SUMMER 1982 VOLUME 3, NUMBER 2

Los Alamos Science

LOS ALAMOS NATIONAL LABORATORY

Inside This Issue

EDITOR'S NOTE

Science and technology try to find and fashion the order in nature, but as much as the planners would have it otherwise, this creative process, rather than being orderly, is filled with paradox and surprise. That a mission-oriented laboratory, devoted primarily to weapons development, provides an environment where this process can flourish is itself paradoxical. But the facts speak for themselves. This issue presents three exciting research projects that emerged in surprising ways from weapons research and development.

The first is the work on gamma-ray bursts. These dynamic stellar events, clues to our changing universe, were discovered as a result of the Vela satellite-surveillance mission to detect exo-atmospheric nuclear weapons tests. The discovery surfaced unexpectedly from persevering, mission-oriented efforts at Los Alamos to remove ambiguities from the data and to differentiate local from cosmic events. The same care and caution that characterized the surveillance studies is present in this issue's article on the current understanding of gamma bursts. While the editors are privy to the authors' lively speculations, the authors preferred to omit them from the article because as part of a national laboratory they see themselves as more vulnerable to criticism than their counterparts in academia. This curious blend of boldness and caution is a fact of life at the Laboratory. It can be both a virtue and a handicap in the process of discovery.

The nuclear microprobe, a new instrument to examine the elemental composition of very small objects, is the second subject in this issue. This instrument, together with other techniques, has given a new lease on life to the Van de Graaff accelerator. Once an indispensable tool in the weapons program for studying low-energy nuclear reactions, its continued importance for this purpose is under discussion. In the meantime it has given birth to a new and very sensitive tool for materials analysis. The nuclear microprobe uses the ions from the Van de Graaff to probe the subsurface region of geologic, biological, and synthetic materials. Interpretation of the data, which depends, of course, on the vast body of low-energy nuclear data collected at the Van de Graaff by nuclear physicists, is leading to greater understanding of the formation of geologic materials, the operation of technological devices, and the synthesis of new materials.

The third subject is an intriguing experiment to measure the solar neutrino flux over geologic times as a test of the standard models of stellar evolution. The experiment entails isolating and counting very rare isotopes of technetium produced by the interaction of solar neutrinos with deeply buried molybdenum. The commercial molybdenum recovery process goes a long way toward isolating these isotopes. The final counting, however, will require drawing on and adding to analytical techniques developed over the years for weapons diagnostics.

These tales of synergy are common at Los Alamos and are appreciated by the new leader of our Life Sciences Division, Mark Bitensky. With bold vision Mark has outlined an astounding array of exciting opportunities in biological and biomedical research made possible by the unique combination of talent and facilities in the Laboratory's forte—the *physical* sciences. What combination of boldness and caution can see through the present tight budgetary climate to the realization of these dreams of synergy?

Necia Grant Cooper

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Errata: Los Alamos Science *apologizes for the misspelling of Roy Feber's name (Volume 3, Number 1, page 34) and for omission of credit to Sheila Satkowski for black and white photo laboratory work in the same issue.*

Los Alamos Science

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CONTENTS

On the Cover.
Artist's conception of the source of a gamma-ray burst. In this hypothetical model a neutron star ejects a fountain of plasma whose base, at a temperature of several billion kelvins, emits gamma-rays. Typically, neutron stars are about the size of a small town whereas the plasma fountain may extend the length of the state of New Mexico.

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THE SOURCE TERM ISSUE

I write to bring you and your readers up-to-date on some recent developments in reactor safety. The iodine issue discussed in Volume 2, Number 2 of *Los Alamos Science* has been enlarged to include careful consideration of all fission products created in a nuclear reactor. This broadened matter is known as the source term issue.*

Briefly, it is now generally conceded that the predominant chemical form of iodine when it escapes from very hot fuel is iodide and probably cesium iodide (CsI). This conclusion immediately raises the question of the chemical form of the remaining cesium, as there are about 11 times as many cesium atoms created by fission as there are iodine atoms. The answer is cesium hydroxide (CsOH), since water (or steam) is always present in a light-water reactor and CsOH is thermodynamically the most stable form after CsI. Thus, the two most important fission products in terms of their threat to the health and safety of the public are in the form of chemical compounds that are not especially volatile (compared to I_2 or Cs) and that are very highly soluble. Once in solution these remain in solution, and little or none is ever again airborne. These fission-product compounds will accumulate in the water and wet steam and on the wet surfaces invariably present in the primary system and containment of a light-water reactor following an accident that ruptures the primary system and allows the escape of fission products from the fuel.

Examination of the behavior of some other less abundant or significant fission products is yielding comparably reassuring results.

These and other studies (for example, on containment integrity) suggest that the WASH-1400 source term estimates for the most dangerous fission products may be too high by a factor of 10 and possibly by a factor of 100 or more. If the new estimates are correct, their use in consequence models of even the worst accidents (including containment failure) would lead to predictions of no early fatalities. Thus, the importance of the source term issue and its resolution is evident. It may be the case that the worst reactor accident is less severe than serious accidents in other industries.

This issue has attracted the attention of the entire nuclear reactor community, both nationally and internationally. Both the NRC and the DOE have investigations underway. The Electric Power Research Institute (EPRI) and an industrial group known as the Industry Degraded Core Rule Making Program (IDCOR) are working on the problem. Abroad, West Germany has analyzed aspects of the issue, and the IAEA has held one meeting on the subject and has scheduled a second. Most recently, the American Nuclear Society has created an ad hoc committee** to prepare a comprehensive document on the source term issue. All of these efforts should be completed in about a year. Clearly, exciting times are at hand in this important technical area and major changes in our perception of the hazards of nuclear power stations are in the making.

W. R. Stratton
Los Alamos, New Mexico

Editor's Notes:

**By source term is meant the fraction of fission products that is assumed to escape from overheated fuel and move to the containment as volatile species should a major coolant pipe rupture and the ECCS fail and then to escape to the atmosphere should the containment be breached. The predicted consequences of a reactor accident depend strongly on the assumed source term.*

***W. R. Stratton has recently been appointed chairman of this committee.*

RADIATION PROTECTION SPECIALISTS LEAD THE WAY

The article entitled "Low-Level Radiation—How Harmful Is It?" in Volume 2, Number 2 of *Los Alamos Science* gave a good general summary of our current understanding on the risk of health effects resulting from low exposures to ionizing radiation, and it also described the various regulations developed to keep exposures to workers within safe levels. The description of the current radiation limits, however, was not correct for DOE contractor workers, such as Los Alamos National Laboratory employees. The annual limit in the current DOE regulations is 5 rems per year, not 12. By approval from the Deputy Assistant Secretary for Environmental Safety and Health, the contractor may get permission in special cases to exceed 5 rems in a year—an administrative procedure that will surely not be tried often. The point is that the DOE regulations are more restrictive than those discussed in the article. That the actual exposures in the workplace are much less than the regulations permit was properly pointed out in the article. Among all Laboratory workers monitored for external radiation for the past 5 years, 98 per cent had annual exposures under 1 rem and 99.4 per cent were under 2 rems.

Radiation effects have been the center of considerable controversy. Why? In my opinion, it is because the risks after typical exposures are so low that there is no way of observing health effects, principally cancer, as compared to the much larger number of cancers from all causes. This leads to multiple models, theories, and speculations without benefit of data at these low exposure levels. There is also the philosophical hurdle of deciding when one is safe. Safe is usually considered being free from harm or risk. There is nothing we do in life that is truly safe. For example, even sleeping for longer periods, like 10 hours, results apparently in a small increase of strokes and blood clots. In radiation matters, scientific committees recommend exposure guidelines that they judge will result in no greater risk after lifetime exposures at the maximum values than the risks for other serious injuries or illnesses in safer industries or occupations. These are experienced judgments that are always open to challenge; hence, controversy.

It is generally not appreciated how unique it was that radiation protection specialists felt that these small, undetectable health risks should be estimated and be used in setting standards. This was new for health protection—that is, to provide protection for levels of exposure that may produce potential effects or disease although these were not observable directly by scientific methods. In contrast, exposure regulations for other toxic materials were set at levels somewhat below those that produced acute or subacute effects, that is, recognizable symptoms or signs of toxicity. The concept of protecting against possible unrecognized injury, such as the small risk of induction of cancer years later, was new with radiation protection. In the past decade or so, this same philosophy of protection is beginning to be applied to regulations on exposure to toxic metals and chemicals in a manner similar to those used in radiation protection for more than 30 years. In effect, radiation protection specialists have led the way. As shown by the swirl of controversy, trail blazing is not an easy task. I believe radiation protection specialists in the formative years of the nuclear industries should be recognized for their foresight and concern.

George L. Voelz, M.D.
Assistant Health Division Leader
for Health and Research
Los Alamos National Laboratory
Los Alamos, New Mexico

PEDAGOGY IN REACTOR SAFETY

I have been giving a series of lectures for IAEA to a group of scientists and engineers from developing countries on the subject of PWR safety. For my main reference in discussing emergency core cooling I used your fine article, "Accident Simulation with TRAC," in the latest issue of *Los Alamos Science*. You provided a clear and vivid picture of the accident and recovery and I believe the students benefited greatly. I was much interested in the pedagogical virtue of your modeling of reactor components as variants on a pipe.

I'm working on a set of simple educational modules in nuclear engineering that include theory, calculation method, computer program, and illustrative example. They are intended to demonstrate concepts and allow the student to vary parameters and modify or expand the program. For the preparation of one on LOCA/ECCS I need to go one step further than the article, to the issue of the model used in TRAC. It would be too big a job for me to learn all the great detail that I know is involved in such a comprehensive code. Can you suggest a program of reading and study that would put me in good position to prepare such a module? Any written material would be helpful. Many thanks and best regards.

Raymond L. Murray
Professor of Nuclear Engineering
North Carolina State University
Raleigh, North Carolina

Editor's Note: In response to this letter, addressed to the authors, John C. Vigil sent the manual for the latest TRAC version to Professor Murray and recommended the references it contained as additional helpful material.

I was delighted to receive a copy of *Los Alamos Science*, Volume 2, Number 2, on Reactor Safety. This is a superb collection of articles on one of the most important technical issues we are faced with.

The timing couldn't have been better as my upper-level graduate course, Two-Phase Flow and Boiling Heat Transfer, is rapidly heading toward application topics which include thermal-hydraulic issues in nuclear reactor safety. I may use *Los Alamos Science* as class notes for this important part of my course.

Arthur E. Bergles
Distinguished Professor and Chairman
Department of Mechanical Engineering
Iowa State University
Ames, Iowa

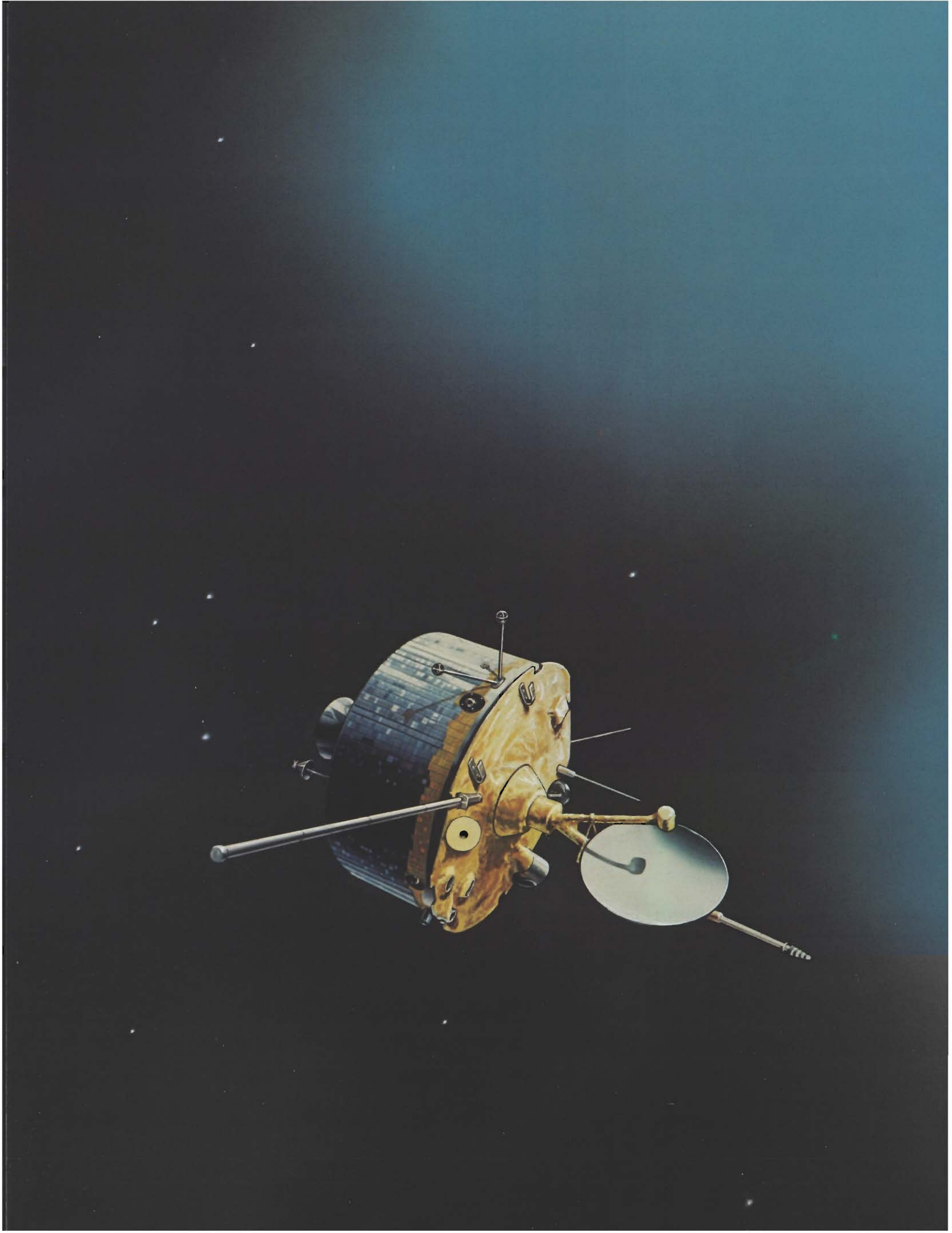
THANKS FROM AGNEW

I'm finally getting around to thank you (Barb Mulkin) for the idea of the interview. In such articles one always wonders afterwards why one said this or that or why one didn't say something else. I believe that you did a great job and I appreciate your endeavors very much. Suggest if you reprint it that the picture on page 155 should carry the caption, "You mean I have to spend another year in San Diego?" Actually it isn't all that bad and each year Beverly and I have a harder time trying to decide what to do.

Keep up the good work and please tell Necia the magazine continues to be a smashing piece of work. Really impressive!

Harold M. Agnew
President
General Atomic Company
San Diego, California

Your comments on articles appearing in Los Alamos Science are welcome. Please address them to Editor, Los Alamos Science, Los Alamos National Laboratory, Mail Stop M708, Los Alamos, NM 87545.



Cosmic Gamma-Ray Bursts

—a continuing mystery

by Ray W. Klebesadel, W. Doyle Evans, Edward E. Fenimore, John G. Laros, and James Terrell

Orbiting detectors have revealed the variable nature of gamma-ray bursts. While the bursts probably originate from neutron stars, the generating mechanism remains enigmatic.

The discovery, in 1973, of cosmic gamma-ray bursts created tremendous excitement in the astrophysics community. These bursts had been recorded by gamma-ray detectors aboard the Vela nuclear-test surveillance satellites. Despite the detection of about a hundred such events in the ensuing years, enthusiasm toward gamma-ray bursts gradually waned because detailed information was lacking. However, on March 5, 1979 an event was recorded that was unprecedented in the annals of gamma-ray burst astronomy. Six of the ten spacecraft recording this event carried the first generation of instruments specifically designed to characterize gamma-ray bursts. The detectors were built to record events ten times more intense than any previously observed burst, yet even these were driven to the brink of saturation. Although distinctly different in important details from typical gamma-ray bursts, this event was closely related phenomenologically, and it inspired vigorous new efforts to model gamma-ray bursts.

The Pioneer Venus Orbiter, a distant member in an international network of satellites that detects and locates cosmic gamma-ray bursts.

The burst originated from the precise direction of an extragalactic supernova remnant in the Large Magellanic Cloud, 180,000 light years from the earth. If the source was, indeed, within the Large Magellanic Cloud, the peak intensity of gamma rays briefly exceeded the luminosity, at all wavelengths, of the entire Milky Way Galaxy. A consensus had been developing that the sources of the bursts must be located within our own galaxy, yet this event—clearly the brightest ever seen and the first for which a source identification could be suggested—seemed to lie within a neighboring galaxy. Theoreticians struggled in attempts to propose mechanisms to explain the event, but many concluded that the suggested association could only be accidental.

To date there is no completely satisfactory explanation of the March 5, 1979 event—or, for that matter, of any other cosmic gamma-ray burst. The data have considerably improved, both quantitatively and qualitatively, since the early 1970s, but the increased knowledge has not yet led to any single model that satisfactorily describes the data. Rather, the data have only eliminated from contention a number of proposed models. In addition to the seriously proposed models, the *National Enquirer* in 1979 fantasized that the explanation was real-life star wars between alien civilizations somewhere in outer space. There is one point, however, on which everyone agrees: Satellite detection of gamma-ray bursts has opened a new window on the universe. These sudden, intense bursts of energy show an aspect of the universe that is much more chaotic and transient than had previously been imagined by either casual star-gazers or professional astronomers.

Our Changing View of the Universe

Ancient astronomers believed that the universe was largely ruled by static regularity, although meteors, comets, and such rare visible supernovae as the one observed in the constellation Taurus by Chinese and American Indian astronomers in 1054 contradicted this picture. With the development of the telescope, more distant, fainter supernovae, as well as other classes of stellar variability, were seen with increased frequency. Nevertheless, the mistaken impression of regularity and slow evolution in the universe persisted into the 1960s.

The feeling that transient cosmic events were rare was certainly prevalent in 1959 when summit meetings were being held between England, the United States, and Russia to discuss a nuclear test-ban treaty. One key issue was the ability to detect treaty violations unambiguously. A leading proposal for the detection of exo-atmospheric nuclear explosions was the use of satellites with instruments that included detectors sensitive to the gamma rays emitted by the explosion as well as those emitted later during the radioactive decay of the fission products. During the discussion of the capabilities of these satellites, Stirling Colgate (currently a Laboratory scientist, but at that time attached to the U.S. State Department) suggested that gamma rays from a supernova might resemble the radiation of a nuclear test explosion closely enough to trigger an alarm by the satellite detection system. Could this rare event lead to dangerous accusations of a treaty violation? Were there characteristics of a supernova outburst that would distinguish between a weapon test and a cosmic burst?

In the early 1960s, Los Alamos scientists Jack Asbridge, Sam Bame, Jerry Conner, Ray Klebesadel, and Sid Singer, directed by Jim Coon, designed and built detectors for exo-atmospheric nuclear-test surveillance. In the period from 1963 to 1970 six pairs of the Air Force Vela satellites carrying these detectors were placed in orbit far beyond the atmosphere (which absorbs gamma rays and other nuclear radiations). While these detectors served a number of valuable scientific functions, the initial examination of the gamma-ray data emphasized the spacecraft's primary mission to gather information critical to U.S. security.

Stirling Colgate and Edward Teller had followed up Colgate's summit meeting comment by making specific predictions in 1965 of gamma-ray emission during the initial stages of the development of supernovae. They suggested that examination of the Vela data might disclose evidence of bursts of gamma rays at times close to the appearance of supernovae. Such searches were conducted; however, no distinctive signals were found.

On the other hand, there was evidence of variability that had been ignored. For example, the earliest x-ray data from small rocket probes and from satellites were often found to disagree significantly. The quality of the data, rather than actual variations in the sources, was suspected as the reason for these discrepancies. Also, a background of transient detector responses in much of the x- and gamma-ray data masked the similar responses to true cosmic bursts. These background responses were generated by a variety of mechanisms, many due to local effects of charged particles trapped in the earth's magnetosphere and others due to instrumental "glitches" (such as high-voltage arcing, electronic crosstalk, or telemetry errors). The Vela instruments responded to these spurious signals frequently enough to discourage careful inspection of every record. However, if the signals were spurious, it would be improbable for more than one Vela satellite to have responded at the same time. Thus, to identify nonspurious events, the data were searched for those occurring nearly simultaneously between spacecraft. However, data records were referenced only to the independent clocks in the spacecraft. These had to be referred to a common time in order to determine simultaneity. Moreover, the detection systems produced copious numbers of spurious records. Only the application of computerized data processing allowed the search for simultaneity to be performed on this volume of data.

Since the concept of a nearly static universe prevailed at this time, it was not expected that the search would reveal anything extraordinary. The intention was to verify that there were no natural background events that would mimic the signature of an exo-atmospheric nuclear detonation. Surprisingly, however, the survey soon revealed that the gamma-ray instruments on widely separated satellites had sometimes responded almost identically. Some of these events were attributable to solar flare activity. However, one particularly distinctive event was discovered for which a solar origin seemed inconsistent. Fortunately, the characteristics of this event did not at all resemble those of a nuclear detonation, and thus the event did not create concern of a possible test-ban treaty violation.

This first tantalizing indication of a cosmic gamma-ray burst had been found in 1969. By 1972, an extension of the search had revealed a surprising number of events—sixteen bursts over a three-year period. Each of these bursts, for intervals of up to several seconds, dominated the gamma radiation of the entire sky. It was only then that the violent behavior of the cosmos became clear: chaos and rapid change prevail in the x-ray and gamma-ray regime.

Evolution of Detector Systems

Despite the remarkable nature of these events, full awareness of the implications of the phenomenon developed only gradually. In fact, other evidence of variability, such as was observed in the quasar 3C273 in 1963, was only then causing astronomers to reconsider seriously their view of the universe. As the picture of the universe changed, new instruments were designed and placed aboard satellites to answer a growing list of questions. However, the long lead times and the space and weight limitations of satellite experiments did not allow rapid action toward answering these questions. Fortunately, scientists associated with other space projects graciously allowed the piggybacking of unscheduled gamma-ray burst experiments, thus circumventing the usual delay of several years until the next generation of satellites could be put into orbit.

One of the first questions to be addressed

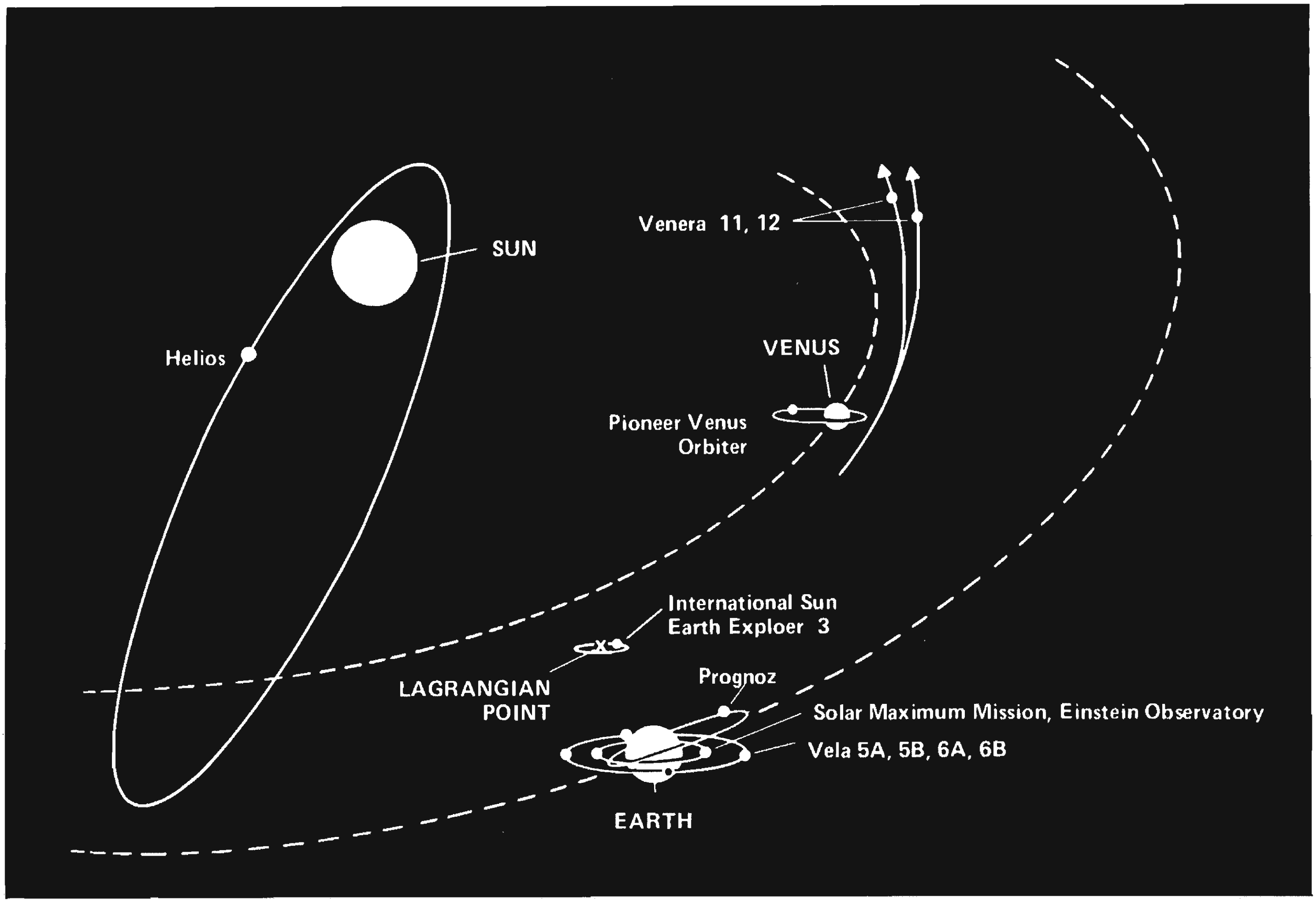


Fig. 1. Satellite network. The four main groups of satellites used from 1978 to 1980 to detect and locate precisely the direction of gamma-ray bursts are here represented schematically. The near-Earth group consisted of eight satellites including four Vela satellites and three others in geocentric orbits. Also considered a member of this group was the International Sun Earth Explorer 3 satellite (ISEE-3) located at one of the gravitationally metastable Lagrangian points. Two "groups" consisted only of single satellites: the Helios 2 satellite in orbit about the sun and the Pioneer Venus Orbiter at Venus. The fourth group comprised the two Soviet Venera satellites in solar orbits past Venus.

was how rapidly the intensity of a burst varied. The original Vela satellites carried Los Alamos instruments designed to respond to, among other things, the gamma rays from the fission debris of nuclear tests. Because such radiation would last for a relatively long time, the earliest Vela detectors provided only 32-second resolution. The third pair of Vela satellites (Vela 3) were sent aloft with detectors that included triggering systems designed to respond automatically to sudden increases in the signal, recording fractional-second time variations. It was an improved version of those detectors, carried by Vela 4, that first revealed the rapid variability found in the gamma-ray energy regime.

It was obvious that an understanding of gamma-ray bursts would be greatly assisted if it were possible to identify the source objects. The Vela observations provided a capability to locate sources of some events to within a few degrees. Although this was sufficient to exclude the sun and the planets, it was totally inadequate to identify uniquely the actual source objects from among the many stars included within this region. Thus, a considerable improvement in the resolution of the source locations was needed. The technique first employed in locating the sources depended on differences in the signal's times of arrival at members of the distributed array of Vela satellites (see sidebar "Time-of-Arrival Location Technique"). This technique could be made more accurate in two ways: by measuring the arrival times more accurately and by increasing the differences between the arrival times (by increasing the distances between satellites). Sufficient improvement in measuring the times of arrival was impractical. The most reasonable approach toward providing improved precision in locations was to increase the distances between satellites. Thus, a number of spacecraft were equipped with modest instruments designed to record these events and were distributed over interplanetary distances.

By 1979 the far-flung network of satellites was in place (Fig. 1 and Table I). The international consortium cooperating to establish this network included scientists from the United States, France, the USSR, and Germany. Tom Cline, at the NASA Goddard Space Flight Center, provided a gamma-burst instrument for the German/American Helios-2 satellite. Another American scientist, Kevin Hurley, at the Centre d'Etude Spatialle des Rayonnements in Toulouse, France, designed detectors that were mailed

TABLE I

INTERNATIONAL ARRAY OF SATELLITES FOR DETECTION OF BURSTS

Satellite	Launch Date	Orbit Description	Institution Responsible for Gamma-Ray Instrumentation	Present Status
Vela 5A, 5B, 6A, and 6B	1969, 1970	Geocentric at 1.2×10^5 km from Earth	Los Alamos	Active
International Sun Earth Explorer 3 (ISEE-3)	1978	At a Lagrangian point 1.5×10^6 km from Earth	One instrument by University of California, Berkeley/ Los Alamos and two other instruments by NASA Goddard Space Flight Center	Healthy
Prognoz 7	1978	Geocentric, highly elliptical	Centre d'Etude Spatiale des Rayonnements (Toulouse)	Telemetry lost in 1980
Einstein Observatory (HEAO-2)[a]	1978	Geocentric, very near Earth	---	Pointing ability lost in 1981
Solar-Maximum Mission[a]	1979	Geocentric, very near Earth	---	Partially active
Helios 2	1976	Heliocentric, highly elliptical	NASA Goddard Space Flight Center	Telemetry lost in 1980
Pioneer Venus Orbiter	1978	Highly elliptical about Venus	Los Alamos	Healthy
Venera 11 and 12	1978	Heliocentric with the two satellites diverging from each other	On each satellite one instrument by Centre d'Etude Spatiale des Rayonnements (Toulouse) and a second by A. F. Ioffe Physico-Technical Institute (Leningrad)	Telemetry lost in 1980

[a] A NASA-launched satellite carrying instruments not specifically designed to observe gamma-ray bursts. The data collected were, however, helpful in analyzing gamma-ray bursts. Several institutions were responsible for the instruments aboard.

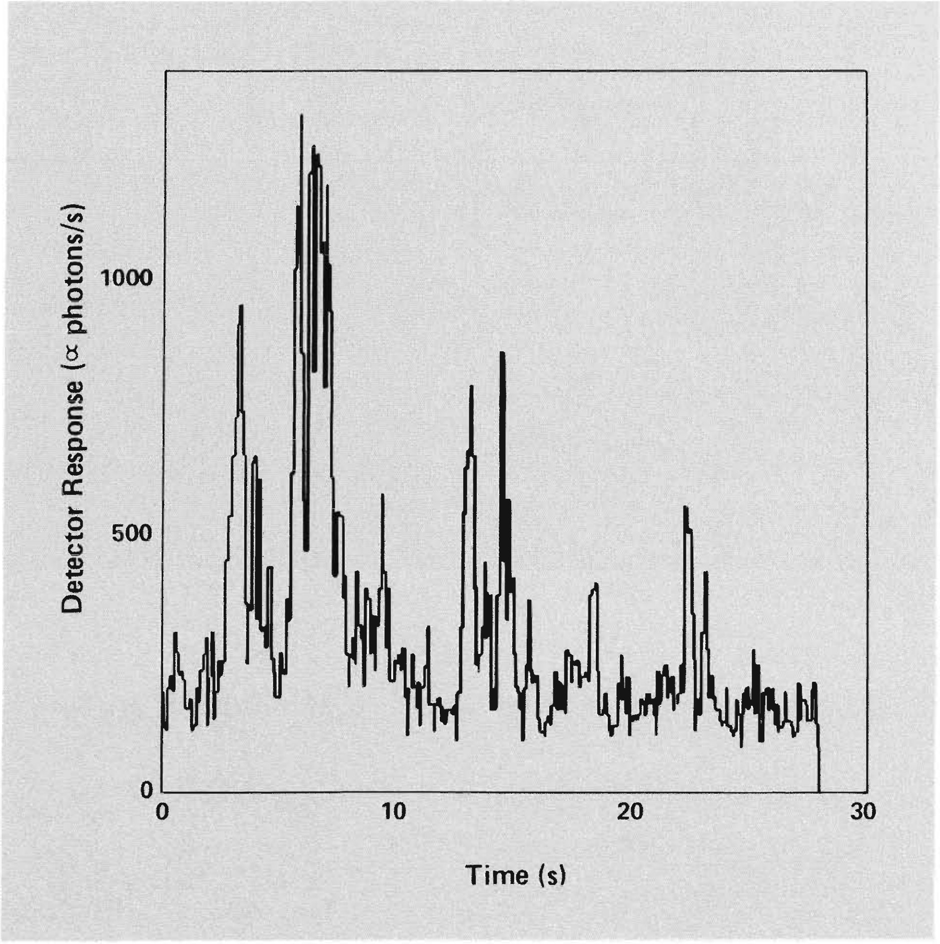


Fig. 2. Time dependence of burst intensity. These data, taken on November 4, 1978 with the Los Alamos gamma-ray detection system aboard the Pioneer Venus Orbiter, illustrates the dramatic, highly variable nature of a typical gamma-ray burst.

to Siberia and placed on Soviet spacecraft. In addition to the instruments aboard the Vela satellites, Los Alamos contributed toward this network with a modification to the University of California, Berkeley Solar X-Ray Spectrometer (aboard International Sun Earth Explorer 3, or ISEE-3) that allowed the instrument to record temporally resolved spectral data for both gamma-ray bursts and solar flares. Also, in a joint development with Sandia National Laboratories, Los Alamos supplied the gamma-ray burst monitor that has been operating aboard the Pioneer Venus Orbiter since May 1978 (see sidebar "Eyes for Gamma Rays" for a description of this system). This network of satellites has been used to determine precise locations for several intense bursts to within one arc-minute of uncertainty.

Typical Gamma-Ray Bursts

Many of the second generation of gamma-burst monitoring instruments were in operation during a burst recorded November 4, 1978. This event is the third most intense burst yet observed, and its features are typical of most gamma-ray bursts. Figure 2 shows a record (from Pioneer Venus Orbiter) of the burst's behavior in time. Its intensity rises and falls dramatically in fractions of a second. A number of distinct outbursts, each lasting on the order of a second, are clearly isolated by periods in which the signal has returned nearly to the background level. Even within the individual outbursts there are statistically significant variations. Although the major peaks suggest a periodicity, detailed analysis does not indicate that the behavior is strongly periodic.

RAPID VARIABILITY. Rise and fall times of about 0.01 to 1 second are characteristic of gamma-ray bursts. These times can be used to obtain a qualitative insight into certain physical attributes of the burst emission region. For example, there is a simple constraint on the source size because the fluctuation time scale cannot be much faster than the travel time of light across a typical source dimension. For a 0.1-second rise time, a source size less than about 30,000 kilometers is inferred. This is extremely small on an astronomical scale and indicates that compact objects such as white dwarfs, neutron stars, or black holes are logical candidates for the burst sources. Of course, if the emission region is very small (a neutron star is only about 10 kilometers across), the characteristic burst time scales probably reflect other dynamical time scales of the system such as a heating or cooling time.

MULTIPLE OUTBURSTS. Another important time-dependent feature of typical bursts is the complexity of burst waveforms, with multiple outbursts occurring over intervals of tens of seconds (Fig. 2). This implies a mechanism that is not catastrophic. For example, a supernova explosion would be expected to produce a single outburst. Further, the multiple bursts do not show strong evidence for periodicities. However, the burst waveforms often contain similar, repeating patterns that suggest systematic and reproducible mechanisms at work. Additionally, Vela x-ray observations have recently disclosed repeated outbursts of x rays associated with gamma-ray bursts. The initial gamma-ray bursts extended to x-ray energies and were followed by additional, weaker x-ray outbursts occurring over intervals of hundreds of seconds. No gamma radiation was observed coincident with these latter x-ray bursts, so the question remains whether these are truly gamma-ray bursts detected only by the x-ray instruments or are softer x-ray outbursts.

THE ENERGY SPECTRUM. The energy to which the Vela 4 instruments responded gave the first indication that gamma-ray photons characterized these bursts, and the difference in energy response of detectors in the Vela 5 and Vela 6 spacecraft further confirmed the

time-of-arrival location technique

Gamma-ray bursts occur unpredictably in time and in location. Instruments with an inherent capability to locate these bursts precisely are extremely complex and, indeed, not yet fully developed. However, the locations of burst sources can be determined with relatively simple instrumentation from the arrival times of the burst wavefront at each of several widely separated satellites. The absolute difference Δt in the arrival time of the signal at any two satellites is directly related to the absolute difference in the path length d over which the signal travels ($d = c\Delta t$). With only two satellites the many locations that satisfy this relationship define a hyperboloid of revolution about the line between the two satellites. As shown in Fig. 1a, this hyperboloid of revolution may be approximated by a cone if the distance to the source is large compared to the distance between the satellites. If observations from a third satellite are available, the allowed locations are reduced to two directions in space defined by the intersections of two such cones (Fig. 1b). One of these is the true location of the source and the other is its mirror image in the plane defined by the three satellites. Addition of a fourth satellite, not located in the same plane, allows discrimination against this mirror image.

In practice the cones are presented as their circular projections on the celestial sphere. Also, in accounting for the uncertainties in defining these circles, they must be presented

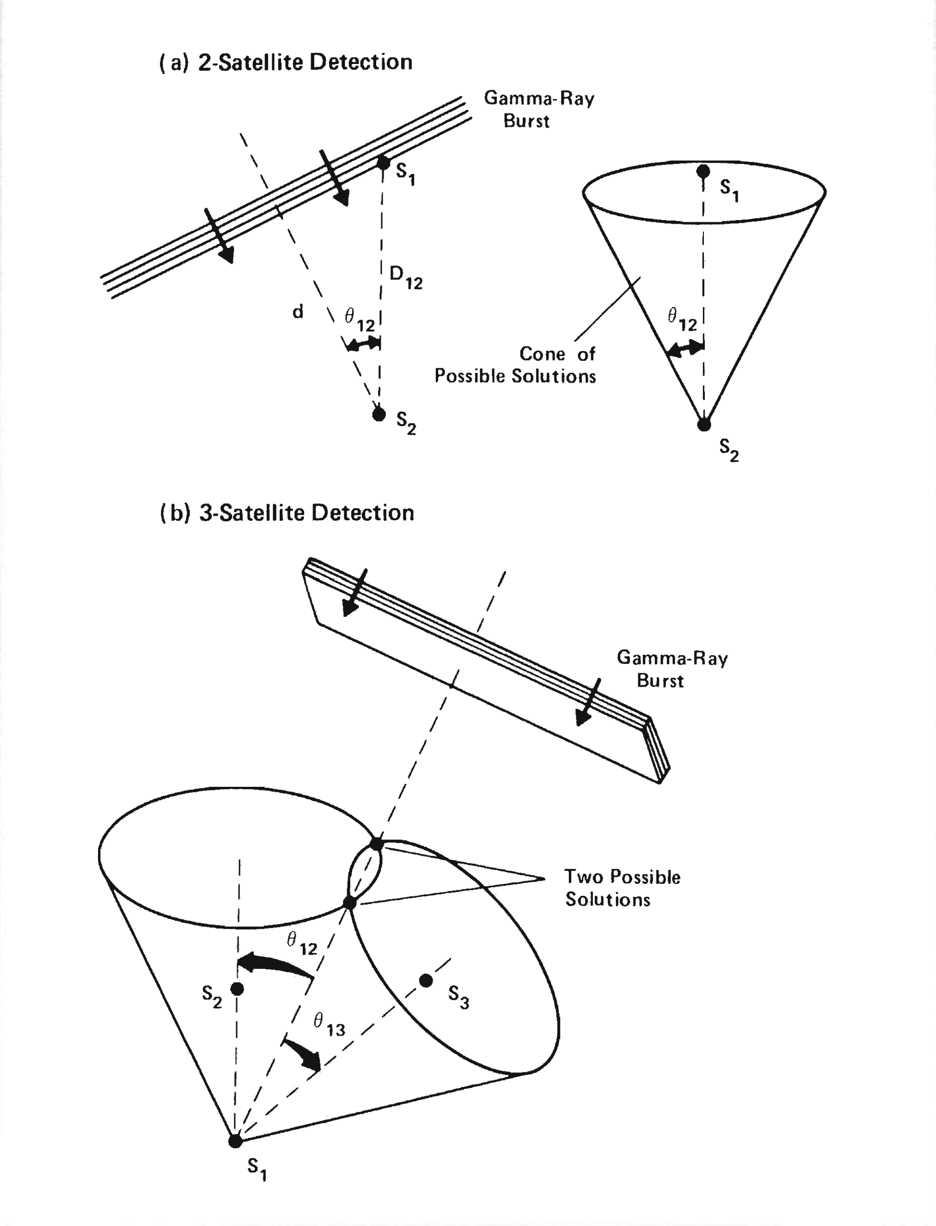


Fig. 1. Time-of-arrival location technique. (a) When a cosmic gamma-ray burst is detected by two satellites (S_1 and S_2), the angle θ_{12} between the line connecting the satellites and the direction of motion of the burst wavefront can be calculated using the known separation D_{12} between the satellites and the distance d determined from the difference in arrival times of the burst at the satellites. This angle gives a cone of possible directions to the gamma-ray burst source. (b) With three satellites, two solution cones are generated, and the intersections of these cones give two possible directions.

Sidebar 1

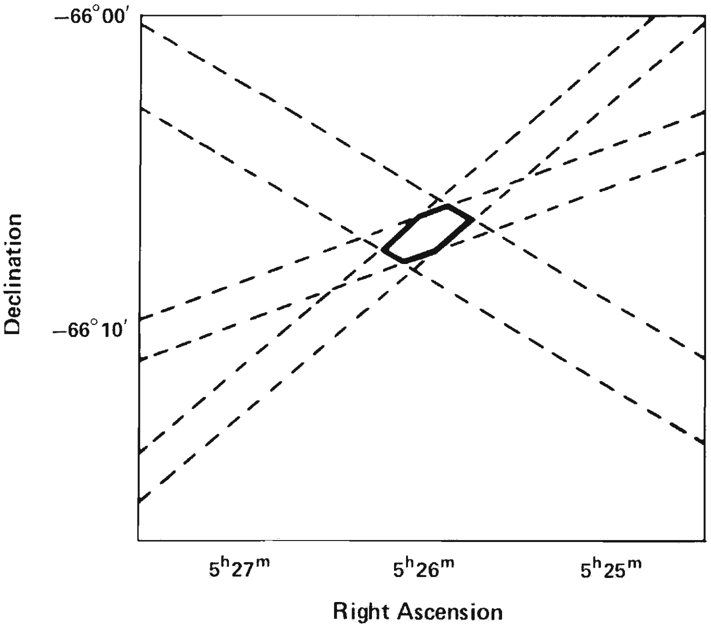


Fig. 2. The location box. The dashed bands here are the projections of the cones and their associated uncertainties onto the celestial sphere for the initial determination of the March 5, 1979 burst. The polygon resulting from the intersections of the bands contains the location of the source.

as annular bands, the widths of which are proportional to the estimated uncertainty. The intersections of these bands define an "error box" that contains the location of the source (Fig. 2).

In the present detection network, satellites that are close to each other (for example, the group in orbit about the earth) do not generally improve the accuracy of the location. However, if a variety of detection systems are present in such a cluster, the data can be crosschecked, systematic errors can often be identified, and the arrival time at this cluster determined with a high degree of confidence. For an observation performed by a single satellite, or two identical satellites, it is difficult to verify that there are no systematic errors remaining in the data.

Thus, various factors, including the intensity of the event, the presence of bold temporal features that can serve as identifiable time markers from detector to detector, the spatial distribution of the members of the array at the time of the event, and the availability of shared data, affect the accuracy with which the location of the source can be resolved. The intensity, rapid rise time, and redundancy of observation of the March 5, 1979 burst gave the members of the international consortium an opportunity to verify the accuracy of the location technique. While a number of systematic errors were disclosed and corrected in the analysis of this event, a discrepancy that exceeds the anticipated errors still remains in the analysis of some other events. ■

nature of the spectrum. The Vela 5 detectors responded to photons with energies between 150 and 750 kiloelectron-volts (keV), whereas the Vela 6 detectors responded to somewhat higher energies between 300 and 1500 keV. A comparison of the response of both systems to the same events provided the first crude indication of the energy spectrum. Soon, however, measurements by true spectrometers became available. For example, instruments aboard two International Monitoring Platform satellites (IMP 6 and 7) measured the spectral distribution of many events more definitively. Over the energy range of the measurements, the observations could be fit by a simple exponential function with a characteristic index of 150 keV; that is, the number of photons at energy E is proportional to $\exp(-E/150)$.

A few bursts, however, have been observed by x-ray detectors with responses down to lower photon energies. One of these measurements (performed from Apollo 16) demonstrated that the spectral distribution for that event was consistent with the shape expected for thermal bremsstrahlung from an optically thin plasma at temperatures of several billion kelvins (thermal bremsstrahlung is discussed below in the section "Radiation Mechanism."). This result is not at odds with the exponential shape defined by the IMP observations, but represents further definition of the spectral shape by extension of the measurement to lower photon energies. Two other gamma-ray bursts were observed by the x-ray detectors aboard the Vela spacecraft, and one of these was also observed by an x-ray detector aboard the Orbiting Solar Observatory satellite, OSO-7. These measurements were also consistent with a thermal bremsstrahlung distribution.

By 1978 the Soviet KONUS experiment began routinely to observe gamma-ray bursts over a wide energy range: 30 to 1000 keV. These observations also indicated a spectral shape consistent with optically thin thermal bremsstrahlung. In addition KONUS had sufficient energy resolution to resolve spectral features. Many KONUS events appeared to have an emission feature around 400 to 450 keV (also observed by the ISEE-3 high-resolution spectrometer), which was explained as radiation from electron-positron annihilation, gravitationally redshifted 10 to 20 percent. Since the gravitational field required to redshift a line by 10 percent is the field expected at the surface of a neutron star, these lines were the first strong evidence that gamma-ray bursts occur on neutron stars.

Low-energy absorption features have also apparently been revealed in the KONUS data. These absorption features have been attributed to cyclotron radiation, implying an exceptionally strong magnetic field (about 10^{12} gauss). Since such magnetic fields can only occur near the surface of neutron stars, this result was taken as further evidence that neutron stars were involved. However, the cyclotron lines are subject to question because the features may be artificially generated in the process of data analysis.

What do these spectral measurements reveal? First, gamma-ray bursts are considerably harder than x-ray bursts; that is, high-energy photons dominate the spectra (Fig. 3). Second, the overall shape of these spectra appears to be approximately consistent with thermal bremsstrahlung from an optically thin plasma. Third, the line features suggest that the bursts occur on neutron stars, probably highly magnetized neutron stars.

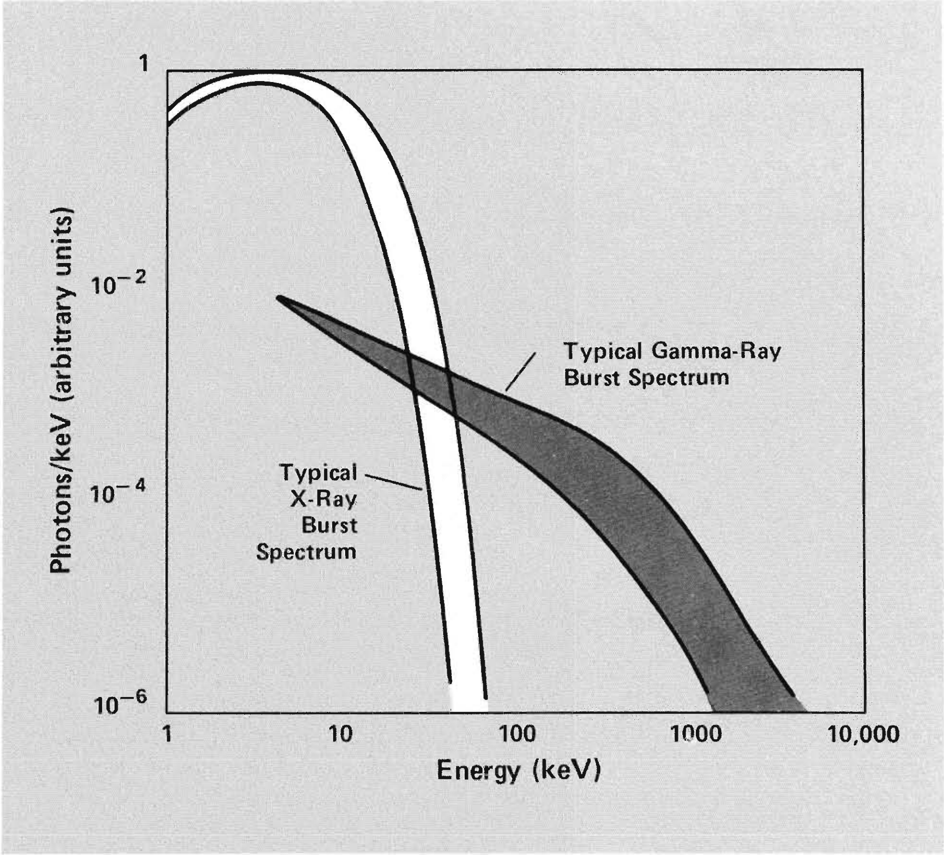


Fig. 3. Gamma-ray and x-ray burst spectra. Each band represents the range of spectral shapes typically observed for both gamma-ray and x-ray bursts. The spectra have been arbitrarily normalized, but indicate the general relationship between the two phenomena. X-ray bursts are typically observed to be much more intense at lower energies, but gamma-ray bursts are much stronger at energies above 100 keV.

SPATIAL DISTRIBUTION. The number of bursts observed as a function of their intensity provides insight into the overall distribution of the sources in the space around us. The apparent intensity of a burst at the detector decreases as the square of the distance to the burster. The volume containing average sources grows with the distance, the exact relationship depending on the type of spatial distribution. If the sources are distributed homogeneously, the volume (and hence the number of burst sources) increases as the third power of the distance. The number N of events observed to be greater than an apparent intensity S should then follow a -3/2 power-law dependence (that is, $N \propto S^{-1.5}$). On the other hand, if the sources are distributed in a thin plane, the number increases only as the square of the distance. The dependence of N on S is then that of a -1 power function ($N \propto S^{-1}$).

Early observations indicated that the intensity distribution was consistent with a -3/2 power law, which implies a homogeneous distribution, but these data were limited by instrument sensitivity. More recently, M. C. Jennings and R. S. White, using data obtained by sensitive balloon-borne instruments, concluded that the event frequency at *low* intensities was inconsistent with an extrapolation of the -3/2 power law from data at high intensity. This suggests that there is some boundary to the spatial distribution of the sources. This boundary would probably be either the extent of our own galaxy or the limit to which the universe can be observed. Since the intensity distribution does not show evidence of what should

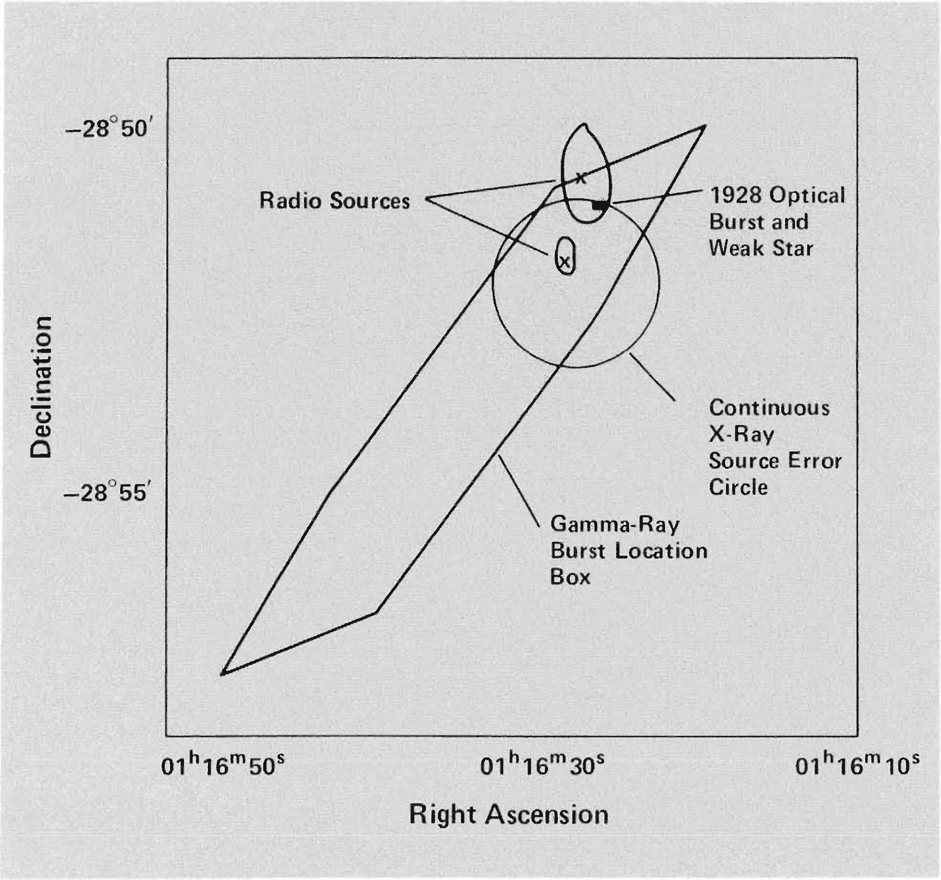


Fig. 4. The locations of the November 19, 1978 burst and associated radio, x-ray, and optical sources. The two radio sources were resolved by the Very Large Array radio telescope; the circle locating a weak x-ray source was determined by an x-ray detector aboard the Einstein Observatory. Falling within the regions mapped for the gamma-ray burst and for the x-ray source is the location of the 1928 optical transient (small rectangle) with a weak (23rd magnitude) star at the same position. [*T. L. Cline* et. al., *The Astrophysical Journal* 246, *L133-L136 (1981) and B. E. Schaefer, Nature* 294, *722-724 (1981).*]

be significant contributions from nearby groups of galaxies, and since levels of energy at the sources would be beyond comprehension if they were as far away as the limit to which the universe can be observed, it can be concluded that the sources lie within our own galaxy.

SPECIFIC LOCATIONS. This indication that the sources lie within our galaxy suggests that the sources might be located near the galactic plane. To the contrary, even the crudely located bursts do not distinctly show such a preference, and none of the directions for the few precisely determined bursts lie close to the galactic plane. Why not? Only the more intense events can be located precisely, and these are also likely to be from the closest sources. Since the galaxy is actually a thick disk rather than a thin plane, objects near to us would appear to be distributed uniformly if their distances were less than the approximately 1000-light-year thickness of the disk.

Because there was no strong preference for the galactic plane where stars are most dense, it was expected that there should be relatively few stars randomly contained within the precisely located regions. Indeed, only a few, very faint stars were typically found—none with any exciting characteristics.

In general there was no association between gamma-ray bursts and objects that had seemed to be remarkable when observed at other wavelengths. Gradually, however, searches for x-ray, radio, and optical sources revealed interesting correlations. An example is the November 19, 1978 gamma-ray burst. This was the second most intense event recorded to date and could be precisely located (Fig. 4). When the x-ray detector aboard the Einstein Observatory (HEAO-2) was directed to scan this field, a marginally detectable, continuous x-ray source was observed. Additionally, the Very Large Array radio telescope in Socorro, New Mexico resolved at least two weak radio sources within the locational uncertainty. Neither the radio nor the x-ray sources, though, were consistent with any optically resolved stellar images down to the 22nd magnitude. Recently, however, Bradley Schaefer of the Massachusetts Institute of Technology discovered a heretofore unknown type of optical transient event in this field. He searched archival photographic plates at the Harvard College Observatory for unusual optical objects at the three published precise gamma-ray burst locations. In the case of the November 19, 1978 event, his search apparently proved successful. On one plate in a series of six made at a station in South Africa on November 17, 1928—almost fifty years to the day previous to the burst!—he discovered a 10th magnitude star that did not appear on any other plate. The image had the characteristics of one formed through the telescope optics, but the negligible trail (compared to the other stellar images) left by the star during the 45-minute exposure suggested that its brightness lasted for only seconds or minutes.

Plates of this region made by Martha Liller of the Harvard College Observatory subsequent to this discovery seem to include a barely observable 23rd-magnitude star at the position of the optical transient. Certainly this must be an unusual subject. It flared up in a brief flash in 1928 to a hundred-million times its present brightness, and then in 1978 it again flared up, being observed as an intense burst of gamma rays. Whether visible radiation and gamma rays were simultaneously present in either case is not, of course, determined. But if this unremarkable—and even almost undetectable—star is typical of the quiet state of gamma-ray burst sources, it will be very difficult to study them at optical wavelengths.

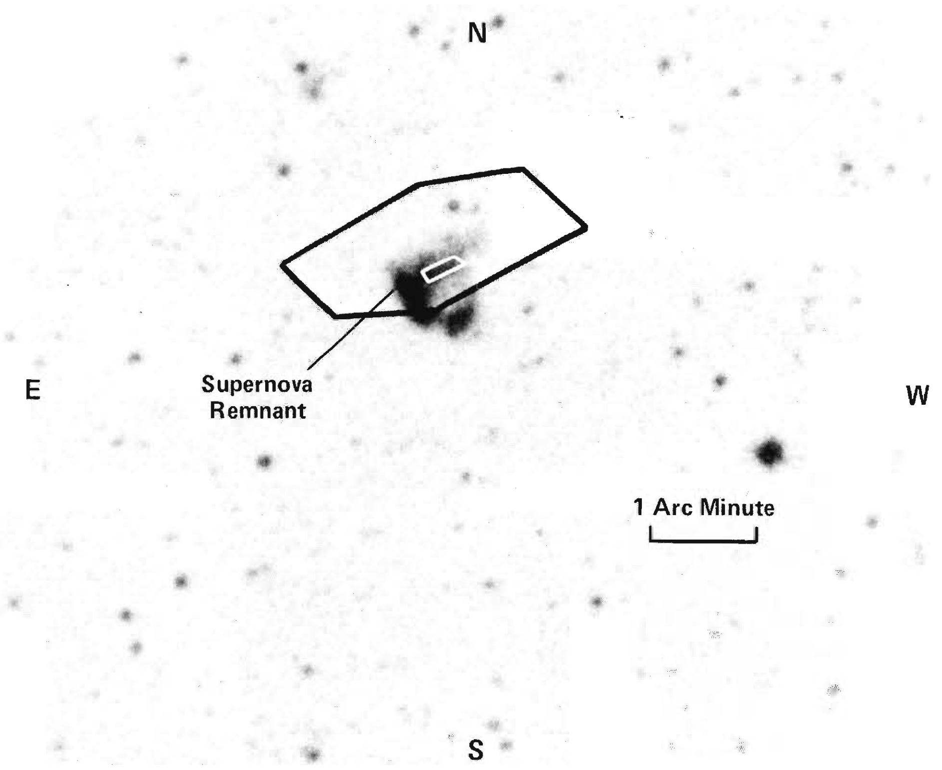


Fig. 5. The location of the March 5, 1979 burst. The initially determined location of the March 5, 1979 gamma-ray burst based on time-of-arrival data from three spacecraft is shown as the outer box on this negative-image field of stars. The hot, expanding cloud of gases of N49, a relatively young supernova remnant located in the Large Magellanic Cloud, lies within this box. After the small systematic errors in the satellite network were identified, the error box outlined in white was determined using data from all ten spacecraft. The new location falls within the supernova remnant and represents an area that is only a fraction of a square arc-minute.

The March 5, 1979 Burst —An Atypical But Important Event

The unusual gamma-ray burst observed on March 5, 1979 was remarkable in many respects, including an intensity ten times greater than previously observed. This event may, in fact, represent a different class of gamma-ray bursts. Features that distinguish it from typical bursts are

- a spectrum that lies between those for typical x- and gamma-ray bursts,
- its possible association with a specific and remarkable object at an implied distance 100 times farther than was thought likely,
- a long, regularly pulsing "afterglow,"
- a rise time more than 10 times faster than previously observed, and
- a recurrence of outbursts observed on a time scale of days.

The spectral characteristics of the March 5, 1979 burst clearly set it apart from typical gamma-ray bursts. The photons had characteristic energies of about 50 keV rather than the more typical 300 keV. The spectral shape was not consistent with optically thin thermal bremsstrahlung. Additionally, this event was the first for which the spectrum was shown to include what was apparently a redshifted annihilation line, indicating that the burst occurred on a neutron star.

This gamma-ray burst was the first for which a precise location was determined. Of the several events now precisely located, only this one suggested an association with a specific source object previously known. Figure 5 shows the location of this burst and its relation to the supernova remnant N49 within the Large Magellanic Cloud, a neighboring galaxy. This association has been thought to be accidental by many astrophysicists because of the great energy implied by the observed flux if the source is assumed to be at the distance of the Large Magellanic Cloud.

An unusual and interesting feature ob-

Sidebar 2

eyes for gamma rays

Scintillation detectors mounted in satellites are the eyes that "see" bursts of gamma rays. Currently, our most distant eye, the Pioneer Orbiter circling Venus, contains a detector designed jointly by Los Alamos National Laboratory and Sandia National Laboratories. This detector consists of two scintillation spectrometers, mounted opposite each other at the periphery of the spacecraft, and a logic and data-storage module (see figure).

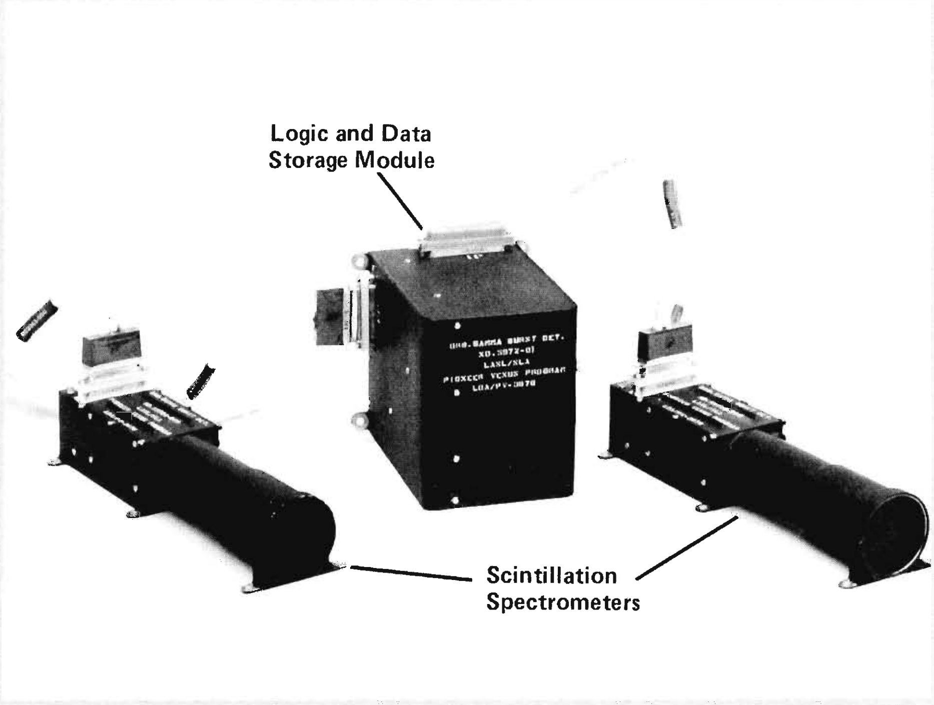
The "retina" in this system is a cylindrical cesium iodide crystal doped with a small amount of thallium. Gamma rays deposit energy in the crystal by kicking electrons from the crystal lattice. As the electrons recombine with positive charges at the thallium impurity sites, photons of visible light are produced; that is, the crystal "scintillates." The number of photons is proportional to the gamma-ray energy. A photomultiplier tube bonded optically to the crystal detects the light and sends a signal to the logic and data-storage module.

Because the penetrating charged particles of cosmic rays also produce scintillation in the cesium iodide, the crystal is surrounded with a shell of plastic scintillator that is sensitive primarily to these particles. Scintillation in the plastic occurs quickly, and the logic circuits use this signal to reject the accompanying but later signal caused by charged-particle interactions in the crystal.

Energy-level discriminators split the signal into four ranges of gamma-ray energy: 100 to 200, 200 to 500, 500 to 1000, and 1000 to 2000 kiloelectron-volts (keV). A trace of radioactive californium-249 deposited on the scintillator is used for in-flight calibration of the system.

When a significant increase in the signal above the average background signal occurs, the system automatically stores the data and the time of the burst in a dedicated solid-state memory. The detector count-rate history is recorded at a basic interval of 12 milliseconds, but the interval can be shortened when the intensity of the signal warrants more rapid sampling. Because the background signal is being continuously stored in memory, the important initial rise of the burst wavefront is captured (for example, see Fig. 2 of the main article). Also, a set of spectral data is recorded with every set of sixteen 12-millisecond samples. These data are retrieved later upon command from Earth.

At present, this detector, and similar detectors on about seven other satellites, are watching the heavens for bursts of gamma rays. Twenty-nine burst events were recorded by the Venus Orbiter during 1979, including the energetic event of March 5, 1979. ■



The gamma-ray detection system aboard the Pioneer Venus Orbiter spacecraft.

served for this burst is the pulsing afterglow, the pattern of peaks in Fig. 6 that was recorded for about 200 seconds after the initial spike. (Although this event is the only observed burst with any regular periodicity, the fact that the afterglow is about 500 times less intense than the initial spike means that it would not be possible to detect such an afterglow in data from weaker bursts.) Fourier analysis of this pattern gives clear evidence of a well-defined periodicity of 8 seconds. There is also present an obvious, but weaker, interpulse. The pulse and interpulse are probably due to the "lighthouse" effect (modulation induced by viewing two oppositely placed source regions on a rotating star, probably at the magnetic poles) rather than to a resonance effect.

This burst also had an exceptionally rapid rise time (≤1 millisecond), which suggests that the size of the source must be less than 1000 kilometers. A rotation period of 8 seconds and a radius less than 1000 kilometers can only be consistent with a neutron star, which might well have been produced by the supernova that formed the visible remnant N49. However, an 8-second periodicity might imply a neutron star whose rotation has slowed considerably and is thus very old (>10^6 years), whereas the supernova remnant is believed to be only 10^4 years old.

Three additional, weaker outbursts were seen from this source on March 6, April 4, and April 24, 1979. These recurrences were similar to the March 5, 1979 event, but were much weaker and thus could not be as effectively studied.

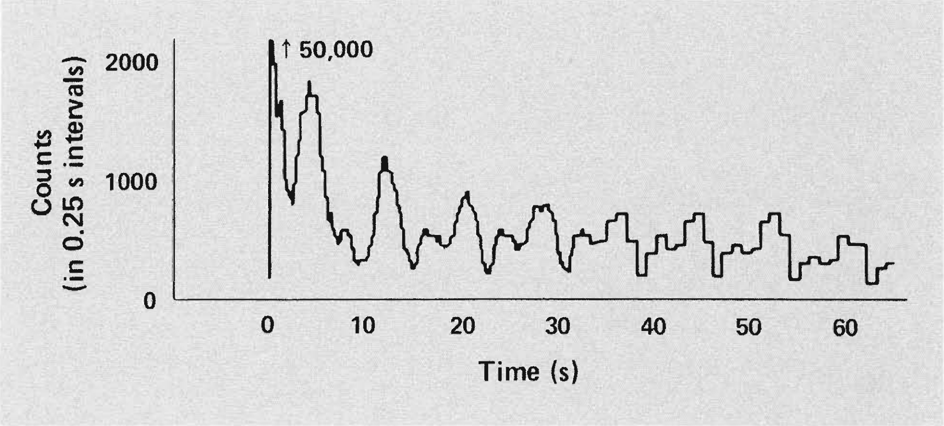


Fig. 6. Periodic "afterglow" of the March 5, 1979 burst, as detected by Venera 11. The 8-second period of the afterglow observed following this intense burst is clearly shown, together with an interpulse. The interpulse is in phase with the intense burst, and is observed to be growing in amplitude through the first four cycles. [*E. P. Mazets, S. V. Golenetskii, V. N. Il'inskii, R. L. Aptekar', and Yu. A. Gur'yan Nature* 282, *587 (1979).*]

Models of Burst Sources

Early in the history of gamma-ray burst observations there were many more source models proposed than there were bursts recorded. In fact, at one of the early scientific meetings, fifteen models were summarized—twelve of which have now been discarded. It has been obvious from the start that most of the proposed models were not capable of reproducing all the observations of this complex phenomenon. However, a general consensus has developed that, in fact, only neutron stars can provide the environment needed to account for the various characteristics observed, although a number of questions remain.

A neutron star is the end product of the evolution of a star several times more massive than our sun. The star has burned all of its nuclear fuel and has then lost about half its mass during a gravitational collapse and ensuing supernova explosion. The collapse crushes the remaining stellar material to a core that is somewhat like a giant nucleus composed of neutrons, with an iron skin. The star is so very small (only 10 kilometers in diameter, about the size of a small town) yet so incredibly massive (nearly a million times the mass of the earth) that a tremendous gravitational field is produced at the surface. It is also generally believed that a strong magnetic field may be condensed along with the stellar mass. Most of the models proposed to explain gamma-ray bursts invoke one or both of these fields.

SUDDEN ACCRETION. For example, some models assume the sudden accretion of a large amount of material onto the surface of a neutron star. The material might spill over in a diffuse form from a companion star or plummet to the surface in the concentrated form of a comet or asteroid. The large gravitational field accelerates the material to speeds near the velocity of light before it strikes the surface of the star. There the material, with the energy it has gained in falling, produces a hot plasma that emits gamma rays. The chaotic behavior in time is frequently attributed to "lumpiness" in the accreted material.

Stirling Colgate and Albert Petschek, and also Arthur Cox and Michael Newman, have developed models of gamma-ray bursts based upon collisions of asteroids with neutron stars. Although this model was directed specifically at the March 5, 1979 burst, variations on it might be relevant to typical gamma-ray bursts. Colgate and Petschek

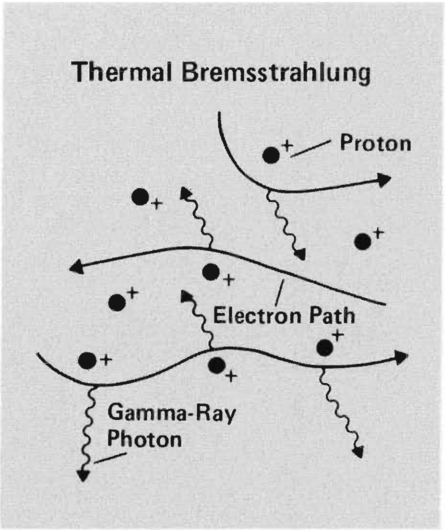


Fig. 7. Thermal bremsstrahlung emission. Very fast, high-temperature electrons are deflected by the Coulomb field of the heavier, slower protons. This acceleration of charge results in the emission of gamma-ray photons when the plasma temperature is greater than a billion kelvins (kT > 100 keV).

found that an iron-nickel asteroid about 6 kilometers in diameter falling toward the surface of a cold magnetized neutron star would be compressed and elongated by the gravitational field. Furthermore, the magnetic field lines flatten the material into a thin knife edge several millimeters thick and several kilometers wide. The material impacts the surface, causing a local explosion, and the hot, radiant material then expands along magnetic field lines into a fan of flux tubes. In fact, the strong magnetic field is essential for restraining the material long enough during this explosion to allow for release of significant amounts of energy. The plasma is supported by radiation pressure at the polar cusps in the tubes. This material continues to emit x and gamma rays while the neutron star rotates, producing the pulsing afterglow. The major uncertainty of this model is the poorly known probability for the occurrence of such a collision between an asteroid and a neutron star.

THERMONUCLEAR FLASH. The thermonuclear flash model also depends upon the accretion of material onto the surface of the neutron star. In this case the accretion, consisting mainly of hydrogen, occurs slowly and rather uneventfully. The hydrogen is heated as it impacts the surface, and, when a sufficient quantity has accumulated, nuclear burning is initiated. This burning proceeds quietly, combining four hydrogen nuclei into one helium nucleus and generating additional heat. The density of helium increases and the temperature rises until a violent, explosive reaction occurs in which helium burns to produce iron-group elements. In the thermonuclear flash model the complex time behavior is explained as a result of the uneven propagation of the thermonuclear reaction through the surface layer of helium. This model predicts that the heated region would produce a long-duration glow of x rays following the gamma-ray burst. However, the limited number of x-ray measurements of gamma-ray bursts do not show evidence of such a glow and thus seem to be inconsistent with the present concept of this model.

Both the sudden accretion model and the thermonuclear flash model have been used successfully to explain x-ray bursters. For a gamma-ray burst, a stronger magnetic field is usually required by the model, modifying the generating mechanism enough to produce gamma-rays rather than x-rays. In fact, in the thermonuclear flash model the accreting material may funnel down the field lines to a magnetic pole, and then again may be constrained by the magnetic field during the violent burning phase so that it spurts vertically off the surface in a fountain-like plume.

STARQUAKE. A third possible mechanism is a "starquake." Many models of neutron stars predict a solid crust at the surface of the neutron star. Stresses can be set up in this crust by changes in the rotation of the star or changes in the magnetic field. Eventually, the strength of the crust is exceeded, and the stresses are relieved by restructuring of the star. This is accompanied by the release of a large amount of energy, probably through injection of a heated plasma into the stellar atmosphere. In fact, this may be the only mechanism able to release enough energy to account for extra-galactic source distances. However, no detailed modeling has been attempted for starquakes because of fundamental uncertainties about the actual dynamics.

Radiation Mechanism

Not only is there no consensus about the energy-releasing mechanism responsible for gamma-ray bursts, but neither is there agreement about how the gamma rays are produced. Three possible emission mechanisms have been considered.

THERMAL BREMSSTRAHLUNG. Early analyses of the spectra found that a reasonable fit to the data could be made by assuming optically thin thermal bremsstrahlung, which is expected from a very dilute and very hot plasma. Bremsstrahlung is the radiation emitted when charged particles are accelerated; in this case, the paths of high-temperature, very fast electrons are bent by the Coulomb field of more slowly moving ions, usually assumed to be protons (Fig. 7). The resulting thermal bremsstrahlung can escape the plasma without further interaction only if the plasma is very dilute, that is, optically thin. On the other hand, if the plasma was optically thick, the spectrum would be modified toward a blackbody distribution. Optically thin thermal bremsstrahlung is particularly simple to model and produces the spectral distribution

$$N(E)dE = \frac{bg(T,E)\exp(-E/kT)}{E} N^2 V dE ,$$

where b is a constant, $g(T,E)$ is the Gaunt factor (a correction for quantum mechanical effects), T is the temperature, k is the Boltzmann constant, N is the number density of the electrons, and V is the volume of the emitting plasma. The temperature T is the only free parameter that affects the shape of the spectral distribution. Typically, a fit of this expression to the data yields a temperature of 3 billion kelvins, which corresponds to an energy (equal to kT) of 300 keV.

The luminosity, that is, the total energy emitted per second, can be found by integrating over the spectral distribution. In principle, the distance to the source can be determined by relating this luminosity to the flux observed near the earth. Unfortunately, neither the electron density N nor the plasma volume V are known. However, it is fairly certain that the burst occurs near the surface of the neutron star and therefore must have a size less than about 10 kilometers. (In fact, most detailed theories predict sizes smaller by a factor of 10.) In addition, because the spectra do not appear to have been modified by Compton scattering, one can put an upper limit on the electron density. These limits on N and V result in an upper limit on the distance to the burst sources of about 3 light years. But the closest star is about 4.3 light years away. Thus, if optically thin thermal bremsstrahlung is the emission mechanism, most of the sources would have to be closer than the nearest visible star. Thermal bremsstrahlung simply does not create enough photons to be consistent with the fluxes we observe at the earth unless the objects are unreasonably close. Also, some detailed spectral observations disclosed that thermal bremsstrahlung did not provide the optimum fit.

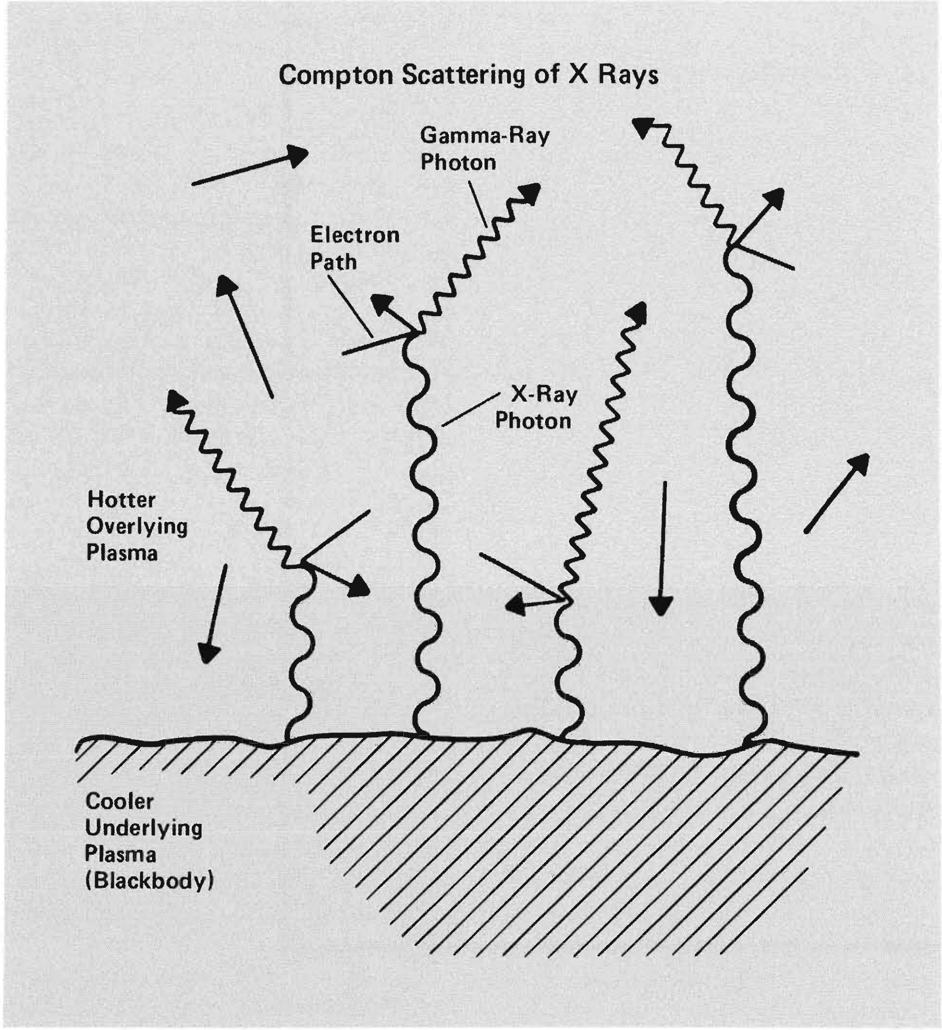


Fig. 8. Comptonized blackbody process. Lower energy x-ray photons with a blackbody spectral distribution are emitted by the cooler, underlying plasma. These photons interact with high-energy electrons in the hotter, overlying plasma and are "kicked" up to gamma-ray energies by inverse Compton scattering.

COMPTONIZED BLACKBODY. A major problem with the optically thin thermal bremsstrahlung model is the inefficient production of photons. Perhaps if another source were provided for the initial production of the photons, a thermal model might be consistent with the observed flux. In one such model the same hot dilute plasma lies over a cooler, more dense plasma that is able to produce the necessary copious supply of photons (Fig. 8). The initial blackbody distribution of photons undergoes inverse Compton scattering as it travels outward through the hotter plasma; that is, the photons scatter from highly energetic electrons and thereby gain energy. But does a Comptonized blackbody spectral distribution adequately fit the observations?

The burst recorded on November 4, 1978 provided excellent data for testing this model. Fortuitously, the source of this event lay within about 1 degree of the ecliptic plane, and, consequently, the emission over a

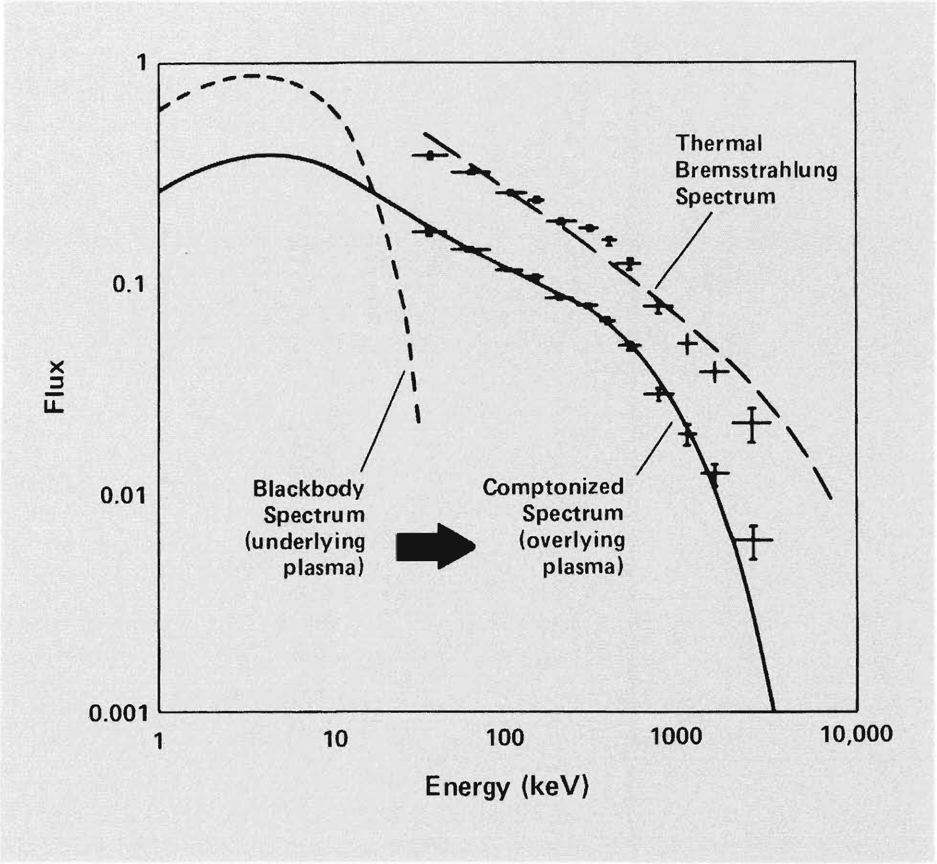


Fig. 9. Modeling of the November 4, 1978 burst spectrum. The data recorded for this gamma-ray burst by the ISEE-3 x-ray spectrometer (crosses) are fit with a Comptonized blackbody and a thermal bremsstrahlung spectrum (data and curves for the two cases are displaced vertically for clarity). The blackbody spectrum calculated for the cooler, underlying plasma in the Comptonized blackbody mechanism is also shown. The Comptonized blackbody spectrum provides a closer fit, yielding values for kT *of about 2.4 keV and 155 keV, respectively, for the cooler and hotter plasmas.*

wide range of energy was measured by the ISEE-3 solar x-ray spectrometer. Designed to observe the sun, the spectrometer viewed the entire ecliptic plane. Furthermore, because the spectrometer was sensitive to photons with energies from 20 to 2000 keV, it provided one of the most definitive measurements by a single instrument of the spectral characteristics of a gamma-ray burst.

To compare the November 4, 1978 burst with a Comptonized blackbody, the Compton cross section of a photon traveling into a very hot plasma was first calculated (including relativistic effects in the angular dependency of the cross section). A three-dimensional Monte Carlo computer program was then developed to track the photons from initial creation until they escaped from the hot plasma. Three free parameters (the temperature and density of the Comptonizing region and the source blackbody temperature) were varied within the program until the resulting spectrum best fit the observed data for the November 4, 1978 burst. Figure 9 shows the results. The short dashed curve is the spectral shape of the underlying, cooler plasma. The solid line is the spectral shape of the photons emerging from the overlying hotter plasma. The data points on the solid curve are for the burst as obtained from ISEE-3. For comparison the best-fit thermal bremsstrahlung spectrum (long dashed curve) is also shown, but it is clear that the Comptonized blackbody model provides a much better fit.

Other observations provide additional evidence that this may be the mechanism responsible for the spectra. One burst, seen on March 29, 1979, appeared spectrally as if the overlying plasma had apparently become temporarily transparent, revealing the underlying blackbody. In the November 19, 1978 burst, the overlying plasma apparently was initially so dense that the photons equilibrated to the temperature of the hotter plasma, producing a distinctive spectral shape known as a Wien peak.

Although the ability of the Comptonized blackbody mechanism to explain both unusual (the March 29, 1979 and November 19, 1978 events) and normal spectra is strong evidence in its favor, the model also has some problems. It predicts that all of the energy can be removed from the hotter plasma in a microsecond, thus necessitating a complex replenishment process. In addition, the model is only compatible with a magnetic field less than 10^9 gauss whereas there was a growing consensus that the bursts occurred on *highly* magnetized neutron stars.

CYCLOTRON RADIATION. There are two reasons why gamma-ray bursts are thought to be associated with very large magnetic fields. First, the plasma is certainly very hot, so hot that it is difficult to see how it could be held even briefly at the neutron star unless it was confined by a strong magnetic field.

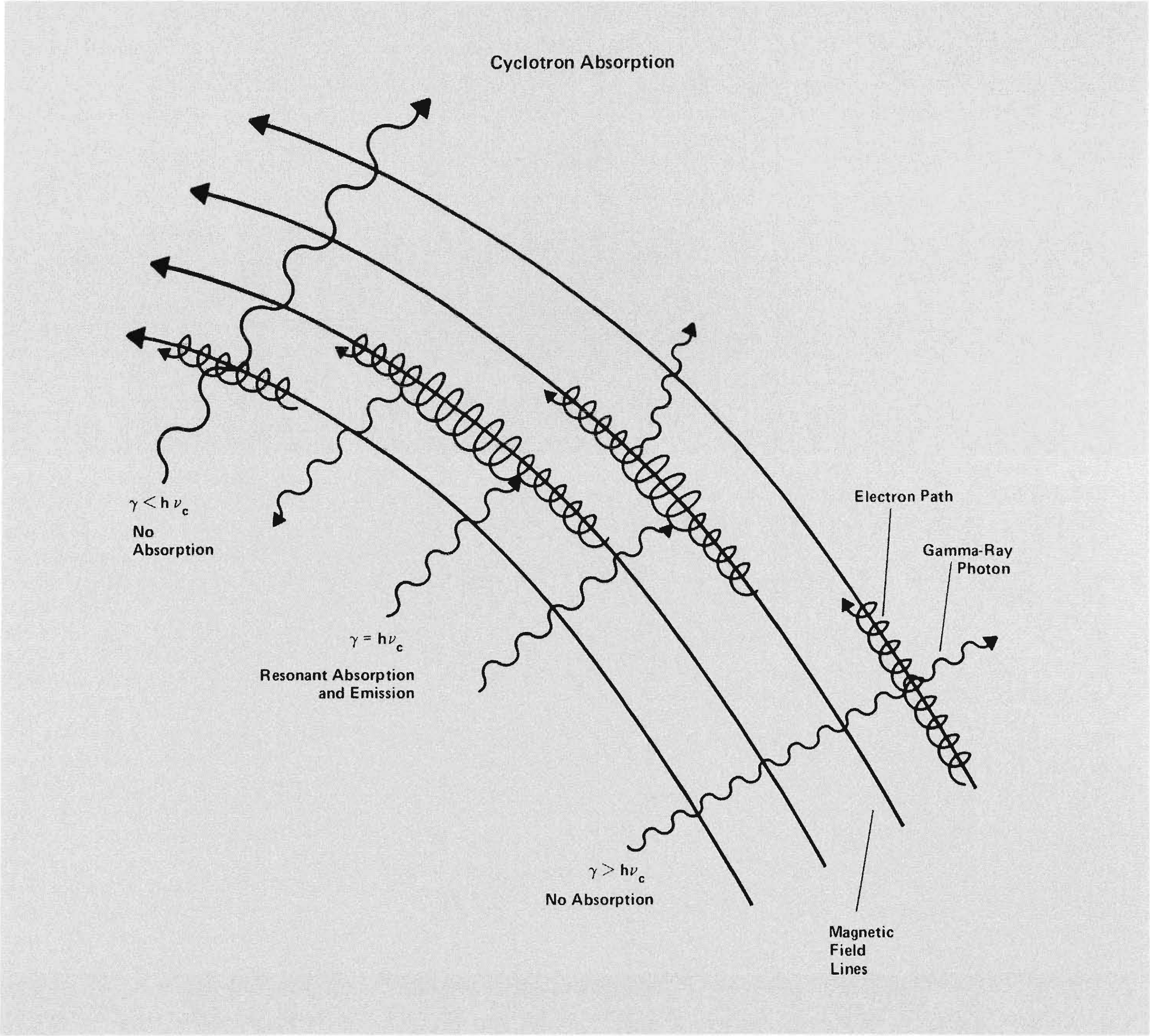


Fig. 10. Cyclotron process. Electrons moving in a strong magnetic field will spiral around the field lines. Here, the interactions of the gamma-ray photons with these electrons are represented schematically. Photons with energies greater or less than $h\nu_c$*, the quantized transition energy of cyclotron absorption, will not be absorbed. Photons with energy equal to* $h\nu_c$ *can be absorbed by increasing the energy of the electron (depicted as a larger helical path). Eventually the electron will return to the unexcited state, emitting a photon with an energy of* $h\nu_c$*. If the electrons are excited to many different orbits by collisional processes, the result of many subsequent deexcitations can, perhaps, produce the observed continuum.*

Second, the absorption features seen by KONUS near 50 keV in some gamma-ray bursts are thought to be the result of an interaction between photons and electrons moving in a strong magnetic field. The magnetic force on a moving electron causes it to describe a helical path about the field lines (Fig. 10). The electron energy is quantized and must satisfy the relation

$$E_n = nh\nu_c = nh(eB/2\pi mc) ,$$

where n is an integer, h is Planck's constant, ν_c is the cyclotron frequency, e and m are, respectively, the charge and relativistic mass of the electron, B is the magnetic field, and c is the speed of light. To change from one energy to another, the electron must either emit or absorb a photon with an energy of $\Delta E = (n_2 - n_1)h\nu_c$. The fundamental cyclotron radiation absorption feature should occur at photon energies equal to $h\nu_c$ (that is, $n_2 - n_1 = 1$). Knowledge of such a feature can be used to calculate the magnetic field ($B = 2\pi mc\nu_c/e$). In this way the absorption line, measured by the KONUS experiment at $h\nu_c$ = 50 keV, gives a magnetic field of about 5 × 10^{12} gauss, a reasonable value for a neutron star.

Unfortunately, there are problems with the above explanation. The plasma is so hot that there is sufficient energy for the electrons to undergo larger energy changes ($n_2 - n_1 = 2$, 3, 4, ...) and one would expect to see cyclotron absorption lines at multiples of 50 keV as well. Such lines are not observed. Also, using data from the ISEE-3 satellite to check the KONUS result, it was found possible to produce a spurious indication of lines if either the instrument calibration was improperly defined or if one was incorrect in assuming thermal bremsstrahlung for the continuum shape.

Even though the cyclotron absorption lines could be spurious, many models require a strong magnetic field to confine the plasma. In such models, a smooth continuum could feasibly be made up of many broadened cyclotron lines. It remains to be seen if the observed continuum can be generated by this mechanism if reasonable parameters are assumed.

Summary

Much has been learned since the initial search to assure that natural phenomena would not affect test-ban treaty verification. Contrary to expectations, gamma-ray bursts were discovered, giving the first illustration of a violent aspect of the universe. This revelation inspired efforts that led to better characterization of gamma-ray bursts as well as discoveries of similar transients at x-ray and optical wavelengths. A decade of study has provided strong evidence that the bursts occur on neutron stars. Although this much has been learned, there is yet no clear picture of the physical process that releases the tremendous energy and produces the remarkable spectra. Greater insight will surely be achieved through further study of the data from existing instrumentation. There is little doubt that a full understanding of this enigmatic phenomenon will hinge upon future developments in space technology. ■

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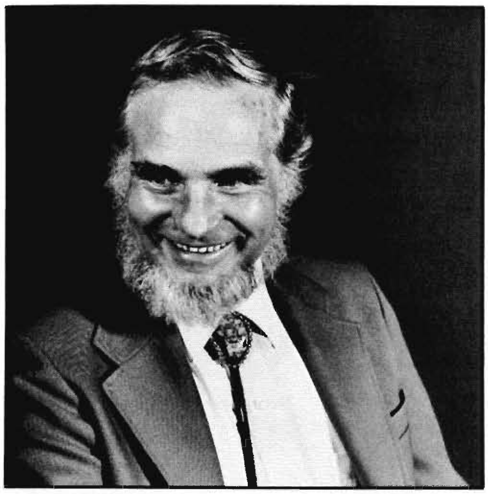
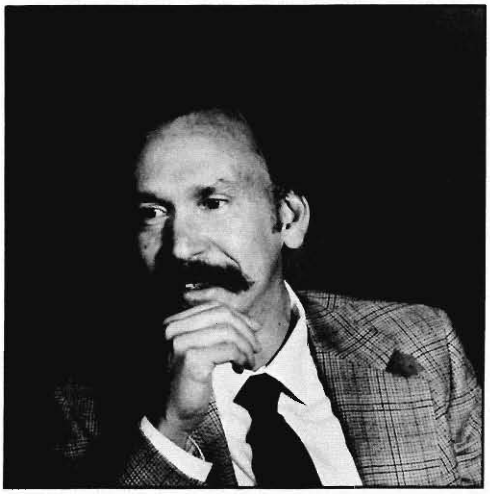


Ray W. Klebesadel earned his Bachelor of Arts in electrical engineering from the University of Wisconsin in 1959. However, a part-time job sorting nuts and bolts in their Physics Department had led to a research assistantship coordinating the installation of the tandem Van de Graaff accelerator. In this latter capacity he was responsible to Professor H. H. Barschall, who is well known to the veterans of the Manhattan Project. Dr. Barschall recommended Los Alamos, feeling the environment to be in tune with Ray's expressed working and living preferences. In 1960, soon after receiving his Master of Science in physics from Wisconsin, Ray joined the Laboratory and the deep-space nuclear-test surveillance project and embarked on the astrophysical research for which this year he received the Laboratory's Distinguished Performance Award.

W. Doyle Evans joined the Laboratory's Space Sciences Group in 1961 with a Bachelor of Science in physics from Louisiana Tech University (1956) and a Master of Science in physics from the University of California, Los Angeles (1958). Previously he had taught at Louisiana Tech University for two years and had spent one year with NASA's Langley Research Center. At Los Alamos he developed rocket and satellite instrumentation for the 1962 high-altitude nuclear tests and x-ray instruments for the Vela satellite program. As a member of the Laboratory's Advanced Study Program he received his Ph.D. in physics from the University of New Mexico in 1966. His primary research interest is x- and gamma-ray astronomy, particularly high-energy transient sources, and he has helped design several satellite and rocket instruments for collecting data from such sources. He was principal investigator for the gamma-ray burst experiment on the NASA satellite that has been orbiting Venus since 1978. Currently, he is Deputy Division Leader of the Earth and Space Sciences Division.

Edward E. Fenimore received his B. S. in physics from Rensselaer Polytechnic Institute in 1970 and his M.S. from the University of Chicago in 1972. He came to Los Alamos in 1974 to work on a doctoral thesis concerning the ionization balance of the solar wind and its relationship to solar conditions. He became a Staff Member in 1978, and in 1980 he received his Ph.D. in astronomy and astrophysics from the University of Chicago. Besides solar-wind physics, his specialties include x-ray instrumentation and x- and gamma-ray astronomy. He has received five patents and a Distinguished Performance Award from the Laboratory for his development of "uniformly redundant array" x-ray cameras and advanced x-ray collimators. Recently he has been studying the mathematical properties of certain binary transformations and emission mechanisms of gamma-ray bursts. He is a member of the Optical Society of America, the American Geophysical Union, and the High Energy Astrophysical Division of the American Astronomical Society.

AUTHORS



John G. Laros became interested in astronomy as early as 1950 but fifteen years of doing mundane work elapsed before he found a way to "break into" the field. At that time he was able to join an astrophysics group at the University of California, San Diego that specialized in x- and gamma-ray astronomy. He remained there for eight years, receiving a Ph.D. in 1973 and holding a postdoctoral position until joining the Laboratory as a staff member in 1974. He has continued his work in x-ray and gamma-ray astronomy, with emphasis on the study of gamma-ray bursts, up to the present. When asked if he became discouraged at any time during his fifteen-year "wait" for his first astrophysics job, Laros replied, "Not really. You see in 1950 I was in the second grade!"

James Terrell, born in Houston, became an Assistant Professor of Physics at Western Reserve University after receiving a Ph.D. from Rice University in 1950. He has used his scientific skills in physics on a variety of problems since joining the Laboratory in 1951. His early work included studies of fission neutrons and relativity. In 1959 he discovered what was then a startling consequence of special relativity—the invisibility of the Lorentz contraction. The 1963 discovery of the obviously highly relativistic quasars caught his interest, and he has since published a series of papers on the time dependence of quasar brightness and on the possible ejection of quasars from the nucleus of our own galaxy. In the 1970s his work also included analyses of the rapid fluctuations of x rays from such objects as Cygnus X-1, the black-hole candidate, and solving optical and diffraction problems of high-power lasers. In 1977 he joined the effort to analyze and model the x- and gamma-ray data collected by various satellites.

COMMENT

The Weapons-Test Connection

by Roger C. Eckhardt

At the test ban summit meetings in 1959, Stirling Colgate watched the attention of the delegates drifting off the technical discussion onto thoughts of wine and women. He refocused their attention with one abrupt question: Would the gamma rays from a supernova trigger the detectors in the proposed test-surveillance satellites? With this question, Colgate connected the political goal of test surveillance with the scientific goal of understanding cosmic phenomena. In the satellite detection of gamma rays this connection has persisted now for two decades. However, it has been perceived in different ways with different consequences by different groups of people.

At one extreme is the opinion represented by the *National Enquirer* story that claimed gamma-ray bursts were evidence of intergalactic star wars. The Air Force Vela satellites were in orbit to watch for nuclear-weapons tests. The alarm bells in these spacecraft were being set off by bursts of gamma rays with an intensity that amazed even the supposedly implacable scientists at Los Alamos. However, the bursts were coming from outer space. Ergo, intergalactic star wars.

A few members of the astrophysics community have viewed the connection between political and scientific goals in another light, reasoning as follows. Gamma-ray bursts weren't "discovered" until almost ten years after the launch of the first pair of Vela spacecraft. Ergo, the classified nature of the surveillance mission must have impeded the use of Vela data for scientific purposes.

What of the point of view of the scientists at Los Alamos closest to the discovery of gamma-ray bursts? Early in the Vela program, data from the gamma-ray detectors *were* searched for enhanced signals in the vicinity of the times of reported supernovae in distant galaxies. When these searches proved fruitless, the idea that an unknown and startlingly different phenomenon might be hiding in the data could not be examined with high priority by the people involved. During the ten-year span they, instead, pursued an answer to a broader version of Colgate's original query: Could a natural background event mimic the signal of an exo-atmospheric weapons test? Although this question was directed primarily toward the political goal, the natural scientific drive to eliminate even minor doubts resulted eventually in a surprise—the discovery of gamma-ray bursts. In truth, the time span was due, not to classification, but to the fact that gamma-ray bursts were totally unexpected.

In the 1960s the primary task at Los Alamos was to monitor the state of health of the Vela systems. For this purpose, a review of the complete record of the original data was unnecessary. In fact, since the Vela 1 and 2 satellites could be monitored only part of the time, only a fraction of the potential data was being transmitted to the Air Force ground-control stations. However, by 1967 gamma-ray detectors had been designed that were more sensitive and that automatically recorded the signal whenever an increased counting rate occurred. These detectors, aboard the Vela 3 and 4 satellites, created a new problem because large numbers of background events or false alarms were now being detected. The events would be recorded, then later flagged for attention by the satellite when they were transmitted. But which of the signals were instrumental glitches and which were caused by natural phenomena?

Instruments to help detemine natural background events had also been placed aboard Vela satellites, starting with the third launch. These included a collimated x-ray detector, an instrument designed to monitor solar x rays, and detectors sensitive to high- and low-energy charged particles. (In ensuing years, the charged-particle instruments were to make significant measurements of the characteristics of the magnetosphere.) While some of the signals were identified by these instruments as, say, due to the local effects of charged particles, many were left unexplained.

Also, Ray Klebesadel, a Los Alamos scientist, was beginning to suspect that certain occasional events were being detected at about the same time at more than one satellite. His suspicion, if verified, would indicate the occurrence of a nonlocal phenomenon. To discriminate such nonlocal events from other signals, all data had to be referred to a common time by accounting in each satellite for drift in the electronic oscillator time base, instrument rise time, data recording delays, transmission delays, and so forth. Klebesadel, with Roy Olson, developed a computer data analysis program for this purpose, but only after lengthy efforts were they able to convince themselves that the timing had, indeed, been placed on a reliable absolute basis.

These changes, both in instruments and in data analysis, caused important changes in how the data were viewed. Previously, the data records were examined only close to the times of known cosmic events. Now valid gamma-ray signals could be catalogued and attempts made to find related cosmic events at the times of the signals. Also, a new method of sampling the universe had unknowingly been implemented. The immediate, practical reason to develop detectors that recorded nothing permanent until triggered by a large signal was the fact that detector memory was too limited to record all data between transmissions. But this automatic feature provided the capability needed to track intermittent, highly variable gamma-ray bursts, as well as serving as a prototype for other instruments used to study the universe at high photon energies.

Despite these changes, it was still difficult to realize that a new gamma-ray phenomenon was, in fact, occasionally being recorded. For example, from May 1967 to August 1968 a manual search of the data revealed that the Vela 4A satellite had recorded 73 events while the 4B satellite had recorded about 100. Of these, only 8 occurred at both spacecraft within 10 seconds or less, and 7 of these recorded counts that were only slightly greater than the steady-state background. Five of the weak signals could be correlated with solar flares. This left three signals of unknown origin including the one strong signal. This latter signal not only was about two orders of magnitude above background, but was recorded by both Vela 4 detectors with the same double-peaked pulse shape, and was even seen by Vela 3 detectors.

In retrospect, the event recorded on July 2, 1967 has been recognized as the first discovered gamma-ray burst. However, in June of 1970 it was felt that the observation of this single event, while extremely interesting, did not merit publication because of many remaining doubts. For instance, might cosmic rays, a solar event, or some other phenomenon associated with the earth or the solar system still be found to be responsible for this single event? Also, there was no evidence of any other astrophysical phenomenon taking place at about the same time as the gamma-ray event. The Los Alamos scientists were worried because, if an event outside our solar system could cause such an intense burst of gamma rays, it seemed there should be evidence at other wavelengths, including the visible.

The Vela 5 satellites were launched in 1969, but the instruments, although greatly improved in many respects, suffered an electronic anomaly that generated a large number of extraneous events. To deal with the copious routine data that were accumulating, automatic computerized scanning routines were obviously needed. Further lengthy efforts were made by Klebesadel and Olson to deal with this problem, including development of these systems for the Vela 6 spacecraft, launched in 1970. Only then was the search for simultaneous events continued, and a dozen bursts were resolved in quick succession.

One of the bursts seemed clearly to be of solar origin—might the others be also? Furthermore, a number of satellites were in orbit, but many events were recorded by only a fraction of the gamma-ray detectors. Each burst had to be examined and reasons found to explain why given detectors had not responded to the event. However, a time-of-arrival location technique applied to data from the four Vela 5 and 6 satellites in geocentric orbit was adequate to eliminate the major members of the solar system as source objects for many of the bursts. Finally, enough data were amassed in 1972 to eliminate nearly all doubts. A new astrophysical phenomenon had been discovered.

A paper announcing the discovery was submitted to *The Astrophysical Journal* by Ray Klebesadel, Ian Strong, and Roy Olson, and the results were discussed at a meeting of the American Astronomical Society in June 1973. Tom Cline at NASA Goddard Space Flight Center had also been moving toward similar conclusions based on strange signals detected by instruments aboard the International Monitoring Platform satellites.

In the last decade much has been learned about cosmic gamma-ray bursts; much remains to be learned. The effort to understand the gamma-ray burst has truly been international, involving satellites orbited for a variety of purposes. However, it is heartening that instruments originally designed to detect nuclear weapons tests eventually helped to reveal a complex and surprising natural phenomenon. ■

THE NUCLEAR MICROPROBE

—Investigating Surfaces with Ions

by Carl J. Maggiore

Focused beams of light ions from a Van de Graaff accelerator nondestructively reveal the three-dimensional distribution of elements in the near surfaces of materials. One hundred times more sensitive than an electron microprobe, the nuclear microprobe has opened up new areas in geologic, biological, metallurgical, and synthetic materials research.

Trace-element concentrations in this thin section of rock (200 by 500 micrometers in area) can be determined by the nuclear microprobe with a spatial resolution of 1 micrometer and a sensitivity of 1 to 10 parts per million. Such spatially resolved data for the two dark sphene crystals at the center of the micrograph provide information about the cooling rates during their formation. The perfect crystal shape indicates that the sphene was the first mineral to crystallize from a magma, incorporating into its structure many trace elements, such as thorium, uranium, and the rare earths. Knowledge of trace-element concentrations in the surrounding granitic rock (feldspars, quartz, and biotite) are useful for many applications, including geothermal energy, solution mining, waste isolation, and modeling ore-body formation. The optical micrograph was taken (with crossed polarizers and a color-enhancing quarter-wave plate) by Rosemary Vidale of the Laboratory's Isotope Geochemistry Group.

Basic to any study of a material is knowledge of what elements it contains and how they are distributed. This knowledge is particularly important for the thin layer near the surface of a solid, where trace-element distributions determine such macroscopic properties as electrical conductivity, chemical reactivity, hardness, and wear resistance. Trace-element distributions are also the key to dating mineral specimens from the earth and from space and to understanding the processes of their formation.

Over the past twenty years a number of new techniques and instruments have been developed to analyze the near-surface region. These include Auger analysis, the electron microprobe, photoelectron spectroscopy, the laser microprobe, secondary-ion mass spectrometry, and scattered-ion spectrometry. Each in its own manner, be it destructive or nondestructive, provides either qualitative or quantitative information about the elemental or chemical nature of the near surface.

Among these the nuclear microprobe has several features that make it a unique instrument for analyzing the near-surface region. It is nondestructive; it is sensitive to trace elements and to monolayers of heavy elements; it has a spatial resolution of a few micrometers; it yields quantitative information about the elements present as well as their depth profiles; and, finally, interpretation of the data is relatively easy and unambiguous. The nuclear microprobe is designed to irradiate the near surface of a specimen with a focused beam of light ions and detect at each point the backscattered ions, nuclear reaction products, and x rays that result from interaction of the incident beam with the specimen. Analysis of these signals yields three-dimensional distributions of elements in a region less than 10 micrometers (μm) deep.

At present there are about ten nuclear microprobes in the world, of which the Los Alamos microprobe has the most intense beam and the potential for the highest spatial resolution. As the beam from the Laboratory's vertical Van de Graaff accelerator passes through an elaborate focusing system, it is fashioned into a very fine stream of nearly monoenergetic ions. The unique feature of this system is the final focusing device, a superconducting solenoid lens specially designed to focus the maximum current into the smallest spot.

The initial motivation for developing this sophisticated microprobe was the examination of new types of compound semiconductor devices. The localized distribution of impurities in these small objects is the key to their electrical properties. This application has been only a starting point. We are currently exploiting the sensitivity and spatial resolution of the microprobe to measure the density of thin-film targets for equation-of-state studies, catalyst migration in fuel cells, and trace-element concentrations in geologic materials. This instrument is opening up to detailed materials analysis the world with dimensions below 5 μm.

Nuclear Microprobe Signals

By the usual standards of surface physics, an incident ion with an energy of a few million electron volts (MeV) presents an

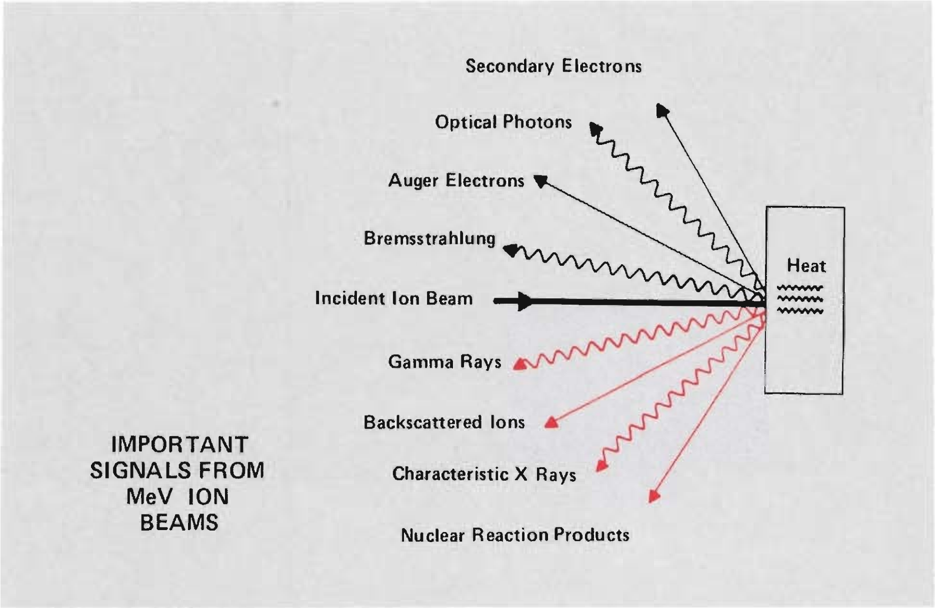


Fig. 1. Possible results of the interaction of few-MeV light ions with a specimen.

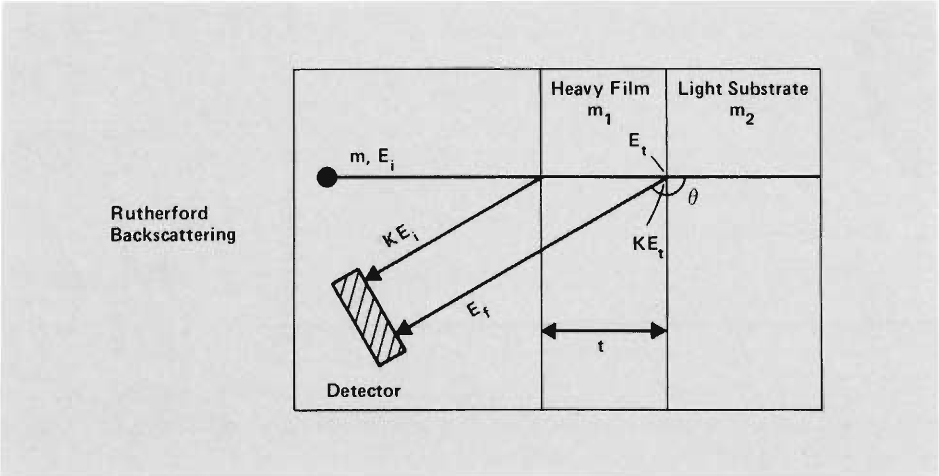


Fig. 2. Setup for a Rutherford backscattering experiment. Incident ions of mass m *and energy* E_i *are scattered by nuclei of mass* m_1 *in a heavy-element film on a light-element substrate. A detector at an angle* θ *relative to the direction of the incident ions records the number and final energies of ions backscattered through* θ. *The final energy of ions backscattered from the surface of the film is* KE_i, *where K is the kinematic factor defined in the text. Also shown are ions backscattered through* θ *from the deepest part of the film. These ions lose energy by traveling into the film, by scattering, and by traveling out of the film. Therefore, their energy at the time of scattering,* E_t, *is less than* E_i, *and their final energy* E_f *recorded by the detector is related not only to the mass of the scattering nucleus but also to the depth at which scattering occurred. Ions scattered by the light elements of mass* m_2 *in the substrate have distinctly lower energies than ions scattered from the heavy-element film.*

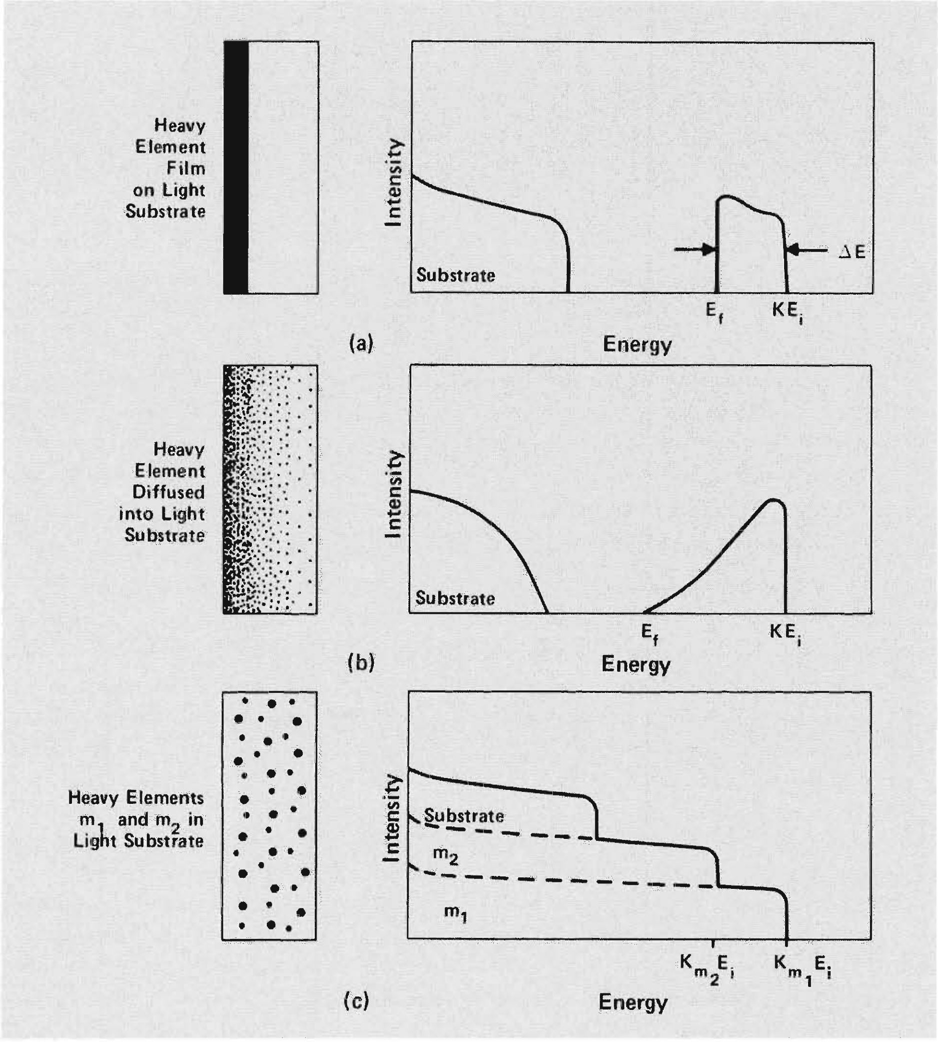


Fig. 3. (a) Rutherford backscattering spectrum of the specimen depicted in Fig. 2, a heavy-element film on a light-element substrate. The mass m_1 ***of the heavy element can be deduced from*** KE_i***. The thickness of the film can be deduced from*** $\Delta E = KE_i - E_f$ ***if the energy losses of the ion per unit path length in the heavy-element film are known. (b) Backscattering spectrum of a heavy element diffused into a light-element substrate. The height of the heavy element's backscattering peak declines rapidly with decreasing energy. This decline indicates that the concentration of the heavy element decreases rapidly with depth. (c) Backscattering spectrum from a light-element substrate in which two heavy elements are uniformly distributed. The mass of each heavy element can be determined from the high-energy edges of the steps and the concentration is found from the step heights.***

enormous perturbation to the specimen being examined. Figure 1 shows some results of the interaction between a beam of light ions (protons, deuterons, tritons, helium-3 ions, or alpha particles) and the specimen's near surface. The multiplicity of results is due to the relatively high energy of the incident ions. The three signals of primary interest for a nuclear microprobe are backscattered ions, nuclear reaction products, including gamma rays, and characteristic x rays. In combination these signals permit quantitative measurement of the near-surface distribution of almost all elements. The perturbations of the system, particularly radiation damage, constitute a major limitation on the use of the nuclear microprobe, but for many applications the information sought can be obtained without destroying it by the act of measurement.

BACKSCATTERED IONS. An ion passing through a specimen undergoes elastic scattering as its Coulomb (electrical) field interacts with that of an atomic nucleus in the specimen. (The scattering is elastic in the sense that the total kinetic energy of the scattering ion and the scattering nucleus remains constant during the interaction.) The process is often called Rutherford scattering in honor of Ernest Rutherford, who was led to his nuclear model of the atom by the fact that some small fraction of the incident ions are backscattered, that is, scattered through angles greater than 90° relative to the initial direction of the ions. Since the cross section, or probability, for Rutherford scattering increases with the square of the charge of the scattering nucleus, ions are more likely to be scattered by the heavier element(s) in a specimen. Therefore, as an analysis technique Rutherford scattering is particularly applicable to specimens consisting of heavy elements distributed within a light-element medium.

The specimens investigated with the nuclear microprobe are usually so thick that the ions scattered in the forward direction come to rest within the specimen. It is only the backscattered ions that escape to tell the tale about the masses, numbers, and locations of the heavy nuclei distributed within the near surface of a light-element medium. A simple experimental setup to determine these quantities is shown in Fig. 2. Ions of known mass m and initial energy E_i are directed at a specimen consisting of a heavy-element film on a light-element substrate, and a suitable detector, such as a silicon surface-barrier detector, measures the number and final energies of ions scattered through an angle θ close to 180°. Because the ions lose energy not only by backscattering but also by other interactions as they enter and leave the specimen, all the ions backscattered through θ do not have the same final energy. Rather the detector records a spectrum of energies whose values depend on the mass of the scattering nucleus and on the depths at which the backscattering occurred.

The maximum energy in the spectrum is the energy E' of those ions backscattered at the surface of the specimen. Energy and momentum conservation in the scattering process determine that $E' = KE_i$, where K, the so-called kinematic factor, is given by

$$K = \left[\frac{m \cos\theta + (m_1^2 - m^2 \sin^2\theta)^{1/2}}{m + m_1} \right]^2$$

and m_1 is the mass of the heavy element. We can thus determine m_1 by using this kinematic relation and the known values of E_i, m, θ, and E'.

Ions backscattered at some depth within the heavy-element film suffer additional energy losses in traveling into and out of the specimen. Since these losses are known as a function of path length and compiled in the literature, we can infer information about the depth distribution of the scattering nuclei from the energy spectrum. The energy losses per unit path length are primarily due to interactions with the electrons in the specimen and vary with the energy of the incident ions. For maximum depth sensitivity the energy of the incident ions should be near the energy at which the energy loss per unit path length is a maximum. This energy is, for example, about 1 MeV for alpha particles in a specimen of medium atomic weight.

The incident ions also backscatter from the light-element substrate. These backscattered ions have transferred more energy and momentum to the lighter scattering nuclei and therefore have lower energies.

Figure 3 shows some typical energy spectra of backscattered ions. Different spectral shapes are characteristic of different depth profiles, such as a heavy-element film on a light-element substrate, two heavy elements uniformly distributed in a light-element matrix, or one heavy element unevenly distributed in a light-element matrix. The shapes of the peaks may horrify a nuclear spectroscopist, but, together with the intensities, they contain enough information to yield elemental concentration versus depth with a depth resolution less than 0.02 μm at normal incidence.

These backscattering measurements are particularly suited to studies of thin films and surface contamination. They are also useful for determining elemental depth profiles of doped materials and of compound materials whose composition changes with depth.

NUCLEAR REACTION PRODUCTS. Because the cross section for Rutherford scattering is much larger for heavy elements than for light elements, backscattering measurements are not sensitive to light elements in a heavy-element matrix. However, nature has obligingly provided a complementary interaction for specimens of this type, namely nuclear reactions. Incident ions with energies of a few MeV can penetrate the lower Coulomb barrier of the light nuclei and react through nuclear forces to create different light ions.

For materials analysis with ion beams, the nuclear reaction must have a high cross section and be free of interferences. Moreover, the reaction must liberate enough kinetic energy that the light-ion products can reach the detector. Fortunately, numerous reactions are suitable. Some common ones involve the reaction of incident deuterons to produce protons or alpha particles or of incident protons to produce alpha particles or gamma rays. These and other reactions of light elements have been well studied by nuclear spectroscopists over the past thirty years; therefore, an adequate data base exists for determining elemental composition from the microprobe data. Depth information is also contained in the data, for the incident ions and reaction products undergo the same type of energy loss in traveling through the sample as was described above for Rutherford scattering. Since nuclear reactions are sensitive to isotopic composition, the nuclear microprobe offers many possibilities for tracer studies with stable isotopes. Further, the nuclear microprobe is unique among near-surface analytical methods in being able to determine quantitatively the depth distributions of hydrogen, deuterium, and tritium.

The energies required to induce nuclear reactions are typically less than 3 MeV, and the reaction products are detected with the same surface-barrier detector used to detect backscattered ions.

CHARACTERISTIC X RAYS. X rays are the third analytical signal readily available from the nuclear microprobe. These x rays are the result of interactions between the incident ions and atomic electrons in the specimen. The electrons are excited to higher energy levels and eventually return to the ground state, emitting x rays with an energy characteristic of the element involved. A lithium-drifted silicon detector can be used to detect the x rays and measure their energy.

Operated in this manner, the nuclear microprobe functions exactly like an electron microprobe but has an important advantage. Because the mass of even a light ion is much greater (by a factor of 1800 or more) than that of an electron, the background bremsstrahlung is reduced considerably. Consequently, the nuclear microprobe can detect elements at concentrations between 1 and 10 parts per million, whereas the electron microprobe is limited to concentrations of about 1000 parts per million. This increase in sensitivity by a factor of 100 or more has opened up important areas of materials research in biology and geochemistry.

Although the x-ray data does not yield any depth information, it does provide a complement to the depth profiles obtained from backscattering spectra. For example, backscattering data may be ambiguous for heavy elements whose mass differences are small. In such cases data from an x-ray spectrometer, which easily distinguishes adjacent elements in the periodic table, can be used to resolve ambiguities in the backscattering spectra.

Design Considerations for High Spatial Resolution

All three analysis methods described

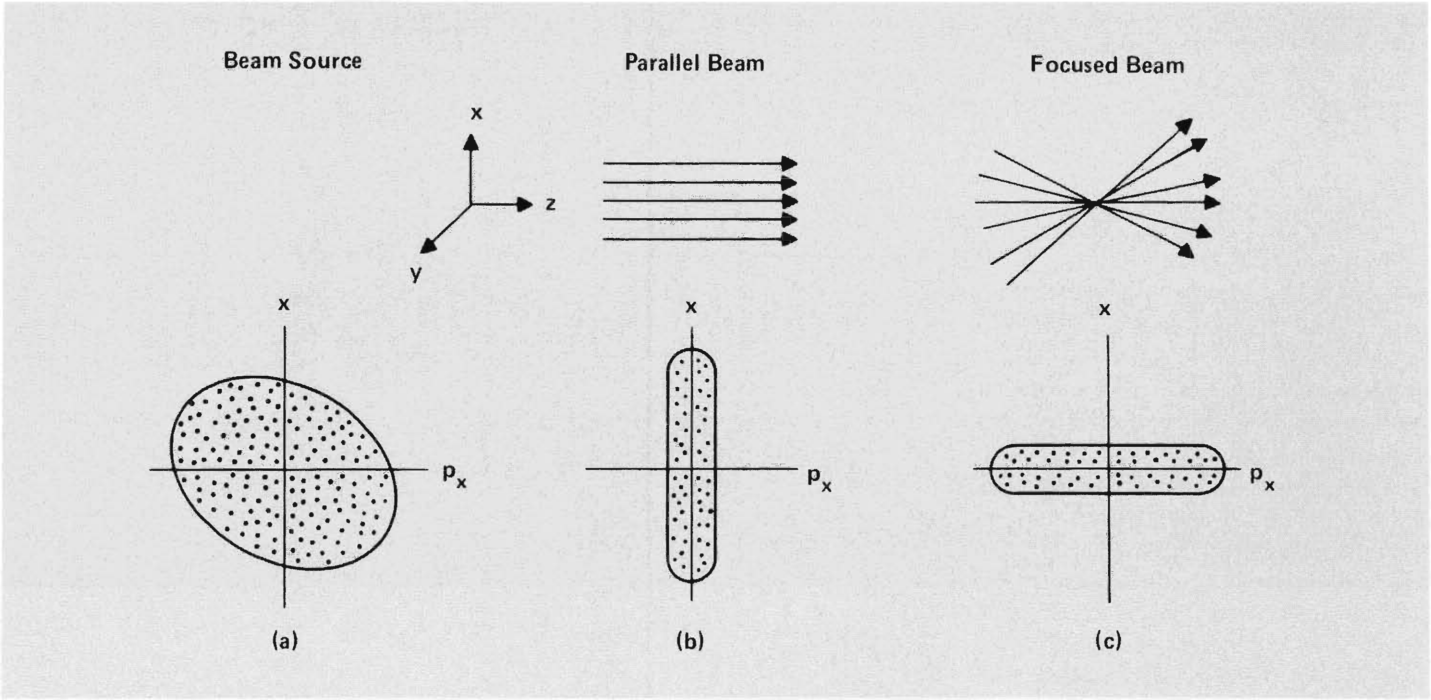


Fig. 4. The phase space occupied by a system of particles is defined by their spatial (x,y,z) and momentum (p_x,p_y,p_z) coordinates. The figure shows the xp_x plane of the phase space occupied by a beam of ions traveling in the z direction. Three beam configurations are depicted: (a) a typical ion source, such as a Van de Graaff accelerator, in which the ions have a substantial spread in both space and momentum; (b) a parallel beam in which the ions are spread in the x direction but have almost no momentum in that direction; and (c) a crossover point where the beam has almost no spatial extent but has a large spread in momentum. Focusing devices can change the shape and area of the phase space occupied by the beam but cannot change the density of points in phase space.

above are well known and well documented in the literature. Moreover, if a sample is uniform over dimensions of a few square millimeters, the methods yield satisfactory results with a direct beam line from any Van de Graaff accelerator. But specimens of technological interest are rarely uniform over these dimensions. Typical structures in semiconductor devices have dimensions of 5 μm or less; separate phases and grains in mineralogical specimens are a few micrometers in diameter; cracks and grain boundaries in solids have dimensions of 1 μm or less; biological structures of interest are often less than a few micrometers in size; and the average "dust" particle has dimensions of a few micrometers. The challenge we faced was to fashion a Van de Graaff ion beam into a tool for nondestructive analysis of this world below 5 μm.

A Van de Graaff accelerator is an appropriate ion source for two reasons: it can accelerate the variety of ions we need for different applications, and it produces a high-current beam with good energy regulation. However, to use a Van de Graaff beam in much the same way that scientists use an electron microscope, we must consider questions of spatial resolution, sensitivity, and radiation damage.

SPATIAL RESOLUTION AND SENSITIVITY. To achieve spatial resolution of a micrometer or two, the beam must be focused to a spot of this dimension. At the same time the current in the spot must be sufficient to generate a measurable signal in a reasonably short time.

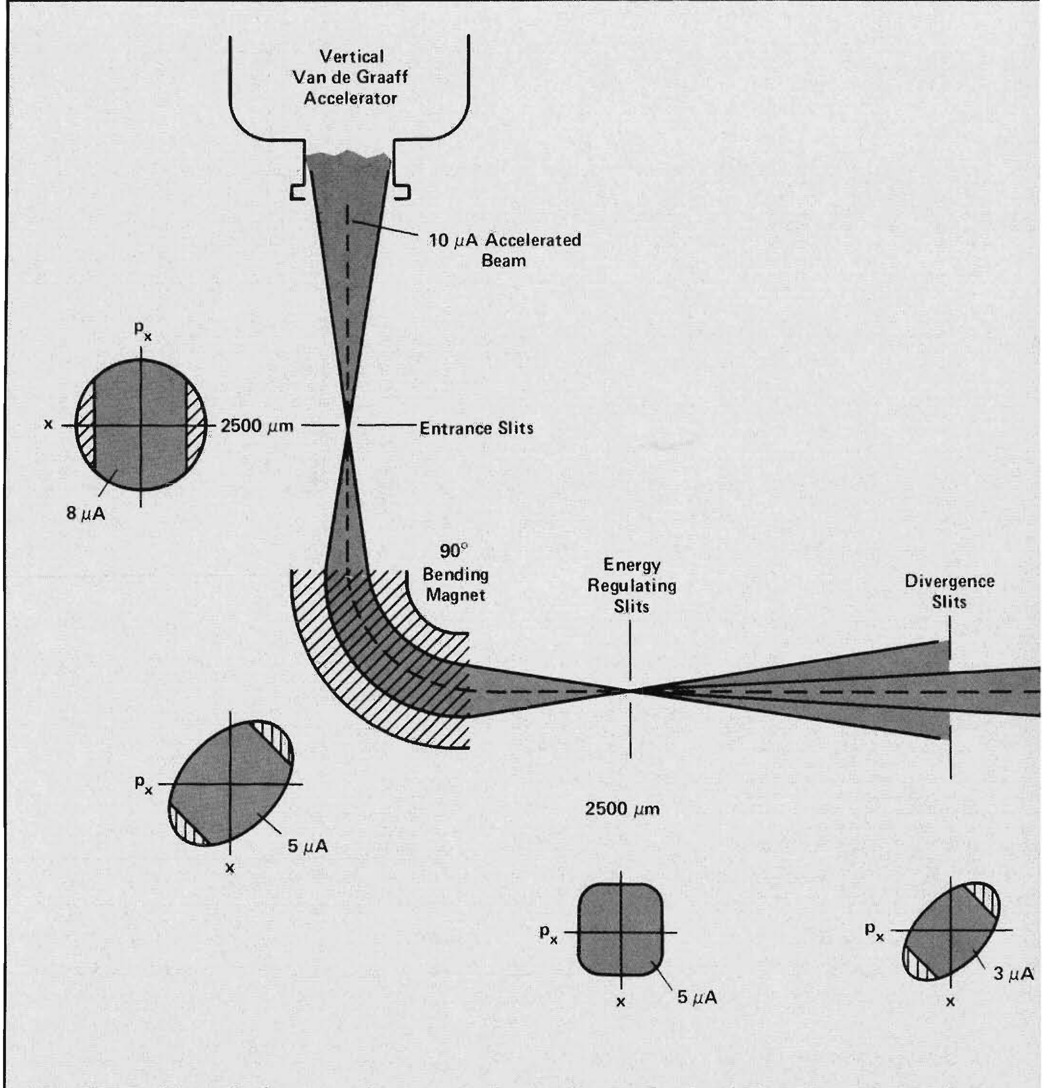
The final spot size and current are not independent quantities but instead are related to the characteristics of the ion source through Liouville's theorem about transformations of the phase space occupied by a system of particles. [The phase space occupied by a system of particles consists of the spatial (x,y,z) and momentum (p_x,p_y,p_z) coordinates of the particles.] The area of phase space occupied in the xp_x plane by a beam of ions traveling in the z direction is a bounded region with a certain density of points (Fig. 4). Liouville's theorem states that any transformation of a bounded region of phase space does not change the density of points in that phase space. In other words, focusing elements and emittance-limiting elements may be placed in the beam line to produce a small spot, but the phase-space density of the particles in that spot cannot be increased beyond that of the source. This theorem places an upper limit on the current in the final spot (i_{spot}) in terms of the current of the accelerator beam (i_{source}):

$$i_{\text{spot}} \leq \frac{(\epsilon_x \epsilon_y)_{\text{spot}}}{(\epsilon_x \epsilon_y)_{\text{source}}} \, i_{\text{source}} \, ,$$

where the normalized emittance ϵ is a measure of the phase space occupied by the beam in units of length times angle times (energy)$^{1/2}$. To estimate ϵ_{spot} we assume a spot size approximately 1 μm in diameter and a semidivergence (angular spread) for the beam of 20 milliradians. With a semidivergence of this magnitude, we can still maintain a spatial resolution of 1 μm in the near-surface region of the sample. The theoretical limit on the current in the spot also depends on the normalized emittance and current of the ion source. For a Van de Graaff accelerator with a duoplasmatron ion source, the typical normalized emittance is 1 to 10 millimeters milliradians (MeV)$^{1/2}$ and the maximum beam current is 10 microamperes. With these numbers we obtain 4 nanoamperes as the maximum current in a 1-μm-diameter spot.

Although optical aberrations in the focusing and emittance-limiting devices may reduce this theoretical limit by a factor of 100, the final current is nevertheless more than sufficient to produce adequate signals in the detector. In fact, some experiments are possible with currents in the picoampere range, and 4-nanoampere currents produce count rates that approach and can exceed the limitations of backscatter and x-ray detectors. Of course, a lower-current beam spot must probe a specimen for a longer time to measure its elemental composition. Typically, an incident charge of 1 microcoulomb is needed to detect either a monolayer of a heavy element or an elemental concentration of 1 to 10 parts per million.

RADIATION DAMAGE. Radiation damage is, of course, a broad term referring to everything from the generation of color centers in alkali halides to the formation of blisters in metals. In microprobe experiments radiation damage refers to a change in a specimen's elemental distribution caused by the ion beam being used to measure that distribution. There are two effects that can move atoms over distances comparable to the microprobe's spatial resolution, thermal diffusion and nuclear recoil.

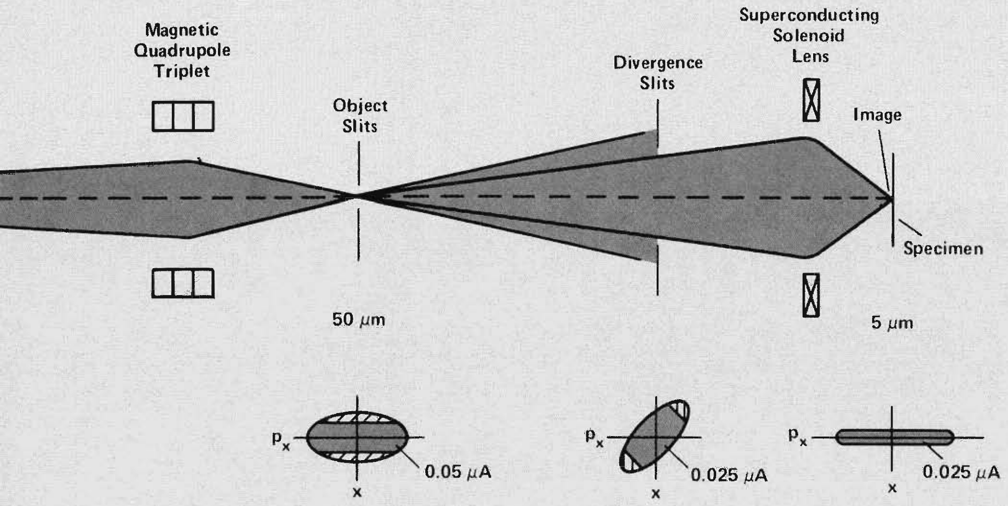


The beam line of the Los Alamos nuclear microprobe is designed to focus the maximum current into a small-diameter spot. The phase-space plots show how each of the various focusing and emittance-limiting elements reshapes the beam. The cross-hatched areas of the phase-space plots represent those parts of the beam discarded by the element. Each phase-space plot is labeled with the current and diameter of the beam at that point. The finite bore of the 90° bending magnet limits the high-divergence ions in the beam. The energy-regulating slits (the exit slits of the 90° magnet) do not limit the beam's phase space if the energy of the ions is constant;

Thermal Diffusion. Localized heating of the sample during irradiation can lead to diffusion of ions out of the sampling area. The local temperature will depend on the thermal conductivity of the specimen. Since most metals and semiconductors have thermal conductivities greater than 0.1 calorie per centimeter second degree, the temperature increase in the irradiated region will be 10 kelvins or less and will not be a problem for specimens of this type. Glasses and biological specimens, however, have much smaller thermal conductivities, 0.01 calorie per centimeter second degree or less. Consequently, irradiation of these materials may lead to a local temperature increase of several hundred kelvins, diffusion, and a change in the elemental distribution.

Nuclear Recoils. Rutherford scattering can impart a significant amount of kinetic energy to the scattering nuclei. For example, if an incident alpha particle with an energy of a few MeV scatters directly backward, the scattering nucleus recoils in the forward direction with an energy greater than 0.1 MeV. The range of the recoiling nucleus depends on its energy, mass, charge, and the matrix, but typically it will move from 0.1 to 1.0 μm farther into the sample. This displacement is much greater than the depth

Los Alamos Microprobe Beam Line



however, if the energy changes, the beam shifts relative to the slits and the amount of current through the rest of the beam line decreases. The first set of divergence slits limits the beam entering the quadrupole triplet. This lens brings the beam to a crossover at the object slits, which define the size of the beam to be demagnified by the final lens. Approximately 95 per cent of the beam is thrown away at this point. The final set of divergence slits limits the high-divergence ions entering the final superconducting solenoid lens. This lens brings the beam to a focus at the specimen. In general, a small spot size is obtained by increasing the divergence of the beam.

resolution (0.02 μm) of backscattering experiments. Thus, the measurement process can significantly perturb the depth distribution of some fraction of the nuclei in the sample.

We can estimate this fraction for an experiment involving, say, irradiation of a 1-μm^2 area of a gold monolayer with a beam of 6.25×10^{12} singly charged, 1-MeV helium-4 ions, that is, with 1 microcoulomb of incident charge (Fig. 5). We assume that only the ions scattered through a laboratory angle greater than 90° cause significant displacement of the scattering nuclei in the forward direction. (The majority of ions are scattered through the forward hemisphere and do not impart sufficient tangential momentum to the scattering nuclei to displace them laterally from the sampling area.) We can easily calculate the total number A of ions that cause significant displacement by integrating the Rutherford cross section over the backward hemisphere. We perform the integration in the center-of-mass frame and assume that the center-of-mass scattering angle is equal to the laboratory scattering angle. (This assumption is valid when the scattering nuclei are much more massive than the scattered nuclei.) Then

$$A = 2\pi Q N t \left(\frac{ZZ' e^2}{4E} \right)^2 \int_{\pi/2}^{\pi} \frac{\sin\theta}{\sin^4(\theta/2)}\, d\theta$$

where Q is the number of incident ions, Nt is the areal number density of the monolayer (1.8×10^{15} nuclei per square centimeter), Z and Z' are the atomic numbers of the gold nuclei and the helium-4 ions, e is the charge of the electron, and E is the incident energy of the ions. Evaluating this expression we find that A is 4.6×10^6. Each of these ions scattered through an angle greater than 90° has produced a significant forward displacement of a gold nucleus. The number of gold nuclei irradiated is the product of the monolayer's areal number density and the irradiated area, or 1.8×10^7. Thus 25 per cent of the gold nuclei are significantly displaced.

In a similar fashion we can calculate the number of backscattered ions that are detected in this experiment, assuming that the detector has an angular acceptance of 10^{-3} steradians and is located at an angle of 175° relative to the incident beam. From this number, 360, we learn that the statistical accuracy of the measurement is about 5 per cent. Thus, 25 per cent of the gold nuclei are significantly displaced by a measurement with a statistical accuracy of 5 per cent. Such a measurement would have altered the specimen by an amount greater than the statistical accuracy of the measurement. To avoid this problem we must increase the beam spot size or be content with lower accuracy. Nuclear recoils represent an ultimate limitation on microprobe experiments; they can, however, be tolerated in many applications.

Los Alamos Microprobe Beam Line

Microprobe measurements with spatial resolution of a few square micrometers are worth pursuing provided the data-acquisition times are reasonable. These times depend on how fast the beam can deliver probing ions to the target area. A beam current density of 50 picoamperes per μm^2 requires a rather long data-acquisition time (about 300 minutes) if 1 microcoulomb of charge is needed. At 1 nanoampere per μm^2 the time required reduces to 15 minutes and becomes more manageable. Therefore, our goal in designing the microprobe beam line and final lens was to maximize the current density in the final spot.

The figure on pages 32 and 33 depicts the microprobe beam line at the Laboratory's vertical Van de Graaff accelerator. Most of the beam-line elements are common to all nuclear microprobes. A 90° bending magnet with variable entrance and exit slits regulates the energy of the ions in the beam by transmitting ions of the correct energy. A quadrupole triplet changes the divergence of the beam to match the angular acceptance of the final lens, and two pairs of crossed microslits define the object that is to be demagnified by the final lens. The unique element in the Los Alamos microprobe is the superconducting solenoid lens that is designed to focus the maximum current density into the final spot.

To focus a relatively large volume of phase space into a small spot requires a lens with a large angular acceptance and a short focal length. The short focal length can be provided by a multiplet of magnetic or electric quadrupoles, the standard lenses for focusing light ions with energies of a few MeV. A multiplet is needed because a single quadrupole produces a nonaxially symmetric field that is converging in one plane and

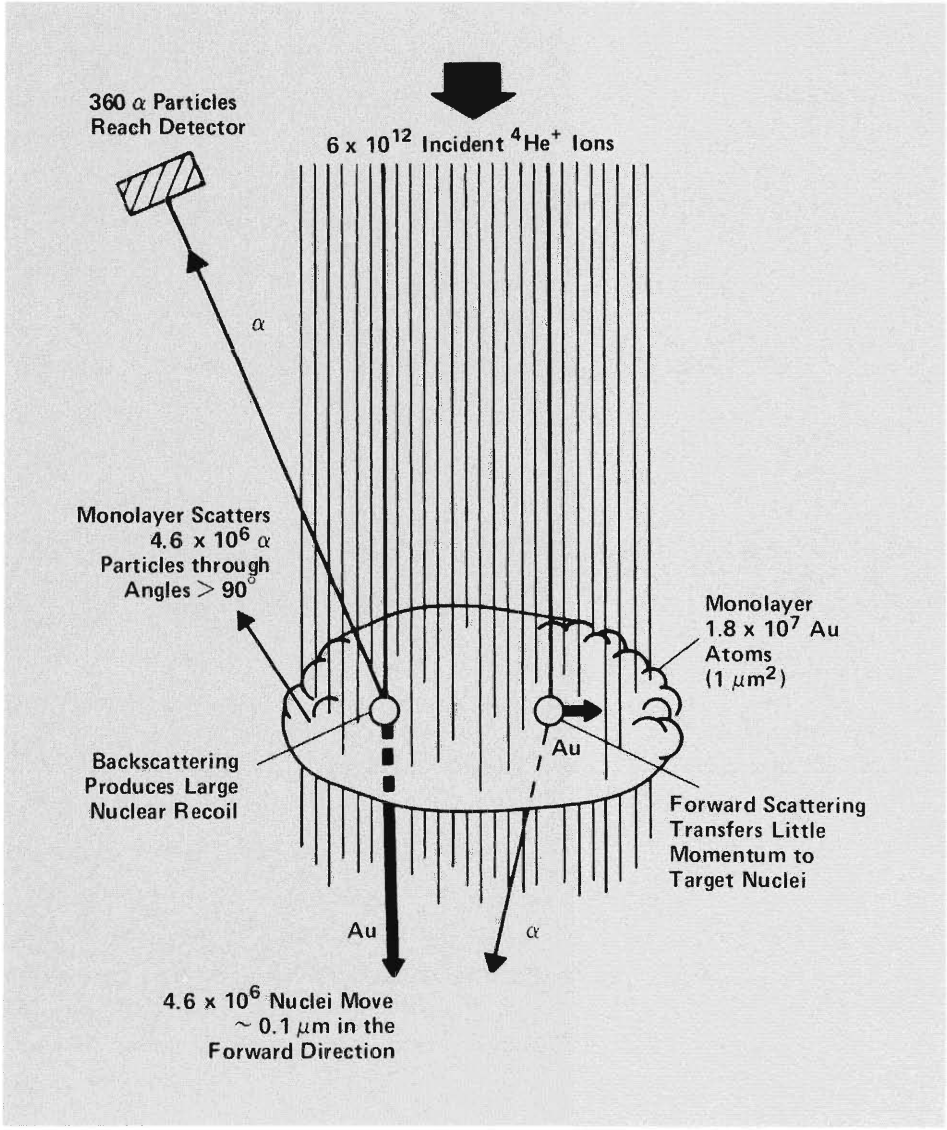


Fig. 5. Nuclear recoils in backscattering experiments. When 6×10^{12} $^4He^+$ ions (1 microcoulomb of charge) are incident on a monolayer of gold atoms, about 360 ions will scatter into a 10^{-3}-steradian detector at a 175° angle relative to the incident direction. The target area (1 μm^2) contains 1.8×10^7 gold atoms. Most of the incident ions pass through the target. Those that scatter in the forward direction transfer only a small amount of momentum to the scattering nuclei. But about 4.6×10^6 ions scatter through an angle greater than 90° and transfer enough forward momentum to the scattering nuclei to measurably change their depth. Thus detecting the presence of a monolayer of gold atoms with a statistical accuracy of about 5 per cent will move 25 per cent of the gold atoms a measurable distance (about 0.1 μm) deeper into the sample.

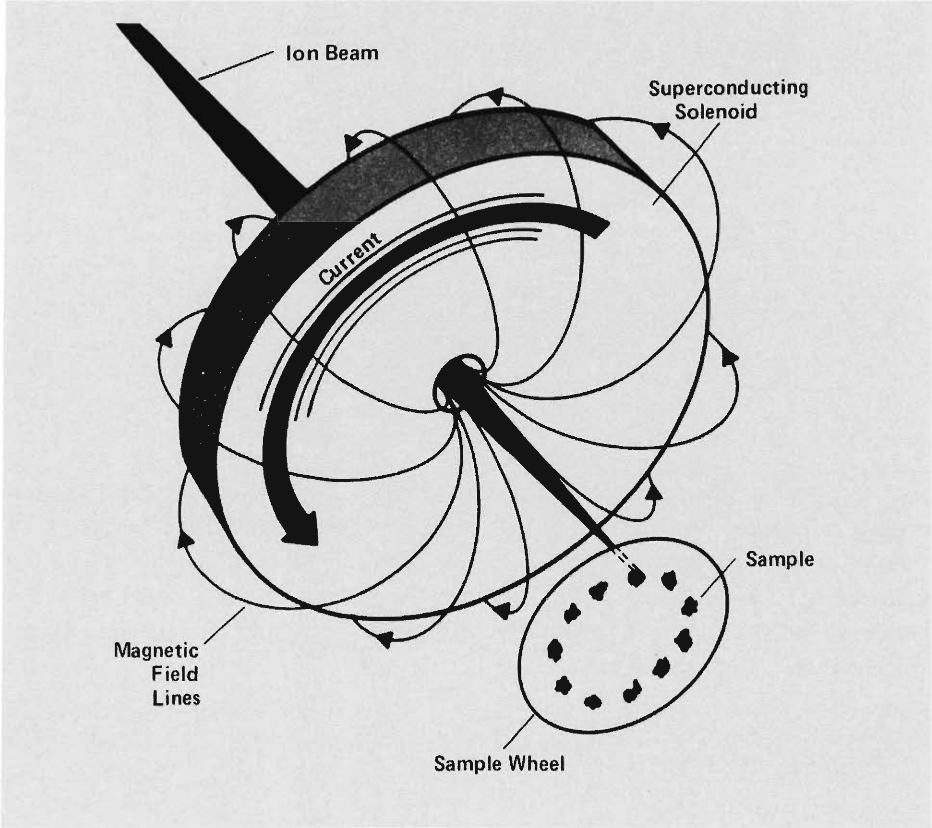


Fig. 6. Focusing action of the superconducting solenoid lens. A 70-ampere current flows through the windings of the pancake-shaped solenoid (5 centimeters thick and 30 centimeters in diameter) to produce an 80-kilogauss field in the lens's room-temperature bore. This field is high enough to focus few-MeV light ions onto a sample 10 centimeters from the center of the lens. To maintain the solenoid at superconducting temperatures, it is contained in a Dewar of liquid helium. Specifications of the solenoid lens are listed in Table I.

TABLE I

SUPERCONDUCTING SOLENOID LENS CHARACTERISTICS

Type	Multifilament NbTi NbTi:Cu = 1:1.3 Epoxy potted
Dimensions	5-cm bore length Three-stage winding r_1 = 2.50 cm r_2 = 5.75 cm r_3 = 9.65 cm r_4 = 15.80 cm
Maximum current density	Stage 1: 1.01×10^4 A/cm^2 Stage 2: 1.43×10^4 A/cm^2 Stage 3: 2.46×10^4 A/cm^2
Maximum current	69.56 A
Maximum field on axis	80 kG
Liquid helium consumption	1.5 ℓ/h at maximum field
Inductance	45.2 H
Manufacturer	Intermagnetics General

diverging in the orthogonal plane. A doublet, triplet, or quadruplet of quadrupoles can produce a converging lens, but to obtain a spot size approaching 1 μm in diameter requires very good electrical, magnetic, and mechanical uniformity. Consequently, design and construction of the quadrupoles demands great care.

We chose instead the conceptual simplicity of a solenoid lens. Its concentric circles of electric current produce an axially symmetric magnetic field whose focusing action is everywhere converging. The angular acceptance of a solenoid lens is limited only by the bore of the magnet. However, a solenoid lens is only weakly focusing and therefore requires much higher magnetic fields than do quadrupoles to produce a short focal length. In fact, the 80-kilogauss fields required to focus ions with energies up to 6 MeV cannot be produced with conventional technology. Long before such strong fields are attained, the high currents required would melt the solenoid wires and an iron core inserted to concentrate the field lines would saturate and be useless. Therefore, we combined the conceptual simplicity of the solenoid with the sophisticated technology of superconductivity. Cooled by liquid helium to temperatures at which its resistance drops to zero, the solenoid can sustain a current of 70 amperes through its windings to produce field strengths of 80 kilogauss. Figure 6 shows the focusing action of the superconducting solenoid lens, and Table I lists its specifications.

The magnetic field produced in the room-temperature bore of the lens is a close approximation to the Glaser field given by

$$B(z) = \frac{B_0}{1 + \left(\frac{z}{a}\right)^2} ,$$

where B_0 is the field strength at the center of the lens, z is the distance in centimeters along the axis from the center of the lens, and a = 6.5 centimeters.

The solenoid lens is not a perfect focusing device but instead has various aberrations that enlarge the beam spot. The dominant ones are spherical and chromatic aberrations. Spherical aberrations (Fig. 7) arise because the focusing action on ions far from the axis of the lens is stronger than on ions near the axis. Spherical aberrations cause the focused beam to have a diameter d_s given by

$$d_s = \frac{C_s}{2}\alpha^3 ,$$

where C_s is the spherical aberration coefficient and α is the semidivergence.

Chromatic aberrations result from the inability of the lens to focus ions with different energies to the same spot. As shown in Fig. 8, the less energetic ions are bent more sharply and are therefore focused at a shorter distance from the lens. The spot diameter due to chromatic aberrations is given by

$$d_c = 2C_c\,\alpha\frac{\Delta E}{E} ,$$

where C_c is the chromatic aberration coefficient and $\Delta E/E$ is the energy variation in the beam. At present the energy variation is about 1 part in 10^3.

The aberration coefficients are related to the properties of the lens and are usually very difficult to compute, but because the field of the solenoid lens approximates the Glaser field, we were able to calculate these coefficients analytically. Then, assuming that the effects of these aberrations add in quadrature, we calculated the beam current versus spot size for the superconducting solenoid lens (Fig. 9). From these calculations we drew the following conclusions.

- ○ Current densities approaching 1 nanoampere per μm^2 in the focused spot are possible.
- ○ Chromatic aberrations cause the greatest increase in the diameter of the focused spot. Therefore, energy regulation of 1 part in 10^4 will be necessary to achieve submicrometer spatial resolution.
- ○ The current densities associated with submicrometer spatial resolution will probably be useful only for inducing x-ray emission.

Since chromatic aberrations impose a fundamental limitation on the beam-spot size, we have attempted to improve the energy regulation of the accelerator at low energies. These efforts have not been particularly successful. But the fact that small variations in the energy of the incident beam do not affect the measurements if the beam remains in focus on the specimen suggests another solution. By changing the focal length of the final lens when the beam energy changes, the spot could be kept in focus and chromatic effects eliminated.

Because of its large inductance, the superconducting solenoid lens cannot be modulated rapidly enough to compensate for the changing incident energy. However, a small electrostatic-quadrupole triplet between the object slit and the solenoid lens could be. We hope to add such a small dynamic focusing element to the Los Alamos microprobe to compensate for the short-term beam-energy fluctuations of the accelerator. The signal to modulate the triplet would be derived from the energy-regulating slits of the accelerator.

The Los Alamos nuclear microprobe is currently being used with currents of 1 to 20 nanoamperes, spot diameters of 3 to 10 μm, and energy regulation of 5 parts in 10^4. Its design has increased the attainable current densities and data-acquisition rates of such instruments. Table II compares the characteristics of the Los Alamos probe and those of similar instruments around the world.

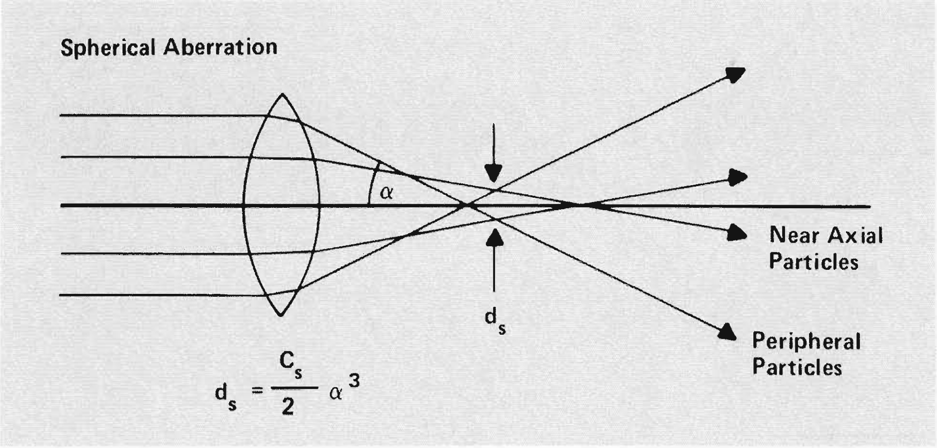


Fig. 7. Spherical aberration. The lens focuses ions far from the optical axis more strongly than those near the optical axis. Because of these spherical aberrations, the area of the focused spot can be no smaller than the "disk of least confusion" of diameter d_s*. The angle α is the divergence half-angle of the focused spot. The calculated value of the spherical aberration coefficient* C_s *for the superconducting solenoid lens is 14 centimeters.*

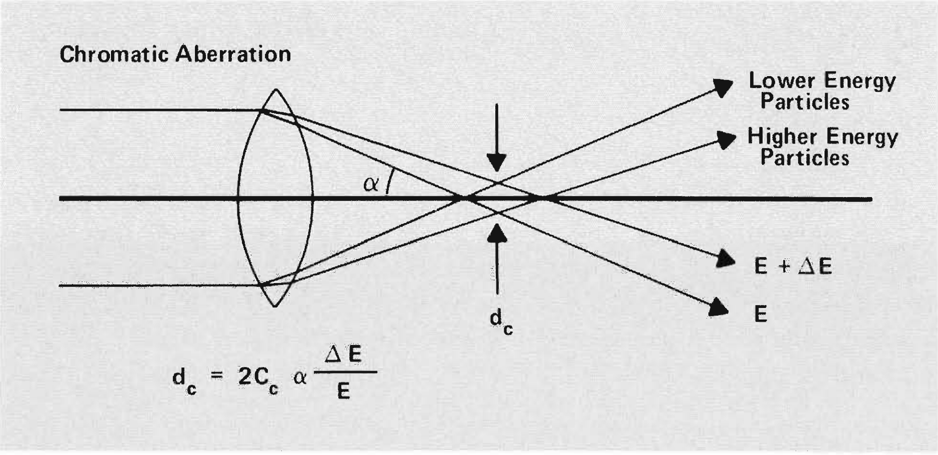


Fig. 8. Chromatic aberration. The lens focuses ions with higher energy less strongly than those with lower energy. These chromatic aberrations produce a focused spot with a diameter d_c***. The calculated value of the chromatic aberration coefficient*** C_c ***for the superconducting solenoid lens is 9.3 centimeters.***

Data-Acquisition System

The data-acquisition system is outlined in Fig. 10. The beam spot has a fixed position, and piezoelectric drivers move the sample

TABLE II

COMPARISON OF NUCLEAR MICROPROBES

System	Magnification		Maximum Acceptance of Final Lens				Phase Space	Drift Space	Focused Spot Dimensions	Current Density in Focused Spot
	M_x	M_y	x (±μm)	y	$\Delta\theta_x$ (±mrad)	$\Delta\theta_y$	(μm² mrad²)	(m)		(pA/μm²)
Harwell "Russian Quad"[a]	0.18	0.18	8.5	8.5	0.62	0.4	18	3.9	---	---
Heidelberg Doublet	0.21	0.038	7	40	0.7	0.39	76	1.9	1.5-μm diam	30
Karlsruhe Doublet	0.43	0.034	3.5	44	1.17	0.47	83	2.7	2.5-μm diam	60
Harwell Triplet	0.114	0.053	13.2	28.4	0.26	0.64	52	3.9	2 by 3 μm²	150
Los Alamos Superconducting Solenoid	0.1	0.1	15	15	2	2	900	1.1	2.5-μm diam	500

[a] *This system produced the first focused probe.*

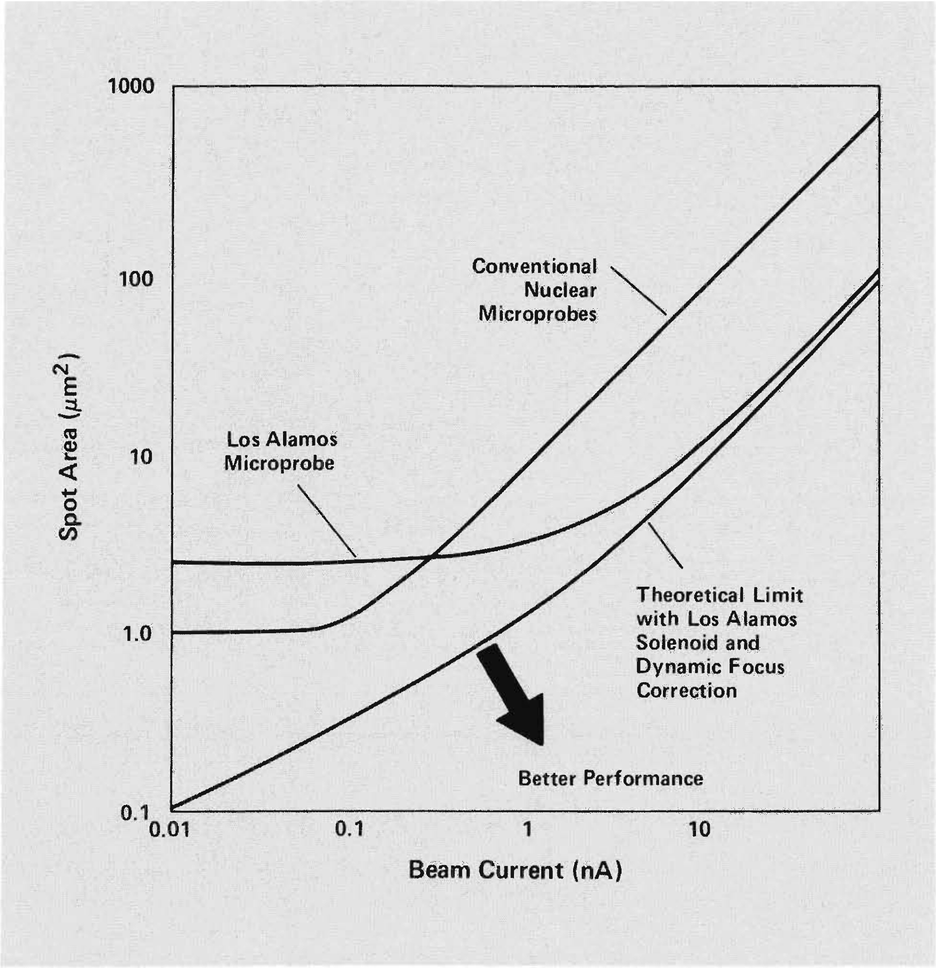


Fig. 9. Demonstrated performance of the Los Alamos superconducting solenoid lens compared with that of conventional nuclear microprobes. The curves for the superconducting solenoid lens include the effects of both chromatic and spherical aberrations. These were calculated analytically by approximating the solenoid's magnetic field with that of a Glaser field. Chromatic aberrations dominate the increase in spot diameter. Improved energy regulation would decrease this effect but is very difficult to accomplish. Dynamic focusing could compensate for chromatic aberrations by altering the focal length of the final lens as the beam energy changes. With dynamic focusing currents of a few hundred picoamperes could be focused into a spot less than a micrometer in diameter.

wheel in a computer-generated raster pattern. The sample wheel is visible in the photograph of the irradiation chamber (Fig. 11). Data at each sampling area are acquired for a preset integrated charge of incident ions. Spectral information from the detectors is recorded on magnetic tape for permanent storage and later analysis. Analysis of the data can provide background subtraction, position averaging, one-dimensional line scans, two-dimensional elemental maps, and elemental depth profiles. The software needs are more than enough to test one's imagination and stamina as a programmer.

The fixed-beam design was intended for semiconductor and metallurgical applications where localized heating was not expected to be a problem. However, fast deflection of the beam would be desirable for specimen positioning and beam focusing to minimize localized heating in specimens of low thermal conductivity. Addition of this capability to the beam line is under study. The instrument is acquiring the features of a scanning electron microscope, but the particles with which it probes give it different analytical capabilities.

Nuclear Microprobe Applications

To biologists, ion-induced x-ray emission is of interest not only because of its sensitivity of 1 to 10 parts per million but also because of its 1-μm resolution. The higher sensitivity of the nuclear microprobe compared with that of the electron microprobe provides more information about the composition of single cells. At a resolution of 1 μm, elements in the nucleus of a cell can be resolved from those in the cytoplasm. The ultimate usefulness of the nuclear microprobe in biology will be determined by the

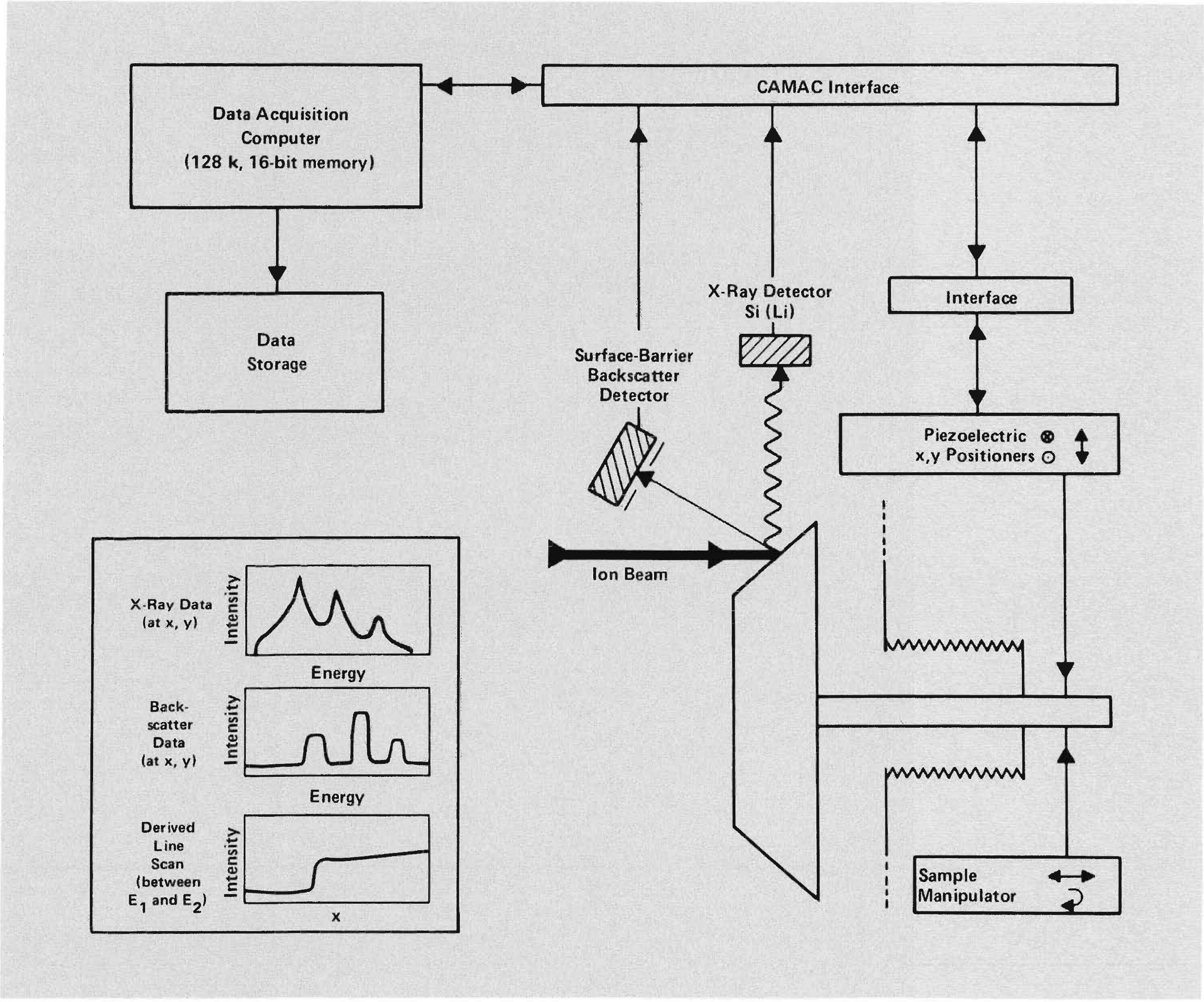
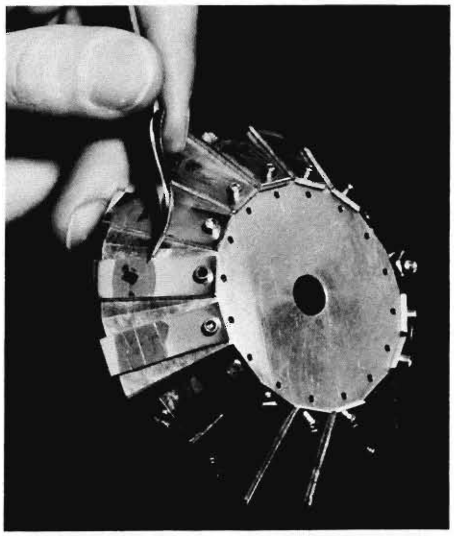


Fig. 10. Data-acquisition system of the Los Alamos nuclear microprobe. Computer-controlled piezoelectric drivers move the sample in a raster pattern relative to the fixed ion beam. At each point x-ray and/or backscattering signals from the detectors are recorded by the computer for a preset integrated charge of incident ions. During data acquisition the computer operates as a multichannel analyzer with up to 72 gates (energy windows) on the two incoming signals. The figure also shows various ways in which the data can be displayed.

susceptibility of biological samples to radiation damage. So far, no special efforts have been made to minimize specimen damage. A systematic look at the problems of specimen contamination during sample preparation and elemental migration during analysis is needed to push the biological applications beyond the studies already performed. Measuring and limiting the movement of ions at a concentration of 10 parts per million over distances on the order of 1 μm will not be simple.

To geologists or geochemists, the utility of the nuclear microprobe arises from its sensitivity to trace elements and its ability to analyze individual inclusions in a complex mineral. When sensitivities greater than 1000 parts per million are needed, the usual procedure has been to use a bulk technique, such as neutron activation or x-ray fluorescence. These techniques are not well suited to study of individual grains or small inclusions in the host mineral. But with the spatial resolution and sensitivity of the nuclear microprobe, we can determine the partitioning of trace elements among coexisting minerals. This information contains important clues about the rock's formation.

For example, by studying the minor amounts of zirconium oxide (ZrO_2) in ilmenite and ulvöspinel in lunar basalts, the equilibrium temperatures and cooling rates of the host rocks can be determined. The Heidelberg proton microprobe has been used to study ilmenite grains from the Apollo 17 mission. These rather special samples provided a test for the sensitivity of the nuclear microprobe. Zirconium was not detected by an electron beam but was readily apparent with the 2-MeV protons of the Heidelberg probe. Similarly, the use of zircons in geochronology studies requires a knowledge of thorium, lead, and uranium distributions in zircon grains. The proton microprobe has the sensitivity and spatial



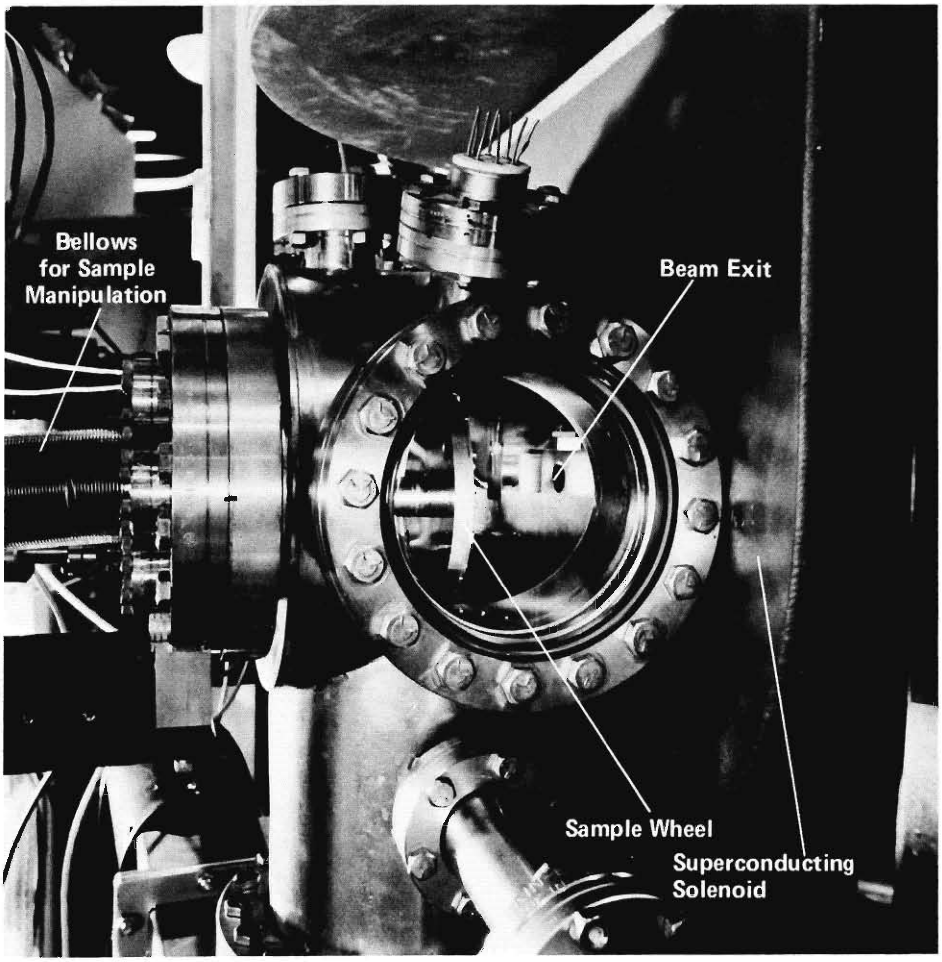


Fig. 11. Top. The microprobe sample wheel with mounts for sixteen samples. Bottom. Target chamber of the nuclear microprobe. The sample wheel and the beam-line exit are visible through the chamber window. The housing of the solenoid lens and the bellows for the piezoelectric drivers and sample manipulator are also visible.

resolution required to follow the 100-parts-per-million lead concentrations in individual zircons.

The most well-developed applications of the nuclear microprobe are metallurgical. This is understandable since the first nuclear microprobe was developed at Harwell, where metallurgical problems associated with nuclear reactors are a primary concern. Hydrogen embrittlement of metals is one such problem, and its understanding requires information about the distributions of hydrogen and deuterium. This information was obtained by detecting nuclear reaction products from the nuclear microprobe. Other problems studied at Harwell include carbon distributions in welds before and after heat treatment, the role of nitrogen in brittle cracking of zirconium alloys, the influence of boron on the ductility of irradiated steels, and beryllium diffusion in metals corroded by copper oxidation.

At Los Alamos the nuclear microprobe has opened up new possibilities in the analysis of thin films, electrochemical systems, and geologic materials. These analyses are discussed in the applications that follow.

Even though the first nuclear microprobe has been in existence for almost ten years, the instrument is still "new." Applications are in their infancy, and many possible uses remain to be explored. An air of excitement and discovery attends the first look at a new specimen. Surprises are frequent in the world below 10 μm, where preconceived ideas are often found to be incorrect. Fortunately, the relative ease and certainty of the data analysis leave little chance for misconceptions to survive. The ease and certainty rest on the great body of experimental and theoretical knowledge about interactions of few-MeV light ions with matter. Nuclear microprobe experiments can apply this knowledge to the study of "real world" problems and fundamental problems in geochemistry, biology, and materials science. The mature science of nuclear physics is being used in ways unimagined by its pioneers. ■

Trace-Element Analysis of Geologic Materials

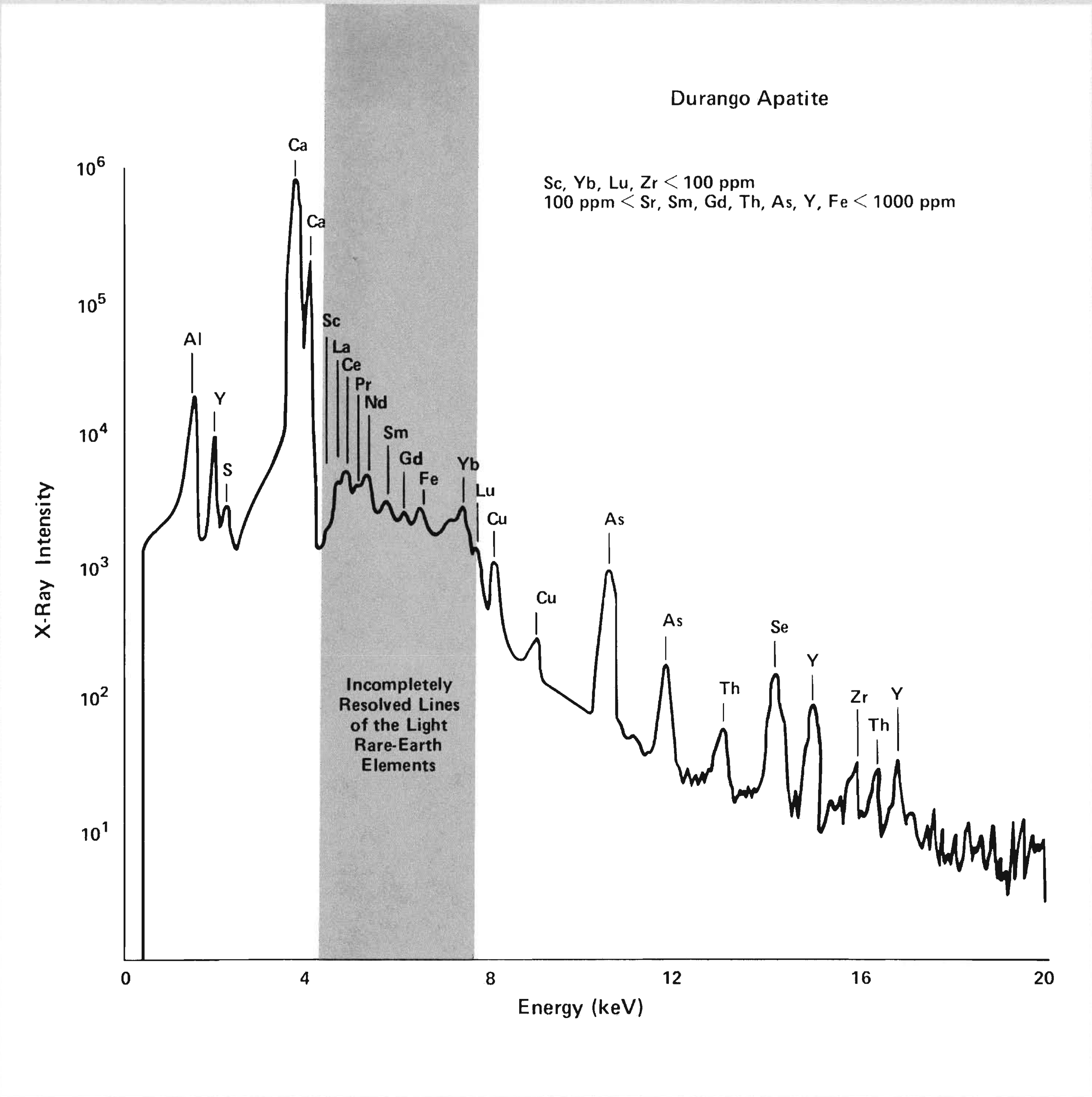
Geologic materials are complex, heterogeneous mixtures of minerals, often small grained and each with a different composition. Study of these materials demands an instrument capable of providing spatially resolved, *in situ* elemental analyses. The electron microprobe is adequate to the task if a sensitivity of 1000 parts per million is sufficient. The nuclear microprobe, which is capable of analysis at the level of 10 parts per million, can measure trace-element distributions in individual mineral grains in addition to major and minor elements. Experiments of this type were not before possible.

For example, consider the problem of determining the relative ages of meteorites, information important to theories of the origin and evolution of the solar system. Relative ages of meteorites can be deduced from the inferred abundances of the isotope plutonium-244. (Plutonium-244 is now extinct; its former abundance in a meteorite can be inferred, for example, from the abundance of its xenon decay product.) Since plutonium has no stable or very long-lived isotopes, this dating technique requires normalizing the plutonium abundance to that of another element in the meteorite. There is evidence suggesting that the geochemical behavior of plutonium is similar to that of uranium and the light rare earths, and therefore one of these elements is usually chosen for the normalization. But the validity of the normalization hinges on whether plutonium and the normalized element undergo similar fractionation during mineral formation. Experiments on synthetic geologic samples have shown that the magnitude of plutonium fractionation is between those of uranium and of the light rare earths. This fact allows application of a proposed "bracketing theorem" leading to the conclusion that if uranium and the light rare earths, when normalized to cosmic abundances, are not fractionated relative to each other in a particular meteoritic mineral, then the plutonium also was not fractionated relative to uranium and the light rare earths. The nuclear microprobe can select those meteorites suitable for plutonium-244 dating by determining that their contents of uranium and light rare earths are unfractionated.

The nuclear microprobe can also be used to study partitioning of trace elements in metal-sulfide-silicate systems. By comparing trace-element concentrations in the rocks of planetary objects with the results of synthetic partitioning experiments, we can obtain information about the differentiation of the planets into metallic cores and silicate mantles. Previously, such studies were hampered by the low concentrations of siderophile (metal-loving) and chalcophile (sulfide-loving) elements in silicate phases, lithophile (silicate-loving) and chalcophile elements in metal phases, and siderophile and lithophile elements in sulfide phases and by the necessity of physically separating the various phases before measuring the trace-element concentrations.

We have undertaken a series of experiments to test the limits of the nuclear microprobe for measuring trace-element concentrations in minerals. The accompanying figure shows the x-ray spectrum from Durango apatite, a calcium fluorophosphate that contains a large number of rare earths and typifies the complexity of geologic materials. Although the nuclear microprobe is able to detect the rare earths at a concentration of 10 parts per million, the solid-state x-ray detector cannot resolve the peaks that overlap. A focusing crystal spectrometer has the necessary energy resolution to resolve these peaks but only about one-thousandth the efficiency of the Si(Li) detector. To overcome this difficulty, the microprobe current could be increased by making use of the high phase-space acceptance of the solenoid. A crystal x-ray spectrometer is being added to the Los Alamos nuclear microprobe to combine high-resolution x-ray spectroscopy with spatially resolved trace-element sensitivity.

This work was performed in conjuction with Timothy M. Benjamin and Pamela Z. Rogers of Los Alamos and Dorothy Woolum of the California Institute of Technology.



Results of a nuclear microprobe analysis of Durango apatite, a mineral containing a large number of rare earths. X-ray emission was induced by a beam of 3-MeV protons.

Catalyst Stability in Fuel-Cell Electrodes

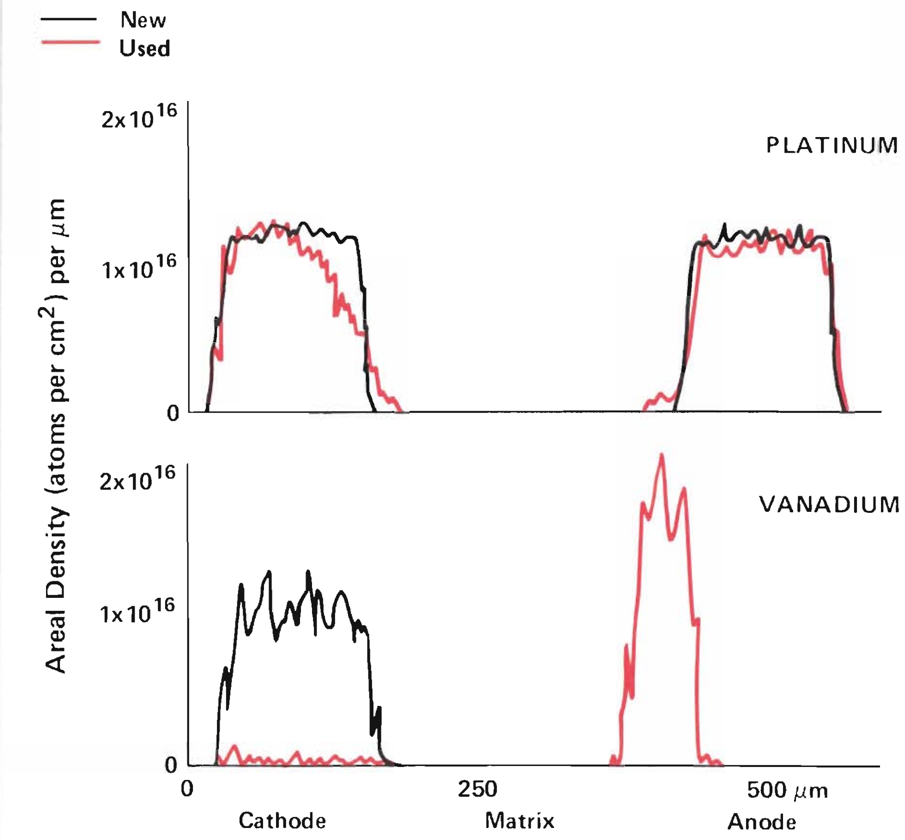
Applications

A fuel cell is a device that converts chemical energy directly to electrical energy, thus bypassing the usual intermediate and energy-wasting conversions to thermal and mechanical energy. A fuel cell based on the reaction of hydrogen and oxygen was conceived and constructed as early as 1839, but the idea was not pursued with much enthusiasm until more than a hundred years later. In recent times the development of fuel cells has been spurred by the search for more efficient and nonpolluting sources of electricity.

Basically, the hydrogen-oxygen fuel cell consists of porous electrodes separated by an electrolyte. Hydrogen and oxygen diffuse through the anode and the cathode, respectively, and undergo reactions that create a potential difference across the cell. At the anode hydrogen molecules dissociate into atoms and then release electrons. The hydrogen ions flow to the cathode through the electrolyte, and the electrons flow through the external circuit. At the cathode oxygen molecules dissociate and accept electrons from the external circuit. The hydrogen and oxygen ions then combine to form water.

To achieve high rates of dissociation and oxidation or reduction of the gases, a platinum catalyst is embedded in the electrodes. Platinum is costly, and, further, its activity for oxygen reduction at the cathode is less than ideal. An attempt has been made to reduce the amount of platinum required and increase the cathode activity by using an intermetallic platinum-vanadium compound as the cathode catalyst. The intermetallic compound shows an initial activity for oxygen reduction greater than that of platinum, but during operation its activity decreases to that of the pure metal.

The performance of a fuel cell may degrade during use, possibly because of loss of the catalyst from the electrodes. In fact, such losses are to be expected since the cathode operates at a potential close to the oxidation potential of the catalyst. We studied the migration process with the microprobe by measuring the catalyst depth distributions in new and used electrodes. The signals detected were backscattered protons from an incident beam of 3-MeV protons. To obtain the depth distribution throughout the regions where the chemical reactions take place, we made a small-angle cut through the electrode and performed a line scan across the bevel.

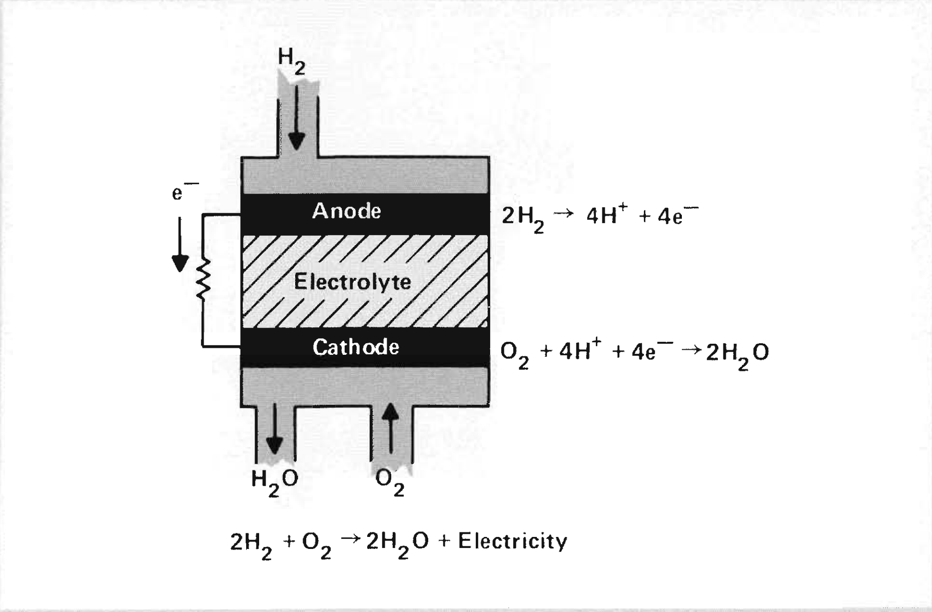


Distribution of catalyst in the electrodes of a fuel cell before use and after about 3000 hours of operation. Initially, the cathode and anode contained catalysts of platinum-vanadium and pure platinum, respectively. Note the loss of vanadium from the cathode and its buildup in the matrix near the anode of the used fuel cell.

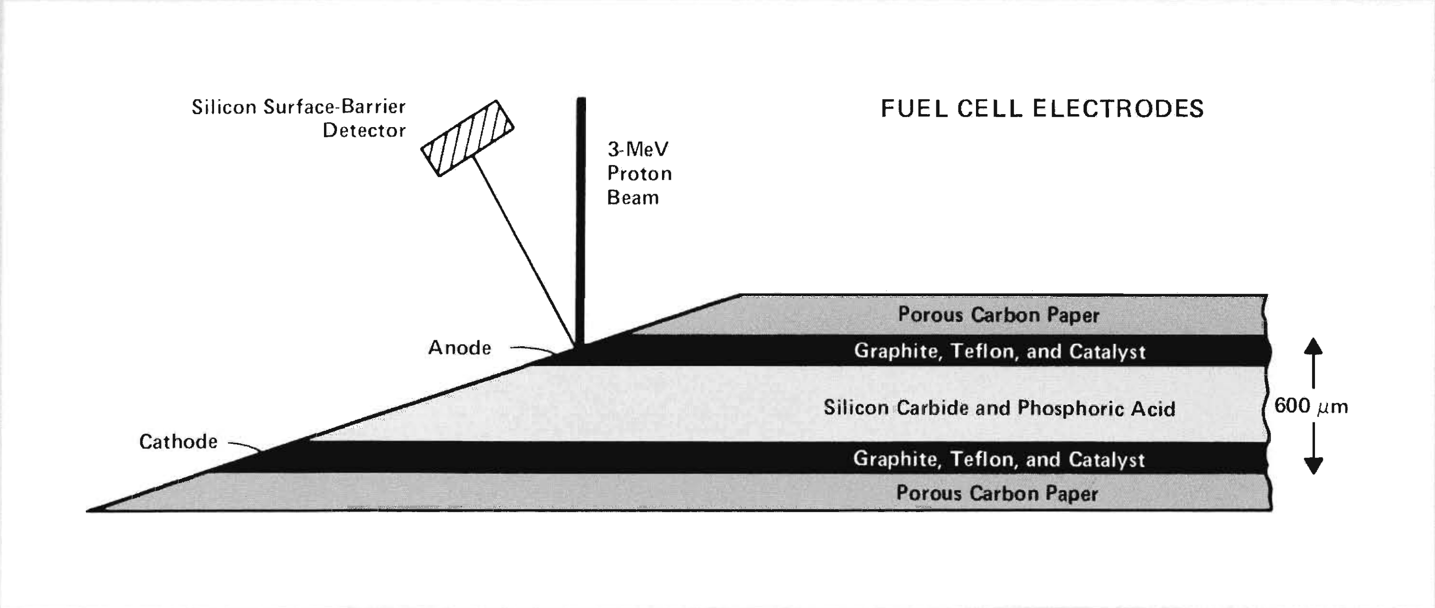
For electrodes containing a catalyst of pure platinum, the catalyst was found to be fairly stable, although there was some loss of catalyst from the cathode after several thousand hours of operation.

More interesting results were obtained for electrodes with platinum-vanadium as the cathode catalyst and platinum as the anode catalyst. In this case we determined simultaneously the depth distributions of platinum, vanadium, silicon, phosphorus, oxygen, fluorine, and carbon in the cathode, anode, and matrix. (The accompanying figure gives the depth distributions of platinum and vanadium.) Our results showed that the vanadium component of the platinum-vanadium catalyst is not stable. The vanadium dissolves in the phosphoric acid, migrates through the silicon carbide matrix, and accumulates near the anode. We are now studying several other intermetallic catalysts with a view to improved and more stable fuel-cell performance.

This work was performed in conjunction with Philippe J. Hyde and S. Srinivasan of Los Alamos.



Schematic diagram of a hydrogen-oxygen fuel cell.



Experimental setup for using the nuclear microprobe to determine the distribution of catalyst in a fuel-cell electrode of current design. The concentration of catalyst in the electrodes is about 1 part in 2000. The Teflon particles prevent flooding of the electrodes by the phosphoric acid electrolyte. The chemical reactions take place close to the three-phase regions where the gases react on the solid graphite-catalyst surface and the liquid electrolyte provides mobility for the hydrogen ions. The conducting carbon paper and graphite provide a path for the electrons.

Densities of Thin-Film Targets

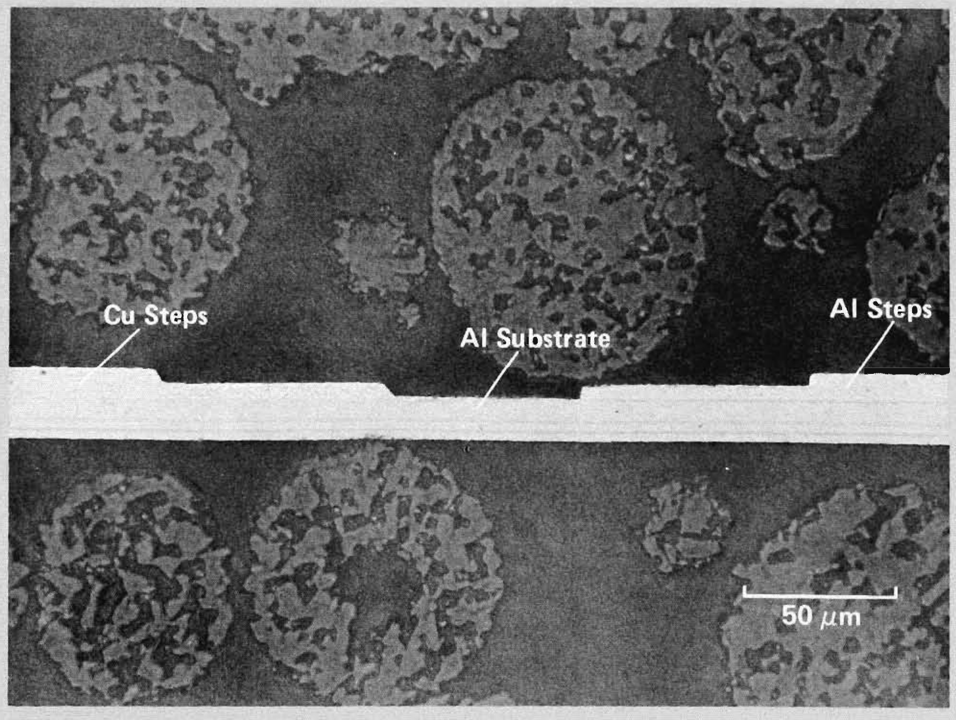
Applications

For several years Los Alamos and Livermore scientists have been using sharply focused high-power, pulsed lasers to produce high-velocity shock waves in thin-film targets. The shock waves create the intense pressures and high temperatures characteristic of the detonation of weapons and other explosives. The purpose of the experiments is to determine equations of state (the relationship among pressure, temperature, and density) for the target materials under these extreme conditions.

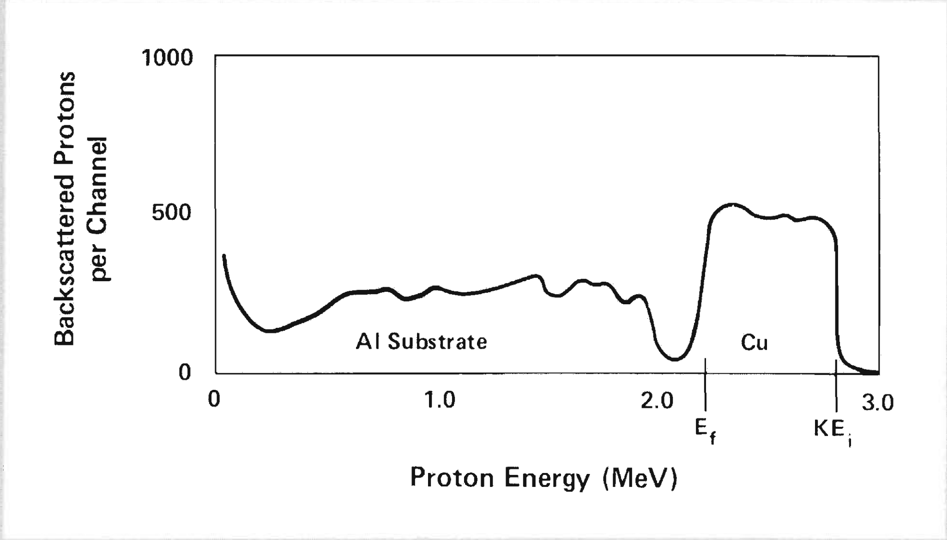
The experiments pose many difficulties, and among them is the need for an accurate measurement of the initial density and uniformity of the targets, which are fabricated by evaporating thin films onto an aluminum substrate. The nuclear microprobe provides a way to measure areal density (mass per unit area) *in situ* and nondestructively. The areal density, which is related to the width of the film's backscattering peak, is then combined with an independent thickness measurement to yield the density with an accuracy of 1 per cent.

Using a few-nanoamperes current of 3-MeV protons focused to a spot 10 micrometers in diameter, we measured the areal density and uniformity of gold, silver, copper, and aluminum targets. [A thin (0.025 micrometer) marker layer of gold between the substrate and the aluminum film permitted a measurement of the aluminum target on the aluminum substrate. The areal density of the aluminum film is then deduced from the observed energy shift of the gold backscattering peak.] In all cases, the areal densities varied from one 10-micrometer-diameter spot to another by less than 1 per cent. The nuclear microprobe is perhaps the only way to obtain such localized information about the areal density. And the superconducting solenoid of the microprobe easily produces the currents and focused beam sizes required to obtain the data in a reasonable time.

This work was performed in conjunction with Lynn R. Veeser of Los Alamos.

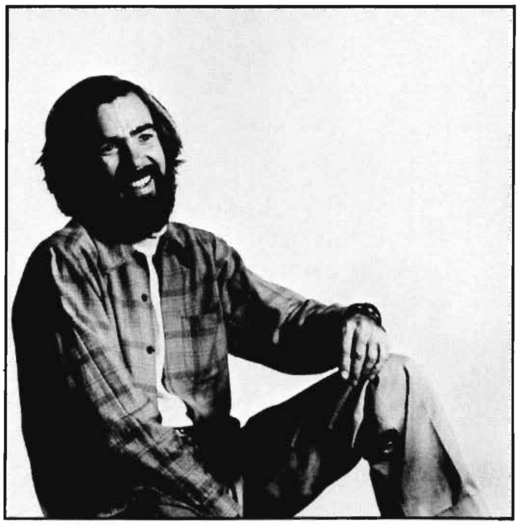


Optical micrograph of the cross section of a thin-film target for equation-of-state studies with lasers.



Spectrum of protons backscattered from a target region containing a 5-micrometer-thick copper film on the aluminum substrate. This spectrum is typical of all those from films heavier than the aluminum substrate. The areal density of the copper film is related to $KE_i - E_f$.

AUTHOR



Carl J. Maggiore earned his Bachelor of Science from Creighton University in 1965 and his Ph.D. in nuclear physics from Michigan State University in 1972. While working at Mt. Sinai Medical School in their Environmental Science Laboratory, he developed instrumentation for microanalysis of small (less than 0.1-μm-diameter) particles and studied transmission and scanning microscopy of particulates in environmental samples and in human organs to determine the health effects of asbestos. Before coming to Los Alamos, he was manager of the X-Ray Analytical Division at Princeton Gamma-Tech, Inc. Currently he is a staff member in the Electronics Division's Research and Development Group. His work there includes developing near-surface analytical techniques involving ion beams for applications in solid-state devices, in electrochemistry, and in catalysis. He is particularly interested in combining channeling/blocking of ion beams with ultra-high-vacuum surface techniques to determine the effects of geometry on the chemical reactivity of surfaces.

ACKNOWLEDGMENTS

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SCIENCE IDEAS

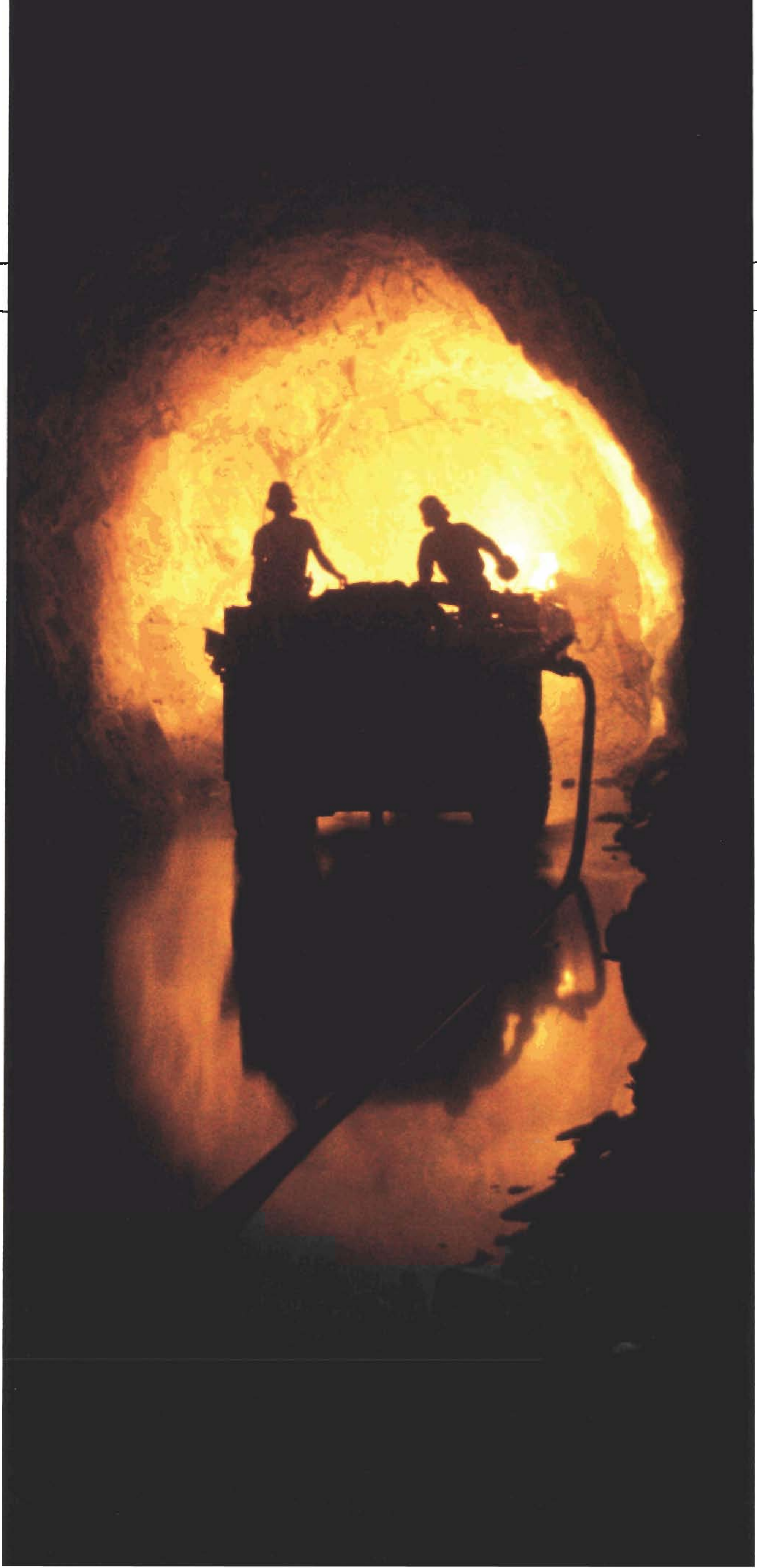


Photo courtesy of AMAX Inc.

Solar Variability, Glacial Epochs, and Solar Neutrinos

by George A. Cowan and Wick C. Haxton

Rare nuclei produced by solar neutrinos deep in a Colorado molybdenite deposit may show that the earth's most recent glacial epoch was triggered by a sudden reduction in the sun's energy output.

"We are all made of star stuff," says Carl Sagan. This tribute to the stars as the cosmic factories of the heavy elements tacitly accepts one of the great extrapolations of modern physics. We have postulated complex thermonuclear reactions occurring deep inside the stars as the source of stellar energy and the natural progression of these reactions as the basis of stellar evolution. Yet our first-hand knowledge of stellar structure is limited, consisting largely of surface observations. How certain, then, is our understanding of the processes governing synthesis of the elements deep within fiery stellar cores?

The sun, by merit of its proximity, provides unmatched opportunities for testing our theories of stellar processes. By any criterion it appears a pedestrian star, somewhat smaller and fainter than the average of its neighbors. Formed some 4.8 billion years ago, the sun has now progressed through half of the main sequence of its evolution, a phase in which almost all of its energy is derived from hydrogen "burning," the conversion of four protons into helium-4 (Fig. 1). The standard stellar theory depicts the main sequence as a relatively simple, steady-state period in a star's evolution. Thus, any failure of the standard theory to predict the present behavior of the sun could indicate a serious flaw in our stellar physics.

We believe that there is disturbing and controversial evidence that such flaws may exist. Part of the evidence is provided by the earth's climatic history, and part by a contemporary experiment that directly monitors the thermonuclear reactions in the solar core. The evidence suggests that variations in the rate of solar energy generation occur, perhaps induced by periodic mixing of the core. We propose a new experiment that may test the long-term stability of our sun.

Solar Variability?

The principal energy output of the sun is the visible electromagnetic radiation leaking from its surface. According to the standard model, the solar luminosity, or the rate at which the sun radiates electromagnetic energy, has remained constant apart from a monotonic increase of 30 per cent over the lifetime of the sun. This increase tracks the rises in the temperature and helium-4 abundance of the solar core as its supply of hydrogen is depleted.

To the extent that the earth's geologic and biologic history provides a record of the solar luminosity, we can check the predictions of the standard model. There appear to be a number of inconsistencies. The low initial luminosity predicted by the standard model suggests a primordial climate for the earth quite different from today's, yet the paleoclimatic record shows no evidence for any significant climatic evolution. On the other hand, there is evidence for unexplained variability, even periodicity, in the sun's behavior over shorter time scales (Fig. 2). Sunspot activity has waxed and waned in a regular eleven-year cycle since 1715. In the preceding seventy years, termed the Maunder Minimum, sunspot activity was nearly absent, and, according to European records, persistently cold weather took its toll on crops. Corroborating evidence for a quiescent sun during the Maunder Minimum exists in the reduced brightness and extent of the sun's corona, a diminished number of auroral displays, and an increased abundance of carbon-14 in the atmosphere. (The latter two phenomena result from a decreased emission of charged particles by the sun.) Two other prolonged perturbations of the earth's climate during the past thousand years, the warm Twelfth Century Grand Maximum and the cold Spörer Minimum of 1450 to 1540, also are correlated with periods of increased or decreased solar activity.

Does such evidence of solar variability indicate that the standard model is incorrect? The short time scales of these events are characteristic of complex physical processes occurring in the sun's convective envelope. For instance, the eleven-year cycle of solar magnetic field reversals, which govern sunspot activity, is thought to be maintained by dynamo action associated with convection and rotation. Thus, the climatic anomalies of the past millenium may indicate merely some lack of detail in standard stellar theory rather than a basic flaw. However, these phenomena do demonstrate that variations in the solar output have terrestrial consequences. A more provocative question then becomes whether there exist some climatic tests of solar behavior over the longer time scales that might characterize possible changes in the solar core, where the basic process of energy generation occurs.

Evidence of long-term climatic variability is found in the repeated advance and retreat of continental glaciers and in the quasi-periodic occurrence of major glacial epochs. The strong correlation between stages of continental glaciation and the periods (10,000 to 100,000 years) of the earth's orbital parameters (its eccentricity, obliquity, and precession) suggest that these changes are governed by the earth's orbital geometry rather than solar phenomena. In contrast, terrestrial explanations of the glacial epochs appear much less convincing. In the last billion years major glacial epochs lasting several million years have occurred regularly, separated by warmer periods lasting several hundred million years. The latest glacial epoch, the Pleistocene, began just three million years ago, and the proximity of its onset indicates that the present is an atypical time in the earth's climatic history.

The similarity of glacial time scales to those governing fundamental solar processes has been discussed extensively. The duration of the glacial epochs is comparable to the thermal diffusion time of the solar core. Their spacing corresponds to a fundamental hydrogen-burning scale, the time required for the ratio of helium-3 to hydrogen (see Fig. 1) to reach equilibrium over an appreciable fraction of the solar core. These observations have stimulated development of a number of nonstandard models in which variations in the solar output are coupled to these thermal and nuclear time scales.

Perhaps the best known of these models is the "Solar Spoon" of Dilke and Gough. Both the time required to reach equilibrium between helium-3 and hydrogen and the equilibrium ratio are sharply decreasing functions of temperature, which itself is a sharply decreasing function of the distance from the sun's center. Thus, as hydrogen burning proceeds, equilibration produces large composition gradients over expanding portions of the solar core. Dilke and Gough found that such gradients would permit large-amplitude excitation of certain nonradial solar oscillations deep in the solar interior, namely, the low-order gravity modes. (The gravity modes thus differ from the familiar five-minute solar oscillations, which are acoustic modes confined to the sun's surface.) The gravity modes become unstable when equilibrium between helium-3 and hydrogen is achieved over a sufficient fraction of the solar core. Dilke and Gough found that the time required for this to occur is 200 million years, and therefore gravity-mode instability should have been reached early in the sun's main-sequence lifetime. Yet

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu \qquad (99.75\%)$$

or

$$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu \qquad (0.25\%)$$

$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow \mathbf{{}^4He} + 2p \qquad (86\%)$$

or

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma \qquad (14\%)$$

$${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu$$

$${}^7\mathrm{Li} + p \rightarrow 2\,\mathbf{{}^4He} \qquad (99.85\%)$$

or

$${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$$

$${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu$$

$${}^8\mathrm{Be}^* \rightarrow 2\,\mathbf{{}^4He} \qquad (0.15\%)$$

Fig. 1. The proton-proton chain, or hydrogen burning, is postulated by standard stellar theory as the principal mechanism of energy generation in the sun during the current stage of its evolution. The net result of this chain of nuclear reactions is conversion of four protons into helium-4, and the energy released is carried off by photons, positrons, and neutrinos. The predicted branching ratios for competing reactions at various steps of the chain are given in parentheses, and the chain terminations in helium-4 are boldface. Another chain of nuclear reactions, which involves carbon, nitrogen, and oxygen isotopes, contributes only a small amount to the sun's energy output but can be important for main-sequence energy generation in stars more massive than the sun.

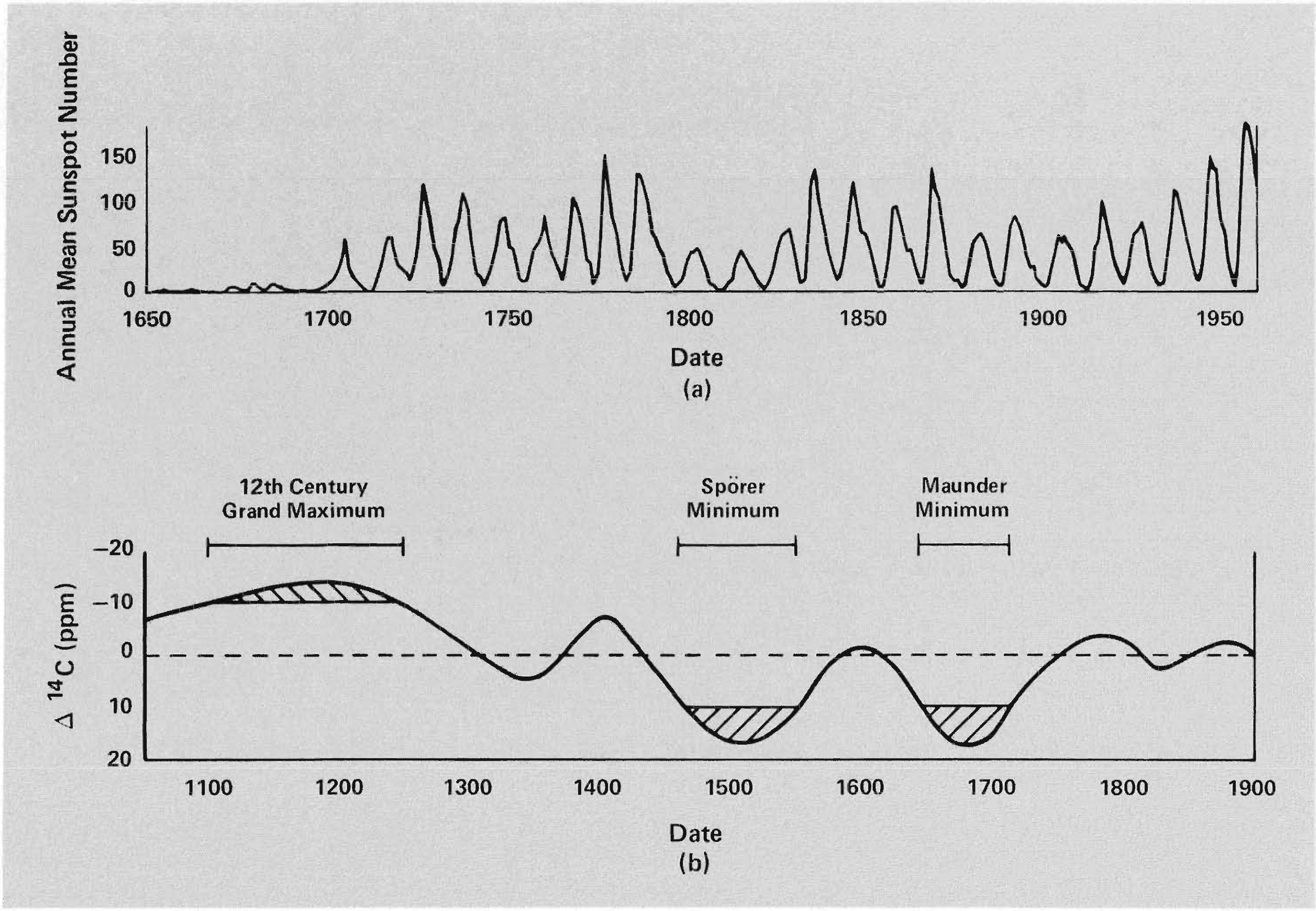


Fig. 2. Evidence for variability of the sun over its recent past. Sunspots, dark areas in the photosphere caused by a lowered surface temperature, are obvious indications of solar variability. As shown in (a), sunspot activity was notably absent during the Maunder Minimum, the seventy-year period between 1645 and 1715. But since 1715 sunspots have been abundant, the number varying in a regular eleven-year cycle [from M. Waldemeier, The Sunspot Activity in the Years 1610-1960 *(Schulthess Polygraphischer Verlag AG, Zurich, 1961)]. Modern evidence that the Maunder Minimum was a period of abnormal solar behavior has come from measurements of carbon-14 abundance in tree rings. This long-lived isotope is formed when evaporation neutrons, which are generated in the upper atmosphere by cosmic-ray interactions, induce (*n,p*) reactions on nitrogen-14. Since the "solar wind" of charged particles from the sun creates a magnetic field that shields the earth from cosmic rays, carbon-14 production varies inversely with the strength of the solar wind. Shown in (b) is the deviation of the carbon-14 abundance from the average [from John A. Eddy, Science* 192*, 1189 (1976)]. The Maunder Minimum is characterized by a deviation greater than ten parts per million, as are two other periods, the Spörer Minimum and the Twelfth Century Grand Maximum. These periods correlate, in both date and magnitude, with climatic extremes: significantly lower temperatures persisted during the Maunder and Spörer Minima, and the "Medieval Climatic Optimum" coincides with the Grand Maximum [see W. L. Gates and Y. Mintz,* Understanding Climatic Change *(National Academy of Sciences, Washington, D. C., 1975), Appendix A].*

today we find no evidence for large-amplitude oscillations of the characteristic frequency (about one hour).

The explanation provided by the Solar Spoon is that such violent oscillations would induce sudden mixing of the solar interior and thus destroy the equilibrium conditions for gravity-mode instability. Further, by enriching the core with hydrogen and helium-3, the mixing increases the rate of thermonuclear energy generation until it exceeds the energy dissipation rate. The core then expands and cools. The cooling causes a decrease in nuclear reaction rates, which in turn leads to a suppression of the solar luminosity by 5 per cent for a period of about three million years. A period of elevated luminosity of somewhat longer duration then follows. When this transient mixing phase passes, the sun again burns in thermal equilibrium for 200 million years, the time required to re-establish the nuclear equilibrium necessary for gravity-mode instability.

The duration and spacing of the transient mixing stages nicely match those of the glacial epochs. It is also widely believed that reduction of the sun's luminosity by 5 per cent would induce major climatic changes and that periodic mixing, by softening the long-term luminosity increase, would yield a primordial value more acceptable than that of the standard model. Furthermore, Sagan and Young contend that extinct Martian rivers indicate an ice-age climate for Mars coincident with the earth's Pleistocene epoch, which further suggests the existence of extraterrestrial controls. Yet we should bear in mind the circumstantial nature of these arguments; other explanations for the glacial epochs, such as the changing distributions of the continents and oceans, may be equally plausible. In addition, the suggested mode of solar variability leaves unexplained other glacial phenomena, such as the steady cooling of the oceans in the ten million years preceding the Pleistocene epoch.

TABLE I
SOLAR NEUTRINO SOURCES, ENERGIES, AND FLUXES

Source reaction[a]	Energy (MeV)	Flux at the earth[b] ($cm^{-2}\cdot s^{-1}$)
$p + p \rightarrow {}^2H + e^+ + \nu$	≤0.420	6.1×10^{10}
${}^{13}N \rightarrow {}^{13}C + e^+ + \nu$	≤1.199	4.6×10^8
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu$	≤1.732	3.7×10^8
${}^8B \rightarrow {}^8Be^* + e^+ + \nu$	≤14.02[c]	5.85×10^6
${}^7Be + e^- \rightarrow {}^7Li + \nu$	0.862 (89.6%) 0.384 (10.4%)	4.1×10^9
$p + e^- + p \rightarrow {}^2H + \nu$	1.442	1.5×10^8

[a] The reactions involving carbon, nitrogen, and oxygen isotopes are part of another chain of nuclear reactions that contributes only a small amount to the sun's energy output.

[b] Flux values are from the standard solar model calculations of J. N. Bahcall, S. H. Lubow, W. F. Huebner, N. H. Magee, Jr., A. L. Merts, M. F. Argo, P. D. Parker, B. Rozsnyai, and R. K. Ulrich, Physical Review Letters **45**, 945-948 (1980).

[c] The energy computed with respect to the center of the broad 2.9-MeV beryllium-8 resonance populated by the beta decay of boron-8.

The Solar Neutrino Flux —A Test of Solar Models

In light of these uncertainties, it is essential to find more direct tests of the assumptions made in the standard solar model. Unfortunately, conventional optical studies of the sun provide little information about the nuclear reactions occurring deep in the solar core. Photons, after completing their ten-million-year journey outward to the sun's surface, clearly retain no detailed memory of these parent reactions. Yet Nature has provided a more direct means of probing the solar interior—the neutrino.

The nuclear reaction chains postulated by the standard model as the mechanism of solar energy generation (see Fig. 1) include a number of weak interactions (electron captures and beta decays) that produce neutrinos. Neutrinos react with matter so weakly that, once born in the solar interior, nearly all pass unaffected through the sun's outer layers and, eight minutes later, through the earth. They retain, in their energy and in their flux, a detailed record of the nuclear reactions that created them (Table I). Thus, a successful program of solar neutrino spectroscopy could test the principal assumption of the standard model. Furthermore, since neutrinos are the only particles that escape immediately from the sun, they are the lone contemporary monitor of activities in the solar core.

Precisely because neutrinos react so weakly with matter, terrestrial experiments to detect them are enormously difficult. At present only a single solar neutrino measurement has been made, that of Raymond Davis, Jr., and collaborators. This radiochemical experiment is based on the inverse beta decay of chlorine-37, $\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$, which is induced by those solar neutrinos with energies greater than 0.81 million electron volts. The target consists of a

100,000-gallon tank of tetrachloroethylene (C_2Cl_4) located 1500 meters underground in the Homestake gold mine at Lead, South Dakota. (This depth of overburden is necessary to shield against cosmic-ray muons, which also can initiate reactions leading to argon-37.) The argon-37 atoms are removed from the tank by periodic flushing with helium and are counted by detecting the Auger electrons emitted as they decay (with a half-life of 35 days) by electron capture.

The measured neutrino capture rate is $1.95 \pm 0.3 \times 10^{-36}$ captures per chlorine-37 atom per second, which is equivalent to the production of one argon-37 atom in the entire target about every three days. This rate is in sharp disagreement with the 8.0×10^{-36} captures per chlorine-37 atom per second predicted by the standard solar model. The efficiency for argon-37 recovery from the target has been demonstrated, and the cross section for neutrino capture by chlorine-37 is known. Thus some flaw must exist in our prediction of the neutrino flux reaching the earth.

This "solar neutrino puzzle" has remained unresolved for more than a decade. The discrepancy may be a symptom of some fundamental difficulty with our understanding of stellar physics. Alternatively, the sun may burn as we expect, but the behavior of neutrinos over astrophysical distances may involve new physics. The latter suggestion has become increasingly plausible with recent indications of massive neutrinos and neutrino oscillations (see "The Neutrino in 1980" in Volume 2, Number 1 of *Los Alamos Science*).

The puzzle can be solved by mounting additional solar neutrino experiments. Alone, the Davis experiment is not definitive because it detects only a very small fraction of the solar neutrino flux, primarily those high-energy neutrinos produced in the beta decay of boron-8 (see Fig. 1 and Table I). This branch of the proton-proton chain is critically sensitive to the central temperature of the sun. If the standard model could be modified to produce the observed solar luminosity with a lower core temperature, the boron-8 neutrino flux could be reduced to a level consistent with the Davis experiment. Although the requisite modifications appear violent, such as postulating mechanisms that reduce the core opacity by maintaining a homogeneous distribution of elements with higher atomic weight, they cannot be dismissed a priori.

Other components of the solar neutrino flux are much less sensitive to possible modifications of the standard model. The flux of low-energy neutrinos from the driving reaction of the proton-proton chain, $p + p \rightarrow {}^2H + e^+ + \nu$, is effectively fixed by the observed luminosity and by the assumption that hydrogen burning is the solar energy source. If the flux of these neutrinos proves also to be strongly suppressed, one would conclude that some failure in our understanding of neutrino propagation, rather than solar physics, is responsible for the solar neutrino puzzle. The best hope for measuring these low-energy neutrinos may be an experiment based on the reaction $\nu + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$. The principal impediment to the experiment appears to be the cost of the requisite quantity (50 tons, or about twice the non-Communist world's annual production) of gallium, which is estimated to be in excess of $25 million.

A Los Alamos Solar Neutrino Experiment

No less strong are the arguments for pursuing new neutrino experiments that probe untested aspects of solar physics. Two years ago we became fascinated by suggestions that secular variations in the sun's energy production could be responsible for both the solar neutrino puzzle and the periodic occurrence of glacial epochs. If core mixing initiated the Pleistocene epoch, the relation indicated by the standard model between photon and neutrino luminosities would not at present be valid because the sun would not yet have returned to thermal equilibrium. Specifically, the calculations of Dilke and Gough show that the depression in the boron-8 neutrino flux following mixing could be of sufficient magnitude and duration to account for the results of the Davis experiment.

How can such speculations be tested quantitatively? Several suggestions have been made in recent years for performing geochemical solar neutrino measurements, that is, measurements of the concentrations of certain long-lived isotopes produced by neutrino-induced reactions in natural ore bodies or salt deposits. Geochemical experiments enjoy a considerable advantage over their laboratory counterparts in that much larger concentrations of product isotopes accumulate over geologic times. Our concern with solar variability over time scales on the order of a million to ten million years suggests another reason for pursuing such experiments: they may provide a quantitative record of past conditions of the solar core.

An intrinsic difficulty associated with geochemical experiments is the inability to control backgrounds. Various nuclear reactions induced by energetic neutrons, protons, and alpha particles can effectively swamp the solar neutrino signal by producing the isotope of interest at a greater rate than do the neutrinos. Sources of such particles include cosmic rays and radioactive nuclides, such as thorium and uranium, which are found in trace quantities throughout the earth's crust. Cosmic-ray backgrounds, which are due principally to reactions induced by protons evaporated from nuclei after interaction with high-energy muons, will be unimportant provided the ore body is deeply buried. (It was to minimize the cosmic-ray background that Davis chose to mount his experiment deep in the Homestake gold mine.) In contrast, the importance of the backgrounds induced by particles from radioactive nuclides depends strongly on ore composition, nuclear reaction thresholds, and Coulomb barriers, and conditions in Nature are usually such that these backgrounds prove fatal. Unfortunately, the magnitudes of these backgrounds are often apparent only after tedious calculations of reaction cross sections.

Thus, although our search for target isotopes yielded several candidates, the upper limits imposed by the background calculations on the thorium and uranium contents of candidate ore bodies eliminated most of these. There remained two possibilities, both involving the production of technetium isotopes from molybdenum:

$$\nu + {}^{97}\text{Mo} \rightarrow e^- + {}^{97}\text{Tc}$$

and

$$\nu + {}^{98}\text{Mo} \rightarrow e^- + {}^{98}\text{Tc}.$$

Fortunately, these reactions probe precisely the time scale and neutrino-flux component of most interest: the boron-8 neutrino luminosity, which is the most sensitive monitor of variations in the solar core temperature, during and before the Pleistocene epoch. (The half-lives of technetium-97 and -98 are, respectively, 2.6 and 4.2 million years; the reaction on molybdenum-98 is induced only by the high-energy boron-8 neutrinos; and the reaction on molybdenum-97 may sample in addition the flux of beryllium-7 neutrinos, which are second only to boron-8 neutrinos in sensitivity to the core temperature.)

Is a geochemical measurement of technetium feasible? The first requirement is to locate a suitable ore body, that is, molybdenum in sufficient quantity and at sufficient depth. Although molybdenum is not a common element, there do exist commercial deposits of molybdenite (MoS_2), an accessory mineral in certain altered granitic rock. If we require the cosmic-ray background to be less than 10 per cent of the neutrino signal predicted by the standard solar model, the minimum depth of overburden for the typical host rock is 1340 meters.

We know of one commercially developed molybdenite deposit that satisfies this depth criterion, the Henderson ore body under Red Mountain in Clear Creek County, Colorado (Fig. 3). The ore contains 0.49% molybdenite on average, is currently being mined at a depth in excess of 1132 meters, and extends to a depth of more than 1500 meters. Furthermore, for a geochemical experiment the effective depth is somewhat greater since the top of the ore body at the time of its formation (about 25 million years ago) lay 1500 to 1800 meters below the surface. The present minimum depth of overburden is at the valley floor through which the deposit is entered. This floor resulted from glacial scouring only 10,000 years ago.

To determine the long-term boron-8 neutrino flux we must extract approximately 10 million atoms (about 10^{-15} gram) each of technetium-97 and technetium-98 from 2000 metric tons of ore (equivalent to 10 per cent of the daily yield of the Henderson mine). The great miracle of this experiment is that a series of coincidences of Nature and commerce render such large-scale isolation of technetium both feasible and affordable.

The commercial world has made its contribution in the fortuitous design of the molybdenum recovery process, which already includes most of the chemistry needed for technetium isolation (Fig. 4). After being mined, the raw ore is finely ground and concentrated by repeated flotation. The resulting concentrate contains 85 to 90 per cent molybdenite. AMAX Inc., the mine operator, then ships the concentrate by rail to a conversion plant in Fort Madison, Iowa, where the molybdenite is converted to the trioxide by roasting with excess oxygen. The concentrate also contains rhenium, an element chemically similar to technetium. It is known that the rhenium forms volatile oxides at the controlled roasting temperature (about 700 degrees Celsius) and passes into the gas stream, which consists largely of sulfur dioxide and air, with efficiencies that can exceed 90 per cent. We believe that most of the rhenium and, presumably, the accompanying technetium are then removed from this gas stream by a scrubbing operation prior to conversion of the sulfur dioxide to sulfuric acid.

We had anticipated having to undertake the costly chemistry of extracting technetium from the effluent of the gas-scrubbing operation. Much to our delight, we learned from early discussions with AMAX officials that this step also was performed at the conversion plant. The company had recently determined that the effluent contained selenium in concentrations that could be damaging to the environment, and last fall had installed a treatment facility to precipitate excess metal from the effluent. Because of their similar chemistry, both rhenium and technetium should precipitate with the selenium.

With the problems of large-scale chemistry circumvented, the remaining hurdle is the development of techniques for isolation and analysis of approximately 10 million atoms each of technetium-97 and -98 residing in kilograms of the selenium-rhenium-technetium sludge. Although the task is formidable, progress made recently in the chemistry and mass spectrometry of technetium would appear to justify our optimism. Standard distillation, solvent extraction, and ion chromotography procedures will be followed in preparing a technetium sample suitable for isotopic analysis, a final task that Nature has greatly simplified.

Technetium is *unique* among the elements in having long-lived but no stable isotopes. Thus, the mass-spectrometric resolution for counting 10 million atoms of technetium-97 and -98 is determined not by the concentration of a stable isotope but by that of a third unstable technetium isotope, technetium-99. This isotope, whose half-life is 0.21 million

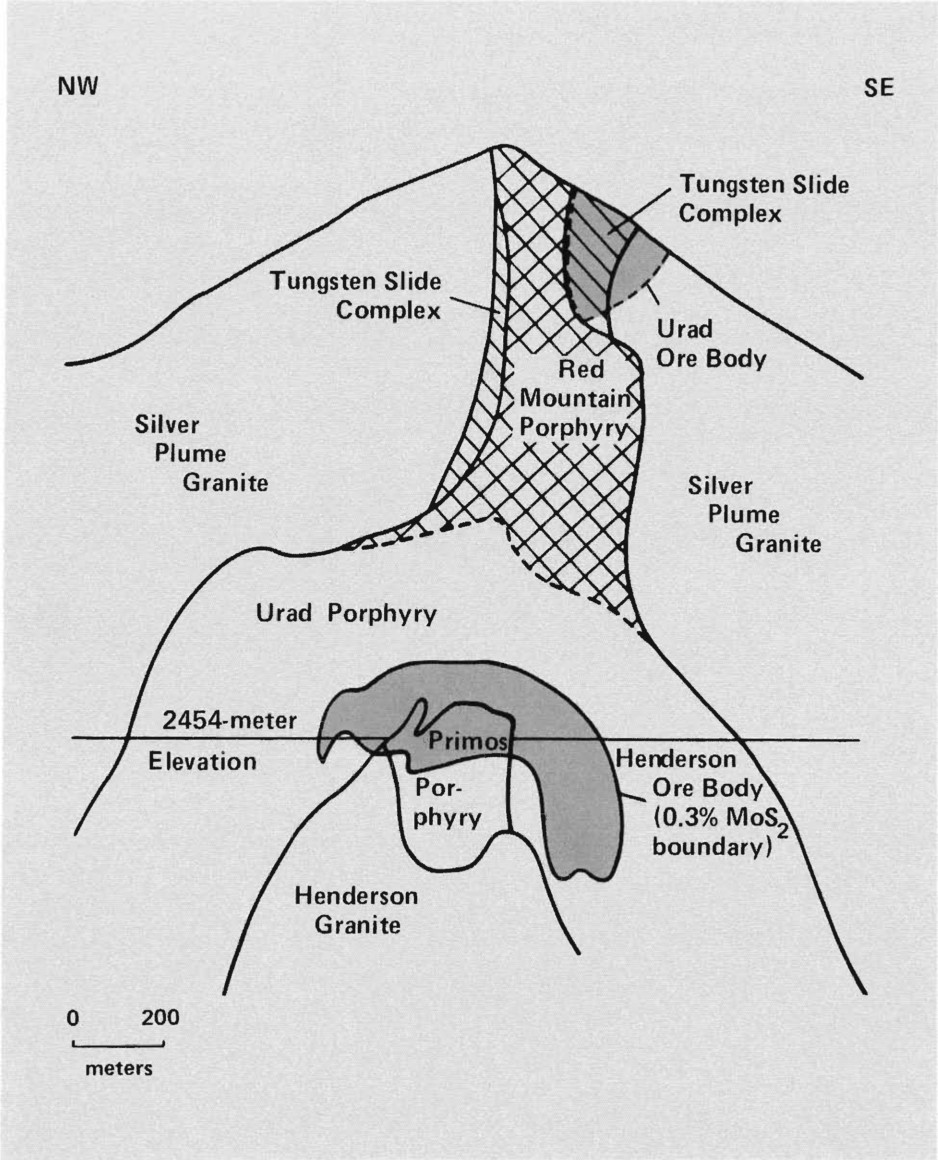
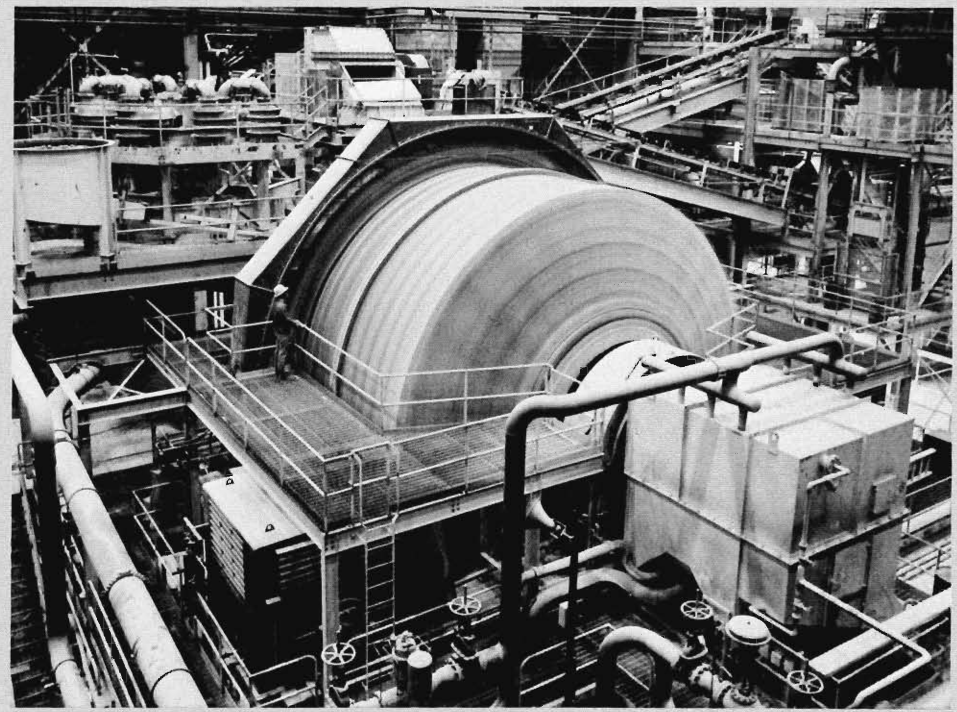


Fig. 3. Geologic section of Red Mountain, Clear Creek County, Colorado. More than 1300 meters below the mountain's summit lies the Henderson ore body, one of the largest known deposits of molybdenum ore in the world. The existence of the Urad ore body, a molybdenum deposit much closer to the surface, led geologists to suspect that Red Mountain might contain more molybdenum, and in 1965 the last of a series of test drillings intersected the fringe of the Henderson ore body. Geologic section from D. E. Ranta, W. H. White, A. D. Ward, R. E. Graichen, M. W. Ganster, and D. R. Stewart in Professional Contributions of Colorado School of Mines: Studies in Colorado Field Geology, *Rudy C. Epis and Robert J. Weimer, Eds. (Colorado School of Mines, Golden, Colorado, 1976).*

years, occurs in the ore principally as a fission product of uranium-238. Resolution of technetium-99 and -98 appears feasible at the expected ratio (less than 7000) of the two isotopes. (Had Nature produced a stable technetium isotope with an abundance of only 1 part per billion in the ore, the ratio of the stable isotope to the mass-98 isotope would be 10^{15}, and the experiment would be impossible with current technology.) In fact, the presence of technetium-99 at a level about 10,000 times that of technetium-98 may prove a great advantage: because its concentration in the ore can be inferred from the known uranium content, it can serve as a monitor of the overall chemical efficiency for recovering technetium.

There are a number of points that must be addressed before we can state definitively that the proposed solar neutrino measurement is practical. We must demonstrate that the loss of technetium over geologic times in the reducing environment of the Henderson ore body is low by establishing that technetium-99 is close to secular equilibrium with its uranium-238 parent; that an appreciable fraction of the rhenium content of Henderson molybdenite can be recovered from the gas-scrubbing effluent; and that our theoretical estimates of the neutrino-capture cross sections, upon which our background estimates are predicated, are reasonable by measuring the Gamow-Teller strength distributions in technetium-97 and -98 with forward-scattering (p,n) reactions. Yet we believe there are substantial reasons for optimism. Certainly the chemical and economic aspects of the large-scale technetium isolation are unusually advantageous. Furthermore, there exists at this Laboratory the unique array of talents required to undertake a multidisciplinary endeavor of this magnitude. (our present and future collaborators include Alexander Gancarz, James S. Gilmore, Charles M. Miller, Nicholas S. Nogar, A. Edward Norris, Thomas L. Norris, Donald J. Rokop, Elizabeth N. Treher, and Kurt Wolfsberg, all of

Recovery of Technetium from Molybdenum Ore



Molybdenum ore is ground to sandlike consistency in mills 8.5 meters in diameter and 4.3 meters long. Within the mill are steel balls somewhat larger than a softball that help pulverize the ore as the mill rotates at 10 revolutions per minute. (Photo courtesy of AMAX Inc.)

Molybdenite in the ore is separated from waste material by flotation. As air is blown through a mixture of finely ground ore, water, and chemicals, particles of molybdenite cling to the air bubbles, which rise to form a froth on the surface. (Photo courtesy of AMAX Inc.)

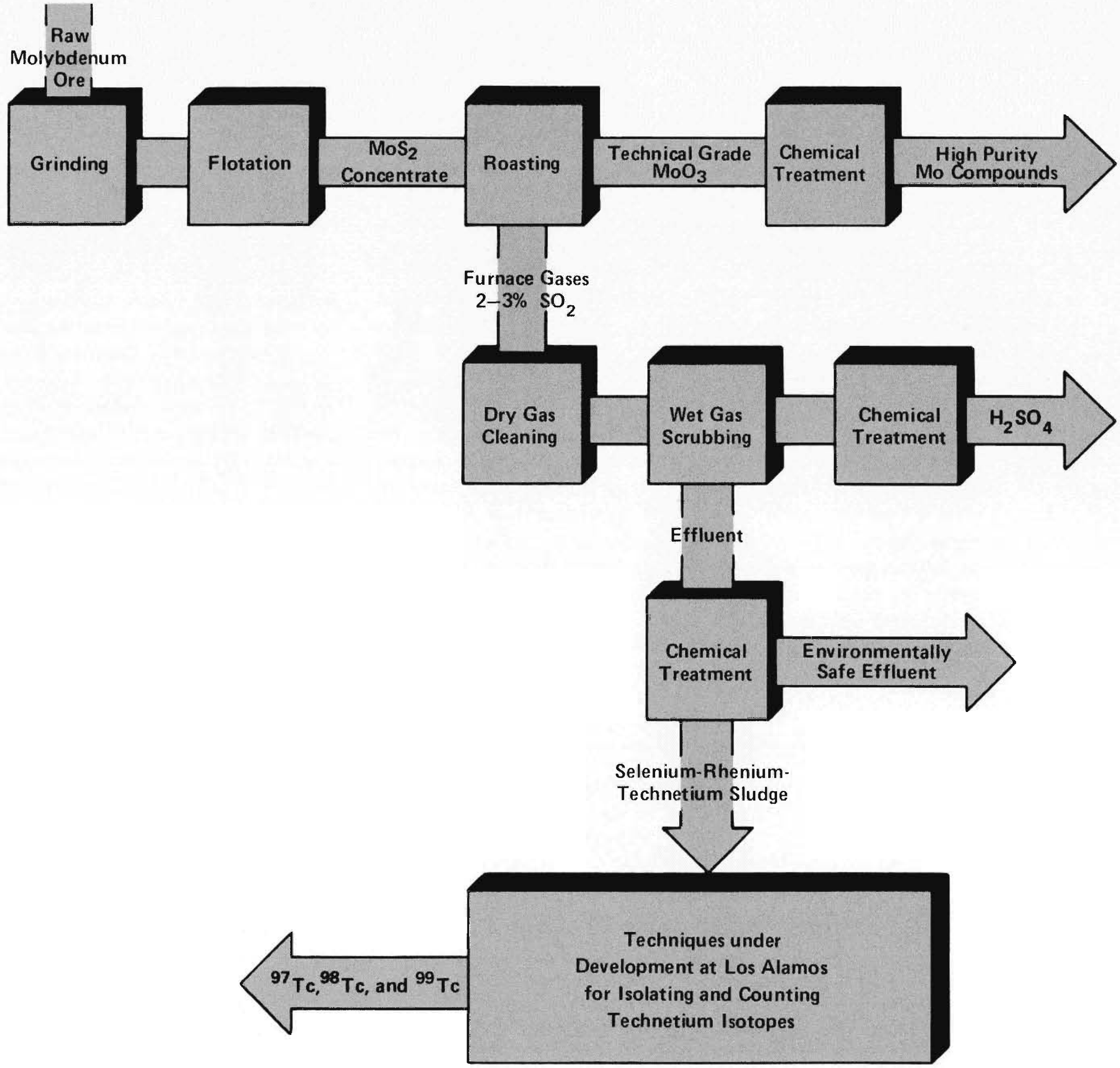


Fig. 4. Raw molybdenum ore is converted to valuable molybdenum products and sulfuric acid by the processes shown here. It is the sludge from the effluent treatment that is of interest to Los Alamos scientists, for it contains extremely minute quantities of technetium formed over millions of years by interaction of solar neutrinos with molybdenum.

Los Alamos, and Anthony Turkevich of the University of Chicago.)

The primary motivation for our efforts is the belief that a quantitative test can be made of nonstandard solar models that suggest a connection between the solar neutrino puzzle, the proximity of the Pleistocene glacial epoch, and the fundamental thermal and nuclear times of the solar core. Specifically, our proposed experiment can test the suggestion that solar mixing about four million years ago initiated the Pleistocene epoch and a persisting depression of the high-energy solar neutrino flux. Clear memory of the steady-state solar phase that preceded mixing should be retained in technetium-98 with its half-life of 4.2 million years. Recovery of this isotope in a quantity lower than that predicted by the standard solar model but significantly higher than that detected by the Davis experiment would support suggestions of solar variability and solar influence on terrestrial climate.

Another justification for this experiment was pointed out recently by Cahn and Glashow. They suggested that chemical isolation of technetium could have important implications for unified theories of the strong and electroweak forces. These theories predict the existence of superheavy elementary particles with masses 10 to 100,000 times greater than that of the proton. If some abundance of integrally charged superheavy particles $X^{\pm}$ was created in the early days of the universe, superheavy nuclei may now exist. In particular, the X^- could bind electromagnetically to ruthenium to form a stable nucleus with the charge of technetium and chemical properties similar to those of both technetium and rhenium. A principal commercial source of rhenium is molybdenum ore, since rhenium disulfide (ReS_2) is often the primary impurity in molybdenite. Presumably, if RuX^- exists, it should also concentrate in molybdenite. We could demonstrate its existence by isolating in the mass spectrometer a minimally deflected "Tc" component with the isotopic distribution of ruthenium. Our experiment should be capable of detecting an average RuX^- concentration in the earth's crust of 1 part in 10^{26}.

Conclusions

A causal relation between solar variability and terrestrial climatic changes during the past millenium can be demonstrated from the records of sunspot activity and carbon-14 production. The solar neutrino puzzle, the proximity of the Pleistocene epoch, and the similarity between the spacing and duration of the major glacial epochs and the fundamental time scales of the solar core then raise the possibility that solar variability may also be the cause of the glacial epochs. Perhaps the lone monitor of the behavior of the solar core over the relevant time scales is the solar neutrino flux. Because of a series of fortuitous circumstances of commerce and Nature, Los Alamos scientists have an opportunity to read the geochemical record of that flux in the abundances of technetium-97 and -98 in a deeply buried molybdenite deposit. Together with the Davis experiment, this reading should provide an unequivocal test of possible variations in the central temperature of the sun during the Pleistocene epoch. ■

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AUTHORS

George A. Cowan received a B.S. in chemistry from Worcester Polytechnic Institute in 1941 and a D.Sc. in chemistry from Carnegie Institute of Technology in 1950. In the fall of 1941, he joined the cyclotron physics group at Princeton University under Eugene Wigner and participated in early neutron-capture cross-section measurements on uranium. He transferred with this group in early 1942 to the Metallurgical Laboratory at the University of Chicago for a stay of three years interrupted by assignments with Mallinckrodt Inc., Massachusetts Institute of Technology, Oak Ridge, and the Pupin Laboratory's time-of-flight neutron spectroscopy group at Columbia University. He first came to Los Alamos in late 1945 to join an overseas group at Operation Crossroads, conducted at Bikini in 1946. He then resumed graduate study and, after completing a thesis in gas kinetics, returned to Los Alamos as a member of its Radiochemistry Group. His research on neutron and charged-particle reactions in weapons led to an assignment as program manager for the development of diagnostic radiochemical detectors inserted in the "Mike" device, which was tested at Eniwetok in November 1952. After serving briefly in 1955 as scientific commander of overseas test programs, he was appointed Group Leader of the Radiochemistry Group and Associate Division Leader of the Test Division. He became Division Leader of the newly formed Chemistry-Nuclear Chemistry Division in 1971, Associate Director for Research in 1979, Associate Director for Chemistry, Earth, and Life Sciences a few months later, and moved to his present position of Senior Fellow in 1981. He was recently appointed to a one-year term on the newly established White House Science Council.

Wick C. Haxton is one of the Laboratory's J. Robert Oppenheimer Fellows and is affiliated with the Theoretical Division's Medium Energy Physics Theory Group. He completed Bachelor of Science degrees in mathematics and physics at the University of California, Santa Cruz, graduating with highest honors in 1971. After receiving his Ph.D. in physics from Stanford University in 1975, Wick held postdoctoral appointments at the Institut für Kernphysik der Universität Mainz and at Los Alamos. He is currently on leave from his position as an Assistant Professor of Physics at Purdue University. His research interests include electromagnetic and weak interactions of nuclei, meson exchange currents, tests of conservation laws, nuclear astrophysics, and many-body techniques in nuclear physics. His avocations include tennis and bicycling. He is a member of the American Physical Society's Nuclear Division Program Committee and of the Theory Users Group of the M.I.T. Bates Linac.

"the war of time against the soul of man..."

—Alfred, Lord Tennyson

An Interview with Mark W. Bitensky

by Judith M. Lathrop

A scientist cannot be asked to do research in an adverse milieu just as a pianist cannot be expected to perform a sonata while wearing mittens.

In January 1981 Dr. Mark Wolfe Bitensky became leader of the Life Sciences Division at Los Alamos. Behind him he left a professorship in Yale University's Department of Pathology; with him he brought ongoing research in biochemistry and extensive training in pathology, clinical medicine, and molecular biology. Here at the Laboratory he seeks those interactions with the physical sciences that will fashion the powerful tools of tomorrow's molecular biology—tools that address, he says, the human term in the equations of energy and defense.

Mark Bitensky is a man who approaches science with driving energy and conviction. As the provocative title he chose for this interview indicates, he is intensely concerned whether the nation at this time fully understands the prudence of basic research. He is well qualified to speak on the subject because of his own life-long dedication to it. He is currently engaged in a three-year study of "Glycosylation of Membrane Proteins in Diabetes" for the National Institutes of Health and in a twelve-year study of "Light Regulated Retinal Enzymes and Cyclic Nucleotides" for the National Institute of Arthritis, Metabolism, and Digestive Diseases. He stresses the importance of "staying with" a piece of fundamental research for the long term. "Only when you know a field as well as you know your own hand do you have the proficiency to break through established dogma."

Bitensky's enthusiasm for science carries the imprint of the ancient Greek "entheos," and those who share in his research soon share his excitement as well. They collect fond anecdotes of his talent for "relating any and every experience to molecular biology." There was, for example, the occasion on which he spotted a potent regulator of the brain enzyme andenylate cyclase in the snack he was having for lunch. Subsequent research verified his brown-bag hypothesis. Indeed, a warm smile lights his eyes each time he exclaims, "Today we talked science!"

Dr. Bitensky is an acknowledged pioneer in the areas of cyclic nucleotide metabolism and light activated enzymes in the retina. He is a Fellow of the New York Academy of Sciences and has become a perennial lecturer at the Gordon Conferences on cyclic nucleotides and sensory transduction. When he speaks of the creative force of excellence in science, he is not just indulging in rhetoric: he is very much involved.

SCIENCE: *Dr. Bitensky, the title you have selected for this interview suggests a serious conflict with time. Do you feel we do battle with time in attempting to shape our research goals?*

BITENSKY: I wish to tell you a parable that is attributed to an ancient Buddhist monk. He was examining a newly completed building in a previously unused portion of the temple grounds. The structure, without trees or shrubbery, seemed naked. This revered elder asked, "How long will it take to grow such great temple trees as grace the older buildings?" "At least a hundred years," he was told. "Then," he said, "we must plant the seeds at once."

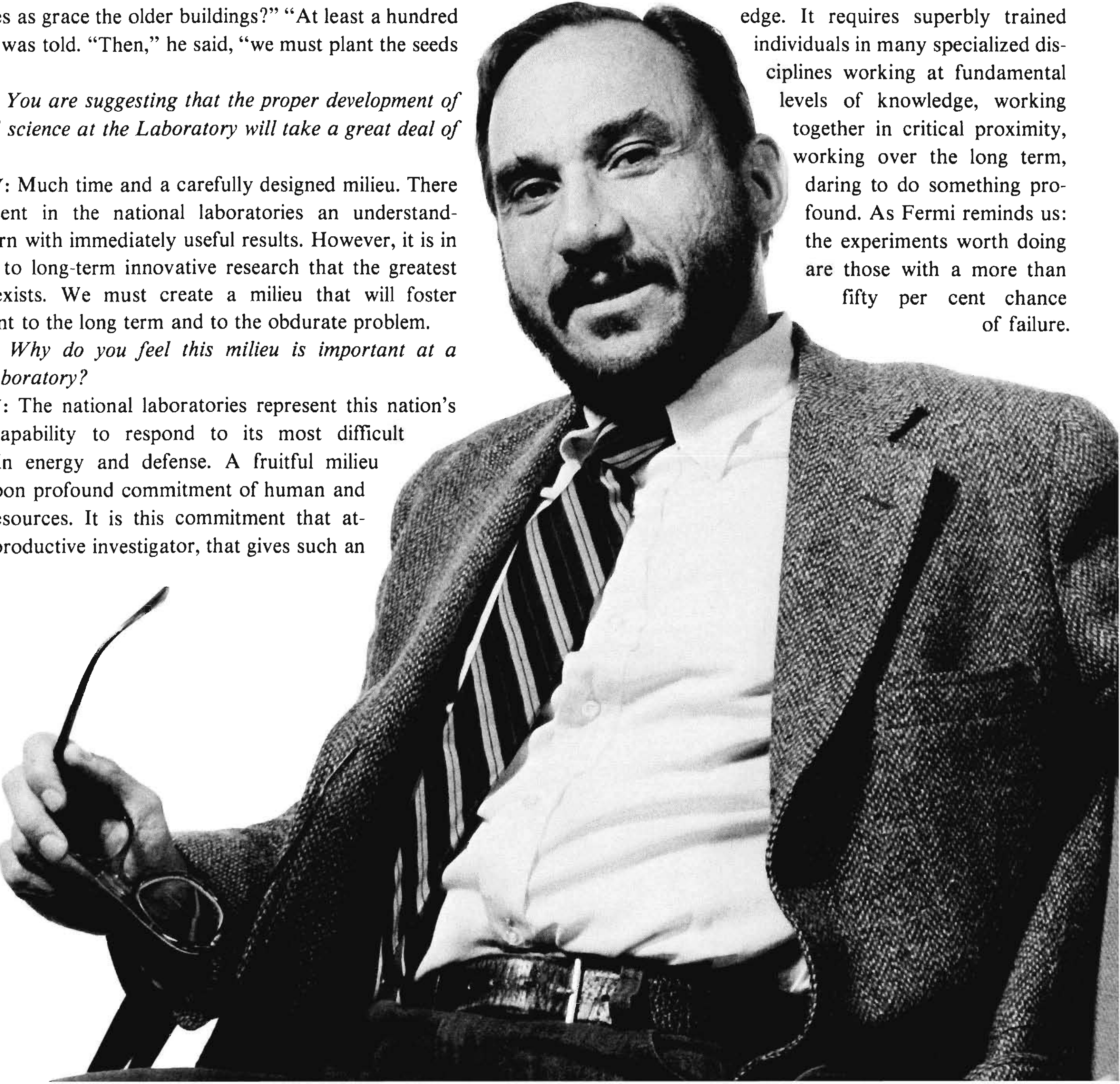
SCIENCE: *You are suggesting that the proper development of biomedical science at the Laboratory will take a great deal of time?*

BITENSKY: Much time and a carefully designed milieu. There is at present in the national laboratories an understandable concern with immediately useful results. However, it is in dedication to long-term innovative research that the greatest potential exists. We must create a milieu that will foster commitment to the long term and to the obdurate problem.

SCIENCE: *Why do you feel this milieu is important at a national laboratory?*

BITENSKY: The national laboratories represent this nation's ultimate capability to respond to its most difficult problems in energy and defense. A fruitful milieu depends upon profound commitment of human and material resources. It is this commitment that attracts the productive investigator, that gives such an investigator the conviction that he can commit his life and talents to a particular line of research. A scientist cannot be asked to do research in an adverse milieu just as a pianist cannot be expected to perform a sonata while wearing mittens.

Only science at the very cutting edge has the analytical and technical power to wrestle with the central problems in physics and biology. A national resource like Los Alamos can provide the environment that sustains that cutting edge. It requires superbly trained individuals in many specialized disciplines working at fundamental levels of knowledge, working together in critical proximity, working over the long term, daring to do something profound. As Fermi reminds us: the experiments worth doing are those with a more than fifty per cent chance of failure.



"the war of time against the soul of man..."

INTERVIEW

SCIENCE: *How do you resolve the perennial dichotomy between basic and applied research?*

BITENSKY: There ought not to be such a dichotomy. Both applied and basic research can be excellent research—relevant, well conceived, carefully executed research. Of course, there is inevitably work of lesser quality in both categories.

Now, you cannot do superb, meaningful "basic" research without eventually having a wonderful, practical result; and, what is just as important, effective and meaningful "applied" research derives from findings and techniques that emerge from the basic laboratory. At the present moment in the Life Sciences Division, our research emphasizes toxicity testing. We do superb inhalation toxicology, Ames testing, carcinogen testing, mutagen testing. But quality testing can't be done in a vacuum; we can't go much beyond the near term without continuing excellence in basic research. We very much need to invest in more of the high-risk research that takes us into the unknown. This is our window of opportunity.

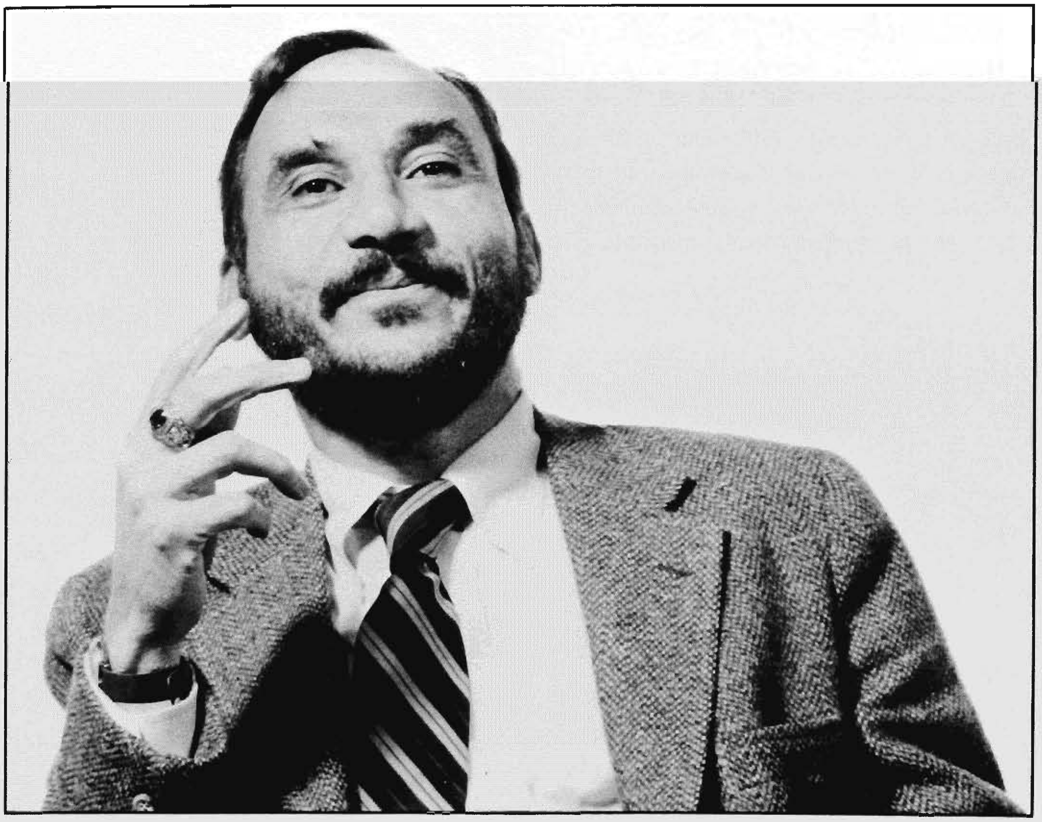
SCIENCE: *You feel that Los Alamos cannot adequately serve the nation unless the Laboratory is engaged and supported in long-term basic research?*

BITENSKY: The vitality of all our programs in energy and defense is inextricably bound to present efforts in long-term, high-risk research. Breakthroughs in fundamental research often depend upon serendipitous and interdisciplinary interactions that are the hallmark of the right milieu. The nation must invest in those studies that will define the boundaries of tomorrow's reality.

SCIENCE: *Can you show us how scientific interaction and serendipity define the boundaries of reality?*

BITENSKY: I can cite the well-known, classic example. Polio vaccine emerged from initially unrelated basic research in virology, epidemiology, cell culture, and immunology. Those were the disciplines that finally interacted in the development of the vaccine. Critical work on the polio vaccine was made possible because people had learned how to grow Green monkey kidney cells in culture. It was this cell type that proved invaluable for subsequent studies of polio virus. No one could

Using stable isotopes and nuclear magnetic resonance, one can actually observe a hormonal influence spread through a living cell.



have guessed, when scientists first began growing such cells in culture, that we were a hair's breadth away from solving a major problem. In contrast to the thousands of 1940 dollars needed for daily care of a patient with bulbar polio, we can now administer the vaccine to children for a few pennies per dose.

SCIENCE: *Has there been this kind of interactive basic research in Life Sciences at Los Alamos?*

BITENSKY: Yes, flow cytometry is a prototypic example. It's multidisciplinary; it uses advanced technology indigenous to the Laboratory; it provides a capacity that didn't exist before; its development depended heavily on both basic and applied research. With it we can rapidly measure cell size, DNA content, cell surface receptors, a variety of cell functions such as phagocytosis, and the shapes and sizes of chromosomes. It's a marvelous and powerful tool, but it wasn't created in a short time. The program began about 1965 under the Atomic Energy Commission and over the years has drawn on the expertise of many Laboratory disciplines: organic chemistry, DNA staining techniques, computer science, electronics, fluid dynamics, laser science, and theoretical modeling. The work brought apparently unrelated technologies together in profound synergy.

Flow cytometry is now used worldwide in research and medicine. At least three U.S. manufacturers offer advanced instruments for sale; the Laboratory has been awarded a five-year grant from the National Institutes of Health to function as a national resource in flow cytometry; physicians from Tokyo to Manhattan to Albuquerque rely upon it to rapidly classify malignancies of blood, brain, and breast tissues.

Another example is the program in stable isotopes that has developed in the Chemistry-Nuclear Chemistry and Life Sciences divisions. The program is making an innovative effort in the study of metabolism. Stable isotopes of carbon are being used to study the metabolic function of cells. These living cells need not be disrupted to be analyzed. Using topical nuclear magnetic resonance spectroscopy, one can follow the flow of sugars, amino acids, and lipids into and out of larger molecules. One can actually observe a hormonal influence spread through a living cell. This technique may be available for totally noninvasive clinical metabolic studies within the next decade.

Offhand, this basic program may not seem critical for either defense or energy. But stable isotopes have already been used to produce tracer molecules that provide precise information about wind flow patterns, information important to defense. Stable isotope studies in cellular metabolism may also help us anticipate and avoid potential health hazards associated with the development of oil shale or other fossil fuels. They could also provide useful tools in our studies of the movement of toxic chemicals through the environment.

SCIENCE: *Can you indicate how energy-related studies in the Life Sciences Division evolve into long-term fundamental research?*

BITENSKY: An illustrative example has emerged from studies of the metal cadmium, which is a significant contaminant of coal and shale. Cadmium is known to be extremely toxic to living cells, and most known living forms have developed a protective program consisting of sulfur-containing proteins. These proteins are quickly synthesized (>20,000 copies per cell) in response to heavy metals. Each protective protein can bind seven molecules of cadmium and thereby prevent cellular toxicity. Genes for these protective proteins have been cloned and sequenced by our genetics group and are now being studied. Studies of the regulation of gene expression are of central importance to our programs in cancer cell biology.

SCIENCE: *You spoke a moment ago of the window of opportunity and of the need to invest in high-risk studies. What are some of the investments you think Life Sciences should be making for the future?*

BITENSKY: We should have the courage to invest in areas of biomedical research where we could exploit the scientific strengths that have been assembled in the national laboratories. We have made virtually no commitment to the sciences of neurochemistry and neurobiology, burgeoning areas which will come to depend more heavily upon sophisticated electronics and computer science.

We must learn enough about the brain and spinal cord to be able to replace damaged parts of the nervous system with prostheses, to be able to reconnect isolated neuronal components, to be able effectively to replace sense receptors. We must attempt to learn enough about data processing by the brain to use such knowledge for computer science.

Now, to some extent that is already happening here at the Laboratory. In the Theoretical Division George Zweig is making a unique effort to discover the algorithms of sensory transduction in hearing: all the events that proceed from the initial sound oscillations in air to the corresponding events

"the war of time against the soul of man..."

INTERVIEW

Ironically, at this moment, which combines extraordinary opportunity in biomedical research and serious fiscal uncertainty, perceptive administrators both in academia and industry are out shopping for our brightest and most gifted research scientists.

within hair cells in the organ of hearing, to our final full preception of meaning. Through painstaking data analysis of electrical recordings from the acoustical nerve and its associate neurological centers, possibilities emerge for understanding the brain's translation of spoken sound into meaning.

SCIENCE: *You've been describing revolutionary discoveries. Can you tell us one or two of the practical developments that can be expected?*

BITENSKY: There are countless practical and productive applications. A laboratory-scale, or "bench," retort is now operational in Life Sciences Division. With this practical research tool we are carrying out a research program to learn more about economic and safe ways to recover valuable hydrocarbons from our vast deposits of oil shale. We are attempting to study how the extraction itself influences the toxic effects of the product; we are attempting to modify the process so that the extraction of energy is maximized and the toxic hazards understood and carefully controlled. Advances in this critical area can have enormous ramifications for energy independence.

Work with photosynthetic microorganisms provides another example. Instead of having perpetually to depend on the dinosaur era for our fuels, we could relax energy needs somewhat by innovative combinations of living organisms and biochemical reactions. Suppose we begin with a photosynthetic organism that efficiently utilizes solar energy. And suppose that organism releases amino acids or other nutrients. A second organism, perhaps a genetically engineered one, might take the metabolites made by the first and convert them into something we need. Imagine combining microorganisms and sunlight with sewage effluent, as a nitrogen source, and obtaining starting materials for the synthesis of plastics and fertilizers or amino acids for cattle feed.

Japanese scientists are working effectively with microorganisms to produce amino acids by fermentation technology. At Los Alamos we combine expertise in recombinant DNA technology, genetic engineering, bacterial fermentation, solar ponds, and waste management in a fledgling effort to explore these possibilities.

SCIENCE: *We can't possibly do it all, can we?*

BITENSKY: There is always a danger in trying to do too much. But there is a built-in safeguard in the compelling requirement for excellence. We must also avoid duplication and, whenever appropriate, promote synergistic interaction with our col-

The Laboratory is a natural center for such work because modern biomedicine is the handiwork of the physical sciences.

leagues in academia, the private sector, and other national laboratories. Above all we must also be careful to retain a healthy balance in our portfolio of scientific investments: it must include not only mature and productive programs but also a suitable admixture of high-risk, long-term investments for the future.

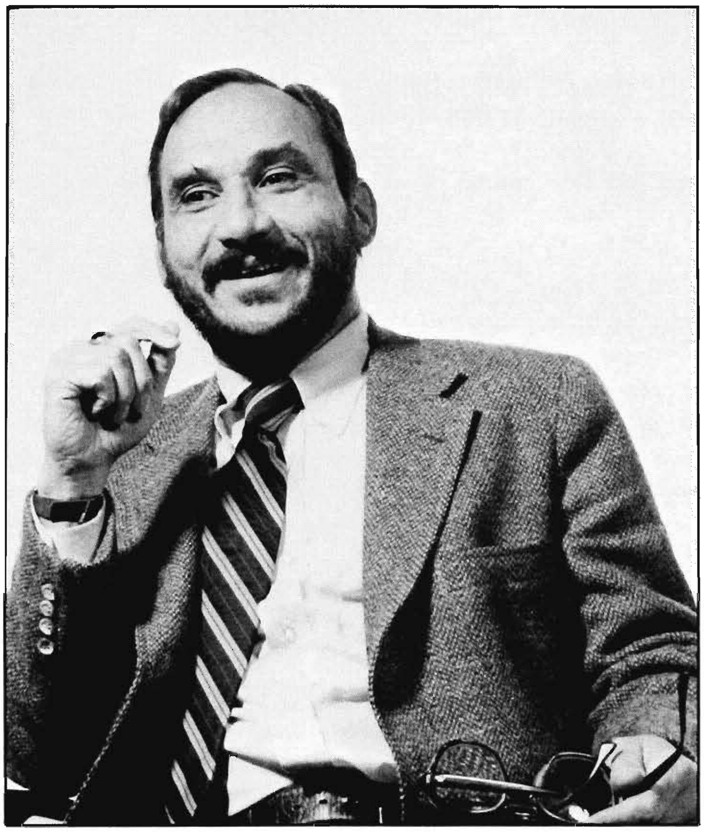
SCIENCE: *How can this work for the future best be undertaken?*

BITENSKY: Well, it can hardly be undertaken at all under the present conditions of uncertain funding. Nor is it the fault of the funding agencies that national problems are currently being addressed on a moment to moment basis. We seem to lack a clear perception of the multidisciplinary potential at the national laboratories. We need a lucid articulation of the long-term benefits that can come from fully developed life sciences within the national laboratories. We need to understand that this nation can afford long-term commitments to excellent science because that is what fashions powerful answers to our problems. While biomedical research has never been a primary mission of the national laboratories, it is nevertheless remarkable that the most powerful democracy on the planet Earth spends less each year on biomedical research in all its national laboratories than does any one of the world's major pharmaceutical houses on new-product development.

At the moment, hard-pressed funding agencies are constrained to seek immediate answers. We are behaving like a fisherman in an old boat. If the boat is sinking because of a hole in its bottom, he will either plug the hole or bail rather than invest in a new hull design that will eventually enable him to catch a hundred times more fish. The tragedy is that, if our nation, because of immediate and valid concerns for frugality, neglects the advantages of innovative research, we will have designed a self-fulfilling negative prophecy. Moreover, we will have missed extraordinary opportunities for productivity.

SCIENCE: *At this moment of fiscal retrenchment, do you see any partial solutions, any immediate and practical steps that can be taken?*

BITENSKY: We are having to perform a juggling act with our current funding. Some projects are supported by the National Institutes of Health. Programs relating to health effects associated with fossil and nuclear energy are largely funded by the Department of Energy. At present we receive less than ten per cent of our support from the Department of Defense. It is essential, if we are to serve the nation well, that stable funding be provided both for our core facilities and for our basic and applied programs. With a more pluralistic, shared form of funding, perhaps deriving from the departments of Energy and Defense and from the private sector, problems at hand could be attacked much more effectively.



Ironically, at this moment, which combines extraordinary opportunity in biomedical research and serious fiscal uncertainty, perceptive administrators both in academia and in industry are out shopping for our brightest and most gifted research scientists.

SCIENCE: *How does long-term, high-risk research survive at all?*

BITENSKY: It is kept alive in the minds of scientists dedicated to it. Often there are wonderful surprises.

More than ten years ago at the Laboratory, Stan Ulam began to wonder how to describe mathematically the biological distance between two protein sequences. He interested other theoreticians, and they set about developing a rigorous mathematical definition of the problem. Using these mathematical approaches and protein sequence data, they tried to deduce phylogenetic trees and rates of protein evolution. Then, about five years ago, there were technological breakthroughs. Suddenly it became possible to determine the sequence of bases in DNA. The results have been quite unexpected in that the mathematical criteria developed for protein sequences have turned out to be useful. Since 1979 Walter Goad and colleagues in the Theoretical Division have been developing computer algorithms for the analysis of DNA and assembling a large library of known sequences in computer-readable form. There is a national program, which includes Los Alamos, for storing in the computer all of the known nucleic acid sequences of mammalian genes. Can the computer find algorithms that will examine DNA and distinguish protein encoding functions, gene regulatory functions, spacer functions? Can it tell whether two genes are related or derive from the same precursor? With this data base, it is possible to design specific nucleotide probes, which can be used to retrieve particular genes from cloned gene libraries.

SCIENCE: *Many of these things sound like dreams. Are we really ready to do them?*

BITENSKY: Fifty years ago few if any scientists or laymen would have believed that genetically modified bacteria would one day synthesize human insulin or human interferon, that organ transplants would prolong active life, that immunization and antibiotics could virtually eliminate infectious disease, or that certain forms of cancer would be curable with chemotherapy.

Molecular biology has just passed through a phase of remarkable growth in generating many new techniques. And the Laboratory is a natural center for such work because modern biomedicine is the handiwork of the physical sciences. Here the freshly emerging technologies of the physical sciences can provide future biomedical advances; here there is a compelling orientation to the needs of the nation; here each facet of science can interact with every other.

For example, in conjunction with the Center for Nonlinear Studies and the Applied Photochemistry Division, Life Sciences is attempting to learn how biochemical energy is communicated along a protein. The work involves theoretical calculations, Raman and ultrafast spectroscopy, and studies with pure proteins. Such work gets you into areas that a biochemist could not really look at alone; it depends upon a unique combination of talents in the Laboratory; it promises to tell us how molecules assembled in living systems produce signaling events and even muscular movement.

SCIENCE: *Is there any one concern that is most important to the Life Sciences Division?*

BITENSKY: Our most serious concern is that the nation realize it makes very good sense to invest in excellence in long-term research. In the war of time against the soul of man, we must not acquiesce to the needs of the moment. In this very trying period, when the nation cannot afford to indulge every option, we as a people must pay careful attention to priorities for the longer term. I use the term "pay attention," and attention is a very precious commodity. Over the last fifteen years the United States has allowed the proportion of gross national product invested in research and development to drop by twenty per cent. Over the same period of time, Japan, West Germany, and the Soviet Union have increased their investments in research by the same percentage or more.* In ways neither possible nor relevant for academia and industry, the national laboratories have a perpetual commitment and vigilant interest in the long-term defense and energy concerns of the nation. Too much is being left to chance with regard to assembling excellent biomedical research in the rich environment of physical sciences available at the national laboratories. We must plant the seeds now. We cannot, in good conscience as prudent scientists or concerned citizens, any longer neglect this remarkable window of opportunity. ■

**U. S. Senator John H. Glenn, "Long Term Economic Rx: Research," Science Vol. 215, No. 4540 (26 March 1982), p. 1569.*

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