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 con-

version 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 Sporer Minimum of 1450 to 1540, also are correlated with periods of increased or decreased solar activity.
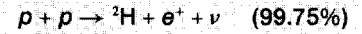
Does such evidence of solar variability indicate that the standard model is incorrect? The short time scales of these events are characteristic of complex physical processes occurring in the sun's convective envelope. For instance, the eleven-year cycle of solar magnetic field reversals, which govern 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
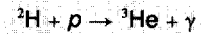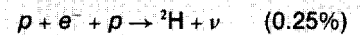
billion years major glacial epochs lasting several million years have occurred regularly, separated by warmer periods lasting several hundred million years. The latest glacial epoch, the Pleistocene, began just three million years ago, and the proximity of its onset indicates that the present is an atypical 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,
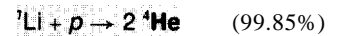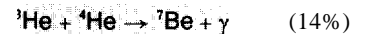
Perhaps the best known of these models is the "Solar Spoon" of Dilke and Gough. Both the time required to reach equilibrium between helium-3 and hydrogen and the equilibrium ratio are sharply decreasing functions of temperature, which itself is a sharply decreasing function of the distance from the sun's 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

$$p + p \rightarrow {}^2H + e^+ + \nu \quad (99.75\%)$$
or
$$p + e^- + p \rightarrow {}^2H + \nu \quad (0.25\%)$$

$$\overline{}$$

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

$$\overline{}$$

$${}^3He + {}^3He \rightarrow {}^4He + 2p \quad (86\%)$$
or
$${}^3He + {}^4He \rightarrow {}^7Be + \gamma \quad (14\%)$$

$$\overline{}$$

$${}^7Be + e^- \rightarrow {}^7Li + \nu$$
$${}^7Li + p \rightarrow 2\,{}^4He \quad (99.85\%)$$
or
$${}^7Be + p \rightarrow {}^8B + \gamma$$
$${}^8B \rightarrow {}^8Be^* + e^+ + \nu$$
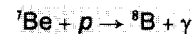$${}^8Be^* \rightarrow 2\,{}^4He \quad (0.15\%)$$

Fig. I. 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.
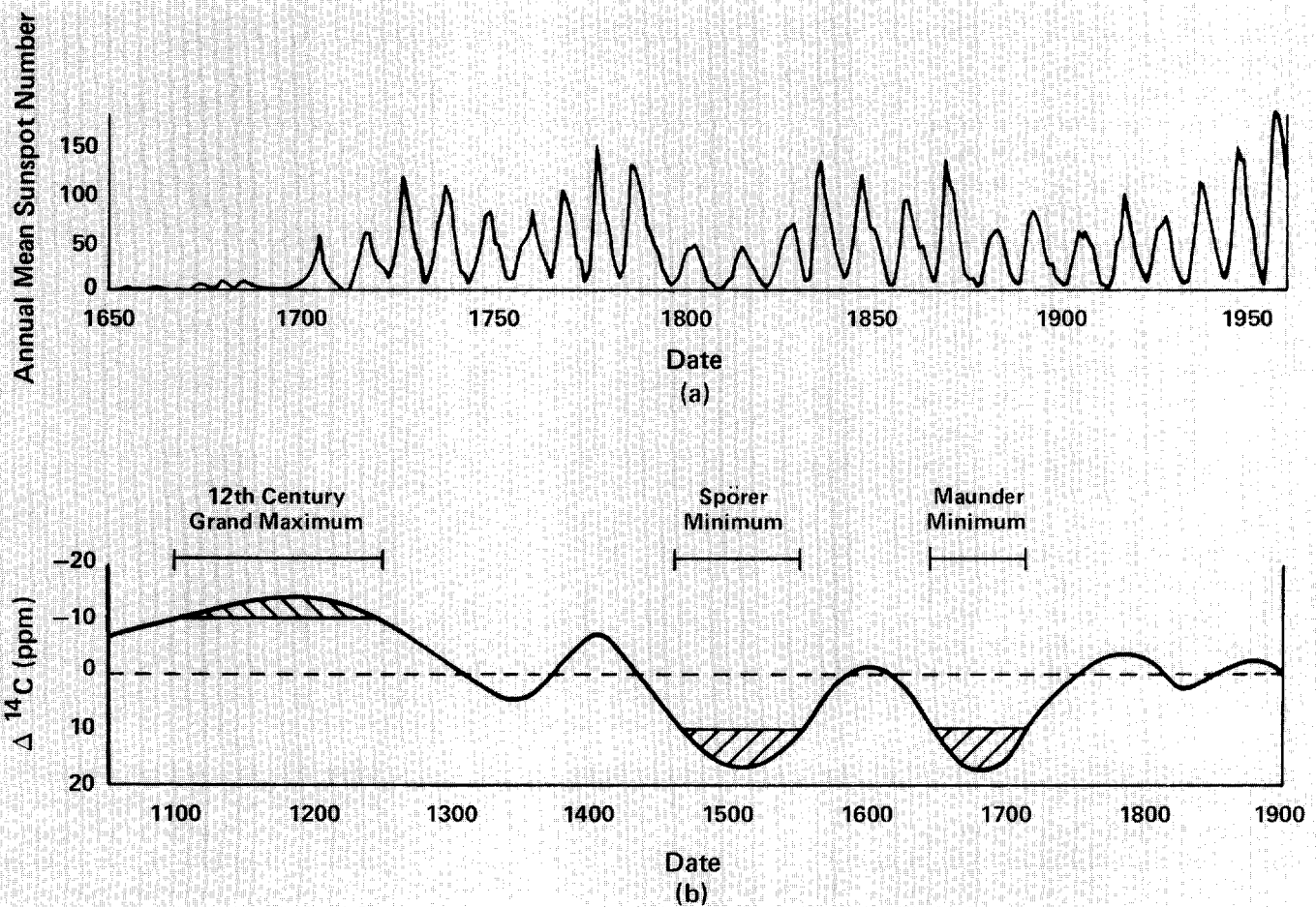
Fig. 2. Evidence for variability of the sun over its recent past. Sunspots, dark areas in the photosphere caused by a lowered surface temperature, are obvious indications of solar variability. As shown in (a), sunspot activity was notably absent during the Maunder Minimum, the seventy-year period between 1645 and 1715. But since 1715 sunspots have been abundant, the number varying in a regular eleven-year cycle [from M. Waldmeier, **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 Sporer 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 Sporer 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
${}^8B \rightarrow {}^8Be^* + e^+ + \nu$	$\leq 14.02^c$	5.85×10^6
${}^7Be + e^- \rightarrow {}^7Li + \nu$	0.862 (89.6%)	4.1×10^9
	0.384 (10.4%)	
$p + e^- + p \rightarrow {}^2H + \nu$	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 criti-

cally 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, $p + p \rightarrow {}^{2}H + e^{+} + \nu,$ 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

$$\nu + {}^{98}\text{Mo} \rightarrow e^- + {}^{98}\text{Tc}.$$
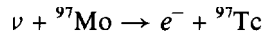
Fortunately, these reactions probe precisely the time scale and neutrino-flux component of most interest: the boron-8 neutrino luminosity, which is the most sensitive monitor of variations in the solar core temperature, during and before the Pleistocene epoch. (The half-lives of technetium-97 and -98 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 back-

ground 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 chromatography 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

NW

SE

Tungsten Slide
Complex

Tungsten Slide
Complex

Urad
Ore Body

Red
Mountain
Porphyry

Silver
Plume
Granite

Silver
Plume
Granite

Urad Porphyry

2454-meter
Elevation

Henderson
Ore Body
(0.3% MoS_2
boundary)

Por-
phyry

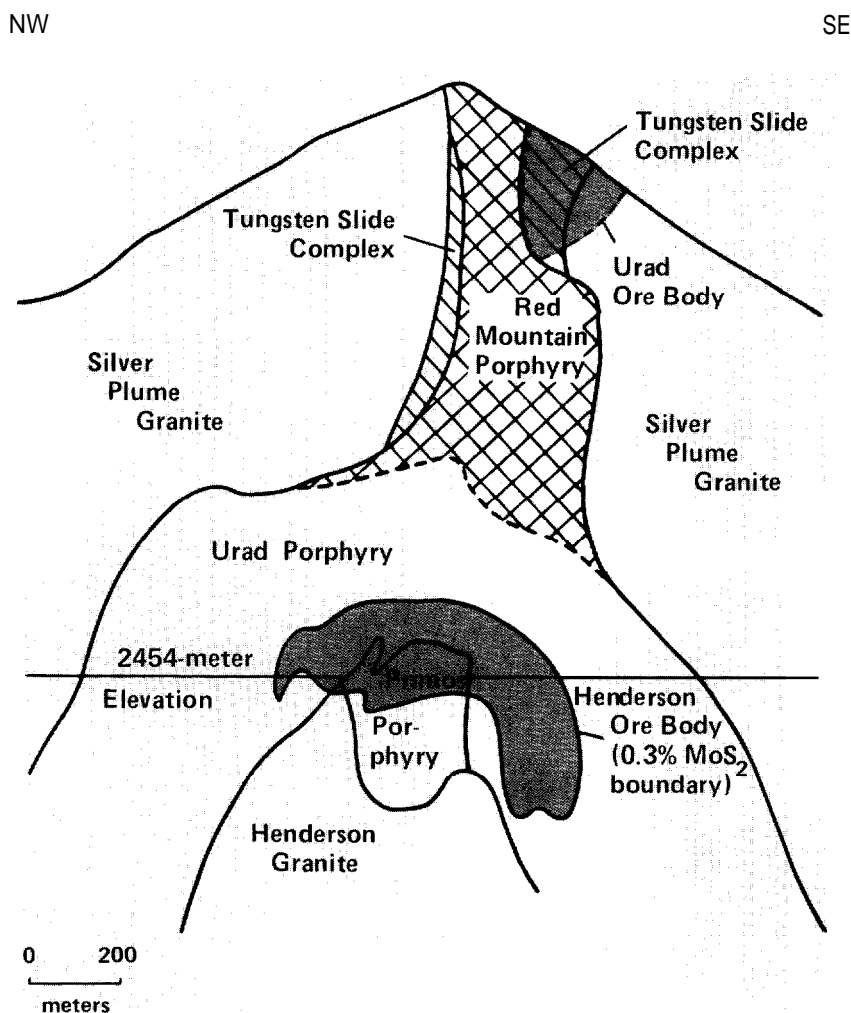Henderson
Granite

0   200

meters

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 one 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 constituency 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.)
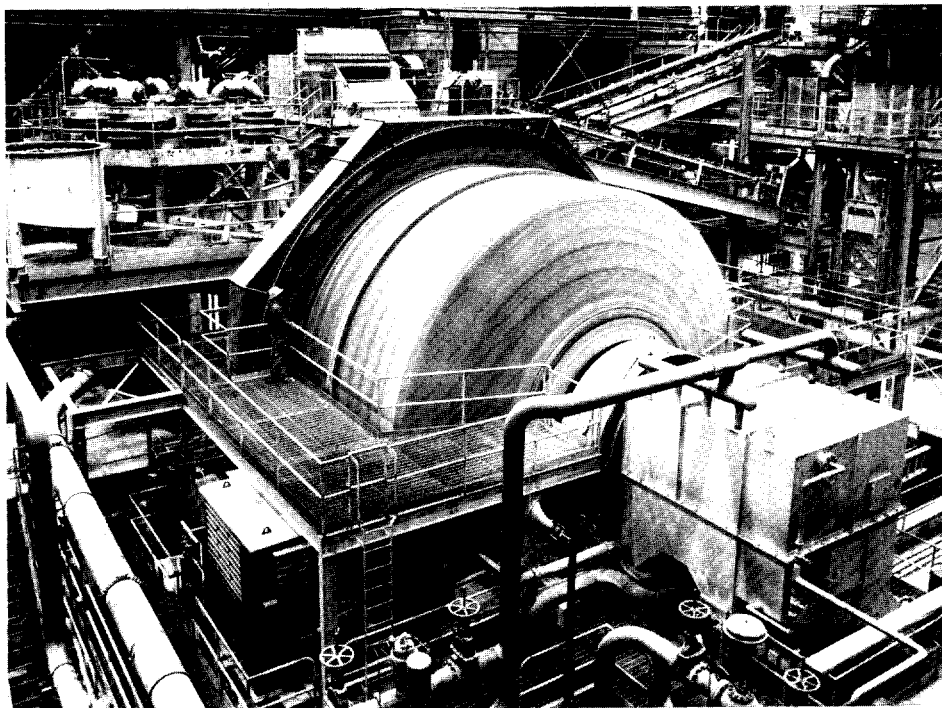
Molybdenite in the ore is separated from waste material by flotation. As air is blown through a mixture of finely ground ore, water, and chemicals, particles of molybdenite cling to the air bubbles, which rise to form a froth on the surface. (Photo courtesy of AMAX Inc.)
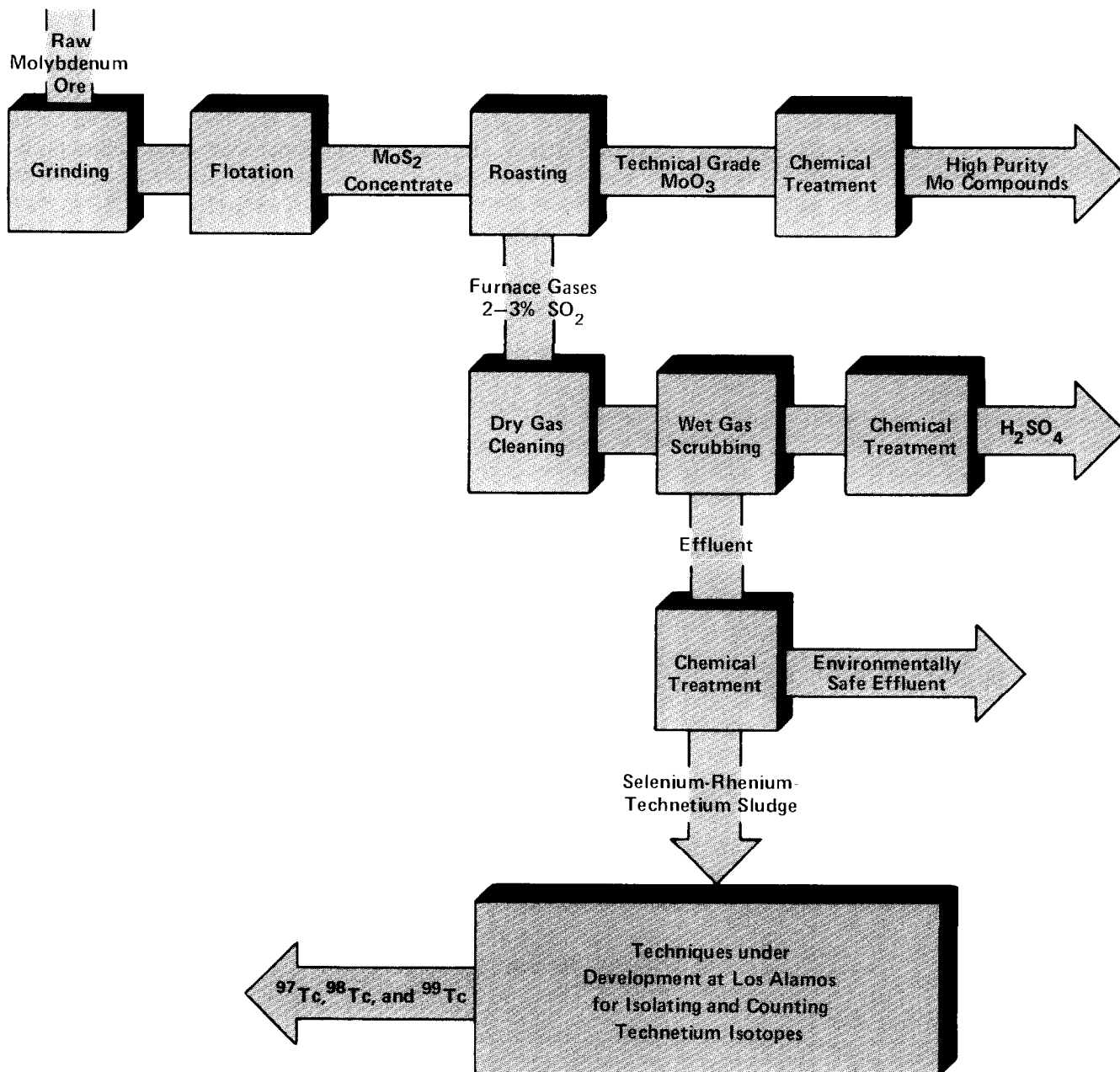
Fig. 4. Raw molybdenum ore is converted to valuable molybdenum products and sulfuric acid by the processes shown here. It is the sludge from the effluent treatment that is of interest to Los Alamos scientists, for it contains extremely minute quantities of technetium formed over millions of years by 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. ∎

Further Reading

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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.

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