degrees minutes after the Big Bang.

The temperature of outer space was not measured precisely until 1964. By then many scientists had forgotten that this radiation had already been predicted, although it was mentioned in popular astronomy books by Gamow. That year Arno Penzias and Robert Wilson of Bell Telephone Laboratories discovered the radiation while they were testing an antenna they intended to use for radio astronomy. Their result was confirmed within a few months by astrophysicists at Princeton University who had just built an apparatus especially designed for the purpose. This radiation, which astronomers call the cosmic background radiation, is a little cooler than predicted, only 2.73 degrees Kelvin. We know it originates from the Big Bang because it comes uniformly from all directions, completely unrelated to any of the objects known to traditional astronomers.

By the time the COBE satellite was being built, astronomers had discovered a new mystery. Maps of the locations of distant galaxies were becoming precise enough to show that the Big Bang could not have been a completely uniform, smooth, featureless explosion. Galaxies are distributed in a very irregular way, with huge groups of them clustered together, and huge empty spaces hundreds of millions of light years across. For this to happen, there must have been something special in the structure of the Big Bang itself that caused this irregular distribution of...
A large cluster of galaxies known as the Coma cluster, in the constellation Coma Berenices. Such superclusters are a fairly common feature in the Universe today. (Courtesy National Optical Astronomy Laboratories)

A large cluster of galaxies known as the Coma cluster, in the constellation Coma Berenices. Such superclusters are a fairly common feature in the Universe today. (Courtesy National Optical Astronomy Laboratories)

matter throughout space. And there should be some traces of this structure in the cosmic background radiation itself. These are the traces that COBE scientists set out to search for.

The COBE Satellite carries three instruments, all designed to observe the relic radiation from the Big Bang and the events that happened soon afterward. It orbits 900 kilometers above the Earth's surface, moving in a circle that is almost above the sunrise-sunset line. In winter it can even be seen from the ground, going from south to north a little after sunset, or from north to south a little before dawn. It can be recognized because its brightness changes as it spins around once every 72 seconds. We chose this orbit because it lets us protect the instruments—the Sun is always off to the side of the satellite and the Earth is always below, so the infrared radiation from both of them does not affect the sensitive instruments. The afterglow of the Big Bang, which comprises 99 percent of all the radiant energy in the Universe, is still 100 million times fainter than the thermal radiation emitted by the Earth.

The first of the COBE instruments to test the Big Bang theory was one designed to measure the spectrum of the cosmic background radiation. This spectrum tells us the color of this radiation—how much energy comes at each different wavelength, from 0.1 millimeter to 1 centimeter. Within two months of the launch of the COBE in November 1989, the team working on this instrument, led by John Mather at NASA/Goddard, had determined that the spectrum was in excellent agreement with the Big Bang predictions. As physicists describe the radiation, it is called "blackbody" radiation, which means that it behaves like thermal radiation emitted by an object that has no color at all and is perfectly black, absorbing all light that falls on it. Astrophysicists breathed an enormous sigh of relief when these data came in, because only a year before another experiment on a small rocket had made similar observations that did not agree with the Big Bang prediction. The COBE data agree almost exactly with the predicted blackbody spectrum. Any discrepancies are less than 1 part in 400, a wonderfully precise verification of the Big Bang model.

The second instrument, the Differential Microwave Radiometer or DMR, was designed to look for primordial hot spots and cold spots in the Big Bang radiation. These spots reflect the density variations that would eventually grow into huge clouds of galaxies and enormous empty spaces. DMR's microwave receivers, not much different from
the circuits in a television receiver, compare the brightness of one part of the night sky with another. The DMR instrument produces over 100 million measurements every year of the sky brightness at wavelengths of 3.3, 5.7, and 9.6 millimeters. We have spent over two years combining these measurements to make comprehensive maps of the entire sky.

After extremely careful rechecking of the work, the team announced its results on April 23, 1992, at the American Physical Society meeting in Washington D.C. As team leader, I described the main results and presented the new maps of the early Universe. Team member Gary Hinshaw described how the data processing was done. Deputy team leader Charles Bennett of NASA/Goddard showed how we separated the signals into cosmic and galactic components. Alan Kogut of NASA/Goddard discussed how we tested our equipment and our computer programs to show that the signals were not the result of our own mistakes. Edward Wright of the University of California, Los Angeles, described how we tested various theories of the Big Bang with our data.

The COBE maps show the full sky, stretched and distorted a little for presentation on a flat piece of paper. They are oriented so that the Milky Way galaxy runs across the middle of the maps from left to right, with its center in the middle. The top picture shows how the sky looks when we take the maps as they come from the computer. There is one dominant feature: the top right part of the map is hotter by about 1 part in 1000, and the lower left part is colder by the same amount. This feature, the dipole anisotropy, is caused mostly by the overall motion of the Earth towards the constellation Leo. The middle map shows what is left after we subtract the effects of our own motion. In this picture, the main feature we see is the Milky Way galaxy with a few streamers sticking up and down. Away from the galactic plane there are warm and cool regions of various sizes. These are the primordial variations created at the birth of the Universe that produce the galaxies, clusters and larger-scale structures observed today. The bottom picture shows what we really want to produce—an image of the early Universe with the effects of the Milky Way removed. This was the most difficult subtraction; it was possible because we mapped the sky at three different wavelengths, and the Milky Way does not affect them all equally. This map shows randomly-located hot and cold spots, most of them only about 1 part in 100,000 hotter or colder than the average. Unfortunately, some of the hot and cold spots are also the result of spurious signals produced in our receivers and by our removal of the galactic effects. When we analyze the new data we are now receiving, these extraneous signals will correctly disappear.

Statistical analysis reveals real cosmological patterns hidden in these maps. The details agree very well with the basic idea of the Big Bang, but taken in combination with observations of the galaxies, they also suggest something very strange and exotic. Apparently about 90 to

Top: The microwave radiation from the sky, as seen by COBE. The radiation has a temperature of 2.73 degrees Centigrade above absolute zero, and the upper right portion of the map is about 0.12 percent warmer than the average. The lower left portion is cooler by the same amount. This tiny difference is caused by the motion of the Earth through the cosmic microwave radiation.

Middle: The same information as in the top panel, but with the effects of the Earth’s motion removed. The Milky Way galaxy is the horizontal band through the middle of the map.

Bottom: The same as in the middle panel, but with the effects of the Milky Way removed. The spots are only 1 part in 100,000 warmer or colder than the rest. They reveal gigantic structures stretching across enormous regions of space.
A map of the sky using infrared radiation to show interplanetary and interstellar dust particles. The horizontal line is due to dust in the Milky Way, looking toward its center. The diffuse, S-shaped curve represents emissions from the interplanetary dust in the plane of the Solar System.

99 percent of all the material in the Universe is unlike ordinary matter—it is invisible! This interpretation is controversial. We can deduce the existence of this "dark matter" from the gravity that it produces, but at present we have no other way to detect it. Hundreds of people are building experiments in laboratories around the world to search for this dark matter, but so far there is no sign of success. Cosmologists have been considering its existence for over a decade, so it no longer seems so bizarre, but in truth we do not know what it is at all. Most of the debates on cosmology now center on deducing the properties and effects of this dark matter.

The third experiment on the COBE has not yet achieved its primary cosmological objectives. Michael Hauser at NASA/Goddard leads a team searching for the infrared light from the first galaxies to form after the Big Bang. This light would have originally been much like that from stars today but the cosmological expansion would have shifted it far toward the red. For the very earliest galaxies this redshift is expected to be so large that the light is shifted past the red to the infrared. It is possible that some of this light was absorbed by dust and re-emitted at even more shifted frequencies, which happens to some of the light from our own galaxy.

This search is extremely difficult because there are many other sources of infrared radiation. So far, this instrument has made maps of the sky using infrared light at wavelengths ranging from 0.001 to 0.3 millimeter. They have shown us the shape of the Milky Way galaxy in a striking new way (see photo above and on cover of this issue). The Earth is not located on this map because it is a map of the surrounding sky. We have also made maps that show the interplanetary dust. This dust is the debris from the asteroids that formed and then collided with one another between the orbits of Mars and Jupiter. Some of it also comes from the remnants of the comets that remain from the formation of the Solar System 4.5 billion years ago. Both the Milky Way and the interplanetary dust are emitting light at the same wavelengths where we think we may detect the first galaxies. We are now busily calculating how much comes from each source so we may subtract it and deduce how much light must have come from the most distant early galaxies.

What does all this mean for science? It is of fundamental importance to understand the nature of matter, and we have strong evidence from the COBE satellite that something crucial is missing from our understanding—the invisible dark matter. Another great hope is to understand the relationships among the four forces known to physicists:
the strong and weak forces, the electromagnetic force and the gravitational force. We already know that the electromagnetic and weak forces are really just different aspects of a single more basic force, two sides of the same coin, and there is excellent progress being made toward unifying them with the strong force too. The Big Bang should have been an event in which all these forces acted under extreme temperatures and pressures to generate everything in the Universe.

The structures discovered by the COBE have much to tell us about this singular event that formed our Universe. The DMR maps reveal the imprints of primordial structures on the cosmic background radiation when the Universe was about 300,000 years old. The structures in these maps were much larger than 300,000 light years across at that time. Thus even movement of matter and energy at the speed of light could not have formed or changed these structures significantly. They are truly primordial, in every sense of the word.

The only way we know how to account for such enormous structures is through the process of inflation—the engine that drove the formation of space-time and caused the universal expansion. We can hypothesize that when the four forces were united the Universe existed in a different state where space-time was very substantial—unlike its condition today. If space-time itself had significant energy density, then its pressure would have been negative, causing the Universe to expand at an exponentially increasing rate. A small region less than a trillionth the size of a proton would have expanded in a tiny fraction of a second to become much larger than 100 meters across. Very small quantum-mechanical fluctuations in this region would have been stretched to macroscopic sizes of cosmological consequence.

Such small fluctuations from the very birth of the Universe may have supplied the seeds from which galaxies, clusters of galaxies and larger-scale structures (such as superclusters) began forming. This transcendent idea links together the microscopic world of particle physics with the macroscopic world of astronomy and cosmology—the unification of forces with the origins of space-time and its contents.

A Surge of New Experiments

COBE CONTINUES TO PRODUCE significant new scientific results, but it is already clear that its voyage represents a watershed in the study of the heavens. The detection of variations in the cosmic background radiation by its Differential Microwave Radiometer (DMR) has stimulated a great surge of new work.

Confirmation of these variations was announced in December 1992 by an MIT group headed by Stephen Meyer (now at the University of Chicago). Using supercooled bolometers as detectors, their balloon-borne experiment viewed about 25 percent of the sky in a heart-shaped pattern. Detailed comparisons of the MIT and DMR data showed that both experiments observed the very same structures. The fact that the effective bolometer frequency was nearly three times that of the DMR bolstered confidence that the signal was indeed genuine.

The Tenerife experiment, which searched for variations at an angular separation of 5 degrees was done by British and Spanish astrophysicists with equipment placed on a mountaintop in the Canary Islands. They appear to see the same bumps and valleys as COBE, but over a much smaller area of the sky.

These experiments tell us about primordial density fluctuations but correspond to larger scales than any structures yet observed in the heavens today—even larger than superclusters and the famous Great Wall, which stretches hundreds of millions of light years across the sky. The search for seeds of structures on these “small” scales has recently become the focus of intense activity. The Berkeley Center for Particle Astrophysics bolometer experiment MAX, which is sensitive to temperature variations at an an angle of 1/2 degree, has made four balloon flights and found evidence for anisotropies in two regions—but at magnitudes differing by more than a factor of 2.

Several groups report temperature variations at the $10^{-5}$ level—just what is needed for the formation of structure through gravitational infall. But these results currently differ in magnitude by factors of 2 to 3—right in the range needed to distinguish among various models of dark matter and structure formation.

A new generation of experiments with greater sensitivity is currently in preparation or under study. The European Space Agency, for example, is considering a proposal from a large group of scientists led by Renato Mandolesi of Bologna and the author to launch the Cosmic Background Radiation Anisotropy Satellite (CORAS), which would map large regions of the sky with half-degree resolution and at sensitivity of a part in a million.
The FUTURE of SCIENCE in RUSSIA
by SERGEI P. KAPITZA

A prominent Russian physicist suggests new directions for science policy in his country.

THE MOMENTOUS CHANGES of the last few years in Eastern Europe and the former Soviet Union will have long-lasting effects on the political, economic and social conditions of much of the world. At a time when even the borders of these countries are changing, it is difficult to expect much attention to the present conditions and future development of science. But if we take a longer and perhaps a more detached view, the future of science in Russia can be seen to be intimately connected with these changes. In such a more distant perspective, science itself will become a crucial factor in the new liberal and democratic world.

Adapted from an article to be published in World Science Report 1993, available in early 1994 from UNESCO Publishing.
The most noticeable feature about the present conditions of Russian science is that most of the state support for science is gone—not only because of the great economic crisis that has hit the country, but also because the country is going through a profound reconsideration of the proper role of science. Under the “ancien régime” the hard sciences were to a great extent subservient to the military effort, which over the decades had contributed to the buildup of a fearful system of armaments. From nuclear weapons to rockets and guided missiles, ships and planes, guns and tanks, science determined the power and sophistication of the armed forces and weapons of mass destruction.

Those who were in charge of the large military-oriented programs were initially generous in their support of science, especially fundamental science. There was an understanding of the overall significance of scientific culture, which is necessary to sustain the high level of development needed by a global power operating on a world scale. But during the last 20 years there has been a systematic decline in the support of what is called Big Science. No large accelerators or research reactors have been commissioned, for example, in spite of promised support. The ambitious space program has also lost much of its gusto. A large fleet of research ships is now stranded because of lack of funds. With the collapse of the Soviet state, the demise of communism, and a marked drop in industrial production, hard science has lost most of its bearing and support.

The soft sciences are in even greater disarray, for the whole system of ideas they served has disappeared. Today literally tens of thousands of teachers of political economy, Marxist philosophy, and the history of the Communist party have lost their jobs as the very substance of their studies has evaporated.

In the Soviet Union the main body that determined the policy and high status of science was the Academy of Sciences. Among its members were many scientists of great distinction. Unfortunately, during the years of decay its high standards were often sacrificed for the sake of political appointees. A marked decrease in the standards of the Academy occurred when the newly formed Academy of the Russian Federation merged with the Academy of Sciences of the former Soviet Union. Right from the start the Academy, the Establishment of Soviet science, associated itself with those who were opposed to change, be it the “Perestroika” of Gorbachev or the reforms of Yeltsin. The conservative policies of
the scientific establishment led to a deep split in the academic community that culminated in the organization of a number of alternative scientific societies, new academies and even universities. Of these one should note the Academy for Natural Sciences, which has strived to unite scientists from a broad spectrum of institutions.

At present the funding for science has been cut. Reportedly funding of the Russian Academy of Sciences with its huge network of institutes, libraries, observatories, publishing houses and expeditions has fallen by a factor of 3 to 5 in real terms. Due to such drastic cuts in funding and the availability of new opportunities in business, many are now leaving science. This happens mainly with the younger and more dynamic generation. Probably a quarter of all scientists will leave science, another quarter may leave the country and of those left a quarter could retire. It would not be surprising if Russia were left with only 20–25 percent of all scientists now actively engaged in research.

We have not yet reached this stage, but one has to keep this trend in mind. These changes are not only imminent but even necessary, however painful and drastic they may be. Science in the Soviet Union was overstaffed and top heavy. For years it tried to develop as a self-contained entity, to a great extent isolated from world science—another reason for change now that the country has opened up. These conditions must be recognized in any attempt to reformulate the national science policy of Russia, to redefine its new priorities. To understand the modern demands and challenges, we should look at the complex interconnections of science with society and the economy.

Let us first consider fundamental science—science pursued for the sake of knowledge. Basic science is motivated by the deep human need to understand and interpret the world surrounding us. On the other hand, applied research is pursued because of its inherent usefulness. Today the profound connections of fundamental science with culture are generally recognized, although these tenuous ties are strained by growing anti-scientific and anti-intellectual forces. The applied sciences, intimately linked with industry, have direct effects on technology and economic development. While it takes decades—even a hundred years—to develop a tradition in fundamental science and ten years to develop
a field of applied research, an industrial enterprise can change to a
new product or model in a matter of a year.

For example, the fundamental discoveries in quantum mechan-
ics led in a generation or two to the invention of the transistor and
then the laser. A century earlier the theory of electromagnetism provided the under-
pinnings for the development of the electric industry, followed by radio, television,
s radar and satellite communications. Today we witness the remarkable impact of dis-
coveries in modern genetics and molecular biology upon the practices of medicine and
agriculture. Fundamental science in close cooperation with modern technology has
had a continuous and very deep effect on our understanding of the world—and on
our well-being and civilization.

The long-term factors that affect the development of fundamen-
tal science can be seen in that only now, almost fifty years after its
defeat in World War II, Germany has regained its prominent posi-
tion in science. In the newly emerging countries of Asia and the
Pacific, their industrial impact and their impact in applied sciences
is far greater than their contribution to fundamental research. The
difficulties of establishing a national or regional tradition of basic
research has even led people to suggest that such attempts should
not be made, because this kind of research is now pursued as a global
intellectual enterprise. But this trend does not mean that in a
developed scientific community fundamental research should not
be pursued, for it is part and parcel of our modern culture and
contributes directly to higher education. Any discontinuity or
severe stoppage of the development of science in Russia may have
long-term effects; it should be of immediate concern both for the
scientific community and the country as a whole.

The current economic reforms in Russia heavily affect industry
and to a great extent applied research. The marketplace laws of
supply and demand can and should determine new patterns for
development. We can expect rapid and profound changes here that
will also affect the huge military-industrial complex of the former
Soviet Union. To a great extent, the transformation to a market
economy is also a change from the military-oriented command
economy of our recent past.
In this state of turmoil, fundamental science has lost its way in Russia. One cannot and should not operate fundamental science by market forces. However important the responsibilities of scientists may be in the way they conduct their business, no short-term bookkeeping can really estimate the benefits of fundamental research. If one wants to reckon its impact, estimates should be made on a long-term basis—encompassing at least decades. The balance is heavily in favor of science, because the power of knowledge has an immense multiplying factor. While inventions, the result of applied science, can lead to major gains, the discoveries of fundamental science open entirely new fields of human endeavor. That is why fundamental science deserves support by state and society.

Fundamental science has a profound effect on our civilization due to the extent to which the next generation is exposed to its new ideas and concepts. In light of this fact, a new long-term contract between science and society must be negotiated and pursued because of the new set of social conditions in the countries of the former Soviet Union. Formerly serving the grandeur of the country, expressed in large and seemingly impressive projects or in sheer military might, Russian science must now redefine its mission.

Then what should we do with Russian science? First it should be integrated much better with the universities—in training the next generation of scientists and engineers, doctors and lawyers, teachers and statesmen. This new generation will be the real instrument of reform, our main hope for the future. The continuity of teaching and training this next generation should have the highest priority both for science and the country.

At all times of drastic social transformation, when a major challenge to the existing system appears, new educational institutions are founded. During the French Revolution, for example, the Grande Ecoles were established. After the Russian Revolution and under the pressure of industrialization in the 1930s, the present system of technical institutes was set up—institutionalizing to a great extent the separation of research and teaching. After World War II the challenges to develop high technology and armaments led to the founding of the now prestigious Moscow Institute for Physics and Technology. It became a very successful, although singular example of uniting teaching and research. It put special emphasis on educating future scientists and engineers with a thorough course of
physics and mathematics, taught by the best talent available. Today this experience can and should be the springboard for new departures in tertiary education. One important development has been the rise of teaching departments at a number of science centers around Moscow, so as to expand the graduate training capacity of these specialized scientific institutes.

More than ever Russia has to sustain and develop its tradition of higher learning. Apart from oil and gas, our brains are probably our principal asset. Among the things that were great and good in the Soviet system, we should certainly count education, the respect for knowledge, and the status of science—which carried on and fostered a long-standing tradition in Russian culture. Now Russia has to learn how to employ this great major asset for best advantage. Here is where we can forge ties between the newly emerging entrepreneurial class and science and technology. The communist regime did not really manage to develop the intellectual potential of society as a dynamic and progressive factor. The Marxist idea of the supremacy of the working class—interpreted in a dogmatic way, subservient to the political interests of the ruling party—contributed to the collapse of the Soviet regime. In no field was this so obvious as in computer science and information technology.

Unfortunately progressive attitudes towards science and technology are under great pressure. A successful profiteer becomes a millionaire in a day, then squanders his money in a night. A taxi driver gets ten times more money than a doctor or a university professor. Bureaucrats, even of the Academy of Sciences, are much better off than practicing scientists. Science has disappeared as a cultural phenomenon; science and technology have vanished from Russian newspapers and TV, from the public mind. Anti-scientific trends are rampant; astrologers and quack doctors flourish. To a great extent these are symptoms of the profound crisis through which Russia is passing.

These developments also reflect a new resentment of science. Have not the Marxists said time and again that theirs is the only true scientific system of ideas, on which to build a Brave New World? Have not the scientists, especially the physicists, promised bliss from nuclear energy, which culminated in the Chernobyl disaster?
Have not other less prestigious projects failed to deliver—the expectation of fusion energy in the immediate future or the expected arrival of room-temperature superconductor technology? How should we now account for the failures of space exploration, after the initial spectacular successes? And what do we do with the mess in our environment?

But Chernobyl was more the result of social and psychological unpreparedness of Russian industry and society to enter the nuclear age, rather than that of defective technology. And the promises of thermonuclear energy and room-temperature superconductors were made by the world scientific community. We should admit that such issues should be addressed not only to Russian science but to the broader global constituency of scientists. For in a certain sense the crisis of Russian science is a phenomenon that reflects in an amplified way some of the critical problems of the entire world.

SECOND PRIORITY OF RUSSIAN SCIENCE policy should be to integrate its science into world science. In applied science this will occur in due course as our industry becomes gradually integrated into the world economy. We can only hope that in this process Russia will cease to be an exporter of raw materials and armaments, and will manage to develop its high-technology and knowledge-based industries for more benign purposes.

The integration of Russia's fundamental science into the world at large cannot happen immediately, for its separatist traditions are deep set, having been cultivated for decades. Here again our foremost priority should be in providing opportunities for the next generation to become involved in world science. At the beginning of Gorbachev's reign seven years ago, there were at least 25,000 Chinese students in the United States. Discussing this matter with our Ambassador in Washington, I showed these figures to him and asked him how many Soviet students and scientists were then in the U.S. Less than 100, was his answer. This message was delivered to Gorbachev, whose action was immediate and supportive, but hardly anything happened. Now, in spite of Tiananmen, there are reportedly 40,000 Chinese students in the U.S. and still only a few thousand Russians!

Today much is said of a brain drain. But in spite of all the publicity, the figures are not as yet alarming. The efflux of scientists should be seen partly as a way of normalizing the connections and
ties of Russian science with the world at large. We have to compensate for decades of self-imposed isolation. In the statistics of international exchange, we can recognize these tendencies in Russian science. With the stabilization of the political situation and a redefinition of priorities, the brain drain will hopefully cease and scientists will return to Russia.

What really hurts is when key members of the academic community leave, when books on science cease to be published, and when the continuity of research and teaching is lost. For example, the revised volumes of the world-famous *Course of Theoretical Physics*, by Landau and Lifshitz, have been stranded for over three years in the Publishing House of the Academy of Sciences for lack of funds. Many senior members of that remarkable school of physics have also left, and the continuity of an internationally recognized tradition may be broken.

We should certainly have nothing against the worldwide traffic of scientists. But when a great professor leaves Russia, nobody ever thinks of paying the institution that for many years trained and nurtured this scientist of distinction. Compare this with the millions paid for the transfer of an outstanding athlete from one team to another. Can we expect in such circumstances to generate in the public mind a positive image of science or support for the sources of such very special talent?

**Exchange and Travel by Scientists Associated with the Russian Academy of Sciences**

<table>
<thead>
<tr>
<th>Purpose of Travel</th>
<th>1991</th>
<th>1992</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attend conferences</td>
<td>6956</td>
<td>5058</td>
</tr>
<tr>
<td>Exchange collaboration</td>
<td>1506</td>
<td>628</td>
</tr>
<tr>
<td>By invitation</td>
<td>8451</td>
<td>7357</td>
</tr>
<tr>
<td>Expeditions</td>
<td>329</td>
<td>112</td>
</tr>
<tr>
<td>Contracts (long term visits)</td>
<td>467</td>
<td>881</td>
</tr>
<tr>
<td>Accompanying persons</td>
<td>1262</td>
<td>1597</td>
</tr>
<tr>
<td>Total</td>
<td>18,971</td>
<td>15,633</td>
</tr>
</tbody>
</table>

*The figures in the table were provided by the Russian Academy of Sciences, which accounts for a tenth of all scientists. They illustrate the prevalent trends, especially in the decline of activities in fundamental science.*

Since the Age of Reason science has promised much. Now it seems that the Day of Reckoning has arrived. It is probably high time that the world scientific community reassesses and redefines its priorities. In Russian science policy, this challenge must be taken much more seriously than ever before. Can such new priorities be defined by the old and conservative academic Establishment,
or are new leaders to emerge? To what extent can the management of science be left to scientists themselves? Can one paraphrase the old maxim that war is too important a business to be left to the generals?

I am not trying to advocate the administrative control of science. In Russia we have had a lot of very unfortunate experience with such means of governing science, with disastrous consequences. But today's critical conditions do demand new ways of resolving the complex issues facing our scientific community. To what extent such decisions could be assisted by international advice is a significant issue. External authority could probably help to overcome the vested interests of the "old boys' club" that until recently—and not without some success—has been running Soviet and now Russian science.

Many question the authoritarian manner in which much of Soviet science was governed and want to extend the new democratic concepts to administering science. This is not an easy matter, but one that must be faced and resolved in one way or another. Probably a new government agency to administer funds, similar to the U.S. National Science Foundation, should be attempted, separating advice from decision making. Of great importance for such an agency would be to execute a new Russian science policy that should be worked out by both the scientific community and the parliament. Such a development can be expected only after the appearance of a new legislature.

The help and assistance recently provided by the world scientific community is worthy of note. Much has been done to provide for the continuity and availability of scientific publications, as most library funds in Russia and the former Soviet republics have been cut off. Very welcome is the publication and distribution at a reduced price of "Nature Monthly," which keeps open a significant channel of communication with world science. Of great help are grants to individual groups of scientists and the support of schools of excellence. Funds for travel are important—especially for young scientists. Of all the foundations supporting Russian science, George Soros' International Science Foundation should be applauded. These contributions are significant at a time of change and frustration, when the fragile body of science can easily collapse.
But such means cannot sustain a long-term science policy. Some even claim that this help may undermine the structure of Russian science—or rather what is left of it. In providing support for individual scientists and science projects, it is very easy to upset the all-important balance between a scientific group and its host, the institution that provides much of the infrastructure and intellectual tradition of a good center of research. Of all centers of study, the universities have more permanence than any other institution. Today we see how mission-oriented centers of research, which were once considered centers of excellence, now have great difficulty in finding support and a socially acceptable meaning for existence.

In the immediate future, the greatest losses will be sustained by experimental research because it is much more costly than purely theoretical work, which always was the stronger side of Soviet science. I have already mentioned the long-term decline in development of Big Science. Should Russia continue to support these large laboratories, which by now have lost time, staff and much of what they had to offer—be it high energy particle accelerators or modern spacecraft? On the other hand, large-scale scientific projects should be pursued for their significant contributions to national goals and to the international scientific community. Here again new priorities have to be defined. Unfortunately the pressure of former commitments and powerful vested interests make it all the more difficult to make the right decisions and carry them out.

Owing to the lack of hard currency, the international obligations of Soviet science taken over by Russian science are now all on hold. International financial assistance and help would be most welcome to meet these payments and debts during a time of transition. Funds currently offered for technical assistance by international institutions could be allocated for the support of research by Russian scientists who cannot at present find sufficient means.

At times of difficulty and strife, moral factors become important. Of all the reasons for the loss of courage and morale by Russian scientists, the worst is probably the lack of appreciation of their work and even their role in society. The change in values now going on in Russia has had a significant effect on the attitudes of the young generation. Anti-intellectual trends now openly expressed in the media, coupled with expressions of rampant nationalism and anti-Semitism, add to the frustration and despair—especially among the young and most promising generation at the post-graduate and post-doctorate level, inducing them to leave science or the country.
Such moral issues and the public attitude toward science matter. Recently, on the initiative of the "Academia Europaea," 20 prizes were granted by an international jury to young scientists of the former Soviet Union, supporting them at a decisive point in their careers. One of the responsibilities of the older generation and of the world scientific community is to recognize this mood. The state of the body may be repaired by money, but its spirit is much more elusive and crucial for the success and future of science.

Of special concern are nuclear weapons laboratories, where some of the difficulties of converting the research branch of the military-industrial complex can best be seen. Right from the beginning, these institutions were off limits in terms of money and resources. Off limits also in terms of contacts not only with world science, but even with most of their colleagues at home. Now that they are open to the world, they have to find new ways of employing the very special talents of their scientists and engineers—the great resources at their command. This is no simple matter, due to the great compartmentalization of these mission-oriented research establishments. And the average age at these institutes only makes change even more difficult. I only hope that this challenge and the ensuing changes do not lead to an intellectual dimension in nuclear proliferation. The professional responsibility and integrity of scientists is ultimately the principal factor in future world security.

The break up of the Soviet Union into a number of independent republics has led to completely new conditions for the development of science. After the euphoria of independence, when scientists in these republics were often the most vocal spokesmen for the new freedoms, we must now face the facts of life. If support for science is low in Russia, things are often worse in many of these now independent countries, and much rethinking and reorganizing has to be done. Professional ties with Russia are now gradually being repaired. Much remains to be done to redefine scientific connections in the Russian-speaking world—in training students, granting degrees, publishing books and journals, organizing and hosting conferences, and supporting the infrastructure of science, now split across this new map of the former Soviet Union and (to a certain extent) Eastern Europe. Science can and should become an integrating factor for these states, and new international professional organizations have a special role to play here. To what
extent these organizations will manage to unite scientists in parts of the world so divided by nationalism remains to be seen.

Although each of these countries has its own specific problems, many of these arose from the way things were organized in the USSR and were copied by its former allies. The crisis of the Academies is probably one of the most common features. The East German Academy of Sciences has been disbanded, for example, and in other countries profound changes are necessary. Of growing importance is to channel funds through various foundations directly to specific projects and individuals rather than to their supporting institutions.

Future science policy, as well as policies in education and technology, will be determined by national priorities. However varied the conditions in these countries, the case of Russia has special meaning. It is here where the challenge of reform is most acute—not only because the policies that must change were pursued much longer than anywhere else, but also due to the sheer scale and complexity of this society. However painful and even traumatic these changes are, they must be viewed in the context of a profound social transformation, the true magnitude of which is yet to be determined.
Intense X-ray beams from storage rings can be used to produce high-resolution images of the human heart.

METHODS DEVELOPED DURING THE past century for the diagnosis and the treatment of disease have been closely linked with technical advances in research on elementary particles. Among the examples that immediately come to mind are the discovery and rapid application of X rays to medical diagnosis in the late nineteenth century; the use of energetic gamma-ray and electron beams for tumor therapy; the development of pion therapy at Los Alamos and of heavy-ion therapy at Lawrence Berkeley Laboratory, and more recently, the development at Fermilab of dedicated proton linear accelerators for cancer therapy. Soon the electron storage ring may enter the pantheon of medical research tools, owing to the fact that circulating electrons emit highly collimated X-ray beams that are millions of times brighter than conventional sources.
The first published human radiograph, thought to be the hand of Anna Bertha Ludwig Roentgen, Wilhelm's wife. The dark blob is probably her ring.

The discovery of X rays by Wilhelm Roentgen nearly one hundred years ago set the pattern for the rapid application of particle physics research to medical imaging. An apparently new particle called the X ray was discovered, interpreted and commercialized within the span of a single year. On November 8, 1895, Roentgen accidentally discovered that barium platinocyanide, a well-known fluorescent material, glowed brightly when situated next to an energized Crooke's tube [the forerunner of the modern cathode-ray tube]. Recognizing that he was onto something quite revolutionary, he sequestered himself in his shade-drawn laboratory, leaving only to eat his meals and sleep a few hours each night. By December 28 he had determined many of the important properties of X rays and submitted them for publication. Among them were the relative transparency of light elements to X rays and the relative opacity, gram for gram, of the heavy elements. Most astonishingly, Roentgen published the first radiograph of a human organ, reputed to be his wife's hand. For his monumental discovery he was awarded the very first Nobel Prize in physics in 1901.

The human radiograph electrified the medical community. Within a few months, in early 1896, diagnostic radiography became a nearly routine method for visualizing skeletal and other injuries to the human body. As X-ray sources improved in reliability and intensity, and as detectors improved in sensitivity, it became possible to visualize tumors and other diseases and injuries that alter tissue density or bone structure.

More recently, a number of new techniques have been developed, which in some cases have replaced—and in others, supplemented—the method of X-radiography. Among them are the methods of ultrasound, magnetic resonance imaging (MRI), and positron emission tomography (PET). With the advent of digital image processing techniques, X rays themselves yield far more information, via the method of computed tomography. In this method, a series of X-ray exposures are taken as the subject [or source] is rotated by 180 degrees. Under favorable conditions, three-dimensional density profiles of the subject can be obtained, offering astonishing detail and clarity.

One important disease that has eluded noninvasive diagnosis is coronary atherosclerosis, the deadly blockage of the 1–3 mm diameter vessels that convey oxygenated blood to the heart muscle. Virtually all adults, particularly women after menopause and middle-aged men, suffer from this accumulation of cholesterol-rich plaque on the interior surfaces of the coronary arteries, which restricts the flow of blood to the heart muscle. More importantly, in the vicinity of such restrictions, a thrombus or clot may suddenly develop which completely occludes the artery leading to a heart attack. In most people this is the very first definitive symptom of heart disease and often the last; only half of the individuals who suffer a heart attack survive.
Treatment is now available for patients with coronary atherosclerosis. This includes bypass of a diseased coronary artery segment with a vein or arterial bypass graft. In addition, coronary arteries can be dilated via the insertion of a catheter-borne balloon. More recently a small burr-tipped catheter device, called the rotoblator, has been developed that disintegrates the deposits, with the resultant pieces being small enough to pass through the capillary system. Finally, this disease can be reversed to some extent by dietary and lifestyle changes, as well as by drug therapy.

Unfortunately, however, the non-invasive diagnostic techniques [exercise testing while monitoring the heart via an electrocardiogram or while imagining the heart muscle using positron emission tomography] are not entirely reliable. An invasive method, coronary angiography, requires the puncture of a major artery followed by the introduction of a catheter under fluoroscopic observation into the artery and subsequent threading of its tip, via the aorta, into one of the coronary arteries. About 35–50 milliliters of an iodine-bearing contrast agent is then injected into the artery, whereupon an X-ray motion picture is made, using a conventional rotating-anode X-ray generator.

This procedure, although nowadays common [over one million angiograms performed each year in the United States], is not without hazard. There are serious complications [heart attack, stroke, death] in about 1 out of every 1,000 cases, and minor complications occur much more frequently. These complications and the radiation dosage [about 35 rads to the skin] disqualify the approach as a serial method in research or as a screening procedure. And so heart disease, which is the single greatest cause of death among adults in the industrialized world, and which is eminently treatable, generally eludes early diagnosis. By the same token, research into the progression of heart disease, and in the efficacy of new treatments, is stymied by lack of diagnostic procedures.

Why are we unable to visualize coronary arteries with any of the remarkable technologies enumerated above? The problem arises from the motion of the arteries because of the heartbeat and the chest motion due to the patient’s breathing. Exposures must be made within 10 milliseconds or so, and with spatial resolution better than 1 millimeter. Conventional X-ray sources are too weak to provide the required signal quality for short exposures if the contrast agent is administered, say, into a peripheral vein. Finally, other objects within the patient, such as the ribs and the spinal column, introduce confusing artifacts, complicating the interpretation of the images. Non X-ray methods are also hobbled by time and spatial resolution limitations.

A possible solution to this dilemma lies in the physics of the contrast agent. Within weeks after the discovery of X rays, Roentgen demonstrated that, gram for gram, heavy elements are more opaque to X rays than light elements—at all wavelengths. It was not until the work of Maurice de Broglie in 1914, however, that the details of the absorption spectra of the elements were elucidated. De Broglie demonstrated that the photoelectric effect gave rise to steplike features in the rate of X-ray absorption, the steps occurring at precisely the energies required to eject electrons from inner shells of the atom. In the case of iodine, for the innermost, or 1s shell, the ionization energy is about 33,160 electron volts, or 33.16 keV. As the X-ray energy rises above this level, there is a six-fold increase in the absorption of iodine [see graph on the next page]. Bone and soft tissue, by comparison, have no comparable structure at such high energies, as the innermost electrons are bound much more weakly [about 3.5 keV in the case of calcium and a few hundred electron volts in the much more common carbon, nitrogen, and oxygen].

The first published account of a method to take advantage of this structure was made by Bertil Jacobson of the Karolinska Institute in 1953. He suggested that greater sensitivity to heavy contrast agents such as iodine could be achieved by taking two successive radiographs of the patient, with the X-ray beams bracketing in energy the 1s, or K-shell, discontinuity. A point-by point subtraction of the two images would, in principle, yield an image only of the contrast agent—and thus of the patient’s vascular system.

Unfortunately, there are great practical problems in achieving intense, monochromatic X-ray beams over a large field of view. As the radiation from a conventional generator is emitted nearly isotropically, diffraction-style monochro-
Mammary generators are impractical. Filters have not worked well either. What has been successful for relatively stationary objects such as the arteries in the neck, however, is a related method called digital subtraction angiography, in which successive images are taken before and after venous injection of an opaque dye. This method is commonly used to diagnose diseases of the large blood vessels.

MeanwhiLe, the High-energy physics community had been witnessing the growth of the seemingly unrelated technology of electron-positron colliding beam storage rings. Originating in the late 1950s and early 1960s at Stanford, Frascati and Orsay, these machines have culminated in the behemoth LEP storage ring at CERN in Geneva. Electrons and positrons circulating in this machine radiate intense beams of highly collimated synchrotron radiation at a characteristic energy of about 50 keV, most of which strikes and heats the water-cooled vacuum chamber walls. Lower energy machines, such as SLAC’s SPEAR, radiate a respectable 56 kW of power at a characteristic X-ray energy of about 5 keV. SPEAR now serves as a dedicated synchrotron radiation source known as the Stanford Synchrotron Radiation Laboratory. Over thirty storage rings are currently in operation or under construction as dedicated synchrotron radiation sources.

In the heady atmosphere of the late 1970s, Edward Rubenstein of Stanford Medical School had a series of discussions with Barrie Hughes of Stanford’s High Energy Physics Laboratory, in which they considered using synchrotron radiation to overcome the X-ray source problem. SPEAR was soon to be dedicated half-time to synchrotron radiation research, and monochromatic X-ray beams were available for the asking (i.e., the submission of a convincing proposal). Wiggler magnets had just been invented, boosting the intensities of hard X rays by several orders of magnitude.

Conventional X-ray sources generate a continuous spectrum of radiation through the collisions of energetic electrons with heavy nuclei. Known as bremsstrahlung ("braking radiation"), this process yields roughly isotropic X rays with energies up to the electron’s kinetic energy. But it is inherently inefficient, with 99.8 percent of the electron’s energy being dissipated as heat in the anode. The practical limit of such sources is determined by the conductivity and melting temperature of the anode.

Synchrotron radiation, by contrast, emerges tangentially from electron storage rings in copious quantities, by virtue of the transverse acceleration imparted by deflection magnets. What’s more, the X-rays are collimated within a pancake with a vertical opening angle of about 0.01 degree, making them very easy to manipulate with reflection and diffraction optics. Rubenstein and Hughes were aware that line-like beams of highly monochromatic radiation were available at SSRL, and that it was easy to change the wavelength. Why not attempt to construct images by taking successive digital radiographs below and above the 33.16 keV absorption edge of iodine, and then subtract them?
The idea was so appealing that Stanford’s Robert Hofstadter, who had been working with Hughes on a SPEAR experiment at the time, joined the collaboration, along with his graduate student John Otis and Research Associate Herbert Zeman. They tested the concept using lucite blocks with iodine-filled cavities and obtained radiographs of surprising clarity. Concentrations of contrast agent comparable to what could be expected in peripheral venous injections of humans were easily visible, and artifacts from simulated bone were easily cancelled.

Having completed this first proof of principle, the group turned to the much more challenging problem of imaging live subjects. The motion of the blood vessels arising from the patient’s heartbeat and breathing clearly required very short imaging times—a hundredth of a second or less—to minimize blurring. The number of photons then available would be inadequate to image the entire field of a human heart in such a short time. But if a 1 mm high, 120 mm wide line image could be obtained in this interval, the patient could be scanned vertically by seating him in an elevating chair. This idea led to the development of a crystal monochromator (by Nelson Hower of SSRL and the author) that could be switched rapidly from below the iodine K-absorption edge to above it. This feat was accomplished by diffracting the line-like synchrotron radiation using a large, nearly perfect silicon crystal. The silicon diffracts 33.16 keV X rays at an angle of 6.8 degrees, and tilting it by 0.01 degree varies their energy by 100 electron volts, easily bracketing the iodine K-edge. A second oscillating crystal, precisely parallel to the first crystal, renders the output beam parallel to the incoming beam, as in a periscope. With this device, our group was able to obtain good images of the coronary arteries of live dogs.

The periscope concept worked well for narrow objects, but it proved to be too difficult to keep the crystals parallel for a field of view as wide as a human heart, roughly 12 centimeters. Accordingly, our group developed a two-beam geometry, in which two crystals intercept the lower and upper halves of the beam, reflecting wavelengths that bracket the iodine K-edge. Because of a tiny difference in the angles involved, the two beams (after intercepting the subject) converged about three meters beyond the crystals, where a position-sensitive X-ray detector was situated. A rotating cam between the monochromator and the patient alternately shuttered the high and low energy beams, with a period of about 10 milliseconds. To obtain a two-dimensional image, the patient was again raised or lowered by means of a motor-driven chair, elevating at a rate of about 12 centimeters per second (roughly that of a slow elevator). Thus a "flash" picture of a single plane of the patient could be obtained.

Medicine, high-energy physics and synchrotron radiation research all converged in May 1986, when we conducted the first human trial. All other research at SSRL was temporarily suspended as the patient, a 52 year old volunteer from the Palo Alto Veterans’ Hospital, threaded his way past arrays of physics equipment entirely unrelated to our goal. To the...
An artist's rendition of the angiography experiment showing the circulating electron beam, wiggler magnet X-ray source, diffracting crystals, a patient seated on a computer-controlled chair, and a dual position-sensitive detector.

delight of the researchers, elements of his coronary circulation were visible in the very first images.

The next obvious improvement in the system was to eliminate the cam-like shutters, and record both beams simultaneously with a pair of linear position-sensitive detectors. This approach improves the signal rate by a factor of 2.4 and greatly simplifies the mechanical arrangements, at the price of one additional detector. Subsequent human trials conducted at SSRL with this improvement in 1987 and 1989 taught us more about timing, contrast concentrations, and patient orientation.

TWO PROBLEMS temporarily interrupted the program at this point. For one, SPEAR operations were severely curtailed during the period 1988–1991, owing to the unavailability of electrons from the two-mile linear accelerator, which was being transformed into a linear collider facility. The second problem was even more challenging. In a way, the Stanford monochromators were actually too good, because they selected such a narrow band of energies that the photon flux was just shy of what was required to achieve satisfactory signal-to-noise ratio.

The solution to the first problem was easy. The angiography program was relocated to Brookhaven National Laboratory, where scientists at the recently-commissioned National Synchrotron Light Source were laying the groundwork for their own program in this field. With a six-pole superconducting wiggler magnet to generate the X rays and a suite of rooms dedicated to the program, the studies could continue without serious interruption.

The solution to the second problem was achieved by means of an elegant invention devised by Peter Siddons, Pecca Suorri, and William Thomlinson of Brookhaven. They developed a broadband monochromator system by making use of transmission diffraction from thin, bent silicon crystals, rather than reflection diffraction from thick, flat crystals [see box on the next page]. A number of human trials have been done using this system at Brookhaven since 1990. In these images much of the coronary circulation is easily visible; defects in the coronary circulation can be readily identified.

The conventional method of coronary angiography results in radiation exposure to the patient of roughly 35 rads (one rad corresponds to the absorption of 100 ergs per gram of bodily tissue) primarily to the skin. This dosage is required in conventional radiography because a sixfold excess exposure is needed to overcome the background due to X rays scattered by atomic electrons. By contrast, the highly collimated geometry that is employed with synchrotron radiation eliminates this background. Trials thus far have

The first synchrotron radiation coronary angiogram recorded on a human subject, taken at SSRL in May 1986. The patient had previously undergone two angioplasties of a lesion in the right coronary artery, designated RCA. The internal mammary arteries (IMA), aorta (AO), left anterior descending coronary artery (LAD) and left ventricle (LV) are clearly visible in this image.
A coronary angiogram made at SSRL of a patient who had previously undergone coronary artery bypass surgery. The left internal mammary artery (LIMA) is a bypass graft to a diseased left anterior descending artery (LAD). Two vein bypass grafts (VBG) are inserted into a marginal branch of the left circumflex and into the right coronary artery. Also evident are platinum surgical clips (CL), the pulmonary vein (PV), the left ventricle (LV), and sternal wires (WS).

resulted in radiation dosages to the patient of about 5 rads per frame, using about the same amount of contrast agent, but injected instead into a central vein. This dose is expected to decrease as we learn more about the optimum patient orientation, iodine concentration, delay time between injection and exposure, and other variables.

Thus far the program has focused on proving the feasibility of this method, although in fact medically useful information has been obtained. The next step is to study a sufficient number of patients to compare the results quantitatively with the well-established invasive method. If these tests are successful, synchrotron radiation may become a powerful tool for medical research. Patients who are treated by various methods, including bypass grafts, angioplasty, rotoblator, or even drugs or diet changes, could be studied repeatedly without the risks associated with conventional angiography. It is not too far-fetched to imagine small storage rings (about 2 GeV) with superconducting wiggler magnets that would be dedicated to medical imaging research in major medical centers. Already, storage rings of this class have been manufactured for basic research by British, American, and Japanese firms, and the costs are coming down rapidly. Such facilities could then be applied to other diagnostic problems, such as disorders of the arteries of the brain and of the skeletal system, which continue to elude existing technologies.

As we approach the centenary of the discovery of X rays, new sources and techniques are revolutionizing their applications. It might just be that imaging science itself will be similarly transformed, in ways that we can now barely imagine.
The XVI International Symposium on Lepton-Photon Interactions

by RAFF H. SCHINDLER

New results on top and bottom quarks highlighted the Cornell meeting of high energy physicists.

CARVED BY POWERFUL GLACIAL FORCES, the Finger Lakes region of upstate New York provided an awesome and appropriate backdrop for this year's International Symposium on Lepton and Photon Interactions. At a time when the physics of $B$ mesons is of central concern to many high energy physicists, Cornell University was a fitting host for this year's Symposium. Despite the seemingly provincial air of Ithaca, the research program spawned there over the past decade and culminating in the upgraded CESR-II storage ring and the CLEO detector, has led to Cornell's emergence as the world's premiere facility for the study of the bottom quark. It has hosted the Symposium twice before, in 1971 and 1983 and, in keeping with past tradition, the CLEO experiment contributed over 30 papers.
About 650 physicists from 46 nations attended the Symposium, held on the main Cornell campus, a short walk to the cafes and shops of Ithaca’s bustling downtown. Umbrellas appearing in each attendee’s registration packages proved to be a wise gesture by the local organizers, enabling participants to deal with the changing New York weather. In the midst of intermittent rain showers, 29 rapporteur talks spanned four and a half days. In addition to theoretical topics ranging from lattice gauge theory to particle astrophysics and superstrings, they covered a wide range of experimental results.

Many thought this would be a year of discovery, or at least a year of some surprises coming out of each of the laboratories. Fermilab seemed poised for the top quark discovery. DESY’s HERA ring had produced its first large sample of high energy electron-proton collisions. Cornell’s CESR-II had accumulated two million events near $b$ quark threshold and is in position to observe very rare decays of the $b$ quark, $c$ quark and tau lepton. LEP at CERN has samples of a million $Z$ decays and, with new microvertex detectors, also stood ready to explore $b$ quark and tau physics, as well as continuing its program of electroweak studies. Finally, the SLC at SLAC, the principal competitor to LEP, had been running steadily at the $Z$ peak since May. It might have released results on precision electroweak parameters, measured in a unique fashion with its highly polarized electron beam.

While some surprises were presented, the past year could not be characterized as one of discovery. Rather, it has been a year of further consolidation of theory, brought on by a wealth of new limits and higher precision measurements of masses, lifetimes, and branching fractions of the fundamental particles. Let me start with the top quark search, potentially the most interesting result of the year, and work my way down in mass.

We waited anxiously until midweek for the first public glimpse of data from the Fermilab Tevatron experiments, CDF and D0. While neither experiment has digested all its data nor completed its analysis, this work constitutes the most sensitive direct search for the elusive top quark. In 1989 CDF placed a lower limit of 91 GeV on the top quark mass. This year the Tevatron has run very well and CDF has logged about five times more data at a center-of-mass energy of 1.8 TeV. Also, the D0 experiment has joined in the search. Even though this was D0’s maiden data-taking run, this group managed to accumulate a sample close to three-quarters the size of CDF’s.

Pairs of top quarks ($t\bar{t}$) can be produced through the fusion of two quarks or two gluons in the protons and antiprotons that collide in the Tevatron. Each top quark then decays via the weak interaction primarily to a charged gauge boson $W$ and a $b$ quark. The experimental signature of the top quark is the unique decay products of the $W$—either an energetic electron or muon (and an undetectable neutrino), or two jets of light quarks. The $b$ quark that is also produced in the top quark decay can appear as a very distinctive jet,
or it can decay to a less energetic electron or muon. A 100 GeV top quark (just a bit heavier than the old CDF limit) would have produced about 1000 events in the D0 or CDF detectors. If it were as heavy as 180 GeV, only about 90 top quark events would be present in the sample. But the CDF and D0 detectors cannot catch every one of these events. The task of separating the remaining top quark events from the backgrounds that mask them is formidable, as each experimental collaboration now has learned.

Speaking for CDF, Paul Tipton from the University of Rochester showed three candidate top events, each with a pair of energetic electrons or muons. A top quark of 160 GeV would have yielded two events with this signature. Unfortunately, CDF expects four background events in this channel. This result leads to a slight improvement in its lower limit on the top mass, from 91 GeV to 113 GeV. In an alternate analysis using jets and leptons, a similar problem of large backgrounds arises, leaving only two events with three being expected from background. When completed, these analyses could be combined to produce an even higher limit on the mass.

The most promising and intriguing result from CDF was obtained by exploiting their silicon vertex detector to isolate the $b$ quark jets from the top decay. Having long lifetimes, $b$ quarks travel several millimeters before decaying. Since microvertex detectors have accuracies much smaller than the flight distance, $b$ quarks can be identified by looking for their decay vertices, well separated from the beam collision point. Using this information, CDF found three events, this time with only 1.2 expected background events. Two of these events are particularly clean. A 140 GeV top quark would have produced about five events with this signature.

The D0 results were reported by Nicholas Hadley from the University of Maryland. Lacking good tracking but having better calorimetry, D0 faced background problems similar to CDF’s. They found two candidate top events, one with an electron pair and one with a muon pair. With 2.7 expected background events, D0 could only set a limit of 88 GeV on the top mass.

CDF and D0 still have more data to analyze, but the material presented at the Symposium leads me to speculate that the top quark may already be in their grasp and that it will perhaps emerge when their analyses are complete. Next cycle, improvements in the Tevatron luminosity should double or triple the number of collisions per unit time, and an increase in the center-of-mass energy to 2.0 TeV will increase $t\bar{t}$ production in each collision by about 30 percent. If CDF and D0 have not reported the discovery of the top by that time, these changes will greatly enhance their ability to find it.

While the Tevatron is providing direct information on the top quark mass and on new gauge bosons, high-precision tests of the Standard Model at LEP and SLC provide an indirect estimate of the top mass. This happens through the small radiative corrections that the presence of a virtual top quark would induce in otherwise pure electroweak processes at the $Z$ resonance. Morris Swartz of SLAC presented the experimental picture of electroweak tests. Wolfgang Hollik of MPI München followed with a concise review of the detailed theoretical framework of radiative corrections, essential for their interpretation. The speakers emphasized that at the present time there are three areas of the Standard Model where there is little or no experimental information: the top quark sector, the pure gauge sector, and the scalar sector (responsible for mass generation). LEP and SLC are only now achieving enough sensitivity to...
detect the presence of virtual heavy particles in loops, pure weak radiative corrections, and the three gauge boson couplings. Through a global fit to observables such as the forward-backward asymmetries of leptons and quarks; the left-right asymmetries of the electron, muon, and tau; the fraction of Z decays into b quarks; and the Z mass (discussed below), width and production cross section; LEP obtained a prediction for the top-quark mass of 166 GeV, with an error of about 25 GeV. However, it is necessary to assume the Standard Model is valid, and to assume the existence of an unseen neutral Higgs boson which, like the top quark, can also produce small changes in observable quantities. Taken together with the Tevatron limits, physicists appear to be closing in on the top quark mass. Stay tuned.

RESULTS FROM THE FIRST long data-taking run of DESY's new electron-proton collider HERA were also presented by John Martin of Toronto and John Dainton of Liverpool. Its performance has improved markedly since last year's turn-on and is already close to one-tenth of its design luminosity. This is being accomplished with lower beam currents than planned, so experimenters are hopeful that HERA may ultimately exceed its design luminosity. Last year, the machine was plagued with short electron and proton storage times, but this year average lifetimes of over three hours for electrons and 25 hours for protons made operation fairly routine.

Both HERA experiments, ZEUS and H1, reported measurements of soft and hard photoproduction at energies about an order of magnitude above existing fixed-target experiments, with clear evidence emerging for two-jet structure. The biggest surprise in this area came from their deep inelastic scattering results. ZEUS and H1 each observed that about 5 percent of the events had an unusual and unanticipated character, a so-called “large rapidity gap” characteristic of diffractive-like production in fixed-target experiments. In reviewing tests of high-energy perturbative QCD, Marjorie Shapiro of LBL indicated that D0 data suggested the existence of similar events at the Tevatron. HERA also provided the strictest limits to date on leptoquarks and compositeness (e*, ν*); mass limits in the 100–200 GeV range were obtained for the former.

Recent nucleon structure function results were reviewed by Rudiger Voss of CERN. Most interesting and
controversial was this year’s round of polarized deep inelastic scattering experiments to verify the Bjorken sum rule, which is considered a fundamental and rigorous test of QCD. Proposed in 1966, it relates the difference of the spin structure functions of the proton and neutron to the ratio of axial and vector weak-coupling constants. Two experiments, SMC at CERN and E142 at SLAC, have published results on polarized scattering on polarized targets of deuterium (= p + n) and $^3$He (= n), respectively. The SMC results are based on three million events with a range in x of 0.006–0.6 and $Q^2$ <30 GeV$^2$, while the E142 results are statistically much stronger (300 million events), but cover a narrower x range at lower $Q^2$. The results of both experiments are consistent with the Bjorken sum rule and the quark contribution to the nucleon spin, but they reach different conclusions about the polarization of the strange quark sea. Both collaborations agree that more statistics for neutron and proton spin structure functions over a larger x and $Q^2$ range are required, and in particular that alternative polarized targets should be used to confirm their nuclear spin properties.

The session was highlighted by the work of a CLEO team from Cornell, Rochester, and Syracuse led by Edward Thorndike and Peter Kim. They succeeded in establishing first evidence for the $b \to s \gamma$ transition, the so-called radiative “penguin” decay. The fundamental importance of this result for understanding both CP violation [the subtle asymmetry between matter and antimatter in the universe] and the charged Higgs beyond the Standard Model—cannot be overestimated. Most common B decays proceed via the weak decay of a $b$ quark into a charmed quark, the $b \to c$ transition. It is thought possible for the $b$ quark to decay weakly to an $s$ quark, if it emits and then re-absorbs a $W^\pm$. In the process it must either radiate a photon or a gluon [the carrier of the strong force], giving either a radiative or hadronic penguin decay. Theorists invoke these very rare $b \to s$ transitions (occurring only one time in about 100,000 B decays) to induce direct CP violation. For CP violation to occur naturally within the Standard Model, it is necessary but not sufficient to demonstrate the existence of these penguin transitions. If direct CP violation were observed in a future B factory, but the penguin decays were not, then we would probably need to postulate a new force of nature.

With a sample of about 1.5 million $\Upsilon$(4S) decays, CLEO has unambiguously isolated a significant number of events in the $B \to K^*\gamma$ final states, thereby demonstrating the existence of the radiative penguin transition. The hadronic decays $B \to K\pi, \pi\pi, \text{ and } K\bar{K}$ can proceed through hadronic penguin transitions as well, but at a tiny rate. Combining the first two channels, CLEO has established a signal with a significance of about 4.1 standard deviations. As the data sample continues to grow, the discovery of hadronic penguin decays may be just around the next corner.
The relevance of these observations goes beyond establishing direct CP violation. In the Standard Model the lightest neutral Higgs must be heavier than 63.5 GeV. The popular minimal extension of the Standard Model, the so-called two-Higgs doublet model, has an additional charged Higgs boson whose mass is unknown. LEP experiments indicate it must be greater than about 43.7 GeV. If this charged Higgs boson exists, it would alter the observed decay rate of the radiative penguin. By comparing the actual decay rate to the Standard Model prediction, without the additional Higgs, CLEO can establish a lower limit of about 250 GeV on the charged Higgs mass. This limit places the charged Higgs boson out of the range of LEP-II and of lower-energy versions of the next linear colliders now under consideration. Models that invoke supersymmetric particles can modify this conclusion; however, for a wide range of the free parameters in those models, the charged Higgs mass remains tightly constrained by the penguin branching fraction. The tenor and implications of these constraints was aptly reflected in David Gross’s theoretical summary talk when he said simply that “such cancellations can be arranged.”

There were two other striking results from CLEO. First, as its data samples steadily grow, “tagged” B decays are coming into common use in analyses. Using about 1000 cleanly tagged events from a total sample close to 10,000, CLEO measured in a direct and model-independent way the ratio of $B^+/B^0$ lifetimes. The other important result was the measurement of the small $V_{ub}$ element of the CKM matrix. Here, ARGUS has also contributed. The CKM matrix tells us how to relate the strongly interacting quarks, when they decay by the weak interaction. The matrix has three real parameters and one phase, whose magnitudes in turn determine the pattern of weak transitions of quarks within hadrons. The phase in the CKM matrix may hold the key to CP violation in the Standard Model. While most $b$ quarks decay via the $b \to c$ transition, the next most common decay is via the $b \to u$ transition. The large downward trend that began last year continued to occur in the value of $V_{ub}$ which governs the rare $b \to u$ transitions. The ratio $|V_{ub}|/|V_{cb}|$ has fallen by two to three standard deviations, from the range 0.10–0.15 down to 0.05–0.10.
CHARM AND BOTTOM production at high-energy fixed-target and collider experiments was reviewed by Jeffrey Appel of Fermilab. In the late 1980s the fixed-target experiments at Fermilab overtook the $e^+e^-$ experiments for the study of charm decay. The technical breakthrough was the use of silicon detectors, which allowed a charm signal to be picked out of a large background by use of its comparatively long decay length. We are now witnessing the entry of the hadron machines into the worldwide competition to carry out serious $b$-physics programs. At the Tevatron, $b$ production is many orders of magnitude greater than at $e^+e^-$ machines such as CESR-II, or even future $B$ factories. Once again, the key is to learn how to trigger selectively and pick out the signature of the $b$ decays. As a start, three fixed-target production experiments are already running. Fermilab E672 (using silicon vertex detectors) and E653 (using hybrid emulsion techniques) are collecting data, while WA78 is running at CERN, tagging $b$'s using displaced $J/\psi$ vertices. At the Tevatron, CDF has already produced a large signal of 14 events for $B_s^0 \rightarrow \psi \phi$ at a mass similar to that of ALEPH's "golden" $B_s^0 \rightarrow \psi \phi$ event at 5368±6 MeV. Encouragingly, CDF has also produced lifetimes and masses for all three species of $B$ mesons, with errors competitive with the rest of the world. With the widespread use of silicon vertex detectors, a number of new and exciting $b$ physics results have emerged from LEP. First, we have witnessed an upward movement of two to three standard deviations in the average $b$ lifetime measured at the Z. All LEP experiments have now moved 0.15 to 0.2 ps higher, close to the average lifetimes reported by ALEPH last year and by CDF independently. A more fundamental result is the dramatic improvement in LEP measurements of $R_b$, the branching fraction for the decay of the $Z$ into $b$ quarks. The value of $R_b$ is significant because in the Standard Model it depends only on the top quark mass. The large mass and favorable couplings of the $b$ quark makes $R_b$ the most sensitive place to hunt for new physics. For example, a charged Higgs could decrease $R_b$ by 1 percent while supersymmetric particles would increase it 1 percent, provided that the top quark mass is about 160 GeV. The errors in the LEP measurements have improved by a factor of 3, to the point where they are just on the edge of sensitivity to new physics. Interestingly, in the absence of new physics, the LEP central value for $R_b$ requires an unphysical negative value for the square of the top quark mass, and by itself sets an upper limit of 210 GeV on this mass.

SOME 17 YEARS since its discovery, the charm quark remains the heaviest charge-$2/3$ quark likely to be studied in any detail, a fact reinforced by the continued inaccessibility of the top quark. Charm studies remain important, because the parameters of the CKM matrix are such that many higher-order charm decays are suppressed in the Standard Model. Mixing and CP violation, two processes that can occur relatively frequently in $b$-quark decay, are expected to be extremely
rare in charm decay, making their observation by experiment a clear signal for a new process that might allow couplings only to charge-2/3 quarks. Charm weak-decay spectroscopy also remains a great interest for physicists, because at a mass of about 1.5 GeV charm lies midway between the difficult-to-calculate regime of strange mesons, and the simpler regime of $B$ mesons. Heavy quark effective theory, illuminated in a review by Mark Wise of Caltech, elegantly ties together many of the detailed properties of charm and bottom quarks. The precision data now emerging from Fermilab, CLEO, and LEP supports the possibility of such a detailed theoretical understanding of all weak decays.

While a great number of new results in charm spectroscopy emerged at the Symposium, I can only single out one of the most fundamental results here, the first observation of purely leptonic decays of the $D_s$ meson. In these decays, the charm quark and anti-strange quark making up the $D_s$ meson annihilate to produce a virtual $W$ that emerges as a charged lepton and an invisible neutrino. The rate for these events to occur depends only on one parameter, the so-called “weak decay constant,” and is proportional to the overlap of the two quarks (and hence their annihilation probability) within the meson. Without strongly interacting mesons to confuse the final state, the decay constant is an unambiguous and fundamental quantity; the ability to correctly calculate its value provides a truly rigorous test of lattice gauge theory techniques within the charm sector.

**The Status of the Tau Lepton**

The heaviest known lepton, was reported by Andreas Swartz (MPI, München). With definite predictions of the Standard Model for each of its many possible decays, the tau provides an ideal laboratory to perform precision tests of that model. Dominating Swartz's review were new results from CLEO, ARGUS and LEP, having samples of $2 \times 10^6$, $4 \times 10^5$ and $5 \times 10^4$ tau pairs, respectively. All experiments now measure consistent electron branching fractions, whose average is $17.34 \pm 0.14$ percent. The analogous decay of the tau to a muon tests tau-electron and tau-muon universality to about one percent. In the Standard Model, the mass, lifetime, and leptonic branching fractions of the tau are unambiguously related. Last year, even with the new tau mass of $1777 \pm 0.3$ MeV from ARGUS, BES, and LEP, there remained a nagging discrepancy of two standard deviations. This year, with the shift in leptonic branching fraction and a shift of two standard deviations in the tau lifetime from the 1992 value of $305 \pm 6$ fs to $294.7 \pm 3$ fs, the relation within the Standard Model agrees to within one standard deviation.

Neutrino masses and mixing were covered by Georgi Smirnov of the Joint Institute for Nuclear Research, Dubna. Experiments at Mainz, Livermore, and Los Alamos provide upper limits of 7–8 eV for the mass of the electron neutrino [$m(\nu_e)$]. The limit on the muon neutrino mass from SIN is 270 keV. Even though CLEO-II has more events, the best limits on the tau neutrino mass still come from the ARGUS collaboration at DESY, which owing to the whims of statistics gives $m(\nu_\tau) < 31$ MeV. A
recent analysis by Dolgov and Rothstein of primordial nucleosynthesis suggests that this limit can be indirectly reduced to about 0.3–0.5 MeV, or below the electron mass. Three double beta-decay experiments place limits on the Majorana neutrino mass to the few eV level. Limits on admixtures of new neutrinos (e.g., 17 keV) to the electron neutrino have been tightened to 0.07 percent or less. Finally, recent data from Homestake and Gallex on solar neutrino counting have failed to offer any new experimental insights into the solar neutrino deficit, and no new astrophysical solutions appear to be forthcoming.

Jack Ritchie of the University of Texas at Austin reviewed the status of rare $K$ decays. Major experiments at BNL, KEK, Fermilab and CERN provide the tightest limits on flavor changing neutral currents and on lepton flavor violation. The former are forbidden in lowest order in the Standard Model but often are masked by long-range contributions, while the latter are not explicitly forbidden but can indirectly test the presence of new physics at a mass scale of 100–200 TeV, well beyond what is accessible at present accelerators. Rare $K$ decays also provide a window on direct CP violation. Ritchie ended by pointing out the 1-to-2 orders of magnitude improvement made by the present generation of experiments. The next round of experiments to be taking data in the 1995–1996 period will approach or exceed the levels of interest in the Standard Model.

One of the more unusual contributions at the Symposium was a presentation by Spencer Klein of the University of California, Santa Cruz, on the results of the first experiment to measure the LPM (Landau, Pomeranchuk and Migdal) effect, which is the suppression of the Bethe-Heitler bremsstrahlung amplitude by multiple scattering of electrons traversing matter. First discussed in the late 1940s, this effect can be intuitively understood within the framework of the Heisenberg uncertainty principle. But it has eluded observation until this year. A most refreshing aspect of this experiment was its very uncharacteristic nature. Reminding us of “the good old days” of particle physics, 11 physicists from SLAC, LBL and American University wrote a brief proposal and got SLAC approval in June 1992. They then built a parasitic electron beam from the primary SLC beam, assembled a tabletop experiment from largely recycled components, collected data over a few weeks and, several months later, reported their elegant results to this meeting. There is hope for all of us still in large collaborations!

We turn now to prospects for the near future. Studies of electroweak effects in the Standard Model start with the three related quantities, often chosen to be $\alpha_{em}$ (the coupling constant of electromagnetism), $G_F$ (the Fermi coupling constant of the weak interaction), and the mass of the $Z$ particle, the poorest known of the three. Elegant measurements have been made of the $Z$ mass at LEP to an error of less than ±7 MeV out of 91,187 MeV [less than 0.1%]. As first suggested by Gerhard Fischer of SLAC, lunar tidal forces around the LEP ring contribute an important systematic error. Using transversely polarized beams to allow frequent energy calibrations, CERN anticipates that an improvement to ±3 MeV is possible.

Central to the unification of the weak and electromagnetic sectors is the Weinberg angle $\sin^2 \theta_W$. The four LEP experiments (each with about 1 million $Z$s) have combined 25 measurements of observables [such as the left-right and forward-backward asymmetries of all flavors of quarks and leptons] to obtain the value of $\sin^2 \theta_W = 0.2321 \pm 0.0006$, with an unprecedented precision of 0.3%.
The SLD collaboration at SLAC projects it will make a single measurement of $\sin^2 \theta_W$ at a precision of $\pm 0.0009$ (using a smaller sample of about 50,000 $Z$s) by comparing $Z$ production rates with the electron beam polarized along and opposite its direction of motion. As Morris Swartz of SLAC emphasized, the SLD performs a simple counting experiment that has almost negligible systematic errors. In the past year, SLAC has made great progress, increasing the beam polarization at the interaction point almost threefold, to about 65 percent. Novel changes in beam optics have reduced spot sizes at the collision point by a factor of three, to 0.8 microns high, thereby increasing the luminosity of the SLC. The SLC has begun an upgrade to allow it to run with higher currents and to correct optical aberrations that limit the spot size. If these improvements work as planned, SLD should reduce the error on $\sin^2 \theta_W$ to $\pm 0.006$ by the end of 1994, providing a direct challenge to the LEP result.

The theoretical aspects of CP violation in kaon and $B$-meson decays was extensively reviewed by Tony Sanda of Nagoya University, while Tatsuya Nakada of Paul Scherrer Institute covered the status of experiments at LEAR, Fermilab and DAΦNE, (the low-energy $e^+e^-$ storage ring at Frascati) to measure CP violation in the kaon and hyperon systems. The elegant CERN and Fermilab experiments NA31 and E731 measuring Re($e^i/e$) will be supplanted in 1994 by NA48 and E832, with improved sensitivities of $10^{-4}$. After years of detailed work, we can anticipate a definitive set of results from these two experiments.

Sanda ended his talk with a plea for construction of a facility to study CP violation in $B$ decays. And as this Symposium came to a close, many new machines such as SSC, LHC, KAON and the U.S. and Japanese $B$ factories sat poised for word of final political decisions. Next year, when we gather again to see how well our physical model of the Universe has survived another round of experiments, at least the direction of the future machines may be a little better understood.
THE 1993 PARTICLE ACCELERATOR CONFERENCE
by ROBERT SIEMANN

Highlights of the biennial conference on the physics of particle beams

The Particle Accelerator Conference returned to the venerable Omni Shoreham Hotel in Washington, D.C. for a meeting with presentations ranging from the detailed and technical to profound, to thought-provoking talks about the future of science and technology. Except for the opening and closing plenary sessions, the four-day conference ran with five parallel sessions at a time, two oral and three poster, and the conference highlights are bound to be different for each participant. The following are mine.
THIRD GENERATION LIGHT SOURCES

The European Synchrotron Radiation Facility (ESRF) and the Advanced Light Source (ALS) are the first of the third-generation light sources, synchrotron light sources designed specifically for producing high brightness photon beams from insertion devices—undulators and wigglers. These storage rings have the extremely strong focusing needed to produce a dense electron beam, and a substantial fraction of their circumference is taken up by straight sections for the insertion devices. These central features of third-generation sources make them qualitatively different from high energy colliders and from earlier synchrotron radiation sources because they introduce potentially serious problems of chromatic corrections, orbit corrections, and beam current limits.

The construction of the ESRF, a 6 GeV storage ring with associated injectors, laboratory and experimental facilities started early in 1988 on a "green-field" site in Grenoble, France. Its successful completion was reported by Jean-Louis Laclare. The injection system reached its target performance by the end of 1991, and in May 1993, 135 mA of current was stored without any problems. The alignment and magnet calibration was done so well that a beam could be injected on-axis and stored. This allowed sophisticated orbit and chromatic corrections to be done with the beam. The current achieved is well above the design of 100 mA, indicating the excellent work calculating and controlling intensity-limiting effects.

The ALS is a lower-energy (between 1.6 and 1.9 GeV) third-generation source located at Lawrence Berkeley Laboratory. Alan Jackson described the construction and commissioning of the ALS, which was as impressive as that of the ESRF. Large currents, slightly more than 400 mA, have been stored, and the lifetime is already up to one and one-half hours even though the full vacuum pumping system has not yet been turned on.

The accelerator physicists and engineers at these two laboratories deserve our congratulations. There is an exciting future for these and other third-generation sources, and for the diverse sciences using their photon beams.

ELECTRON-PROTON COLLISIONS AT HERA

The first luminosity was delivered to experiments at HERA in May 1992, a year before the conference. Its construction, commissioning, operation and future prospects were presented by DESY Director Bjorn Wiik in an opening plenary session talk. The HERA proton ring is providing our first experience with the most important accelerator physics issue of large hadron colliders—superconducting magnets operating with a large ratio of injection and storage energies. [For HERA those energies are 40 GeV and 800 GeV.] Persistent currents in these magnets, which depend on the energy ratio, produce sextupole fields that limit the effective aperture and could make injection difficult or impossible. Sextupole fields in test magnets hooked up in series with the ring magnets are...
measured at HERA, and corrections are made based on those measurements. This approach gives a small but sufficient aperture and some beautiful data about the effects of nonlinear fields upon it.

Collisions of electrons and protons have not led to any unpleasant surprises provided the electron and proton beam sizes are matched, which produces good lifetimes. The luminosity per bunch is close to the design value, and the limit on total luminosity is coming from the proton current that can be accelerated and stored. The immediate plans are to increase the number of bunches by roughly an order of magnitude. This should bring HERA close to its expected performance, and the H2 and ZEUS experiments can begin exploring its unique high-$Q^2$ electron-proton physics.

THE NEXT MAJOR PARTICLE PHYSICS FACILITIES

The status of the SSC and LHC were described in summary talks by Richard Briggs and Giorgio Brianti, respectively. There were numerous parallel session talks and poster presentations on the specifics of both accelerators including lattice design, long-term stability, advances in magnet technology and production, system tests, and the injector chains. One can’t help but be impressed by the amount and quality of this work.

There is considerable debate about the best approach for the next-generation linear collider. The choices are between superconducting and room temperature rf, and for room temperature rf the frequency is still an open question [see Beam Line article by Greg Loew, Vol. 22, No. 4, 1992]. These choices will be narrowed down through the development of specific components such as accelerator structures and rf power sources, system prototypes, and experience with collisions at the SLC. The progress of prototype facilities was particularly striking. Linacs using different candidate technologies are being developed at DESY, BINP and SLAC; a modern damping ring that will produce record low-emittance beams is under construction at KEK; a prototype final focus system is being commissioned at SLAC; and the generation of the drive beam for a two-beam accelerator is being tested at CERN. These prototypes will give crucial information about cost and feasibility that will help build a consensus about the best technology.

FOREFRONT ACCELERATORS

While most of the conference was devoted to conventional accelerators, there were important talks about advanced accelerator concepts and forefront applications. One session opened with John Blewett, the Wilson Prize winner this year, reminiscing about his career that started at a 1.3 MeV Van de Graaff and extended to work on the 200 GeV design that became Fermi National Accelerator Laboratory. It seemed appropriate that this eloquent reminder of the progress possible in a person’s lifetime was followed by Christopher Clayton of UCLA reporting a major accomplishment in the field of advanced accelerators, the acceleration of electrons in a plasma accelerator.
The UCLA laser acceleration group has accelerated injected electrons in a "beat-wave" accelerator where an accelerating gradient is developed in a plasma by the beating of two lasers with slightly different frequencies. In the past, field gradients produced by the beat-wave mechanism have been measured by laser light scattering, and acceleration of plasma electrons has been observed, but the UCLA experiment is the first demonstration of acceleration of injected electrons by a plasma beat-wave mechanism. Electrons with an energy of 2 MeV were accelerated up to 20 MeV in roughly 1 cm of plasma indicating a gradient of 1.8 GeV/m. There is a long way between results of this type and a working accelerator, but remarkable progress is possible in a person's lifetime.

Ultimately there may be limits to the center-of-mass energy coming from hadronic interactions in p-p colliders or electromagnetic processes in linear colliders. Maury Tigner of Cornell University explored this connection in the closing talk of the conference. He concluded that these limits do not come into play at the SSC/LHC, in 0.5 TeV linear colliders, or even in the generation following these, but after that they present a hard limit. For example, a restriction to 1 GW of power dissipated in the hadronic interactions of a p-p collider would limit the center-of-mass energy to $E_{cm} \sim 4000$ TeV. Since that energy limit scales as the cube root of the power, it will be reached at energies well below the Planck scale. These extrapolations are enormous and Tigner concluded correctly that discoveries will change them totally, but this type of calculation does highlight the strong connection between center-of-mass energy and power consumption as we push to higher energies.

High-current proton accelerators, with 0.1–0.3 A of average current and roughly 1 GeV of energy, have enormous potential as intense neutron sources for wide-ranging applications from research with spallation neutrons to transmutation of long-lifetime radioactive wastes. Robert Jameson of Los Alamos National Laboratory gave an extremely interesting talk on an important accelerator physics problem—the control of beam losses to prevent activation and limit the need for remote handling and maintenance. With the type of currents being called for today, this amounts to controlling beam halos that are a very small fraction of the total current. A recent insight is that a single particle interacting with a beam core that is not stationary in time can lead to halos. This insight is leading to new understanding of optimum parameters, matching in longitudinal and transverse phase.
space, and misalignments. There is potential for enormous benefit to society from this work on high current proton accelerators.

A VIEW FROM IBM

Paul Horn, Director of the Advanced Semiconductor Technology Laboratory at IBM and a former synchrotron radiation researcher, gave a thought-provoking talk about the economic benefits of large scientific projects. These benefits are a major reason that society makes multi-billion dollar expenditures in basic research projects. The understanding of the basic forces in nature coming from a project like the SSC is the primary motivation of its supporters, but economic benefits and spinoffs are featured prominently in public debate. Every large scientific or technical project strengthens and develops the particular technology it employs (large scale superconductivity for the SSC/LHC), and this type of spin-off from a basic research project is no different from that from any other large customer. A second type of economic benefit comes from the results of the research itself, and here, Horn asserts, the case for large particle physics facilities has not been made very well. He also presented some daunting facts about industrial R&D. IBM expects $20 of return for each $1 invested in “basic” research, and economic benefits from this research should be realized in seven years. The research results are widely dispersed after that, and the original research funder no longer has any special advantage.

This talk wasn’t popular with the audience, but it was the opinion of an experienced researcher and industrial manager. It is a challenge for practitioners of basic research to think about and justify the economic benefit of their work—and for the academic world to understand and meet the needs of industry. It is also a challenge for particle physicists to develop genuine cost sharing for future facilities. We must develop mechanisms for sharing costs in a way that all contributors, not just the host country or region, can share economic benefits. This challenge was mentioned, but not discussed extensively, at the recent ICFA seminar at DESY. It deserves some serious attention.

BANQUET NIGHT

The banquet is always a highlight of the Particle Accelerator Conference (PAC), partly because of the food and entertainment, but mostly because of the recognition of achievements of colleagues. John Blewett (retired from Brookhaven National Laboratory) was awarded the Robert R. Wilson Prize of the American Physical Society (APS) for his many contributions to accelerator physics and technology beginning in the 1930s. A new member of the accelerator physics community, John Palkovic of the SSC Laboratory, was given the APS Award for his Ph.D. thesis on the physics of low-energy ion beams.

The capabilities of accelerators are often linked to those of the particle sources at the front end. Particle sources are always at the forefront of accelerator science, and it was appropriate that awards were given for two different source developments. The Institute of Electrical and Electronics Engineers (IEEE) awarded one of the two PAC Technology Awards to Louis Anderson of the University of Wisconsin and Yoshiharu Mori of the National Laboratory for High Energy Physics for their invention of an optically pumped polarized negative hydrogen
James Griffin, left, of Fermilab and Tom Collins, retired from Fermilab, winner of the IEEE PAC Technology Award "for his invention of long straight sections for synchrotrons and storage rings, and his design of the lattices of the Fermilab Main Ring, Tevatron, and Antiproton Source."

John Palkovic, SSC Laboratory, winner of the APS Award for Doctoral Thesis Research in Beam Physics.

Marc Ross, SLAC, one of the three winners of the U. S. Particle Accelerator School Prize for Achievement in Accelerator Physics and Technology.

Yoshiharu Mori, KEK, one of the three winners of the IEEE PAC Technology Award.

Events since the PAC have shown that accelerator technology and physics are in a time of transition. The accelerator community has much to offer and will be an important resource in helping the United States develop basic research and technology policy in the coming years. The strength and vitality of that community were clear from the PAC.

The other IEEE and USPAS awards were given to individuals I have had the pleasure of working closely with, Tom Collins and Marc Ross. Tom Collins (retired from Fermi National Accelerator Laboratory) was cited by the IEEE for his many innovative magnet lattice designs, and Marc Ross of SLAC was given a USPAS Prize for measurements and analysis of the SLC that have been essential for the progress there. Congratulations to all!
We continue our low-budget tour of relatively unspectacular stars that are one way or another a bit puzzling and may be trying to tell us something about unusual phases of stellar evolution.

The tram stops are labeled Geminga (bright in gamma rays but optically negligible), faint X-ray sources, FG Sagittae, and dwarf carbon stars. Feel free to get off at any intermediate point and join those working on the problem.
GEMINGA FINALLY EXISTS

Geminga is both the Gemini gamma-ray source and Milanese dialect for “is not there” or “does not exist,” the latter reflecting its prolonged resistance to detection at any other wavelength. With a ratio of radio and optical luminosity to X- and gamma-ray luminosity well below the normal range for any standard sort of astronomical object, Geminga spent more than a decade seemingly a member of a class of one.

It has now been demoted to “nearest gamma-ray pulsar” out of five or more. Identification of its 0.237 sec rotation period in X-ray data collected with the German ROSAT satellite led to finding a slightly faster period in gamma-ray data from 15 years before. If you agree with the masses that pulsars are rotating, magnetic neutron stars, then values for the rotation period and its derivative suffice to calculate the age of the object (about 350,000 years), its magnetic field (1.5x10^{12} Gauss, a typical pulsar value), and its total luminosity (3.5x10^{34} erg/sec).

Geminga must be quite close to us for two reasons. First, the flux we see in X-rays and gamma rays must not be more than the total available. Second, the source is galloping across the sky at 0.17 arc sec/year. This may not sound like much, but it is 16° over the age of the object, and if Geminga were more than about 400 pc away, the corresponding linear velocity would mean that it is not a permanent member of our Milky Way galaxy. Measurement of this motion is a triumph of hard work over scarcity of photons. The optical object, found by Giovanni Bignami and Patrizia Caraveo of Milan, has an optical brightness of 25.5 magnitude, a factor of 100,000,000 below the naked eye limit.

Neutron stars are supposed to result from supernova explosions; and a supernova this close to us, even 350,000 years ago, might have left other traces. Neil Gehrels and Wan Chen (Goddard Space Flight Center) think we may actually be living inside its supernova remnant, a local bubble of hot, low density interstellar gas. In addition, the blast of gamma rays at its birth should have produced C^{14}, Be^{10}, Cl^{36}, and other unstable isotopes in the earth’s upper atmosphere. These rain down onto the surface and can be trapped in living creatures, polar ice, and so forth. Arctic and antarctic ice cores show some evidence of such an event about 35,000 years ago. Physicists at the Physico-Technical Institute in St. Petersburg and elsewhere are currently attempting to extend their Be^{10} records backward with...
sufficient precision to look for signs of the hypothetical Geminga event.

Amid all this triumph, is there anything left to worry about? Two items. First, if the X-ray and gamma-ray pulses are aimed at us, radio pulses should be as well. But prolonged searches have yielded only upper limits for pulsed (or unpulsed) radio flux. Second, the current “best buy” model for producing gamma rays from pulsars is supposed to work only for rotation periods less than about 0.15 sec. The other four all comply. Geminga does not.

Secretly, though, I remain most puzzled by just how faint this particular star is. The second or third brightest gamma-ray source in the sky has an optical counterpart fainter than all the billions of stars and galaxies recorded on the Palomar Observatory Sky Survey plates, with flux hitting earth a factor of nearly $10^8$ below the naked eye limit. This is the sort of contrast that can be modeled, but not intuitively grasped!

THE FAINT X-RAY SOURCES IN GLOBULAR CLUSTERS: CV OR NOT CV?

A proper X-ray binary consists of a neutron star accreting gas from a less compact stellar companion. The deep gravitational potential heats the inflowing gas to keV temperatures, and it radiates X-rays at $10^{36-38}$ erg/sec. The Milky Way harbors a hundred or two of these (some are quite variable), and at least 12 are in globular clusters. Since the clusters (Beam Line 22, No. 3, Summer 1993) contain at most $10^{-3}$ of galactic stars, 10 percent or so of the X-ray binaries is far more than their fair share. The generous supply arises, it seems, because stars are so close together in the clusters that collisions, two- and three-body capture processes, and exchanges of stars between pairs are possible or even common. No other part of the galaxy (except maybe the invisible core) can make this claim. But neutron stars—the corpses of smaller stars like the sun—are common. Thus the processes that have given us a dozen or more neutron star X-ray binaries should also have made hundreds or thousands of white dwarf binaries, many per cluster.

Astronomers have a name for these binaries—cataclysmic variables, or CVs for short. The name, apparently coined by Cecilia and Sergei Gaposchkin, describes their propensity to brighten suddenly and unpredictably, owing to instabilities both in gas transfer from the normal star to the white dwarf and in nuclear burning on the white dwarf’s surface. Emission lines from atomic levels of fairly high ionization and excitation potential are another signature.

Do the globular clusters have the expected swarms of CVs? Not so much as you would notice. Two classical novae (T Sco, 1860, in M80 and a 1948 one in M14) are probable cluster members. Two dwarf novae in cluster fields have been spectroscopically confirmed by Bruce Margon (University of Washington) and others, and two possible DNe are additional candidates, but membership is not firmly established for any. A foreground or background star will not share the radial velocity of the cluster, and a member will, but good data are still lacking. Searches for the collective emission lines from CV populations in a few promising clusters have been similarly non-definitive. Something must be wrong. Either cataclysmic variables are a lot harder to spot than they should be, or stellar interactions do not produce neutron star X-ray binaries in the advertised fashion.

Against this background, a 1983 paper by Paul Hertz of the Naval Research Laboratory and Josh Grindlay of the Center for Astrophysics, Cambridge, was most welcome. They had examined archival data from the Einstein X-ray satellite and found 14 new sources in 7

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1Only one, you say in disbelief? Well, no. There are the classical novae, dwarf novae (SS Cyg, U Gem, Z Cha, and SU UMa types), recurrent novae, symbiotic stars and novae, nova-like variables, AM Her (polar) and DO Her (intermediate polar) stars, AM CVn’s, and maybe a few others.
clusters, all with $L_{\text{X-ray}} = 10^{34}$ erg/sec (assuming cluster distances). Were these the tip of the CV iceberg? Field CVs are often X-ray sources (though typically not quite so bright), and Hertz and Grindlay thought so. Optical counterparts, whose spectra might be examined, proved elusive. Einstein data could not yield very precise positions on the sky, and clusters are crowded. The first few optical identifications were for sources furthest away from the packed cluster cores. These turned out to be foreground objects (stellar coronae) and background ones (active galaxies). A gentlemanly but firm polarization of the community into CV or not CV gradually arose.

We all knew what was needed to sort things out. First, a new X-ray satellite to pick up some additional, fainter sources and to locate both old and new ones accurately on the sky. The German ROSAT [Roentgen Satellite] has provided these, finding at least five sources in the nearby cluster NGC 6397 and three or more in NGC 6752. Second, sharper optical images, so that you can say with confidence that this X-ray dot is the same as that visible dot. Data from the Hubble Space Telescope are not “given” as the etymology implies. They are extracted with enormous toil, but they do have the requisite resolution. A first round of images reveals colors at least suggestive of CVs. And third, spectra of the candidates to search for the diagnostic emission lines. The competing proposed source types, ordinary X-ray binaries in quiescence and RS CVn stars, will also show emission lines, but with different patterns of ionization and excitation states.

If all has gone well, an HST spectrogram of one source in NGC 6397 is being recorded even as I write this, though data processing and analysis will take many moons. You may want to defer voting on the nature of the faint cluster X-ray sources until these spectral photons are in, though it is conceivable that the issue may still not be resolved even then. Meanwhile, I too am reluctant to place bets. Cecilia Payne Gaposchkin wrote, “I will not accept the conclusions of another astronomer simply because I am fond of him, or reject them because I dislike him (though I admit there is a temptation here).” I am at least as prone to the former category of error as she was to the latter, and there are good friends in both corners of the ring.

What do the cluster names mean? Those beginning with M indicate relatively bright groups of stars (or galaxies or other fuzzy looking things), because M was Messier, who began compiling his catalogue in 1758 and had only a small telescope. Objects are numbered in the order he found them. NGC is New General Catalogue, because it appeared in 1888, long after the original, old, Herschel’s General Catalogue. It includes fainter objects (with the Messier ones as a small subset), which are numbered roughly across the sky from west to east.
FG SAGITTAE: SLINGS AND ARROWS

Most stellar evolution takes millions or billions of years. But FG Sagittae has been tramping around the Hertzsprung-Russell diagram lately almost faster than we can follow it. It brightened by a factor of 40 (at least in visible light) between 1894 and 1965 and cooled from about 18,000K to 5650K between 1955 and 1985. Simultaneously, its mean pulsation period increased from about 10 to 100 days, corresponding to a factor of 100 decrease in atmospheric density as the star cooled and expanded. In the 1970s, it blossomed forth with absorption lines of Y, Zr, Ce, La, and other elements produced by slow neutron capture on iron. These strengthened for a decade and were joined by lines of Eu and Gd, elements normally attributed to rapid neutron capture in supernovae.

At times, the cooling went as fast as 200 K/year, and one began to worry that the star might fall completely off the right-hand edge of the HR diagram and cease to be available for study. This danger has been averted. Slight reheating occurred in 1988–90, while the optical brightness showed semi-regular variability and visual magnitude of 9.1–9.3. Then, in fall 1992, the optical brightness dropped precipitously by a factor of 30 or so, taking the star back almost to where it had been in 1900. Ultraviolet and infrared fluxes also dropped, though some colors became bluer, and the behavior of total brightness over all wavelengths is not very well established. Gradual recovery at optical and infrared wavelengths began in December.

Can all this possibly be modeled? Of course it can. The ingenuity of theoretical astrophysicists is unlimited. In fact, behavior very much like that of FG Sagittae had been predicted by Icko Iben [Illinois] for low mass stars late in life, when their death march to electron degeneracy is interrupted by one last flash of helium burning.

FG Sagittae is by no means a near neighbor, but to have caught the critical 100 years out of a multi-billion year evolutionary history for even one star is remarkably lucky. In case you prefer not to push your luck quite this much, Iben and Mario Livio have suggested an alternative, commoner explanation [cloud forming in the stellar atmosphere] and observational tests of the two mechanisms.

WITH A LITTLE BIT OF HELP FROM THEIR FRIENDS: DWARF CARBON STARS AND OTHER VICTIMS OF BINARY POLLUTION

The history of astronomy could be written as a sequence of bandwagons overtaking, and sometimes colliding with, each other. Explanations of practically everything in terms of magnetic fields or black holes or
mass transfer in interacting binaries are three recent ones, the last of which, at least, I propose to ride here. But let’s start in the late 19th century, when observers of stellar spectra began to recognize the enormous range of types, with lines of familiar elements in wildly different ratios. Initial wisdom supposed that what you see is what you get, and imagined a star like the sun would consist of about the same elements as the earth, in about the same proportions, dominated by oxygen, iron, and silicon. Other stars were different.

Application of the Saha and Boltzman equations in the first third of our century led to a major reversal of opinion. Not only were the spectra best explained by overwhelming proportions of hydrogen (almost three-quarters) and helium (about one-quarter) compared to everything else, but the line ratio variations could be accounted for by temperature and density differences. All stars were chemically identical, except for a small subset of giants with carbon-bearing molecules instead of oxygen-bearing ones.

The ink was barely dry on the Henry Draper Catalogue of stellar spectra (published in 1918–24 and reporting more than 200,000 spectral types that were interpreted primarily as a temperature sequence), when Paul Merrill in 1926 reported a subset of cool stars, called type S, with remarkably strong 4554 Å lines of ionized barium. The specific category of “barium stars” came into existence in a 1951 paper by William Bidelman (Case Western Reserve University) and Philip Keenan (Ohio State University). The stars were normal giants, not supergiants, and were carbon rich, though not so much so as true carbon stars (with C/O >> 1, vs. about 0.4 in the sun). And all the authors could suggest by way of explanation was that the excess carbon somehow changed the atmospheric structure in a way that favored production of Ba II (and Sr II) lines. Not a word was said about excess barium.

We now jump only a few calendar years, but an intellectual millennium, to the conviction that, while the early universe made “all the elements up to helium,” nucleosynthesis of everything else occurs in stars. It is not a coincidence that the first two authors of the millennial paper (B2FH, as abbreviation for G.R. Burbidge, F.M. Burbidge, W.A. Fowler, and F. Hoyle) were also the first to carry out a quantitative analysis of a barium star and find true excesses not just of barium, but also of several other elements produced by slow addition of neutrons to iron (the s process). Since free neutrons first turn up in stars at the same time that helium nuclei are fusing to make carbon it is not a surprise that the barium stars are carbon rich. The correspondence between S-type stars and s-process elements is generally advertised as a coincidence, but B2FH when naming the latter were, of course, fully aware of the former.

A time scale for the s-process is set by the presence of technetium in some S stars. The longest-lived isotope hangs on for less than 10^6 years, and Paul Merrill,
finding Tc in 1952 (in spectrograms taken by Ira S. Bowen during the commissioning phase of the 200-inch telescope) deduced "a comparatively transient phase of stellar evolution." Later authorities concur. Tc and other s-process nuclides are produced and brought to the surface late in stellar evolution, when hydrogen and helium, both burning in thin shells around an inert core of carbon and oxygen, create zones of convection that chase each other back and forth through the stars. Stars in the relevant phase (called the asymptotic giant branch or AGB) end by expelling their envelopes and dying as white dwarfs about as fast as the Tc decays away. The mixing process is somewhat inelegantly called dredge-up.

So everything is accounted for and we can all go home? Even Merrill’s set of eight S stars had one (R Leo) with no Tc. In samples with less bias toward the very brightest stars, it is more like half with and half without. Apparently the phase lasts longer (or the Tc shorter!) than we expected. Worse is to come. The classic barium stars are not asymptotic giants. They are fainter ordinary giants, still burning only hydrogen, and not yet capable of dredge-up.

Then there are the CH stars—old, metal-poor, but carbon-rich, inhabitants of the galactic halo. The classic ones, picked out by our barium star friend Keenan in 1942 are, at least, giants, and so may have produced and dredged up enough carbon to be seen. (This is actually easier among metal-poor stars, since there is less oxygen needing to be soaked up in CO.) But CH subgiants also exist, and their 1974 discoverer, Howard Bond of the Space Telescope Science Institute, knew at once that they presented A Problem for the dredge-up model, since they are too faint even to have begun helium burning.

By now, I hope it is clear what these stars are doing in this article. Though all are brighter than the sun, the barium stars, CH subgiants, and some S type stars are too faint to have reached the evolutionary stage where they can pollute their own surfaces with carbon and s-process materials. The problem became acute with the discovery of the first dwarf carbon star by Conard Dahn of the U.S. Naval Observatory and his colleagues in 1977. Rejoicing in the name G77-61, it is about 1 percent as bright as the sun and has surely never done anything in its long, innocent life except proton-proton fusion of hydrogen. But it is carbon rich; and the discoverers suggested that it might have had carbon drizzled on it by an expanding asymptotic giant branch companion, now a white dwarf that has faded below visibility. The geometry of the equipotential surfaces around an orbiting pair of stars makes transfer of material from the big one to the little one almost 100 percent efficient in some circumstances. The surfaces are called Roche lobes (same guy as the Roche limit, and nearly the same geometry).

Interacting binary models for these problem stars caught on in a big way in 1980, when Robert McClure of the Dominion Astrophysical Observatory and others found that nearly all traditional barium stars were variable in velocity, that is, binaries with faint companions. A few of the white dwarfs can actually be seen (one pair eclipses), at least at ultraviolet wavelengths, where the hotter white dwarf has an advantage over the cooler barium star.

The polluting-companion explanation for barium stars met with initial resistance from many (including the present author), because it implied that carbon and s-process excesses should be just as common among main sequence stars as among giants. But barium stars, CH giants, and such were many, while only one dwarf equivalent had been found. Admittedly, that one, G77-61, is actually a spectroscopic binary, with a period of about a year.

Meanwhile, Hollis Johnson (Indiana University) was suggesting, and gradually accumulating evidence to show, that the S-type stars with Tc are mostly single, while those without Tc are all or mostly binaries, whose companions could also be the white dwarf relics of deceased AGB stars responsible, via mass transfer, for the chemical anomalies. The transfer, naturally, ended long ago, so that only stable s-process products remain,
and no technetium. Johnson presented this scenario very persuasively at a 1991 Symposium of the International Astronomical Union in Cordoba, Argentina. At any rate, it left me psychologically prepared for the next event.

Dwarf carbon stars turn out to be quite common. The inventory now exceeds the three required to constitute “a well known class of astrophysical object.” And when the news of numbers two through four arrived last spring, one could only exclaim, “They must be mass transfer binaries.” They are also very faint. This has two bad aspects and one good one. First, even finding them is a challenge. Second, if the others have velocity variations as small as the 5 km/sec of G77-61, detection of the companion is going to be a challenge. But, third, you see only the nearest ones, so that the five identified so far probably imply a total pool at least as large as that of giant carbon stars.

To recapitulate, both very bright, highly evolved stars and also fainter ones still in early, hydrogen-burning phases can show the same kinds of abundance anomalies—excess carbon and $s$-process elements—on their surfaces. The first sort did it to themselves through dredge-up; the second sort have been dumped on by now-deceased binary companions. Sorting out exactly which is which may take some time still, but I think we are almost ready to go home.

**PS: ABOUT THE TITLE**

Early in Act I of *All's Well that Ends Well*, Helena describes her feelings for Bertram as “...That I should love a bright particular star, And think to wed it, he is so high above me.” Since the play is a comedy, it naturally ends with them together (under happier circumstances than, say, Romeo and Juliet in Act V). The astronomical connection, apart from the obvious stellar one, is that Cecilia Payne Gaposchkin dedicated one of her books to “Sergei, that bright particular star.” But, as I said, her story is for another time.
A Research Physicist at Lawrence Berkeley Laboratory (LBL), GEORGE SMOOT is also a member of the Center for Particle Astrophysics and the Space Sciences Laboratory, both at the University of California, Berkeley. After earning his Ph.D. degree from MIT, he became involved in astrophysics at LBL, where he worked under Luis Alvarez.

In 1974 Smoot began measurements of the cosmic background radiation, leading a team that detected the "dipole" anisotropy caused by the Earth’s motion through the Universe. This led naturally to his current role as head of the group that developed the Differential Microwave Radiometer for NASA’s COBE satellite and used it to measure tiny ripples in this primordial radiation. In 1991 he was awarded the NASA Medal for Exceptional Scientific Achievement.

SERGEI KAPITZA earned his Ph.D. in geophysics at the Institute of Geophysics and a D.Sc. degree in physics from the Institute for Nuclear Research (Dubna) in 1961. Since 1956 he has been a member of the Institute for Physical Problems of the Russian Academy of Sciences. He is also Professor of Physics and Chairman of the Physics Department at the Moscow Institute for Physics and Technology, working on particle accelerators and synchrotron radiation.

Kaptiza has been extremely active in Soviet, Russian and international science policy circles, having served as Vice President of the European Physical Society from 1977 to 1980. He is currently Vice President of the Academy of Natural Sciences of Russia and president of the Euroasian Physical Society.

Since 1991 GEORGE BROWN has been a member of the Physics Faculty at the University of California, Santa Cruz. He did graduate work at Cornell University in high energy physics in the early 1970s, which led him into a synchrotron radiation research program at Bell Laboratories. In 1977 he came to Stanford to continue his studies in physics, biology and diagnostic medical imaging. Eventually he became head of the Accelerator Research and Operations division at Stanford Synchrotron Radiation Laboratory (SSRL). He continues to be active in synchrotron radiation research at SSRL, as well as in the planning for the Advanced Photon Source at the Argonne National Laboratory.
RAFE H. SCHINDLER is an Associate Professor at Stanford Linear Accelerator Center. After graduating from Rochester, he completed his Ph.D. at Stanford University in 1979 on the Mark I and Mark II experiments at the SPEAR storage ring. He spent several years at CERN, studying advanced hadron calorimetry techniques. Upon returning to the U.S. in 1983, he resumed his research interests in the weak decays of charm at Caltech, joining the Mark III experiment at SPEAR.

In 1985, Schindler joined the SLAC faculty and became a spokesman of the Mark III collaboration. He is an active member of the SLD doing b physics at the Z° and recently joined the PEP II detector effort at SLAC for the B Factory.

ROBERT SIEMANN is a Professor in the Accelerator Theory and Special Projects Department at SLAC. He spent 17 years at Cornell University before coming to SLAC three years ago and is well known throughout the world for his expertise in accelerator physics. He has worked on a number of high energy accelerators, including CESR, the Tevatron, and the SLC. He has written extensively about the single-beam stability, beam diagnostics, and the beam-beam interaction in electron-positron colliders. At present he is concentrating on aspects of the SLC operation including replacing the damping ring vacuum chambers to increase the intensity of the SLC.

VIRGINIA TRIMBLE comes naturally by her interest in stars, having graduated from Hollywood High School (also Toluca Lake Grammar School, Le Conte Junior High, UCLA, and Caltech). She has just handed over the chairmanship of the High Energy Astrophysics Division of the American Astronomical Society to a more deserving successor, but continues to serve as associate editor of the Astrophysical Journal, editor of Comments on Astrophysics, and vice-president of the International Astronomical Society Commission on Galaxies.
DATES TO REMEMBER

Feb. 16–18  Astrophysics Symposium on Dark Matter: Critique of the Sources of Dark Matter in the Universe, Berkeley, California [to be held in conjunction with Workshop on Strategies of the Detection of Dark Matter Particles, Feb. 20–23, 1994] (Melinda Laraneta, UCLA, Physics Department, 405 Hilgard Avenue, Los Angeles, CA 90024-1547 or LARANETA@PHYSICS.UCLA.EDU).

Feb. 20–26  Lake Louise Winter Institute on Particle Physics and Cosmology, Lake Louise, Canada (The Secretary, Lake Louise Winter Institute, Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1 Canada or LLWI@PHYS.UALBERTA.CA).

Mar 8–10  22nd INS International Symposium on Physics with High Energy Colliders, Tokyo, Japan (K. Hata, Institute for Nuclear Study, University of Tokyo, 3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan or INSSYMP @INSHEP.INS.U-TOKYO.AC.JP).

Mar 12–19  29th Rencontres de Moriond: Electroweak Interactions and Unified Theories, Les Arcs, France (Rencontres de Moriond Secretariat, Bat. 211, Universite de Paris-Sud, F-91405 Orsay, Cedex France or MORIOND@FRCPN11).

Mar 23–25  Harmonic Oscillators, Cocoyoc, Mexico (HO II: CIFMA AC: Apdo. Postal 139-B, 62191 Cuernavaca, Morelos, Mexico (CIFMA@CE.IFISICAM.UNAM.MX).

Mar 25–26  10th Pacific Coast Meeting, Corvallis, Oregon (Tevian Dray, Department of Mathematics, Oregon State University, Corvallis, OR 97331 or TEVIAN@MATH.ORST.EDU).

Mar 28–31  Workshop on Gamma-Gamma Colliders, Berkeley, California (Joy Kono, Center for Beam Physics, Lawrence Berkeley Laboratory 71-259, 1 Cyclotron Road, Berkeley, CA 94720 or (510) 486-5792 or CBP@LBL.GOV).

Apr 13–15  Conference on Quarks: The Third Generation—The Top and Bottom Quarks and Weak Interactions, Santa Barbara, California (James S. Langer, Director, Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106-4030 or DOREN@SBITP.UCSB.EDU).

Apr 15  Abstracts and summaries due for the 1994 IEEE Nuclear Science Symposium and Medical Imaging Conference, Norfolk, Virginia, October 30–November 5, 1994 (Rene Donaldson, SLAC, MS 68, Box 4349, Stanford, CA 94309 or RENED@SLAC.STANFORD.EDU).
Apr 20–24  International Workshop on Superconductivity and Particle Detection, Toledo, Spain (Ms. Mercedes Fatas, Instituto de Fisica Nuclear y Altas Energias, Universidad de Zaragoza, 50009 Zaragoza, Spain or FATAS@GAE.UNIZAR.ES).

Apr 21–27  Computing in High Energy Physics, San Francisco, California (M. O. Field, Lawrence Berkeley Laboratory, 50F, 1 Cyclotron Road, Berkeley, CA 94720 or CHEP94@LBL.GOV).

Apr 25–27  5th Annual REXX Symposium for Developers and Users, Boston, Massachusetts (Cathie Burke Dager, SLAC MS 97, Box 4349, Stanford, CA 94309 or CATHIE@SLAC.STANFORD.EDU or BEBO@SLAC.STANFORD.EDU).


May 14–17  Supersymmetry 94, Ann Arbor, Michigan (Kate Logan, University of Michigan, Ann Arbor, MI 48109 or LOGAN@MICH.PHYSICS.LSA.UMICH.EDU).

May 26–31  14th International IUPAP Conference on Few Body Problems in Physics, Williamsburg, Virginia (Conference Coordinator, CEBAF, MS 16A, 12000 Jefferson Avenue, Newport News, VA 23606 or FBXIV@CEBAF.GOV).

May 29–Jun 3  Neutrino 94: The 16th International Conference on Neutrino Physics and Astrophysics, Eilat, Israel (Neutrino 94 Secretariat, Mrs. Elizabeth Youdim, Department of Physics, Technion, Israel Institute of Technology, Haifa 32000, Israel or NEUTRINO@VMSA.TECHNION.AC.IL).


Jun 29–Jul 14  1994 DPF Summer Study on High Energy Physics: Particle and Nuclear Astrophysics and Cosmology in the Next Millennium, Snowmass, Colorado (C. M. Sazama, Fermilab, Box 500, Batavia, IL 60510 or SAZAMA@FNAL.GOV).

Aug 8–Aug 19  22nd Annual SLAC Summer Institute on Particle Physics, Stanford, California (Conference Coordinator, MS 62, SLAC, Box 4349, Stanford, CA 94309).

Oct. 30–Nov. 5  IEEE Nuclear Science Symposium and Medical Imaging Conference, Norfolk, Virginia (Rene Donaldson, SLAC, MS 68, Box 4349, Stanford, CA 94309 or RENED@SLAC.STANFORD.EDU).