AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 2

***Institute of
Geophysics and
Planetary
Physics***

***Lawrence Livermore
National Laboratory***

***1993
Annual Report***

*October 1, 1992 through
September 30, 1993*

***Edited by
Frederick J. Ryerson and Christina M. Budwine
Institute of Geophysics and Planetary Physics
University of California***

MASTER

rp
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Acknowledgments

Arlene L. Manning prepared the manuscript for this report. Carolin Middleton was the publication editor, and John Danielson was the graphic designer. Other members of the publication team were Cara Corey, technical editor, and Irene Chan, Gary Bergren, and Jody Johnson, artists. Charles Alcock, George Zandt, and William Nellis assisted in the technical reviews.

Section I. Overview _____ 1

Section II. Highlights of Fiscal Year 1993 _____ 5

Center for Geosciences _____ 5

Center for High-Pressure Sciences _____ 17

Astrophysics Research Center _____ 20

Section III. Research Summaries of Collaborative Projects _____ 29

Geosciences _____ 29

Monazite as a Thermochronometer for Prograde Metamorphism
T. Mark Harrison, Kevin D. McKeegan, Frederick J. Ryerson, and William T. Akers _____ 29

Electrical Properties of a Mantle Rock
Steven Constable and Alfred G. Duba _____ 31

A Critical Test of the Applicability of $^{10}\text{Be}/^9\text{Be}$ Ratios in Authigenic Minerals for
Determining Soil-Formation Rates
Devendra Lal, Mark W. Caffee, Robert C. Finkel, and John R. Southon _____ 35

Effect of Petroleum on Sandstone Reservoirs, San Joaquin Basin, California
James R. Boles, Carol J. Bruton, Yong I. Lee, and David Lea _____ 38

Diffusion Rates in High-Pressure Mantle Phases
Quentin Williams, Frederick J. Ryerson, Daniel Farber, and Cliff Gill _____ 40

Cosmogenic Isotopes Applied to Development of Longitudinal Profiles in Bedrock
*William E. Dietrich, Marc W. Caffee, Robert C. Finkel, G. Bryant Hudson, and
Michele A. Seidl* _____ 42

Microbial Mediation of Glass Alteration: Rates and Mechanisms
A. A. Yayanos, H. Staudigel, William L. Bourcier, and Roger A. Chastain _____ 44

Models for Long-Term Earthquake Correlations
David D. Jackson, Yan Kagan, John Rundle, and David Potter _____ 47

Global Positioning System Measurement of the White Wolf Fault, Greater
Los Angeles Region
Louise H. Kellogg, John B. Rundle, Andrea Donnellan, and Gerald Bawden _____ 49

Regional and Near-Receiver Velocity Structure and Broadband Waveforms in Southern
California: Teleseisms and Regional Nuclear Explosions
Jean B. Minster, George Zandt, and G. Eli Baker _____ 51

Study of Crust and Upper-Mantle Attenuation in Central and Northern California <i>Barbara A. Romanowicz, Kevin Mayeda, Susanna Loper, Lind Gee, and Ted Bohn</i>	54
Shear-Wave Velocity Structure beneath Central California from Surface-Wave Dispersion <i>Jiajun Zhang and William R. Walter</i>	56
Subsurface Crustal Imaging Using Seismic, Gravity, and Attenuation Data <i>Craig Nicholson, Jay Zucca, and Jonathan M. Lees</i>	59
The Inversion of Surface-Wave Phase-Velocity Measurements for Lithospheric Structure beneath the Western United States <i>Charles J. Ammon and Howard Patton</i>	61
Determination of Three-Dimensional Velocity Variations in the Crust and Upper Mantle beneath Costa Rica <i>Susan Y. Schwartz, George Zandt, and Marino Protti</i>	63
High-Pressure Sciences	65
High-Pressure Synthesis and Deformation of Alkali Halides <i>Jeff Wolfenstine, Mark Beeman, Hiep Duong, Tom Wu, and Frank Shih</i>	65
Development of Anisotropy in Ice <i>Hans-Rudolf Wenk, William B. Durham, Andrew J. Gratz, Stephen H. Kirby, Laura A. Stern, and Kristin Bennett</i>	69
Investigating Shock Effects in Porous Meteoritic and Terrestrial Materials <i>John T. Wasson, William J. Nellis, Andrew J. Gratz, Paul Warren, and Kurt Knesel</i>	72
Preparation and Characterization of Iron and Iron Alloy Thin Films on Diamond Substrates <i>David J. Webb, Choong-Shik Yoo, Neil C. Holmes, Christopher Pike, and David Gettman</i>	76
Shock Compaction of Ferromagnetic Nanoparticles <i>M. Brian Maple, William J. Nellis, and Ricky Chau</i>	78
Dynamic Compaction of Alumina-Zirconia Ceramics <i>Joanna McKittrick, William J. Nellis, and John Freim</i>	81
Shock Synthesis of Amorphous Fayalite <i>Raymond Jeanloz, Andrew J. Gratz, William J. Nellis, and A. Kavner</i>	83
Investigating the Shock Compaction of Powders <i>David J. Benson and William J. Nellis</i>	85
Bonding in SiO ₂ : First-Principles Calculations for Several Crystalline Configurations <i>Mark S. T. Bukowinski, David B. Boercker, Lin H. Yang, and Huoyi Zhang</i>	88

Astrophysics	91
Optical Properties of Nearby Radio Galaxies <i>Hyron Spinrad, Wil J. M. van Breugel, and Arjun Dey</i>	91
High Angular Resolution Imaging in the Mid-Infrared <i>James R. Graham, Christopher J. Skinner, and Matthew Richter</i>	94
Extreme Ultraviolet Observations of Cataclysmic Variables with EUVE and ALEXIS <i>Oswald H. W. Siegmund, Christopher W. Mauche, Howard A. Scott, and John Warren</i>	96
The r-Process in Supernovae and Accretion-Induced Collapse <i>Stanford E. Woosley, Grant J. Mathews, James R. Wilson, B. S. Meyer, and Robert D. Hoffman</i>	99
Design Study for a Survey for Earth-Crossing Asteroids <i>Christopher W. Stubbs, Charles Alcock, Edward Bowell, Eugene Shoemaker, and John Angione</i>	103
Cosmic Microwave Background Constraints on Topological Defect Models of Cosmic Structure Formation <i>Philip Lubin, David Bennett, Sun Hong Rhie, Peter Meinhold, Todd Gaier, Jeff Gunderson, and Jeff Schuster</i>	104
The Excitation of the Crab Nebula <i>Jonathan Arons, A. Bruce Langdon, T.-Y. Brian Yang, and Yves Gallant</i>	107
The Relationship between Supernova Dynamics, Nucleosynthesis, and Closure Mass Neutrinos <i>George M. Fuller, Grant J. Mathews, James R. Wilson, Ron Mayle, Karsten Jedamzik, and Yong-Zhong Qian</i>	111
Atmospheric Characterization for Adaptive Optics <i>Stanley M. Flatte, Claire E. Max, and L. William Bradford</i>	113
Hamilton Echelle Spectroscopy of Solar Flares <i>Gibor Basri, Suzanne L. Hawley, and Christopher M. Johns</i>	116
Section IV. IGPP-LLNL Seminars and Workshops	121
Center for Geosciences	121
Center for High-Pressure Sciences	122
Astrophysics Research Center	123

Section V. Bibliography	129
--------------------------------	-----

Section VI. Fiscal Year 1994 IGPP-LLNL University Collaborative Research Program	135
---	-----

The Institute of Geophysics and Planetary Physics (IGPP) is a Multicampus Research Unit of the University of California (UC). IGPP was founded in 1946 at UC Los Angeles with a charter to further research in the earth and planetary sciences and in related fields. The Institute now has branches at UC campuses in Los Angeles, San Diego, Riverside, and Irvine and at Los Alamos and Lawrence Livermore national laboratories.

The University-wide IGPP has played an important role in establishing interdisciplinary research in the earth and planetary sciences. For example, IGPP was instrumental in founding the fields of physical oceanography and space physics, which at the time fell between the cracks of established university departments. Because of its multicampus orientation, IGPP has sponsored important interinstitutional consortia in the earth and planetary sciences. Each of the six branches has a somewhat different intellectual emphasis as a result of the interplay between the strengths of campus departments and Laboratory programs.

Established in 1982 by the Regents of the University of California, the IGPP branch at Lawrence Livermore National Laboratory (LLNL) emphasizes research in seismology, geochemistry, cosmochemistry, high-pressure sciences, and astrophysics. IGPP-LLNL provides a venue for studying the fundamental aspects of these fields, thereby complementing LLNL programs that pursue applications of these disciplines in national security and energy research. IGPP-LLNL is directed by Charles Alcock and is structured around three research centers. The Center for Geosciences, headed by George Zandt and Frederick Ryerson, focuses on research in geophysics and geochemistry. The Center for High-Pressure Sciences, headed by William Nellis, sponsors research on the properties of planetary materials and on the synthesis and preparation of new materials using high-pressure processing. The Astrophysics Research Center, headed by Charles Alcock, provides a home for theoretical and observational astrophysics and serves as an interface with the Physics Department's Laboratory for Experimental Astrophysics and with other astrophysics efforts at LLNL.

IGPP-LLNL, like IGPP-Los Alamos, facilitates scientific collaborations between researchers at the UC campuses and those at the national laboratories in areas related to the earth and planetary sciences and astrophysics. It does this by sponsoring the University Collaborative Research Program (UCRP), which provides funds to UC campus scientists for joint research projects with LLNL. The goals of UCRP are to enrich research opportunities for UC campus scientists by making available to them some of LLNL's unique facilities and expertise and to broaden the scientific program at LLNL through collaborative or interdisciplinary work with UC campus researchers. UCRP funds (provided jointly by the Regents of the University of California and by the Director of LLNL) are awarded annually* on the basis of brief proposals, which are reviewed by a committee of scientists from UC campuses, LLNL programs, and external universities and research organizations. Typical funding for a collaborative research project ranges from \$5,000 to \$25,000 per year. Funds are used for various purposes, including support for graduate students, postdoctoral fellows, and visiting faculty; experimental facility costs; released-time salaries for LLNL scientists; and the costs of supercomputing time and laboratory work at LLNL.

*Further information about the University Collaborative Research Program, including guidelines for submitting proposals, may be obtained from Christina Budwine, Operations Manager, IGPP-LLNL, L-413, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551 (telephone: 510-423-4476; e-mail address: budwine@sunlight.llnl.gov).

Although the permanent LLNL staff assigned to IGPP is relatively small (about seven full-time equivalents), IGPP's research centers have become vital research organizations. Each year, IGPP supports a substantial group of resident postdoctoral fellows, funds 30 or more UCRP projects, and hosts a variety of visitors, guests, and faculty members on sabbatical leave, from both UC and other institutions. To focus attention on areas of topical interest in the geosciences and astrophysics, IGPP-LLNL hosts conferences and workshops, and it organizes a seminar series for each research center: astrophysics, high-pressure sciences, and earth sciences. Section IV lists the seminars given in FY 1993.

In FY 1993, 139 people worked on 38 UCRP projects: 34 UC faculty members, 44 LLNL investigators, 44 UC students, and 17 UC staff researchers (Figure 1). Table 1 lists the distribution of awards and related activities for each center. In addition, IGPP has hosted an increasing number of scientific visitors. In FY 1993, 26 scientists spent a week or more in residence in our buildings.

Figure 1. Breakdown of the personnel involved in UCRP projects. These projects involve a broad spectrum of scientists from UC campuses and LLNL.

Table 1. Distribution of UCRP awards and related activities for each IGPP research center at LLNL.

Research center	No. of projects	Funding (\$)	Supercomputing time (h)	No. of seminars
Astrophysics	11	213,577		58
Geosciences				9
Geochemistry	7	127,200		
Geophysics	8	103,401		
High-Pressure Sciences	12	175,038		9
Total funded	38	619,216	1080	76
Total requested	61	1,361,132	1160	

Since FY 1987, IGPP-LLNL has maintained a bibliography of published research papers resulting from UCRP projects and from research by IGPP staff, postdoctoral fellows, and consultants. Section V gives the bibliography for FY 1993. Note that, because of the extensive peer-review process for most scientific journals, several papers submitted by the principal investigators are still in progress. Therefore, we cannot give an accurate total of 1993 papers published until we receive formal notification from the journals and authors. At present, we have published 64 papers in refereed journals or conference proceedings: 44 by UCRP participants and 20 by IGPP researchers. Figure 2 compares the total papers published for the last three years. As a measure of research productivity, the results are gratifying. The abundance of publications from IGPP collaborative projects is a measure of the significance of the results obtained in these projects. The refereed-journal publication rate for IGPP-related projects corresponds to more than 1 paper/year for each UCRP faculty member, 2 papers/year for each IGPP postdoctoral fellow, and 2 papers/year for each IGPP staff member.

To prepare for the future, IGPP-LLNL is exploring new directions in its research. These ventures, some of which are described in this report, include new applications of technologies developed for astrophysics experiments, research in geodesy, and our use of isotope analysis of rock samples to map tectonic movements over long periods.

Figure 2. Total number of papers published in refereed journals and conference proceedings from 1991 through 1993.

Center for Geosciences

The primary purpose of the IGPP-LLNL Center for Geosciences is to promote collaborative research in the earth sciences between LLNL and UC researchers. Many subdisciplines within the geosciences are employed by LLNL's mission-oriented programs in national security and energy research. IGPP is able to draw on these capabilities and expertise and to act as a focal point for research in the more fundamental aspects of these areas. In doing so, we hope to consolidate the many talents and capabilities at LLNL and provide an easily identifiable avenue for LLNL-UC collaborations. The Center for Geosciences is the physical and scientific focus for interactions with visitors for academic (UC and other universities), industrial, and government geoscience research institutions. The Center's past research emphasis on the physics and chemistry of the solid Earth, including seismology, geochemistry, experimental petrology, mineral physics, and hydrology, continues along with a recently initiated effort in interdisciplinary studies of active tectonics.

The Center is located in and partially supported by the LLNL Earth Sciences Department. It has strong ties with several programs in the Earth Sciences Department and in the Nuclear Chemistry Division, which contributes scientific expertise and facilities to support collaborative efforts in geochemistry. The Center provides access to computational, experimental, and analytical research facilities and supports fieldwork for geophysical and geochemical studies.

Operational responsibilities for the Center are shared by George Zandt and Rick Ryerson. Zandt is a seismologist with interests in upper-mantle and crustal structure and tectonics and in developing seismic underground imaging techniques. He provides oversight for research projects in seismology and observational geophysics. Ryerson is a petrologist with interests in diffusion in rock-forming minerals, rheology of partially molten crustal rocks, and high-pressure and high-temperature mineral-melt phase equilibria. He provides oversight for projects in geochemistry, mineral physics, and experimental geophysics. He is also actively involved in field studies in Tibet and southeast Asia.

The Center for Geosciences is located in an area with minimal access controls, thus allowing university collaborators ready access to LLNL computational facilities. This area houses the Center's library and several computer workstations for use by visitors and staff, and it is the focus of our activities in seismology and geophysics. State-of-the-art seismological field equipment is available for collaborative studies. Portable broadband seismic stations can be deployed worldwide to provide data for crustal and mantle structure investigations in terrains with difficult access.

The newly opened Nuclear Chemistry facility houses an ion microprobe, an electron microprobe, an inductively coupled plasma (ICP) mass spectrometer, and clean laboratory facilities for preparing accelerator mass spectrometry (AMS) samples. The laboratories for thermal ionization mass spectrometry also were reclassified to allow access by UC participants. The Earth Sciences' experimental facilities include apparatus for high-pressure gas media deformation experiments; piston cylinder and multi-anvil laboratories; and laboratories for electrical conductivity measurements, crystal growth, diamond cell experiments, and cryogenic deformation experiments. In addition, we have laboratories for x-ray diffraction analysis and infrared spectroscopy.

Aaron Velasco joined the IGPP Center for Geosciences in 1992 with the prestigious University of California Presidential Postdoctoral Fellowship. Velasco recently completed his Ph.D. studies at UC Santa Cruz, where he developed and

Williams from UC Santa Cruz were frequent visitors working with Ryerson on diffusion at high pressure. Craig Lundstrom from UC Santa Cruz also completed a study of uranium–thorium–lead partitioning between clinopyroxene and melt. He performed this study in conjunction with his campus advisors, Williams and James Gill, and with Ryerson, Shaw, and Phinney at LLNL.

Research Highlights

The Collaborative Bolivian–Altiplano Seismic Experiment

The Altiplano is one of the two highest plateaus in the world, and its structure and formation are a major geologic mystery. The 1994 Collaborative Bolivian–Altiplano Seismic Experiment (CBASE) is a collaborative effort with the University of Arizona, the Carnegie Institution of Washington, DC, and the Observatorio San Calixto in La Paz, Bolivia. We will deploy eight IGPP portable seismic stations along a 400-km-long north–south profile on the Altiplano for one year to record local, regional, and global earthquakes (Figure 1). Our university collaborators will simultaneously deploy 18 recorders along an 800-km-long east–west profile crossing the entire Andes Cordillera. The data from the stations will be analyzed to estimate the deep structure of the region.

During FY 1993, two intermediate-depth earthquakes occurred near the Bolivia–Argentina–Chile border with near-source raypaths sampling the thickened crust of the Andes Altiplano. To obtain preliminary estimates of crustal structure in the region of our planned deployment, George Zandt, Aaron Velasco, and Susan Beck (University of Arizona) used these earthquakes to estimate crustal parameters for the Bolivian Altiplano. Slant-stacking of broadband seismograms from western U.S. seismic stations (Figure 1b) revealed small but clear precursors to both the pP- and sS-depth phases. We interpret these precursors as underside reflections from the Andes–Altiplano crust–mantle boundary. The ratios of the S-wave differential times to the P-wave differential times are direct estimates of the V_p/V_s for the crust and upper mantle above the sources. For one event sampling a pure Altiplano path, the estimated V_p/V_s is an anomalously low value of 1.5 ± 0.1 for the crust and a more typical mantle value of 1.9 ± 0.1 for the upper-mantle wedge between the crust and subducting Nazca Plate. We obtained the best fit to the data from synthetic forward modeling using a model with an average crustal velocity of 6.0 to 6.2 km/s and a crustal thickness of 80 to 85 km. This large crustal thickness is among the thickest in the world, comparable to the estimates of crustal thickness beneath the Himalayas–Tibet region.

The Nonproliferation Experiment—University of Arizona Deployment

As part of the University of Arizona seismology group, George Zandt deployed 10 portable broadband stations along a 200-km east–west profile to record the Nonproliferation Experiment (NPE) explosion. During the deployment, an $m_b = 6.2$ earthquake at Chiapas, Mexico, was recorded by 9 of the 10 stations. Receiver functions computed from the P waveforms were used to estimate crustal thickness across the line. The crustal thickness has up to 5 km of short wavelength relief within the east-central Basin and Range and thickens by nearly 20 km in the western Colorado Plateau, reaching nearly 50-km thickness east of the Hurricane Fault.

Figure 1. (a) Locations of planned seismic deployment shown on a generalized geologic map of the central Andes Altiplano. (b) Position of seismic stations in the western United States from which data were obtained for preliminary analysis of the crust and upper-mantle structure beneath the Andes Altiplano. (c) Region encompassed by the geologic map in (a).

Estimates of V_p/V_s based on the timing of crustal multiples within the receiver functions show the Colorado Plateau has high average V_p/V_s corresponding to a Poisson's ratio of 0.28. High Poisson's ratio is characteristic of an overall mafic composition, consistent with geochemical evidence for the composition of the Colorado Plateau crust. Teleseismic P-wave travel-time residuals measured for the Chiapas earthquake show relatively small interstation variations across our profile. Once corrected for crustal thickness variations based on our receiver function model, the relative residuals indicate a mantle lid that is an estimated 100 km thicker under the Colorado Plateau than that in the adjacent Basin and Range. In addition, we infer a strong correlation between variable crustal thickness and mantle-lid thickness within the Basin and Range. The correlation, in conjunction

with geologic estimates of upper-crustal extension amounts, strongly supports the crustal welt model for Cenozoic extension in the east-central Basin and Range. The thick, strong mafic crust and thick mantle lid under the Colorado Plateau probably explain the relative geologic stability and subdued magmatism of the plateau during Laramide compression and Cenozoic extension compared with the stability and magmatism found in surrounding regions.

The Southern Sierra Nevada Continental Dynamics Project

The Southern Sierra Nevada Continental Dynamics (SSCD-1993) Project is a multidisciplinary, multi-institutional investigation to determine the cause of the uplift of the Sierra Nevada and its relationship to extension in the adjacent Basin and Range. A broad range of geologic and geophysical data has been collected as part of this project. These data include both passive and active seismic, gravity, and magnetotelluric experiments. Three seismic refraction/wide-angle reflection profiles were recorded: (1) a 325-km-long north-south profile extending from just east of Mono Lake southward across the Garlock fault; (2) a 400-km-long east-west profile extending from Death Valley westward across the Sierra Nevada Mountains to the San Andreas Fault; and (3) a 480-km-long east-west profile for the NPE extending from Beatty, Nevada, westward across the Sierra Nevada along the previously recorded east-west profile, continuing nearly to the Pacific Ocean. Up to 675 seismic recorders were deployed for each profile. Stan Ruppert, an IGPP post-doctoral fellow, coordinated the efforts to develop the field logistics and design of the active seismic portion of the experiment, and he led the field operations. Other than LLNL, participating universities and institutions comprising the Southern Sierra Working Group include Duke University, University of California at Riverside, University of Texas at El Paso, California Institute of Technology, Princeton University, University of Nevada at Reno, U.S. Geological Survey, Geological Survey of Canada, and the U.S. Department of the Navy Geothermal Program office.

This study, funded by the National Science Foundation and DOE, will examine the deep crustal structure of the southern Sierra Nevada by making cross sections of seismic velocity and electrical resistivity. Xenoliths, which are fragments of the deep crust and upper mantle, will also be collected, so rock types can be assigned to the seismic and geoelectric cross sections. Our goal is to resolve the cause of uplift of the Sierra Nevada and determine its relationship to the adjoining Death Valley extensional province and the southern San Joaquin basin. Currently, two end-member models for uplift of the range have been presented: (1) isostatic compensation of a deep crustal root and (2) upwelling of the asthenosphere associated with extension to the east. These two models have fundamentally different consequences for the dynamic behavior of the continents, particularly in the manner in which crustal sections are either (1) underplated by materials from the upper mantle or (2) weakened and extruded to fill in extensional voids. In addition to the uplift and related extension of comparable mountain ranges worldwide, several globally significant features will be better understood by our resolution of the Sierran Root questions, such as: factors controlling the manner in which sialic basement nappes detach; how collision zones collapse under their own burden; and how intracontinental transform faults partition strain to and beneath the Moho. The extensive amounts of data collected will allow us to develop refined models of the crustal and upper-mantle structure of the southern Sierra Nevada and to evaluate alternative hypotheses for its uplift and for Basin and Range extension.

Garnet/Aqueous Fluid Partitioning of Trace Elements at Upper-Mantle Conditions

To constrain the role of aqueous fluids as agents of chemical modification in the upper mantle, James Brennan, Henry Shaw, Douglas Phinney, and Rick Ryerson are measuring garnet/fluid partition coefficients ($D_{\text{gar/fl}}$) for an array of trace elements (Th, U, Nb, Ta, Pb, Sr). Chips of iron-bearing natural crystals of pyrope garnet with excess $\text{SiO}_2 + \text{MgO}$, trace elements (as dried nitrate solutions, where the sum of all trace elements ≤ 300 ppm), and H_2O are encapsulated in platinum-lined nickel and subjected to 2.0 GPa and 900°C for about 3 days. Iron loss to platinum, accompanied by dissolution and reprecipitation, results in the growth of thick ($>100\ \mu\text{m}$), iron-poor rims that are readily distinguished from starting materials. These newly formed pyrope-garnet rims are analyzed with the ion microprobe, and trace-element concentrations are determined by comparison with appropriate standards. Then $D_{\text{gar/fl}}$ values are calculated from mass balance.

Figure 2 shows preliminary $D_{\text{gar/fl}}$ values ($\times 10^{-3}$), which are 15, 7.1 (U); >4.8 (Th); 1.3 (Pb); 0.032, 0.098 (Ba); 0.40 (Sr); 11 (Nb); and 100 (Ta). Multiple results for one element are for two different garnet compositions. Values are similar to those measured for garnet/silicate-melt partitioning, except D_{Sr} is at the low end and D_{Th} and D_{Pb} are at the high end of reported ranges. Bulk analysis of quenched solute from these experiments yields major-element compositions similar to fluid in equilibrium with lherzolite at similar pressure and temperature. Therefore, with the important exception of an absence of other complexing agents (e.g., Cl^- , CO_3^{2-}), the fluids in our experiments are likely to be similar to aqueous fluids in the mantle. Our results suggest that metasomatism by water-rich fluids and silicate melts will produce similar signatures for these trace elements. However, this conclusion is unlikely to hold for mantle fluids containing significant amounts of other ligands, given the known effects of these agents at enhancing the partitioning of trace elements into fluids.

Figure 2.
Comparison of
garnet-fluid and
garnet-melt partition
coefficients for Ba,
Th, U, Nb, Ta, Pb,
and Sr.

Compositional Controls on the Partitioning of U–Th–Ba–Sr and Zr between Clinopyroxene and Haplobasaltic Melts: Implications for Uranium Series Disequilibria in Basalts

Observed secular disequilibria among the uranium (^{238}U) decay series nuclides have received a great deal of attention as tracers of mantle melting processes. The half-lives of the intermediate nuclides are short relative to the time scale of mantle evolution; therefore, they can be assumed to be in secular equilibrium at the initiation of melting. Thus, unlike many other isotopic and elemental tracers in basalts, for which the observed characteristic is the end result of processes influencing the source both prior to and subsequent to the initiation of melting, secular disequilibria in the ^{238}U decay series nuclides are largely a function of melting and melt migration processes. Secular disequilibria are observed because of the fractionation of parent and daughter nuclides during anatexis and melt migration. To fully exploit the temporal information contained in ^{238}U decay series disequilibria and to further constrain the responsible processes, we wanted to understand the fractionation of parent and intermediate nuclides among the various mineral phases comprising the mantle, fluids, and melts as a function of composition and external variables. Craig Lundstrom, Quentin William, and James Gill (UC Santa Cruz) working with Henry Shaw, Douglas Phinney, and Rick Ryerson obtained new data on the partitioning of uranium, thorium, lead, and barium (an analog for radium) between clinopyroxene and a haplobasaltic melt.

This study had two major goals: (1) to evaluate the extent to which the oxygen fugacity and thus the valence state of uranium control the relative partitioning of uranium and thorium; and (2) to refine the values of partition coefficients for uranium, thorium, and the radium analog, barium, as a function of bulk composition. We paid particular attention to the potential effects of aluminum substitution in the clinopyroxene on the partition coefficients. Then we used the results to simulate the evolution of uranium decay series nuclides during polybaric melting and ascent.

We measured the partitioning of U, Th, Sr, Zr, and Ba between coexisting chromian diopsides and haplobasaltic liquids at oxygen fugacities between the iron–wüstite buffer and air. The samples were characterized using secondary ion mass spectrometry. The partition coefficients for Th, U, and Zr show a strong dependence on the aluminum and sodium content of the clinopyroxene. A good correlation between D_{Al} and D_{Th} exists for all recent thorium partitioning studies, providing a simple explanation for the D_{Th} varying from 4×10^{-4} to 3×10^{-2} . We suggest the tetrahedrally coordinated aluminum in clinopyroxene may be the best indicator of the relevant partition coefficient.

While these compositional variations affect the absolute value of the thorium and uranium partition coefficients, they have no effect on $D_{\text{Th}}/D_{\text{U}}$. Our results reinforce the inference that clinopyroxene partitioning cannot explain observations of excess ^{230}Th in basalts. Nevertheless, under the oxygen fugacity relevant to mid-ocean ridge basalt (MORB) petrogenesis, clinopyroxene has little ability to fractionate uranium from thorium (Figure 3, $D_{\text{Th}}/D_{\text{U}} = 2$), implying that disequilibrium transport is not required to preserve excesses generated in the garnet stability field. If the barium partition coefficient serves as an analog for radium and the partition coefficient of oxidized uranium (U^{+5}) serves as an analog for protactinium (Pa^{+5}), then ^{226}Ra and ^{231}Pa excesses could be produced through clinopyroxene partitioning. Using compositionally dependent partition coefficients and a forward melting model, we can show that equilibrium porous flow is capable of explaining uranium series observations from the East Pacific Rise better than dynamic melting models using instantaneous transport.

Figure 3. D_{Th}/D_U vs $-\log$ oxygen fugacity. All of the compositional effects were removed by taking the ratio of the partition coefficients indicating that the compositional variations have the same effect on thorium as uranium.

Tectonic Evolution of Southern Tibet

It has long been appreciated that a portion of the convergence in the Indo-Asian collision has been accommodated by major intracontinental thrusts in the Himalaya, e.g., the Main Central Thrust, Main Boundary Thrust, and Main Frontal Thrust. The mechanisms that led to the uplift of the Tibetan Plateau north of the Himalaya are less clear, however. Although the collision started about 40 to 50 Ma, observations of compressional features originating after this period are rare. This is at least in part due to the size and relative inaccessibility of the area. In FY 1993, Mark Harrison and An Yin (UC Los Angeles), Peter Copeland (University of Houston), William Kidd (State University of New York at Albany), and Rick Ryerson (IGPP) identified a new thrust fault system in southern Tibet, which we call the Gangdese Thrust System (GTS). The GTS is composed of a north-dipping thrust fault, the Gangdese thrust, which outcrops in southeastern Tibet near Zedong, and a south-dipping backthrust, which outcrops to the west near Xigaze. The Xigaze group, forearc sediments deposited south of the Andean margin that existed in Asia prior to collision, is bounded on the south by the Gangdese thrust and on the north by its backthrust. In many areas, the Gangdese thrust is truncated by a younger south-dipping thrust, called the Renbu-Zedong thrust (RZT). Figure 4 shows the field relationships between the GT and RZT.

In FY 1993, we continued to obtain thermochronologic data relevant to the development of these structures. We obtained thermal histories from feldspars separated from granitic rocks near the GT, which are indicative of rapid cooling near 27 Ma. Feldspar and apatite fission-track ages for granitic rocks north of the GT become progressively younger to the north. We believe that this is a result of northward propagation of the uplift associated with south-directed movement along the GT and confirms the regional significance of this structure. We also obtained ages of ~18 Ma for undeformed dacitic dikes that cut the Xigaze group and the underlying Gangdese plutonics. These data indicate that movement along the GT backthrust was over by this time, and by implication, so was movement along the GT.

The GTS is the first evidence of postcollisional, pre-Miocene deformation in southern Tibet. The coincidence of the GT and RZT in the region of the intercontinental suture suggests that the suture is a composite structure variably marked by

Figure 4. (a) Geologic map of the area near Zedong, showing the relationship of the Gangdese Thrust to the younger Renbu-Zedong Thrust. (b) Cross section along section A-A'. (c) Cross section along section B-B'.

the juxtaposition of these two structures. The 27-Ma onset of movement along the GT still leaves a 13-Ma gap between the beginning of collision and the first evidence of distributed shortening. On the basis of our previous work along the Red River shear zone, which records the cessation of strike-slip deformation at ~20 Ma, we contend that between 40 and 27 Ma, the collision was accommodated primarily by continental extrusion. We will return to southern Tibet to perform additional mapping and to collect samples near the GTS and RZT in FY 1994.

Island-Arc Petrogenesis and Implications for Chemical Recycling

Island-arc volcanoes are the dramatic result of continuous and dynamic interaction between the down-going oceanic slab, the overlying mantle wedge, and the lithospheric mantle and crust of the Earth. This tectonic environment marks the principal area for the return of the Earth's crust to the mantle from which it was once derived. Thus, island arcs are key areas of focus for investigations aimed at understanding the evolution of the Earth's crust and upper mantle. In terms of chemical mass balance, the interactions between the subducting component (oceanic crust, sediment, and fluid) and the overlying mantle are far from understood. For example, there is controversy about determining (1) whether sediments deposited on the seafloor and carried down with the subducted oceanic crust are melted and recycled into the arc crust via magmatism or continue into the deep mantle; (2) whether the oceanic slab is partially melted and incorporated into the arc crust; and (3) the nature of the metasomatic fluids resulting from dehydration of the subducting component and their importance in the chemical mass-transfer process.

Figure 5. The location of the transect of volcanoes in Japan, Klyuchevskoy Volcano, and sediment core locations (881–884) are designated by black symbols. The solid triangles indicate the direction of the subducting Pacific Plate.

The chemical and isotopic composition of the mantle, subducting oceanic crust, oceanic sediments, overlying mantle wedge, and the arc lithosphere can be distinct and thus offer the potential of being used as geochemical tracers to more precisely quantify the recycling process between the Earth's mantle and crust. To gain a better understanding of the net chemical fluxes involved in recycling in island-arc settings, Annie Kersting has begun detailed trace-element, radiogenic, and stable-isotope (Pb, Nd, Sr, O) studies of Quaternary volcanoes from two island arcs: Kamchatka, Russia,¹ and Honshu, Japan. In addition, we analyzed sediments recently collected from the North Pacific, proximal to the Kamchatkan arc (Figure 5).

Lead isotopic ratios ($^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$) were measured (using LLNL's thermal ionization mass spectrometry facilities) on a suite of Klyuchevskoy basalts that span the chemical spectrum of the erupted lavas. The lead isotopic ratios of the Klyuchevskoy basalts define a narrow range that overlaps with Pacific mid-ocean ridge basalt (MORB) values and are the least radiogenic island-arc basalts measured to date (Figure 6). In contrast, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are shifted to slightly more radiogenic values for a given ϵ_{Nd} value compared to MORB.

During 1992, the International Ocean Drilling Project (ODP) drilled and collected samples of sediment and oceanic crust in the northwestern Pacific near the Kamchatka and Aleutian arcs. We obtained a set of sediment samples recovered from drilling near the Kamchatkan Trench. These samples, ranging from Miocene to Pleistocene in age, represent the best analog of material that has previously been subducted down the Kamchatkan Trench. The lead isotopic ratios of the sediments are more radiogenic than the Klyuchevskoy basalts and the Pacific MORB field (Figure 6).

These data in conjunction with major- and trace-element data support the conclusion that the dominant chemical source in the production of the Klyuchevskoy lavas is the mantle wedge. In addition, a fluid flux resulting from the dehydration of altered oceanic crust imparts a high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (from seawater interaction) coupled with a relatively unradiogenic mantle lead composition. We further suggest that sediments are not melted and incorporated in the Klyuchevskoy magmas but are carried deeper into the mantle, further contributing to the chemical heterogeneity of the mantle.

To address the influence of the lithospheric component on the diversity of island-arc magmas, Annie Kersting (IGPP) and Richard Arculus (Australian National University) began a large sampling effort, collecting more than 200 rock samples from 13 primarily basaltic volcanoes in Honshu, Japan. The northeast-southwest trending chain of arc-front volcanoes in Honshu results from the interaction of the westward subduction of the Pacific Plate, mantle wedge, and the overlying crustal lithosphere. These Quaternary volcanoes cross-cut a major tectonic boundary where two different crustal terrains are juxtaposed. The interaction of down-going Pacific Plate with the mantle wedge beneath Honshu has created an arc of volcanoes located on two chemically distinct lithospheric terrains.

Petrographic mineral, major-, and trace-element whole-rock data are being collected. Initial measurements of lead isotopic ratios lie well above the MORB field using a conventional lead isotopic ratio diagram. We interpret this to reflect crustal contamination in the generation of these magmas. In addition, an elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratio has been interpreted to reflect crustal involvement in some of the volcanic centers.

Figure 6. The lead isotopic data for Klyuchevskoy basalts (black oval) and Japan basalts (black square). The lead isotopic data for the sediments fall within the outlined black triangle. The small black dots are Pacific MORB values. Lead data from other island arcs and Pacific sediments are shown by dark gray and by white, respectively, for comparison. References: Pacific MORB,² ODP and Pacific sediments,^{3,4} Marianas,⁵ Aleutians,⁶ Martinique,⁷ and N. Luzon.⁸

Center for High-Pressure Sciences

The Center for High-Pressure Sciences makes available LLNL's high-pressure experimental, theoretical, and computational modeling capabilities for collaborations between university researchers and LLNL scientists. The collaborations include the use of experimental facilities at LLNL, joint theoretical research, use of LLNL supercomputers, and experimental work prepared at university campuses on specimens and subjected to high pressures at LLNL. University faculty, graduate students, and postdoctoral researchers participate in the program. IGPP high-pressure research encompasses geophysics, planetary physics, condensed-matter physics, chemistry, materials science, and engineering. LLNL researchers in High-Pressure Sciences are located in the Condensed-Matter Physics Division (H Division) and in Earth Sciences. The Center Head is William Nellis. Peter Fiske is a postdoctoral fellow.

Principal facilities and capabilities at LLNL include

- *Two-stage light-gas guns* to measure equations of state; shock-wave profiles; electrical conductivities; and emission, Raman, and absorption spectra of minerals, liquids, and metals shocked to dynamic pressures up to 100 GPa (1 Mbar) and up to several thousand kelvins. A gas gun is also used to synthesize new materials by application and rapid quenching of high dynamic pressures and temperatures.
- *Diamond anvil cells* to measure equations of state up to 100 GPa by x-ray diffraction, laser heating, and Raman spectroscopy.
- *High-pressure systems* to determine stress-strain behavior, ultrasonic velocities, permeability, phase equilibria, fracture and flow properties, diffusion kinetics, and electrical and optical properties of minerals and ceramics up to 25 GPa and 2500°C.
- *Condensed-matter theory*, including electron-band theory of bulk and layered materials, fluid perturbation and mixture theories, Monte Carlo and molecular-dynamics methods, and dense-plasma theory.
- *Computational simulations* of the response of materials to high pressures.

These high-pressure facilities complement each other, and many offer unique research opportunities, some of which are in unclassified areas. Computational simulations and theories of high-pressure phenomena are strong capabilities at LLNL. Therefore, researchers from the University of California and other universities, industrial partners, and LLNL programs interact with the Center on issues of scientific importance.

For example, the two-stage gun achieves pressures up to 100 GPa, temperatures up to several thousand kelvins, and quench rates up to 10^{12} bar/s and 10^9 K/s in specimens that are recovered for characterization. Quartz has been shocked in this way, and its microstructure shown to agree with that found in the Cretaceous-Tertiary boundary, the stratigraphic level at which the dinosaurs became extinct. Facilities at both LLNL and the National Institute of Standards and Technology (NIST) have been integrated into one project. For example, Hans-Rudolph Wenk and Kristin Bennett of UC Berkeley and William Durham of LLNL deform ice and ice-rich specimens at LLNL's low-temperature, static high-pressure facilities. The crystallographic phases and textures induced at LLNL are characterized by neutron diffraction spectroscopy using a reactor and a low-temperature specimen holder at NIST.

Research Highlights

Planetary Fluids

Shock compression of liquids produces high pressures and temperatures comparable to those in the giant planets Jupiter, Saturn, Uranus, and Neptune. The high interior pressures arise because of the large mass of these planets. High interior temperatures arise because the thermal conductivity is so low that the planet cannot cool after it forms. The most abundant constituent of these planets and thus of the solar system is hydrogen. The external magnetic fields of Jupiter and Saturn, for example, arise from convective flow of H_2 within the outer envelopes. Neil Holmes and William Nellis are measuring the first temperature data for hydrogen at high shock pressures. In these experiments, pressures range up to 100 GPa, and temperatures range up to 5000 K. The temperatures are obtained from the graybody spectrum of the radiation emitted from the shock-compressed hydrogen. Preliminary results indicate that the temperatures produced by the first shock in liquid hydrogen are in good agreement with theoretical predictions. Thus, our use of theoretical temperatures to analyze our previous electrical conductivity data of hydrogen is valid.⁹ As a result, the density and temperature dependencies of the electrical conductivity of dense molecular hydrogen are known over a large range of planetary pressures. At higher pressures above 20 GPa, achieved when the first shock in the liquid reflects off a window, the measured temperatures are lower than predicted. This systematic lowering of the temperature is probably caused by a continuous dissociation of the molecular phase to the atomic phase at high temperatures. The experiments and analysis are not yet complete. However, these results suggest that the so-called molecular layer in Jupiter is actually two layers. Thus, our results would lead to a different estimate of the interior temperature distribution in Jupiter and provide a mechanism to justify the existence of an additional layer inside the planet.

Impacts and Phase Transitions in Geologic Materials: How Rocks from the Moon and Mars Came to Earth

Certain varieties of meteorites found in Antarctica have the chemical characteristics indicative of those that originate on the moon and on Mars. It has been proposed that these rocks were ejecta from an impact crater on these nearby bodies of the solar system. However, it was also thought that such ejecta would be strongly shocked if caused by a high-speed impact; that is, the crystal lattice of these minerals would have many shock-induced defects characteristic of a strong impact shock. Since these rocks have few defects, the question arose as to how weakly shocked ejecta could be generated by an impact. A theory from the University of Arizona proposed that high-speed ejecta from an impact actually come from a weakly shocked zone around an impact site. To test this idea, Andrew Gratz, William Nellis, and Neal Hinsey developed a technique to collect selectively the high-speed ejecta from around an impact.¹⁰ This selective collection was done by using a soft foam. Under optical examination, the high-speed ejecta were found to be weakly shocked, as predicted. The impact we investigated was achieved with our two-stage gas gun, a representative velocity of 4 km/s, and a granite target. We chose a granite target because it will readily show shock features if they are present. In this way, we demonstrated that high-speed ejecta, which can travel to an adjacent body in the solar system, are weakly shocked and that this is the likely way rocks from the moon and Mars came to Earth.

Natural Pressure Markers for Impacts

When impactors strike the Earth, they cause changes in the crystal structure and the microstructure of minerals. Therefore, we are impacting minerals in the laboratory and determining their structure for comparison with observations on natural minerals. Zircon is a mineral widely found in nature in trace amounts and relatively robust to high shock pressures. Peter Fiske and William Nellis are subjecting zircon to shock pressures up to 30 GPa and characterizing the effects on this mineral.

The Melting of Iron at Pressures and Temperatures in the Earth's Core

The melting of iron at high pressures provides a critical constraint for modeling the energy balance and chemical composition of the Earth's core. The core contains mostly iron distributed in two layers. The inner layer is solid and nearly pure iron. The outer core layer is liquid alloyed with lighter elements, which reduce the density and melting temperature relative to pure iron. Thus, the melting temperature of iron at the pressure of the boundary between the Earth's inner and outer core, 330 GPa, should provide an upper limit on the temperature at this boundary in the Earth.¹¹ The only way to access this region in the laboratory is by shock compression. Therefore, Choong-Shik Yoo, Neal Holmes, and Marvin Ross of LLNL and Dave Webb and Chris Pike of UC Davis measured the temperatures of iron films deposited on single-crystal diamond substrates.¹² The temperature was determined from the spectra of the optical radiation and the diamond remains transparent up to very high shock pressures. The results yield a melting temperature of 6830 ± 500 K at 330 GPa.

Astrophysics Research Center

The Astrophysics Research Center serves the aims of the IGPP-LLNL in the area of astrophysics. This includes managing the astrophysics part of the UCRP and facilitating contacts between UC scientists and their LLNL counterparts. The Astrophysics Research Center also serves as the focus of astrophysics activities at LLNL by organizing the weekly astrophysics colloquium, by hosting visitors and collaborators, by editing an annual Observatory Report that covers all astrophysics activities at LLNL (and is published in the *Bulletin of the American Astronomical Society*), and by providing various other service functions. The staff and postdoctoral researchers of the Astrophysics Research Center carry out a significant program of astrophysics research within the Center.

The scientific staff of the Center are Charles Alcock (Center Head), Claire Max, and Willem van Breugel. Administrative support is provided by Christina Budwine (Operations Manager), and by secretaries Arlene Manning and JoAnne McGuire. Alan Edwards manages the network of computers in the Center. He has been assisted by Deanne Proctor, who supported the astronomical image processing codes AIPS and IRAF, and by Susan Peterson, who has taken responsibility for daily maintenance and for acquisitions.

Much of the research in the Astrophysics Research Center is carried out by the postdoctoral fellows, who have proved to be an energetic and stimulating group. Some fellows are supported entirely by IGPP funds, while others are supported partially by other groups at LLNL. In FY 1993, the postdoctoral fellows were David Bennett (previously at Princeton University), Leigh Brookshaw (Yale University), Susana Deustua (University of Michigan), George Hawkins (UC Los Angeles), Suzanne Hawley (Observatories of the Carnegie Institute of Washington), Matthew Lehnert (Johns Hopkins University), Scott Olivier (UC Santa Cruz), and Christopher Skinner (University of Manchester). Suzanne Hawley has been supported by a Hubble Fellowship. In addition to the IGPP postdoctoral fellows, Maurice Aufderheide, Stephane Charlot, and Ted Ressel, who are postdoctoral fellows in the Physics Department's N Division, sit in the Astrophysics Research Center, participate in all the activities, and contribute to the intellectual vitality of the group.

The Center hosts a large number of scientific visitors, many from the UC campuses and from around the United States and the world. These visitors stay for lengths of time ranging from a day to a year. Some who are affiliated with more local institutions spend large, ongoing portions of their time in the Center. A prominent example is Robert Becker, a professor at UC Davis, who spends two or three days a week at the Center and contributes significantly to the scientific program.

The Center and its offices are housed in Building 319, which is close to the offices of many LLNL astrophysicists and is subject to minimal access controls. These features make the Center ideal for the many collaborations that have developed between UC researchers and LLNL scientists.

The Astrophysics Research Center has access to a variety of machines for computing. Most day-to-day work, which includes code development, image processing, and symbolic manipulation, is carried out on the Center's network of Sun workstations. This network comprises three server machines, sixteen Sparcstations, and a few low-end workstations. One of the servers is on loan from UC Davis and is primarily used by Becker for processing radio astronomy data. This network has increasingly been used for large-scale processing with codes that use a large fraction of the network for parallel processing; such processing is especially effective at night, when most of the network is otherwise quiet and the "invasive" code will not

adversely affect the image-processing work. In addition, much greater computing power is available in other parts of LLNL: an eight-processor Solbourne and a network of 14 IBM Risc stations are located in the Physics Department, and Cray supercomputers are located in the LLNL Open Computing Facility and in the National Energy Research Supercomputer Center.

Research Highlights

The Astrophysics Research Center has developed a research program that exploits the traditional strengths in astrophysics at LLNL and that also opens up new areas not previously represented at LLNL. This research ranges from smaller-scale theoretical and observational projects carried out by the staff and postdoctoral fellows to large collaborative ventures that involve scientists from outside IGPP.

Astronomical Adaptive Optics and Laser Guide Stars

Claire Max, James Brase, and Herbert Friedman are working with four other LLNL collaborators and five collaborators from three UC campuses to develop adaptive optics and laser guide stars for astronomy. The purpose of the project is to improve the angular resolution obtained at ground-based telescopes by factors of 10 to 100. The angular resolution of ground-based telescopes is limited to about 1 arcsec because of turbulence in the atmosphere. In principle, one can use adaptive optics to correct for these wavefront distortions by measuring the aberrations with a high-speed wavefront sensor and then deforming a flexible auxiliary mirror to make the wavefront nearly flat. Correction of the turbulent distortion using this method would allow ground-based telescopes to be used at their diffraction limit. For example, at a wavelength of 0.5 μm , the diffraction limit would be 0.03 arcsec for a 3-m telescope such as that at UC's Lick Observatory, and about 0.01 arcsec at 10-m telescopes such as the new Keck telescope. These represent improvements in resolution of factors of 30 and 100, respectively, relative to the atmospheric resolution of about 1 arcsec.

To accomplish this correction in the visible range, however, one needs a bright reference source within a few arcseconds of the object being imaged. The number of bright stars is such that only a tiny fraction of the sky is accessible for diffraction-limited viewing, if nearby stars are to be used as the wavefront references.

To make up for the lack of bright reference stars, we are developing the ability to produce artificial stars using a powerful laser. Specifically, the idea is to tune a laser to the sodium D lines and resonantly excite the atmospheric sodium layer at an altitude of 90 km, thus making an artificial star to use as a reference beacon.

In the first phase of this long-term effort, a copper-vapor-pumped dye laser, which was developed for LLNL's Atomic Vapor Laser Isotope Separation Program, was used to create an artificial star. The artificial star was fifth magnitude in brightness when the laser power was 1100 W. The return power from the artificial star has been measured as a function of laser power, and the experimental results were in good agreement with theoretical predictions. Wavefront information was obtained from the artificial star using a wavefront sensor on a 0.5-m telescope, and the results were similar to those from a natural star.

Based on the success of this earlier program, a program to develop adaptive optics was started. A prototype adaptive optics system has been developed for use on the 1- and 3-m telescopes at the Lick Observatory, and a compact solid-state pumped laser has been designed, which will provide a laser-generated artificial star for the adaptive optics system on the 3-m telescope. The prototype system has been

tested using natural stars on the 1-m telescope, yielding up to a factor of 10 in image peak intensity and a factor of 6 reduction in image full width at half maximum (FWHM). Figure 7 shows an example of the image improvement.

One long-term goal of this project is to participate in establishing a laser guide star adaptive optics system on the Keck 10-m telescope, which is operated by the University of California and the California Institute of Technology at Mauna Kea, Hawaii. Design studies for such a system are being performed as part of this project, in collaboration with many other UC, Caltech, and Keck Observatory scientists.

Searching for Dark Matter

Over the last two decades, astronomers have established that most of the mass in our galaxy, the Milky Way, is presently invisible to astronomers. This dark matter is known to exist and to be distributed in a large, spherical "halo." It comprises at least 90% of the mass of the Milky Way. The constitution of this matter is unknown, since it emits no detectable radiation. Most hypotheses for the constitution of this matter involve speculations drawn from particle physics. Alternatively, the dark matter could be made up of planets, brown dwarfs, and black holes (now collectively called MACHOs, for massive compact halo objects). These objects represent the conservative hypothesis for the constitution of the dark matter.

The MACHO project is an experimental search for this dark matter. It was initiated here at LLNL and now involves scientists from five institutions: Charles Alcock, Robyn Allsman, Timothy Axelrod, David Bennett, Kem Cook, and Hye-Sook Park at LLNL; Stuart Marshall, Mark Pratt, and Christopher Stubbs of the Center for Particle Astrophysics at UC Santa Barbara; Kim Griest and Matthew Lehner of the Center for Particle Astrophysics at UC San Diego; Saul Perlmutter and Will Sutherland of the Center for Particle Astrophysics at UC Berkeley; and Kenneth Freeman, Bruce Peterson, Peter Quinn, and Alex Rodgers of the Mount Stromlo and Siding Spring Observatories in Australia. The experiment will ultimately be sensitive to objects in the mass range $10^{-7} M_{\odot} < M < 1 M_{\odot}$.

If the dark matter is made of MACHOs, they will occasionally amplify the light from extragalactic stars by the gravitational lens effect. The amplification can be large (up to factors of many). An event can be recognized by fitting a theoretical light curve to the observations (three-parameter fit) and by the lack of color variation in the event (it is achromatic). Unambiguous recognition by microlensing thus

Figure 7. Images of α Aurigae with and without adaptive optics compensation, at 700 and 850 nm. AO/TT = adaptive optics/tip tilt.

requires that there be adequate numbers of data points on the light curve (>10) and measurements in at least two filter bands. The expected event rate, however, is low: it is necessary to monitor millions of stars for several years to detect tens of events. The original design goal was to detect at least 10 "good" events per year of operation (a good event has maxima greater than 0.44 magnitudes, more than 10 points per light curve, good three-parameter fit, and no color variation), if MACHOs make up the halo. The experiment will operate for a minimum of four years.

The MACHO project is operating with the 130-cm reflecting telescope of the Mount Stromlo Observatory (the Great Melbourne telescope), near Canberra, Australia. Operating at prime focus with an innovative optical system gives a field of view 1 deg in diameter, and the use of a dichroic filter allows simultaneous imaging in two spectral bands, doubling the effective exposure rate. The beams leaving the beamsplitter are imaged onto mosaics of four 2048×2048 -pixel charge-coupled devices (CCDs) ($15 \mu = 0.6$ -arcsec pixels). The typical exposure is 300 s, followed by about 60 s to read out the CCD chips. The data rate from this experiment is large, with an average rate of 4 Gbytes/night. The data are processed at the telescope using a dedicated computer system and software developed for the project. This system can measure the brightnesses of several million stars, once or twice per night, in the Large Magellanic Cloud. Working in the crowded regions at the central bar in the Large Magellanic Cloud, it is possible to record more than 600,000 stars in one image. When the Large Magellanic Cloud is not high enough in the night sky to observe it with the telescope, similar observations are made of the Small Magellanic Cloud or of fields near the center of the Milky Way.

During FY 1993, the first extensive analysis of data for large numbers of stars was carried out. Among the first 1.8 million light curves that were analyzed, a very plausible candidate for gravitational microlensing was detected. Figure 8 shows the data for a 100-day stretch that encompasses the event (the full light curve extends from day 200 to day 500), with the theoretical best-fit microlens amplification curve drawn through the data. This event is highly significant and remarkably suggestive that we have indeed seen the signature of MACHOs for which we have been searching.

It is premature to interpret this one, albeit spectacular, event in terms of the fraction of the dark matter that is in MACHOs. It does, however, validate the approach we have taken and establishes that the experiment is working. With this system, the MACHO group expects to answer definitively whether the dark matter in our galaxy is made up of objects with mass in the range of $10^{-7} M_{\odot} < M < 100 M_{\odot}$.

Variable Star Astronomy

The telescope system described above is especially well suited to the study of variability in all categories of astronomical objects. We have learned how to recognize and classify variable stars in our data and have commenced the physical studies of the objects themselves.

We started with the periodically varying stars. Of these (we have identified more than 9000), most fall into one of three well-known classes: the Cepheid variable stars (relatively massive stars that pulsate with time), the RR Lyrae stars (lower-mass counterparts of the Cepheids), and the eclipsing binary stars. In each of the cases we study, we now have the best data for investigations of these classes of phenomena: We have the largest numbers of examples, and for each example, we have the best studied photometric histories. These data will be exploited to study the properties of the stars themselves and to probe the three-dimensional structure of the Large Magellanic Cloud.

Optical Properties of Radio Galaxies

An important result from observational studies of radio galaxies has been that at high redshifts, their parent galaxies are clumpy and elongated in the direction of the associated radio sources. Several radically different interpretations of the aligned structures have been proposed, including jet-induced star formation; scattered light from hidden, quasar-like active galaxy nuclei; optical synchrotron emission associated with shocks in jets; inverse Compton scattering off microwave background photons by relativistic electrons; or thermal bremsstrahlung from shock-heated gas. In nearly all cases, the optical continuum is expected to be blue compared with the spectrum of a normal elliptical galaxy. In addition, in the cases of synchrotron emission and scattering, one expects the continuum to be polarized.

A better understanding of this alignment effect in radio galaxies is crucial to the study of: (1) the origin and evolution of (active) galaxies and their environment; (2) unification schemes of active galaxy nuclei (AGN) and quasars; (3) the effects of collimated outflow and ionizing continuum on ambient material; and (4) cosmology, since radio galaxies span a large redshift range.

Since high-redshift radio galaxies are very faint, a detailed study of this alignment effect is difficult. Therefore, Willem van Breugel and UC Berkeley graduate student Arjun Dey conducted a systematic continua imaging survey of a nearby, redshift-limited ($0.08 < z < 0.2$) sample of powerful radio galaxies to find low-redshift examples of aligned ultraviolet continua and line emission in nearby radio galaxies. Such objects then can be studied with better linear resolution and at higher signal-to-noise ratios than their much more distant, fainter counterparts at high redshift. More than 30% of the complete sample showed evidence for such aligned, very blue continuum knots, nearly all of which also showed strong associated line emission.

Figure 8. Observed flux in the (a) blue and (b) red for the event. The theoretical curve, fitted to the data, is shown by the smooth line. (c) Ratio of red/blue fluxes.

Detailed studies of a number of these radio galaxies have now been made, and evidence was found that several of the possible interpretations of the alignment effect indeed may occur. We discovered the first example of star formation that was induced by outflow associated with a powerful radio lobe as well as the most luminous synchrotron hotspot in any radio galaxy known so far. Most importantly, we found evidence for the occurrence of scattered light in one of the nearby radio galaxies, with very blue continua along the radio source axis extending over as much as 70 kiloparsec. On the basis of these results, we have begun an extensive project to determine the optical polarization properties of the aligned optical light in radio galaxies using ground- and space-based (Hubble Space Telescope) observatories.

Another important topic in active galaxy studies is the investigation of possible relationships between central starbursts and the fueling of AGN. By combining large radio surveys with the Infrared Astronomy Satellite (IRAS) Far-Infrared (FIR) survey, we constructed a sample of radio-loud AGNs embedded deep in gas- and dust-rich (star-forming) parent galaxies. The Lick Observatory 3-m and other 3- to 4-m-class telescopes were then used to obtain optical identifications and spectroscopy of this sample. We discovered a significant class of gas- and dust-rich AGN that are characterized by very large FIR luminosities and that are intermediate in radio luminosity, FIR color, and optical spectral class between FIR ultraluminous galaxies and powerful quasars (Figure 9). The majority of these objects are LINERs, Seyfert 2 galaxies, and post-starburst active galactic nuclei (PSAGN). The latter are characterized by strong Balmer absorption lines, Seyfert 2-like emission lines (Figure 10), and compact, often almost stellar, optical morphologies.

The absorption lines often have extremely large equivalent widths (as much as $1.5 \mu\text{m}$) and are very broad (FWHM of $3 \mu\text{m}$). Such lines are normally seen only in individual A-type stars. They imply a large coeval population of stars, and it is interesting to speculate that these PSAGN may contain the central massive star clusters responsible for fueling AGN. The emission-line spectra of the PSAGN are surprisingly similar to that of the most luminous, high-redshift ($z = 2.3$) IRAS galaxy F10214+4724 with its strong rest-frame UV emission lines, suggesting an AGN, and the absence of $\text{H}\beta$ emission, suggesting strong underlying $\text{H}\beta$ absorption because of a large population of young stars.

Further followups to these observations are under way, at millimeter-wavelengths to measure the cold, molecular gas and dust contents (the star formation reservoir) of these objects, and spectropolarimetry to search for evidence of scattered light from hidden, quasar-like AGN.

Figure 9. IRAS 60- μm luminosity vs 365-MHz radio power for radio-loud IRAS galaxies and quasars. A large fraction of the intermediate luminosity objects (open circles) are post-starburst AGN.

Infrared Astronomy

Christopher Skinner and his collaborators have an ongoing program studying mass loss in stellar winds during the transition phase from asymptotic giant branch (AGB) stars through the planetary nebula (PN) phase. They image dust in these winds in the thermal infrared, using the Berkeley–Livermore mid-infrared camera. Skinner and Margaret Meixner (formerly UC Berkeley, and now University of Illinois) have made detailed analyses of two well-known objects of this kind. One (known as HD161796) is thought to be a low-mass star in the post-AGB transition phase, with an optical spectral type of F2. Mid-IR images taken at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii, show that the star underwent a burst of extremely rapid mass loss, probably lasting only a few hundred years, as it departed the AGB. This is the first direct observational evidence for a “superwind,” which it appears will eject a significant fraction of the AGB star’s initial envelope mass in a very short time and lead the star rapidly to the PN phase of evolution. The images obtained in this project were used in conjunction with earlier mid-IR spectra (also taken at UKIRT) to develop a model for the star’s complete spectral energy distribution. Using this model, we have determined for the first time the distance and hence the luminosity and mass-loss rate of HD161796. Our results show that HD161796 is a Population II star, formed very early in the history of our galaxy. The images also show that the superwind ejected mass preferentially in the equatorial direction, generating a dense, dusty torus (or donut) around the star. This equatorial torus will cause HD161796 to evolve, like most low-mass stars, into a bipolar PN, which is the first direct evidence in favor of the idea that bipolar nebulae form in this way. It also is the first indication that the torus already exists at the time the star leaves the AGB. The dimensions of the torus indicate that HD161796 left the AGB only 240 years ago, which shows that the central star is evolving very rapidly at this stage.

Searching for Asteroids

Kem Cook and Charles Alcock, working with Christopher Stubbs (UC Santa Barbara), Eugene Shoemaker (US Geological Survey), and Ted Howell (Lowell Observatory), are developing a new CCD camera to use for a preliminary search for near-Earth asteroids. The camera is a natural outgrowth of the cameras previously developed for the MACHO project, with the modification that they are used in

Figure 10. Optical spectrum of a typical post-starburst AGN (see text).

"scan" mode, in which the camera/telescope system is moved rapidly along great circles across the sky, and the CCD chips are read out constantly. This two-CCD system will scan a swath of sky that is 3.2 deg wide (about six times the diameter of the moon). This mode is an effective way to cover very large regions of sky with short effective exposure times, which will be needed for our project. The camera will be installed on the 24-in. Schmidt telescope at Anderson Mesa, Arizona, and is expected to go into operation in 1994. This system should greatly enhance the present discovery rate for near-Earth asteroids and will also serve as a development stage for the much more ambitious Spaceguard Project, which aims to detect more than 90% of all large (>1 km) near-Earth asteroids.

References

1. Kersting, A. B., and R. J. Arculus (1994), "Klyuchevskoy Volcano, Kamchatka, Russia: The Role of High-Flux, Recharged, Tapped and Fractionated Magma Chambers(s) in the Genesis of High- Al_2O_3 from High-MgO Basalt," *J. Petrology* **35**, 1.
2. Hofmann, A. W. (1988), "Chemical Differentiation of the Earth: The Relationship between Mantle, Continental Crust, and Oceanic Crust," *Earth Planet. Sci. Lett.* **90**, 297.
3. Chow, T. J., and C. C. Patterson (1962), "The Occurrence and Significance of Lead Isotopes in Pelagic Sediments," *Geochim. Cosmochim. Acta* **26**, 263.
4. Ben Othman, D., W. M. White, and J. Patchett (1989), "The Geochemistry of Marine Sediments, Island-Arc Magma Genesis, and Crust-Mantle Recycling," *Earth Planet. Sci. Lett.* **94**, 1.
5. Woodhead, J. D., and D. G. Fraser (1985), "Pb, Sr, and ^{10}Be Isotopic Studies of Volcanic Rocks from the Northern Mariana Islands: Implications for Magma Genesis and Crustal Recycling in the Western Pacific," *Geochim. Cosmochim. Acta* **49**, 1295.
6. Kay, R. W., S. S. Sun, and C. N. Lee-Hu (1978), "Pb and Sr Isotopes in Volcanic Rocks from the Aleutian Islands and Pribilof Islands, Alaska," *Geochim. Cosmochim. Acta* **42**, 263.
7. Davidson, J. P. (1986), "Isotopic and Trace-Element Constraints on the Petrogenesis of Subduction-Related Lavas from Martinique, Lesser Antilles," *J. Geophys. Res.* **91**, 5943.
8. McDermott F., M. J. Defant, C. J. Hawkesworth, R. C. Maury, and J. L. Joron (1993), "Isotope and Trace-Element Evidence for Three-Component Mixing in the Genesis of the North Luzon Arc Lavas (Philippines)," *Contrib. Mineral. Petrol.* **113**, 9.
9. Gratz, A. J., W. J. Nellis, and N. A. Hinsey (1993), "Observations of High-Velocity, Weakly Shocked Ejecta from Experimental Impacts," *Nature* **363**, 522.
10. Nellis, W. J., A. C. Mitchell, P. C. McCandless, D. J. Erskine, and S. T. Weir (1992), "Electronic Energy Gap of Molecular Hydrogen from Electrical Conductivity Measurements at High Shock Pressures," *Phys. Rev. Lett.* **68**, 2937.
11. Anderson, O. L. (1990), *J. Geophys. Res.* **95**, 21697.
12. Yoo, C. S., N. C. Holmes, M. Ross, D. J. Webb, and C. Pike (1993), "Shock Temperature and Melting of Iron at Earth Core Conditions," *Phys. Rev. Lett.* **70**, 3931.

Geosciences

Monazite as a Thermochronometer for Prograde Metamorphism

Principal Investigators: T. Mark Harrison and Kevin D. McKeegan (UC Los Angeles)
LLNL Collaborator: Frederick J. Ryerson
Student: William T. Akers (UC Los Angeles)

Abstract

The high retentivity of monazite for lead, its high uranium and thorium concentrations, and its emergence in staurolite zone metapelites suggest that it may be used as a prograde thermochronometer. However, the monazite-producing reactions in pelites are as yet incompletely understood. In FY 1992, we ruled out rhabdophane, a light rare-earth element (LREE) $\text{PO}_4 \cdot \text{H}_2\text{O}$, as a precursor to monazite in pelitic compositions. Thus, in FY 1993, we began examining the possibility that monazite forms from a reaction of apatite with LREE oxides. We also are investigating the stability of monazite in pelites using a natural pelite. In related experiments, we are using natural monazites to try to estimate lead diffusion rates, and we have acquired several candidate standards for use in developing a uranium-lead microanalysis technique.

Objectives

Our goal is to develop the monazite prograde thermochronometer. To accomplish this task, we require information from three distinct, but related, studies: (1) stability and reaction kinetics of LREE oxides and hydrous LREE phosphates in pelitic assemblages, (2) lead diffusion in monazite, and (3) development of the uranium-lead microanalysis of monazite.

Progress

Stability and reaction kinetics of LREE oxides and hydrous LREE phosphates in pelitic assemblages. Having ruled out rhabdophane as a precursor to monazite in metamorphosed pelites,¹ we began examining the possibility that monazite forms from a reaction of apatite with LREE oxides. Initial experiments were conducted by placing a small neodymium-monazite seed crystal (10–30 μg) in a silver-palladium capsule along with a mixture of a LREE oxide (lanthanum or cerium), apatite, quartz, andalusite, albite, and water. The capsules were placed in cold-seal bombs and run with a graphite-methane buffer at 2 kbar at temperatures between 450 and 650°C for one to two weeks. The monazite crystals were then removed from the capsule, cleaned, and weighed to ascertain if growth had occurred.

Because of the difficulty in working with these very small seed crystals, recent work has concentrated on growing larger monazite crystals for use in these experiments. Montel² was able to grow millimeter-sized monazite crystals from LREE gels and phosphoric acid in cold-seal bombs at 3 kbar and 600°C for 7 days. We grew several crystals using this method that approach the size reported by Montel,² and we are working on improvements in the experimental setup that may increase the size and yield from each of the runs.

We also began investigating the stability of monazite in pelites using a natural pelite. We collected six samples of the Bright Angel Shale from the Marble Mountains in southeastern California. The shale from this location has experienced only low-grade metamorphism.³ To study the stability of monazite, we plan to combine a rock powder from this shale with a pure lanthanum end-member monazite seed crystal and some water in silver-palladium capsules and run it under a range of hydrothermal pressure-temperature conditions. We will then remove the seed crystal from each run and examine it using UC Los Angeles's ims 1270 ion probe to determine if monazite growth occurred. Growth rims produced in this manner should have LREE contents that reflect the LREE content of the shale and should be easily distinguishable from the pure lanthanum-monazite core.

Lead diffusion in monazite. Diffusion measurements have been hampered by the presence of lead inclusions in synthetic monazites, formed from a lead-phosphate flux. We initiated experiments at LLNL using natural monazites and are awaiting those results. Depending on the outcome, we may adopt an alternative method using synthetic monazites grown in a lead-free environment, either hydrothermally or in a sodium-tungstate flux.

Uranium-lead microanalysis of monazite. We acquired several monazites as candidate standards for uranium-lead microanalysis. Monazite from the Tioga Ash appears promising in this role and has permitted preliminary assessment of uranium-lead dating using the ion microprobe. Mass spectra in the vicinity of 204 to 208 obtained from a lead-free, synthetic neodymium-monazite indicate no significant interferences of the lead isotopes from rare-earth elements phosphate molecules at a mass-resolving power of 5000. Lead sensitivity is reasonably high (>30 cps/ppm lead/nA O₂⁻), and interelement calibrations for uranium, thorium, and lead appear to be feasible at the percent level.

References

1. Akers, W. T., M. Grove, T. M. Harrison, and F. J. Ryerson (in press), "The Instability of Rhabdophane and Its Unimportance in Monazite Paragenesis," *Chem. Geol.*
2. Montel, J. M., F. Lhote, and J. M. Claude (1989), "Monazite End Members and Solid Solutions: Synthesis, Unit-Cell Characteristics, and Utilization as Microprobe Standards," *Min. Mag.* **53**, 120.
3. Kingsbury, J. A., C. D. Miller, J. L. Wooden, and T. M. Harrison (in press), "Monazite Paragenesis and U/Pb Systematics in Rocks of the Eastern Mojave Desert, California: Implications for Thermochronometry," *Chem. Geol.*

Electrical Properties of a Mantle Rock

Principal Investigator: Steven Constable (UC San Diego)

LLNL Collaborator: Alfred G. Duba

Abstract

We examined the electrical conductivity of an olivine-rich rock, lherzolite (31% orthopyroxene, 3% clinopyroxene, 65% olivine $Fo_{91.3}$, and 1% spinel), with a grain size of about 1 mm. Electrical conductivity (σ) in olivine as a function of oxygen fugacity (f_{O_2}) is well modeled by a mixture of threshold and f_{O_2} -dependent terms: $\sigma = \sigma_0 + \sigma_1(f_{O_2})^{1/5.5}$. Step-function changes in the $CO:CO_2$ gas mix that controls f_{O_2} during measurements of σ may be used to estimate the diffusion coefficients associated with point defects responsible for reequilibration of conductivity.

Diffusivities, κ , obtained by nonlinear least-squares fits to the conductivity data are in excellent agreement with those obtained by Mackwell et al. using measurements of transient creep.¹ The use of electrical conductivity is superior in its ability to obtain data at lower temperatures (800–1200°C), and the more precise measurements show a clear distinction for κ between oxidizing and reducing runs:

$$\kappa_{\text{oxd}} = 2.55 \times 10^{-4} \text{ e}^{-182\text{kJ}\cdot\text{m}^{-1}/\text{kT}}, \quad (1)$$

$$\kappa_{\text{red}} = 3.18 \times 10^{-4} \text{ e}^{-173\text{kJ}\cdot\text{m}^{-1}/\text{kT}}. \quad (2)$$

The two activation energies are not significantly different and are slightly lower than those obtained by Mackwell et al., who interpreted their results in terms of magnesium vacancies.¹ Thus, reequilibration of V_{Si}'''' and/or O_{O}^x must be governed in some part by reactions at the surface of the mineral or is perhaps related to a blocking potential at the electrode-sample interface.

Objectives

Our objectives were to examine the conductivity of rocks representative of the upper mantle as a function of temperature and f_{O_2} . The upper mantle is thought to be composed primarily of the minerals olivine and pyroxene, with olivine being the dominant mineral both in terms of its volume fraction and σ . The dominant defect responsible for conduction at temperatures of 700 to 1300°C is inferred to be the “small polaron” Fe^{3+} (Fe_{Mg}^+ in Kroger–Vink notation) produced by oxidation of Fe^{2+} Fe_{Mg}^x .² Support for the polaron mechanism is provided by a positive thermoelectric coefficient below 1390°C, dielectric measurements, and the increase of σ with iron content. Support is also provided by the positive dependence of σ on oxygen fugacity because increasing f_{O_2} increases the number of Fe^{3+} available for conduction.

In a previous IGPP–LLNL project, changes in experimental f_{O_2} were modeled for spherical grains to recover the diffusivity of the defect responsible for conveying the oxidation state to the grain interiors. The size of the diffusivity thus obtained (about $10^{-11} \text{ m}^2/\text{s}$ at 1000°C) is comparable to that obtained and interpreted by Mackwell et al. to be for magnesium vacancies.¹ The relationship between conduction and f_{O_2} is described by the following reaction in which oxygen is adsorbed and forms the polarons responsible for conduction:

The polarons are presumably very mobile and rapidly removed from the site of oxygen adsorption. The magnitude of the diffusivity suggests that removal of magnesium vacancies is the rate-limiting step for further adsorption of oxygen. Because diffusion of silicon is slower than magnesium, the generation of silicon vacancies either does not impede further oxygen adsorption or is satisfied by interstitial silica in the olivine.

In the earlier experiment, we did not anticipate our ability to recover diffusivities by modeling the change in conductivity during changes in f_{O_2} ; therefore, the gas mix changes were not necessarily clean step-functions, making it difficult to extract diffusion data. Our goal was to repeat the experiments with careful regard to the changing of gas mixes. By characterizing the rate-limiting step in the relationship between the oxidation state and conduction, we obtain insight into the nature of electrical conduction in mantle rocks and the factors affecting it.

Progress

The apparatus used for conductivity measurements as well as oxygen fugacity control and measurements is described by Duba et al.³ A disk-shaped sample, sandwiched between iridium foils, is inserted between platinum–rhodium thermocouples in the apparatus. The platinum leg of each thermocouple pair is used as the lead for measuring conductivity. Oxygen fugacity is controlled by continuously passing a metered mix of CO:CO₂ through the apparatus at atmospheric pressure.

After measurement runs of more than 4000 h, 71 changes in f_{O_2} were made at temperatures between 800 and 1200°C and 1 to 10⁴ Pa. Extremes in f_{O_2} were avoided to prevent changes in conductivity associated with oxidation (high f_{O_2}) and iron loss to electrodes (low f_{O_2}).

Figure 1 shows the difference in the conductivity–time function for a one-order-of-magnitude change in oxygen fugacity from relatively reducing (10⁻³ Pa) to relatively oxidizing (10⁻² Pa) and back to the same relatively reducing f_{O_2} after

Figure 1. Normalized conductivity as a function of time for oxidizing and reducing f_{O_2} changes between 10⁻³ and 10⁻² Pa.

equilibration at the relatively oxidizing f_{O_2} . The asymmetry between oxidation and reduction must be ascribed to a surface reaction or process because it cannot be associated with bulk diffusion. We speculate that it is related to a limitation in the sample's ability to extract oxygen from the experimental atmosphere. Similar experiments on MnO show lower diffusivities if the CO:CO₂ mix is diluted with argon or lowered in pressure. This is also consistent with the slight trend to higher diffusivities for the oxidizing runs as the f_{O_2} is increased, because more oxygen is available in the experimental atmosphere at the higher f_{O_2} . These numbers then would represent lower bounds for the bulk diffusivity associated with the rate-limiting step related to oxidation or reduction of olivine.

Diffusion was modeled by the average defect concentration in a sphere of radius (a) of 0.575 mm:

$$\sigma(t) = \sigma_i + \sigma_0 \left[1 - \frac{6}{\pi^2} \sum_{i=1}^{\infty} \frac{1}{i^2} e^{-1^2 \pi^2 (t - t_0)/a^2} \right] \quad (4)$$

where t is time of measurement. Diffusivities, κ , are obtained by nonlinear least-squares fits of this equation (Figure 2).

If we average data taken between 10^{-2} and 10^{-3} Pa to avoid systematic errors associated with high and low f_{O_2} , we see the asymmetry between oxidation and reduction very clearly. We see excellent agreement with similar experiments performed by Mackwell et al.¹ but which measured the response of creep to f_{O_2} changes rather than the response of conductivity. The greater precision of the electrical measurements and the ability to operate at lower temperatures than creep measurements is evident. We see that diffusivities are slightly higher than, but in basic agreement with, diffusivities for magnesium vacancies measured by Nakamura and Schmalzried⁴ and Wanamaker.⁵ Mackwell et al. inferred that their data were associated with magnesium vacancy diffusion.¹ This is consistent with the polaron model, which generates magnesium vacancies as oxygen is absorbed.

Figure 2. Diffusivity vs reciprocal temperature.

References

1. Mackwell, S. J., D. Dimos, and D. Kohlstedt (1988), "Transient Creep of Olivine: Point Defect Relaxation Times," *Philos. Mag.* **A57**, 779.
2. Duba, A., and S. Constable (1993), "The Electrical Conductivity of Lherzolite," *J. Geophys. Res.* **98**, 11885.
3. Duba, A. G., R. N. Schock, E. Arnold, and T. J. Shankland (1990), "An Apparatus for Measurement of Electrical Conductivity to 1500°C at Known Oxygen Fugacity. The Brittle-Ductile Transitions in Rocks, The Heard Volume," *Geophys. Monogr. Ser., Am. Geophys. Union* **56**, 207.
4. Nakamura, A., and H. Schmalzried (1984), "On the Fe²⁺-Mg²⁺-Interdiffusion in Olivine(II)," *Ber. Bunsenges. Phys. Chem.* **88**, 140.
5. Wanamaker, B. J. (1986), *The Kinetics of Crack Healing and the Chemical and Mechanical Reequilibration of Fluid Inclusions in San Carlos Olivine*, Ph.D. thesis, Princeton University.

A Critical Test of the Applicability of $^{10}\text{Be}/^9\text{Be}$ Ratios in Authigenic Minerals for Determining Soil-Formation Rates

Principal Investigator: Devendra Lal (Scripps Institution of Oceanography, UC San Diego)

LLNL Collaborators: Mark W. Caffee, Robert C. Finkel, and John R. Southon

Abstract

We have studied the concentrations of cosmogenic ^{10}Be (half-life of 1.5 million years) and ^9Be in (1) two sections of a deep-sea sediment core having a well-preserved magnetic stratigraphy (Ocean Drilling Program [ODP], Leg 126, holes 791B and 792A at 31°N , 141°E) and (2) several loess–paleosol profiles from the Chinese loess plateau, which have been magnetically and stratigraphically fully characterized. The results unambiguously show the potential of using the cosmogenic nuclide ^{10}Be for characterizing sedimentary sequences and studying in situ development of soils based on ratios of ^{10}Be and ^9Be concentrations. The ODP sediments accumulated during the Brunhes–Matuyama reversal show a large excursion in the $^{10}\text{Be}/^9\text{Be}$ ratio as expected. The loess–paleosol samples show distinct records of large climatic fluctuation and varying degrees of in situ development of paleosols. These measurements give considerable confidence in the use of cosmogenic ^{10}Be as a tracer for studying a host of geophysical processes in the past 5 to 7 million years.

Objectives

Our goal was to test the usefulness of cosmogenic ^{10}Be (half-life of 1.5 million years) for studying sediments and soil dynamics. In particular, we wanted to explore the usefulness of the $^{10}\text{Be}/^9\text{Be}$ ratio, as proposed by Lal and others to quantitatively determine in situ soil-formation rates.¹ Two specific studies were carried out. The first study was designed to learn about ^{10}Be fallout during a geomagnetic reversal. We studied magnetically characterized Pacific marine sediments deposited in the Brunhes–Matuyama transition zone (ODP cores from Leg 126). The second study was carried out jointly with the Institute of Geology at the Chinese Academy of Sciences and was designed to learn about the records in the loess–paleosol sequence. For this study, we selected well-documented and well-characterized loess samples up to 2.5 million years in age and the red clay (residual soils) deposits exceeding 2.5 million years in age; both sets of samples were from the Chinese loess plateau.

Progress

Measurements of ^{10}Be concentrations have been completed in two ODP core sections: 791B and 792A. Measurements of ^9Be have been completed only in section 792A. In section 792A, the $^{10}\text{Be}/^9\text{Be}$ ratios and the ^{10}Be concentrations show a marked transition during the reversal compared to before and after. We are now examining the hypothesis that their observations preliminarily reflect changes in the global production rate of ^{10}Be associated with a low geomagnetic field during the magnetic transition.²

We measured the concentrations of cosmogenic ^{10}Be and ^9Be in different sizes and chemical fractions of loess–paleosol samples, and in red clay samples from four cores of the Chinese loess plateau: Zhaitang (39.6°N , 116.0°E), Jixian (35.0°N ,

110.6°E), Weinan (34.3°N, 109.3°E), and Lingtai (35.2°N, 103.5°E). Our results are in general agreement with the earlier data published for the acid-leach fraction only by Shen and others for Luochuan (35.6°N, 109.3°E).³

The loess samples generally show lower ^{10}Be concentrations than the paleosol samples. Furthermore, we observe that the ^{10}Be concentrations in the loess–paleosol samples and in the red clay samples decay monotonically with depth, in accordance with an age estimate based on paleomagnetic stratigraphy (Figure 1). The data are consistent with a period of about 6 million years for the duration of the whole sequence down to the lowest levels of the red clay deposition. We also observed that the paleosols have undergone an appreciable in situ weathering, which can be quantified based on $^{10}\text{Be}/^9\text{Be}$ ratios and ^{10}Be concentrations. These results support the model proposed earlier by Lal and others for using ^{10}Be to study soil-evolutionary histories.¹

The ^{10}Be concentrations in the loess samples, decay-corrected to the time of deposition, are in the bracket (2 to 2.5×10^8 atoms/g), which is consistent with a single-source region for the loess. The development of paleosols at the sites of deposition is clearly dependent on the local climate, which determines the extent of its in situ weathering and is consistent with the recent studies of ^{10}Be in various soils.⁴ The higher the weathering, the higher the ^{10}Be concentrations. Comparing with $\delta^{18}\text{O}$ SPECMAP data, we deduce that the extent of weathering of paleosols was determined primarily by the amount of precipitation.

The loess samples have not undergone any appreciable in situ weathering, which is consistent with lower precipitation and temperatures during their deposition. However some sections in Weinan show appreciable in situ weathering, possibly indicating episodes of dramatic climatic change toward warm conditions.

Figure 1.
Concentrations of
 ^{10}Be in loess, paleosol,
and red clay samples
plotted vs their ages,
determined by strati-
graphic methods.

Figure 2.
Concentration profiles of ^{10}Be in the paleosol S1 samples from Luochuan and Zhaitang. (a) After Heller et al.⁵ (b) Recent work.

Comparing the ^{10}Be concentration profile of the last interglacial paleosol (S1) samples from Zhaitang and Luochuan (Figure 2),⁵ the ^{10}Be data support the field observation that the former was developed from fluvial sediments and the latter was formed during appreciable influx of sediments (dust).

1. Lal, D., E. Barg, and M. Pavich (1991), "Development of Cosmogenic Nuclear Methods for the Study of Soil Erosion and Formation Rates," *Current Science* **61**, 636.
2. Athanassopoulos, J., S. Cisoulki, D. Lea, M. Fulle, R. Weeks, D. Lal, and J. Southon (1993), "Correlation of ^{10}Be Data with Magnetic Intensity Data for the Matuyama–Brunhes Polarity Reversal in High Sedimentation Rate Marine Sediments from the Izu–Bonin Arc," *EOS Trans. Am. Geophys. Union* **74**, 110.
3. Shen, C. D., J. Beer, T. S. Liu, H. Oeschger, G. Bonani, M. Suter, and Wölfli (1992), " ^{10}Be in Chinese Loess," *Earth Planet. Sci. Lett.* **109**, 169.
4. Barg, E. (1993), *Studies of Beryllium Geochemistry in Soil: Feasibility of Using $^{10}\text{Be}/\text{Be}$ Ratios for Age Determination*, Ph.D. thesis, University of California, San Diego.
5. Heller, F., C. D. Shen, J. Beer, X. M. Liu, T. S. Liu, A. Bronger, M. Suter, and G. Bonani (1993), "Quantitative Estimates of Pedogenic Ferromagnetic Mineral Formation in Chinese Loess and Palaeoclimatic Implications," *Earth Planet. Sci. Lett.* **114**, 258.

References

Effect of Petroleum on Sandstone Reservoirs, San Joaquin Basin, California

Principal Investigator: James R. Boles (UC Santa Barbara)

LLNL Collaborator: Carol J. Bruton

Postdoctoral Fellow: Yong I. Lee (UC Santa Barbara)

Student: David Lea (UC Santa Barbara)

Abstract

Petrographic, geochemical, and thermodynamic calculations on petroleum reservoirs in the San Joaquin Basin show that oil affects the reservoir rock by releasing organic acids during an in situ "maturation" process. These acids enhance the dissolution of detrital plagioclase and subsequent precipitation of kaolinite and calcite within the oil zone of the reservoir. Trace elements, including rare earths, are concentrated in these late calcites.

Objectives

Our goal was to investigate the effect of oil on petroleum reservoirs in the San Joaquin Basin. The distribution of minerals relative to oil and gas distribution at North Coles Levee has led to the hypothesis that oil affects reservoir mineralogy.¹ This study was designed to further test this hypothesis by expanding the observations to other areas in the San Joaquin Basin and looking in greater detail at geochemical signals in the fluids and minerals for indications of the presence of the oil. In addition, thermodynamic calculations on mineral equilibria were compared with observed mineralogy. In particular, the effect of organic acid complexing was included in the equilibrium calculations.

Progress

Distribution of plagioclase porosity relative to oil distribution. Petrographic studies of several hundred thin sections at North Coles Levee, South Coles Levee, and Ten Section fields indicate that the dissolution of plagioclase feldspar and precipitation of kaolinite is a late process related to the presence of oil. Plagioclase porosity and the presence of kaolinite is much reduced or absent in the gas cap, in spite of the presence of similar water saturation in both oil and gas zones. These observations lend credence to the hypothesis that oil is "maturing" in the reservoir, apparently releasing organic acids to the formation water that enhance plagioclase dissolution. All of these fields have a simple burial history to their present burial depth and very late migration history of oil into the reservoir.

At the Kettleman North Dome Field, 110 km north of the Coles Levee fields, plagioclase dissolution occurs throughout several oil and gas zones. Possible reasons for differences from fields to the south are different types of oil and a complex burial history including 1 km of uplift.² Plagioclase dissolution at the Kettleman Field may have occurred during maximum burial, whereas oil emplacement may have occurred after uplift and has been superimposed over a preexisting plagioclase dissolution pattern.

Fluid compositions. Oil and water samples have been collected from several reservoirs in the basin to establish relations between oil and water compositions. Carothers and Kharaka,³ MacGowan and Surdam,⁴ and Fisher and Boles⁵ have shown that organic acids are abundant in San Joaquin waters. Such acids enhance aluminosilicate dissolution,⁶ and our petrographic data suggest that these acids are coming directly from the oil. We have oxygen analyses of oils from North Coles Levee, South Coles Levee, and Paloma Fields that show that these oils presently

contain about 0.6 wt % oxygen. The initial oxygen content of these oils at the time of emplacement is unknown, but mass balance calculations show that less than 1% oxygen could produce the abundance of organic acids observed today in these fields.

Trace-element composition of carbonates. Prior work has shown that Sr in calcite cements at North Coles Levee is derived from dissolution of plagioclase.⁷ In this study, we investigated the trace metal composition of calcite cements at North Coles Levee using an inductively coupled plasma (ICP) mass spectrometer. Results indicate that late cements are significantly enriched in trace metals relative to early cements. Specifically, late calcite cements formed at temperatures between 80 and 106°C have twofold greater bromine and yttrium; two- to threefold greater zinc, cerium, lanthanum, and neodymium; and eightfold greater lead relative to cements forming at 40 to 50°C. Nickel decreases by a factor of 2 in late cements relative to early cements. These observations suggest that trace elements are significantly more abundant during late cementation. We do not know the extent to which trace metals are complexed and transported into the reservoir by the oils or released by local dissolution of plagioclase within the reservoir. We are analyzing another suite of samples to answer these questions.

Thermodynamic calculations. Thermodynamic calculations of fluid–mineral equilibria in the San Joaquin Basin indicate varying degrees of correlation with petrographic observations. Using EQ3/6 (GEMBOCHS database), we calculated mineral equilibria for water analyses supplied by Fisher and Boles.⁵ The significance of these calculations is that they take into account the organic acid complexes in the waters. The major problem with the thermodynamic calculations is obtaining a reliable constraint on subsurface pH and aluminum and iron activity.

Albite, K-feldspar, and kaolinite are oversaturated, whereas anorthite is undersaturated, in accordance with petrographic observations. Acetate and propionate are in equilibrium. Both kaolinite and muscovite calculate as oversaturated, yet only kaolinite is observed as a significant diagenetic phase. Zeolites are up to an order of magnitude oversaturated but are not found in the intervals from which the waters were sampled. Carbonates (calcite, dolomite, siderite, and witherite) are generally slightly to significantly oversaturated, yet only calcite has been found as a late diagenetic carbonate.

1. Boles, J. R. (1991), "Plagioclase Dissolution Related to Oil Residence Time, North Coles Levee Field, California," *AAPG Bull.* **75**, 544 (abstract).
2. Merino, E. (1975), "Diagenesis in Tertiary Sandstones from Kettleman North Dome, California, I. Diagenetic Mineralogy," *J. Sed. Petrol.* **45**, 320.
3. Carothers, W. W., and Y. K. Kharaka (1978), "Aliphatic Acid Anions in Oil-Field Waters—Implications for Origin of Natural Gas," *AAPG Bull.* **62**, 2441.
4. MacGowan, D. B., and R. C. Surdam (1990), "Carboxylic Acid Anions in Formation Waters, San Joaquin Basin and Louisiana Gulf Coast, U.S.A.: Implications for Clastic Diagenesis," *Appl. Geochem.* **5**, 687.
5. Fisher, J. B., and J. R. Boles (1990), "Water–Rock Interaction in Tertiary Sandstones, San Joaquin Basin, California, U.S.A.: Diagenetic Controls on Water Composition," *Chem. Geol.* **82**, 83.
6. Surdam, R. C., S. W. Boese, and L. J. Crossey (1984), "The Chemistry of Secondary Porosity," in *Clastic Diagenesis*, D. A. McDonald and R. C. Surdam, Eds., *AAPG Memoir* **37**, p. 127.
7. Schultz, J. L., J. R. Boles, and G. R. Tilton (1989), "Tracking Calcium in the San Joaquin Basin, California: A Strontium Isotopic Study of Carbonate Cements at North Coles Levee," *Geochim. Cosmochim. Acta* **53**, 1991.

References

Diffusion Rates in High-Pressure Mantle Phases

Principal Investigator: Quentin Williams (UC Santa Cruz)

LLNL Collaborator: Frederick J. Ryerson

Students: Daniel Farber and Cliff Gill (UC Santa Cruz)

Abstract

We measured diffusion rates of divalent cations in Mg_2SiO_4 -olivine and its high-pressure polymorphs, β -phase, and γ -spinel at pressures between 2 and 14 GPa, and temperatures of 1200°C. These measurements represent the first characterization of diffusion rates in the phases presumed to predominate in the Earth's mantle at depths between 400 and 670 km. Our results document that the high-pressure phases of Mg_2SiO_4 have diffusion rates approximately three orders of magnitude faster than in the low-pressure olivine phase. This difference has major geophysical implications for the rates at which geochemical heterogeneities are homogenized in the deep Earth, as well as for possible changes in rheology and electrical conductivity as a function of depth within the planet.

Objectives

Knowledge of chemical transport properties is crucial for constraining several geophysical problems. First, such chemical diffusion rates are closely related to the rates at which minerals are able to flow via diffusional creep in the mantle of the Earth. Because solid-state creep is the mechanism by which the Earth's mantle convects, producing both plate motion and transporting heat from the Earth's deep interior to the surface, the rates at which diffusion occurs at high pressures are vital in determining whether the mantle at depth may flow significantly faster (or slower) than the mantle that directly underlies the plates.

Second, diffusion controls the time scale over which chemical heterogeneities are homogenized in the deep Earth. Specifically, subducted plates certainly induce geochemical heterogeneities in the mantle. These relatively long-lived heterogeneities, in turn, may influence the chemistry of a wide range of mantle-derived magmas (particularly those that produce ocean islands such as Hawaii and Iceland). Mantle convection acts to thin out such heterogeneities, but their ultimate erasure depends on diffusion rates. Despite the crucial importance of diffusion measurements at the relevant pressure and temperature conditions of the Earth's mantle, no studies have been conducted on diffusion rates in the high-pressure polymorphs of olivine, the most abundant mineral within the upper mantle. These phases, β -phase and γ -spinel, are stable between depths of 400 and 670 km within the planet. Accordingly, our studies address the question of how fast diffusion occurs within the phases presumed to predominate in the deep upper mantle of the planet.

Progress

We have conducted the first measurements of chemical diffusion rates in two of the three phases thought to be prevalent in the upper 670 km of the Earth: Mg_2SiO_4 in the β -phase structure and in the γ -spinel structure. These experiments required developments in experimental techniques (both producing and preserving on decompression the diffusional interfaces necessary to conduct these measurements) and in data analysis (analyzing diffusion profiles in a multiple-phase aggregate with moving phase boundaries).

Figure 1 shows representative results of our studies.¹ Contrary to simple density-oriented diffusion systematics, the high-pressure phases of Mg_2SiO_4 have diffusion rates that are two to four orders faster than the lower-pressure olivine phase. Thus, we anticipate that the deep upper mantle of the planet, between depths of 400 and 670 km, where β -phase and γ -spinel are the dominant phases, will probably erase chemical heterogeneities significantly faster than the shallow, olivine-dominated upper mantle. Thus, this region of the planet could effectively homogenize the anomalous geochemical signature associated with slabs on time scales at least a factor of 2 faster than the region above the 400-km depth.

Moreover, our results are consistent with a relatively large difference in transport properties occurring across the seismic discontinuity at the 400-km depth, where olivine converts to β -phase, while only a small difference is expected across 520 km (the transition from β -phase to γ -spinel). Our results are also relevant to the electrical conductivity properties of the deep upper mantle: Because cation diffusion is inferred to be the dominant mechanism of charge transport at these depths, we anticipate that the conductivity of the deep upper mantle will be two to four orders of magnitude higher than the shallower upper mantle. This observation is in general accord with inversions of the mantle conductivity profile and explains the apparently large increase in electrical conductivity with depth.

Figure 1. Diffusion coefficients as a function of pressure in the olivine, β -phase, and γ -spinel structures of Mg_2SiO_4 measured at 1200°C. The negative trends of diffusion coefficients as a function of pressure are produced by the activation volumes for diffusion in each of these phases.

1. Farber, D. L., Q. Williams, and F. J. Ryerson (1993), "First Measurements of Chemical Diffusion in High-Pressure Olivine Polymorphs: Implications for Deep Upper Mantle Transport Properties," *EOS Trans. Am. Geophys. Union* **74**, 610.

References

Cosmogenic Isotopes Applied to Development of Longitudinal Profiles in Bedrock

Principal Investigator: William E. Dietrich (UC Berkeley)

LLNL Collaborators: Marc W. Caffee, Robert C. Finkel, and G. Bryant Hudson

Student: Michele A. Seidl (UC Berkeley)

Abstract

We measured cosmogenically produced isotopes in olivine samples collected along the length of a Hawaiian river valley with a pronounced waterfall, or knickpoint. Surface-exposure ages calculated from the nuclide concentrations have implications for landscape evolution and surface-exposure age dating techniques. Exposure ages calculated for samples located downstream of the knickpoint are consistent with a wave of incision passing up valley; in contrast, samples collected above the knickpoint are consistent with steady-state erosion occurring above the feature. These data support the theory that knickpoint propagation is a primary incisional mechanism operating in bedrock valleys. Large boulders may remain in the valley for hundreds of thousands of years. The long residence time of the coarse material in the valley bottom also suggests that to incise the bedrock underlying the boulders necessitates propagation of a knickpoint under the boulder pile, in the absence of which the valley may continue to aggrade slowly for long time periods. Comparisons of ^{10}Be , ^{26}Al , ^{21}Ne , and ^3He concentrations measured in the Kauai olivine samples indicate that of the two radionuclides, ^{10}Be provides more accurate dates once the meteoric ^{10}Be has been removed. The olivine samples have abundant stable aluminum, which results in high $^{27}\text{Al}/^{26}\text{Al}$ ratios, making it harder to measure ^{26}Al . Of the two noble gases measured, ^{21}Ne appears to be retained in the olivine, whereas our data indicate ^3He may diffuse out of the olivine on the time scale of millions of years.

Objectives

Our goal was to date surface-exposure ages at selected sites along a river's longitudinal profile on Kauai, Hawaii, to test our theory regarding the process by which rivers carve into rock and to construct a theory that describes overall profile development. We hypothesized that analysis of selected samples would allow us to differentiate between the relative importance of two proposed incisional mechanisms: knickpoint retreat and abrasion of the channel bed by transported particles. This study was motivated by our theory that knickpoint retreat is a primary incisional process, important in carving river valleys into rock.¹ In the first year of the project, our scientific goals became broader as it became clear that several methodological issues needed to be addressed prior to data interpretation. Specifically, a protocol describing the extraction of ^{10}Be and ^{26}Al from olivine samples had to be developed, and meteoric ^{10}Be had to be removed from the surfaces of the olivine grains prior to measurement of in situ ^{10}Be . In addition, inconsistencies between the radionuclide and noble gas data were investigated in a final series of noble gas experiments conducted at LLNL.

Progress

Olivine samples collected from basalt flows on western Kauai were analyzed for ^{10}Be , ^{26}Al , ^3He , ^{21}Ne , and ^{36}Cl . The combination of radionuclide and noble gas data collected constitutes a unique data set that sheds light both on river profile development and methodological issues, including geochemical extraction techniques and nuclide retention.

Geomorphology. Both bedrock outcrops and large boulder surfaces were dated along Kaulaula Valley on Kauai. The former exposure ages provided information on the pattern of erosion, and the latter provided data on profile evolution and direct measurements of sediment residence time. The exposure dates indicate that surfaces generally decrease in age in the upstream direction and remain fairly constant above the knickpoint. When analyzed in concert with our understanding of long-term erosion rates in the basin, this pattern indicates steady-state erosion above the knickpoint and decidedly nonsteady-state erosion below the knickpoint. Such a pattern is consistent with knickpoint migration, and the nuclide data provide the first concrete evidence that large knickpoints may be extremely important in bedrock channel incision and drainage basin development.² As such, the exposure-age data are consistent with our theory of longitudinal profile evolution¹ and indicate that boulder-sized sediment can reside for hundreds of thousands of years in valleys. These data have additional implications for sediment transport and routing. Indeed, these are the first data of their kind and have important ramifications for overall valley development.

Geochemical extraction. Meteoric ^{10}Be was successfully leached from the olivine grain surfaces, and in situ ^{10}Be and ^{26}Al were successfully extracted and measured. In our FY 1992 progress report, we stated that a series of decanted leach experiments had solved this contamination problem. However, subsequent ^{10}Be measurements indicated that too much ^{10}Be remained relative to the ^{26}Al concentrations measured. We conducted an additional experiment in which rock aliquots, rather than decanted liquid, were analyzed for ^{10}Be and ^{26}Al after a series of etches. These results have already been put to use by other investigators.

Noble gas systematics. Preliminary ^3He and ^{21}Ne data, obtained in May 1992, did not agree with the ^{10}Be and ^{26}Al data generated in late 1992 and early 1993. Additional noble gas data were needed, and a final series of experiments was conducted in October 1993. Data from these experiments indicate that ^3He is not retained, relative to ^{10}Be and ^{26}Al concentrations, in olivine samples collected from the Kauai flows. This result has ramifications for the study of surface-exposure age dating and indicates a possible need for caution when analyzing ^3He exposure ages derived from rocks on the order of millions of years old. It is likely that the primary factor in this diffusion is the degree of weathering to which the olivine is subjected, not the absolute age of the rock. However, at this point, we can only measure the age of the rock; we cannot assess "weathering age."

In this project, we developed a greater understanding of how longitudinal profiles develop into bedrock. We also generated a method to measure ^{10}Be and ^{26}Al in olivine samples and determined that ^3He may not be a viable tool in exposure age dating studies when the rocks being analyzed are millions of years old.

1. Seidl, M. A., and W. E. Dietrich (1992), "The Problem of Channel Erosion into Bedrock," in *Functional Geomorphology Landform Analysis and Models, Catena Supplement*, K. H. Schmidt and J. de Ploey, Eds., vol. 23, p. 101.
2. Seidl, M. A., W. E. Dietrich, and J. W. Kirchner (1993), "Longitudinal Profile Development into Bedrock: An Analysis of Hawaiian Channels," *J. Geol.* (submitted).

References

Microbial Mediation of Glass Alteration: Rates and Mechanisms

Principal Investigators: A. A. Yayanos and H. Staudigel (UC San Diego)

LLNL Collaborator: William L. Bourcier

Other Collaborator: Roger A. Chastain (UC San Diego)

Abstract

We monitored the dissolution of a synthetic glass in seawater under sterile conditions and in the presence of both natural populations of microorganisms and cyanobacteria. The synthetic glass had a nominal composition of Na₂O (18.2%), CaO (6.0%), Al₂O₃ (11.7%), B₂O₃ (8.4%), and SiO₂ (55.7%). Pure cultures of bacteria that attach to glass were isolated, partially characterized, and cryopreserved for future study. We used scanning electron microscopy (SEM) and electron probe microanalysis (EPMA) to detect changes in the exposed glass surfaces. Visibly dramatic alteration was seen using SEM on glass surfaces that were incubated with and colonized by a filamentous cyanobacterium and by natural populations of microorganisms. The glass surfaces in flowing seawater developed elongated pits or channels about 0.4 μ m wide and often exceeding 50 μ m in length. Glass incubated in a culture of cyanobacteria developed a pitted and eroded texture.

It seems clear that the chemistry in the space between microorganisms and the glass to which they attach is particularly conducive to glass dissolution. These results confirm findings from another study using basaltic glass. EPMA also showed that surfaces colonized with cyanobacteria were the most altered. We found no dramatic changes on the glass surfaces incubated in sterile solutions either by SEM or EPMA.

Objectives

Current research on inorganic silicate dissolution is aimed at understanding the kinetics and mechanisms of dissolution.¹ Solids are submerged with fluids of varying composition for a given time and then analyzed for development of leached and altered layers, etch pits, and secondary phases. The surface changes are used along with solution data to develop a consistent dissolution model. Recent studies show examples in nature of bacteria occupying etch pits and porous (honeycombed) alteration layers on actively growing basaltic glass.² These bacteria may affect the glass dissolution rate by attaching to the glass surface and modifying the local environment, in particular by altering the pH, to promote breakdown of the glass structure and make available nutrients and metals (such as magnesium) for bacterial metabolism. Increasing the pH to 10, for example, increases the dissolution rate by more than an order of magnitude.³

Such processes must be better understood from the standpoints of nuclear waste glass alteration^{4,5} and natural glass dissolution.⁶ For example, microorganisms might be mobilizing elements in volcanic ash and thereby contributing to the high fertility of volcanic soils. Our objective was to carry out a series of first-order experiments to evaluate the effects of bacterial biofouling on glass in a marine environment.

Progress

We used a synthetic glass with a nominal composition of Na₂O (18.2%), CaO (6.0%), Al₂O₃ (11.7%), B₂O₃ (8.4%), and SiO₂ (55.7%). We polished the wafers of this glass with 600-grit polish. Some wafers were placed in an opaque, polyvinyl chloride (PVC) 5-cm-diam pipe set up as a flow-through chamber. Glass wafers were mounted in the chamber. Seawater was circulated through the chamber for more than one year.

Other wafers were incubated with a culture of cyanobacteria, and control incubations were set up using sterile seawater. The bacteria with an affinity for attaching to glass were isolated from a glass wafer in the PVC flow cell, characterized for their ability to attach to glass, biochemically characterized, and preserved at -70°C for possible future work.

Glass incubated in sterile seawater for 225 days was coated with gold and examined using SEM and EPMA. The glass surface appeared to have a fine deposit of an unidentified material. Glass that had not been exposed to seawater had a clean appearance with an occasional pit. EPMA of the glass surface incubated in sterile seawater showed a slight but consistent increase of 1 to 2% of SiO_2 . Because boron was not analyzed using EPMA, the possibility remained that the increase in SiO_2 could be due to a dissolution of boron. A glass wafer was similarly incubated for 128 days and then cleaned by sonication prior to analysis. This glass surface did not show any difference from the untreated glass by either SEM or EPMA.

Glass was incubated in a continuously flowing stream of seawater in the dark in a PVC pipe. The glass was cleaned by sonication and then analyzed using SEM and EPMA. SEM revealed extensive alteration, especially the appearance of channels about $0.4\text{ }\mu\text{m}$ wide, some of which were longer than $50\text{ }\mu\text{m}$. These channels were similar to the ones hypothesized by Thorseth et al. to be caused by cyanobacterial activity²; however, we did not determine if these channels formed in the flowing seawater system were caused by cyanobacterial activity. EPMA of the glass surface incubated in flowing seawater did not show the large change in the weight-percent composition of SiO_2 that was found on glass incubated with cyanobacteria.

Glass wafers were incubated in a culture of cyanobacteria for 126 days and under illumination. The glass was cleaned by sonication and then examined using SEM and EPMA. Pits and an eroded texture were the prevalent surface alteration. EPMA of the glass surface showed a systematic overall depletion of silicon and sodium.

Bacteria from a glass wafer in the flowing seawater system were sampled and put into pure culture. Several of the isolates were tested for their ability to attach to glass and were partially characterized physiologically. The isolates were then stored using a standard cryopreservation technique to allow future study.

Bacteria attaching to glass have a visible effect on glass structure and can produce changes in the chemical composition of glass. Experiments seeking to determine the effect of solution chemistry on glass alteration should be done under sterile conditions to eliminate possible confounding effects of biofouling microorganisms. Future studies of nuclear-waste glass alteration should include an evaluation of the role of microorganisms indigenous to the waste repository site. The role of surface-attaching microorganisms in the biogeochemistry of elements from natural basalt should be studied with more vigor.

1. Thorseth, I. H., H. Furnes, and M. Haldal (1992), "The Importance of Microbiological Activity in the Alteration of Natural Basaltic Glass," *Geochim. Cosmochim. Acta* **56**, 845.
2. Casey, W. H., and B. Bunker (1990), "Leaching of Mineral and Glass Surfaces During Dissolution," in *Mineral-Water Interface Geochemistry, Reviews in Mineralogy*, M. F. Hochella and A. F. White, Eds., vol. 23, p. 397.
3. Mazer, J. J. (1987), *Kinetics of Glass Dissolution as a Function of Temperature, Glass Composition, and Solution*, Ph.D. dissertation, Northwestern University, Evanston, IL.
4. Grambow (1990), "Status in Understanding and Modeling Radionuclide Release from High Level Waste Glass and Spent Fuel," in *Proc. Symp. on Safety Assessment of Radioactive Waste Repositories* (OECD, Paris, France), p. 439.

References

5. Grambow and Muller (1990), "Chemistry of Glass Corrosion in High Saline Brines," in *Scientific Basis for Nuclear Waste Management, XIII Symp. Materials Research Society*, V. M. Oversby and P. W. Brown, Eds. (Materials Research Society, Pittsburgh, PA), p. 229.
6. Staudigel, H., and S. R. Hart (1983), "Alteration of Basaltic Glass: Mechanisms and Significance for the Oceanic Crust-Seawater Budget" *Geochim. Cosmochim. Acta* **47**, 337.

Models for Long-Term Earthquake Correlations

Principal Investigators: David D. Jackson and Yan Kagan (UC Los Angeles)

LLNL Collaborator: John Rundle

Student: David Potter (UC Los Angeles)

Abstract

We studied the statistical properties of earthquake catalogs to investigate how the stress perturbations of past earthquakes affect the likelihood of future earthquakes. The information available in earthquake catalogs suggests the general type of models that should be used to describe seismicity: a stochastic, multidimensional, tensor-valued point process with the independent variables time, latitude, longitude, depth, scalar moment, strike, dip, and rake. The temporal correlations and size distributions of earthquakes are best described by power laws. We have found that the spatial distributions of earthquakes and the stress fields causing and resulting from earthquakes are also scale invariant. We considered procedures for testing models for earthquake prediction and forecasting. Generally, deterministic models, such as the seismic gap models, perform poorly compared to models that explicitly recognize the inherent randomness of earthquake occurrence.

Objectives

Clearly, earthquakes must be related to stress. They are caused when the stress exceeds the strength of rock, and they reduce the average shear stress on a ruptured fault plane. Yet aftershocks occur abundantly on or near the rupture surface, and occasionally larger earthquakes occur on or near the recently ruptured fault. Our goal was to study this enigma, primarily by describing quantitatively and precisely how earthquake occurrence depends on the time, location, size, and orientation of past earthquakes.

Progress

It has long been accepted that earthquake sizes obey a power law model. We have found that the relevant exponent appears to be a constant, independent of region, when earthquake size is described by scalar seismic moment. This fact does not impose strong constraints on models of earthquake occurrence: Percolation models, self-organized criticality models, and critical branching process models all predict this result. The spatial and temporal correlations among earthquakes obey power law models as well. Fault zones for shallow earthquakes cannot be described by one or a few planes; instead, they must be nonplanar and fractile.

The power law behavior of temporal clustering implies that earthquakes are more likely than average just following a previous earthquake, with a probability per unit time decreasing slightly with time. This behavior conflicts with the commonly assumed quasi-periodic behavior in which the probability per unit time is small following a previous earthquake and grows with time thereafter. We have tested a few published quasi-periodic models against available earthquake catalogs, and they fail to explain the data.

Our theoretical studies show that the stress distribution resulting from continued earthquake occurrence should have a symmetric stable distribution, and our empirical studies confirm this: The rotations of focal mechanisms, presumably caused by stress perturbations, behave according to the Cauchy distribution.

The fractile behavior of earthquake occurrence in time, space, and moment and the random behavior of earthquake stress orientations pose immense challenges for modeling earthquake sources. No simulation model yet proposed has the capacity to

reproduce the observed statistical properties in three dimensions for systems of realistic size. Unfortunately, the random properties of the stress field and, specifically, the evolution of the tensor stress field with time are probably necessary to understand the temporal behavior of earthquakes.

Global Positioning System Measurement of the White Wolf Fault, Greater Los Angeles Region

Principal Investigator: Louise H. Kellogg (UC Davis)

LLNL Collaborator: John B. Rundle

Other Collaborator: Andrea Donnellan (Jet Propulsion Laboratory)

Student: Gerald Bawden (UC Davis)

Abstract

Understanding the earthquake cycle is essential to assessing the seismic hazard of faults. It is essential to know, for instance, what motion takes place during the time period between earthquakes on seismogenic faults. Because earthquakes occur relatively infrequently and the rate of motion is small, the earthquake cycle is poorly understood. To date, motion throughout the complete cycle has not been recorded for a thrust fault. We used global positioning system (GPS) technology to measure deformation on the White Wolf Fault in southern California. This fault was responsible for the 1952 M7.2 Kern County earthquake. Extensive horizontal and vertical geodetic measurements performed before and soon after this earthquake indicate that the rate of strain was twice as high as the normal rate. By measuring the rate of strain for the past several decades, we may be able to assess whether the increased strain rate was a precursor to the 1952 earthquake. The White Wolf Fault is similar to locations now exhibiting high rates of strain in the greater Los Angeles area. A more complete understanding of the behavior of thrust faults in the Los Angeles region will help us better evaluate the seismic hazard on several faults in this heavily populated area.

Objectives

It has been suggested that the rate of strain on seismogenic faults increases shortly before an earthquake occurs, dropping to normal levels after the earthquake. If so, increased strain rate on seismogenic faults may be a diagnostic precursor to an earthquake. Alternatively, the rate of strain on some seismogenic faults may be high throughout the earthquake cycle. Our objective was to test these two models for the White Wolf Fault in southern California by measuring the rate of strain during the period between earthquakes.

The White Wolf Fault, approximately 120 km north-northwest of Los Angeles, was responsible for the 1952 M7.2 Kern County earthquake. In 1981, Stein and Thatcher used extensive leveling and triangulation networks to estimate the temporally and spatially varying pattern of strain surrounding the Kern County earthquake.¹ For 0.2 to 20 y prior to the earthquake, the horizontal shear strain rate near the fault, as evidenced by both the vertical and horizontal data, was 0.7 ± 0.1 mrad/y, twice the ambient strain of the region (0.35 ± 0.1 mrad/y). For the decade following the earthquake, the strain rate $\dot{\epsilon}$ was about 0.7 mrad/y for the entire region.

Our goal was to use GPS technology to resurvey the network of monuments used by Stein and Thatcher so we could measure the rate of deformation along the White Wolf Fault in the three decades since the last measurements were taken. By resolving ambiguities and taking advantage of a well-defined fiducial network, we determined the relative positions of monuments to a few millimeters for short baselines (less than 50 km). Comparing these results with historical observations enables us to obtain results after a single occupation.

Progress

Our study had five phases: (1) reconnaissance of the sites, (2) GPS occupation of the sites, (3) processing and interpretation of the data, (4) modeling the deformation, and (5) publication of the results. We undertook reconnaissance of the sites in the spring of 1993 using descriptions of the network sites from the Southern California Earthquake Center. Several of the monuments had been destroyed or buried, but a sufficient number were located and determined to be in good condition. Figure 1 shows the locations of the monuments.

We originally scheduled the GPS observation for March 1993, but late rainstorms in southern California caused us to postpone the survey until July during the dry season. Four GPS receivers, along with technical support for troubleshooting during the occupation, were provided by Jet Propulsion Laboratory. The GPS receivers proved to be very robust in the field.

Data processing is nearly complete using a network of workstations at UC Davis with GIPSY software developed at Jet Propulsion Laboratory. This software, along with user training and technical support, was provided at no charge by Jet Propulsion Laboratory. We are currently comparing the results of the occupation to historical data.

Figure 1. Location of the White Wolf Fault, southern California, and occupation network used. Symbols denote the network of monuments used by Stein and Thatcher in 1981. Triangles denote sites that were located and used in the 1993 GPS survey conducted for this experiment. Squares denote monument sites used by Stein and Thatcher but found to have been damaged, destroyed, or buried since. Diamonds denote sites not used during the 1993 occupation.

References

1. Stein, R.S., and W. Thatcher (1981), "Seismic and Aseismic Deformation Associated with the 1952 Kern County, California, Earthquake and Relationship to the Quaternary History of the White Wolf Fault," *J. Geophys. Res.* **86**, 4913.

Regional and Near-Receiver Velocity Structure and Broadband Waveforms in Southern California: Teleseisms and Regional Nuclear Explosions

Principal Investigator: Jean B. Minster (UC San Diego)

LLNL Collaborator: George Zandt

Student: G. Eli Baker (UC San Diego)

Abstract

We are completing a study of near-receiver structure at Piñon Flat Observatory (PFO) using teleseismic body waves, the results of which have implications for tectonic studies beyond the region sampled. Particularly, Moho topography and uppermost mantle structure bear on the nature of compensation for the topographic relief about PFO. To further both our understanding of regional southern California tectonics and the relation between velocity structure and broadband waveforms, we have expanded our studies to include the modeling of broadband regional nuclear-explosion waveforms recorded at PFO and other regional stations.

Objectives

Our objective is to better understand the relation of broadband seismic waveforms and the velocity structure through which they propagate. A complementary goal is to achieve a greater understanding of southern California tectonics. Using Nevada Test Site (NTS) events in our regional study, which provide us with well-constrained source locations and mechanisms, gives us the opportunity to pursue another objective, namely investigating the nature of nuclear-explosion Pn waveforms for use in discrimination.

Progress

Near-receiver structure at PFO. Differences between Moho topography inferred from seismic results and that inferred from the gravity modeling suggest variations in the crustal strength beneath the San Jacinto Mountains and the Salton Trough. More spatially extensive investigations such as may be provided by a regional propagation study, which is discussed below, are now being pursued. Such a study may also provide an independent check on uppermost mantle discontinuities inferred from velocity spectrum stacks (VSS) of receiver functions at PFO.

Previous work. Two important regional seismic phases are (1) the P wave (Pn) that propagates through the uppermost mantle and (2) the P wave (Pg) that propagates through the crust. In a study to assess the utility of regional broadband Pn for discrimination of nuclear explosions, significant variation of the Pn/Pg amplitude ratio south of NTS was interpreted as evidence of a rapid velocity increase or discontinuity within the mantle lid (the region of the mantle just below the crust and above the mantle low-velocity zone).¹ Our research tests work done studying propagation at NTS and extends it to southern California.

Data. We have collected three-component seismograms of nuclear explosions from NTS recorded at three broadband stations in southern California: Landers (LAC), Pasadena (PAS), and PFO. For the nuclear explosions, source parameters are well constrained. That and the range of distances available from the source distribution enable us to observe the development of phases with distance. Furthermore, because the sources are all similar, we may attribute many of the differences we see between different events recorded at a single station to structure along the propagation path. We have, therefore, an opportunity to test the hypothesis of a travel-time triplication due to upper-mantle structure.¹

We also have recordings of three of the explosions from a temporary 28-station, broadband, three-component array located at PFO, which enable us to distinguish the direction of arrival and wave type of various phases using both array and three-component analysis techniques. This ability complements our modeling of the broadband source-array records by corroborating our interpretations of phases.

Results. Variations in amplitude, timing, and frequency content of Pn and Pg waveforms are observed for the same events recorded at different stations, as well as for different (but similar) events recorded at the same station. Variations are illustrated in record sections made up of different events at each station (Figure 1). We plotted two-sided envelope functions (excluding some records for clarity) for the first 15 s of each event. Note that the distance scales are not equal.

Figure 1. Envelope record sections for NTS events recorded at (a) LAC, (b) PAS, and (c) PFO. Note: Horizontal scale varies.

The zero line is at the first arrival. The second line, moving out with distance, is the predicted arrival time of the P wave that reflects off the base of the crust (PmP).² Figure 1 illustrates several important differences between the records at different distances and stations. The small initial peak at PFO contrasts with the large one at PAS. This could be interpreted as supportive of the triplication hypothesis, where PAS is at the distance of intersection of two phases and so has a large initial peak. Then at the slightly greater distance of PFO, the phases separate. Some lateral variation is indicated, however, at least in the depth of the discontinuity or gradient, as the relative amplitude variation is sustained throughout the distances for which PAS and PFO overlap. The crustal phases also vary significantly from station to station. The PmP phase arrives precisely at the predicted time at LAC; however, it is approximately 3 s early at PAS. At PFO, the PmP phase is indiscernible.

Synthetic seismogram modeling. We are using the generalized ray code of Helmberger³ and the frequency wave-number code of Saikia and Burdick.⁴ The advantage of generalized ray synthetics is the insight gained regarding the phases that make up various portions of a seismogram. The trade-off is that ray paths must be specified, making complete solutions impractical to obtain for any but the simplest structures. Frequency wave-number synthetics, however, include all phases for a complete solution, although with this technique we cannot tell which path the propagating energy has traversed. From preliminary modeling, it is apparent that no simple one-dimensional model will provide a match to the waveforms at or near 1 Hz of energy. Observed variation in Pn waveforms may indicate lateral variation or complicated one-dimensional structure in the upper mantle. These will be critical phases to understand and will be the target of further study.

Future work. The observed variation with distance of both Pn/Pg ratios and Pn waveforms is suggestive of lateral variations in the crust and upper-mantle structure of southern California. More detailed modeling of the Pn waveforms should be performed to distinguish triplication phases, low-velocity-zone reflected phases, or other path effects from depth phases. This should be complemented by array and three-component analyses, both to distinguish the previously mentioned phases and separate out multipathing and near-receiver scattering effects. Comparison of earthquake waveforms and nuclear-explosion waveforms having similar propagation paths will also be important for distinguishing near-source scattering from path effects.

1. Burdick, L. J., C. K. Saikia, and N. F. Smith (1991), "Explosion Source Phenomenology," *Geophys. Monogr. Series, Am. Geophys. Union* **65**, 197.
2. Helmberger, D. V., and G. R. Engen (1980), *Bull. Seismol. Soc. Am.* **70**, 1699.
3. Helmberger, D. V. (1983), "Enrico Fermi," in *Proc. Int. School Phys. Course, LXXXV, Earthquakes: Observation, Theory, and Interpretation*, H. Kanamori and E. Boschi, Eds. (North Holland Publishing Co.).
4. Saikia, C. K., and L. J. Burdick (1993), Phillips Laboratory Science Report, WCCP-R-93-01.

References

Study of Crust and Upper-Mantle Attenuation in Central and Northern California

Principal Investigator: Barbara A. Romanowicz (UC Berkeley)

LLNL Collaborator: Kevin Mayeda

Other Collaborators: Susanna Loper and Lind Gee (UC Berkeley)

Student: Ted Bohn (UC Berkeley)

Abstract

We tested the applicability of a new method to estimate earthquake magnitudes using data from the Berkeley Broadband Digital Seismic Network. The method is based on the amplitude of the envelope of scattered seismic waves (coda) arriving after the main body-wave phases sent via P and S waves. The advantage of the technique is that coda waves are much less dependent on the details of the earthquake source and path effects. Work has been completed on finding the correct parameters for the methodology for this data set. Initial results are promising that stable coda-magnitude estimates can be established for northern and central California.

Objectives

Our goal was to test Mayeda's method for estimating magnitude from coda amplitudes.¹ This method was originally developed and tested using regionally recorded nuclear explosions from the Nevada Test Site. Our objective is to explore the application of this method to regional earthquakes in California.

Progress

We collected a data set of more than 100 events in northern and central California, recorded by the Berkeley Broadband Digital Seismic Network between September 1991 and March 1993. Each event was recorded at two to eight stations from our network. As the first step in applying Mayeda's methods to these data, we visually examined the data to sort out recordings with sufficient signal-to-noise ratio. The resulting data set contained 167 three-component recordings, representing approximately 60 events.

The data were processed by band-passing at different test frequencies and generating a smooth envelope of energy density as a function of lapse time; then five different energy windows were computed and normalized to a reference energy level. Figure 1 shows an example of these energy windows, for 25-s windows of data band-passed from 1 to 2 Hz.

We tested a range of filtering and windowing parameters and compared the data to synthetic-energy envelopes generated with different values for albedo and mean-free paths (parameters to characterize a randomly heterogenic medium), attempting to find the best fits to the data. With the preliminary synthetics, we estimated magnitudes from the data and compared magnitudes estimated using different stations.

Mayeda was able to use the same filtering corners and time window lengths for all events in his Nevada study, but we found that with the wide range of event sizes and locations in our data set, we needed to vary frequency band and time window length as a function of source-receiver distance. (For example, for a small nearby event, the fourth or fifth 20-s time window might be well into the noise, while for a larger distant event, using five 20-s energy windows may not sample a long enough

portion of the coda.) This procedure could be automated and incorporated into the magnitude calculation, and the initial comparisons of magnitude estimates suggest that the stable coda magnitude estimates Mayeda found in his Nevada study could also be achieved for northern and central California earthquakes.

Figure 1. Hypocentral distance vs normalized energy for a collection of northern and central California earthquakes recorded by the Berkeley Broadband Digital Seismic Network. The data were bandpass-filtered from 1 to 2 Hz, and the average energy was calculated for five 25-s windows and normalized to a reference energy 100 s after the Lg arrival.

1. Mayeda, K. (1993), "Mb (LgCoda): A Stable Single Station Estimator of Magnitude," *Bull. Seismol. Soc. Am.* **83**, 851.

References

Shear-Wave Velocity Structure beneath Central California from Surface-Wave Dispersion

Principal Investigator: Jiajun Zhang (UC Santa Cruz)
LLNL Collaborator: William R. Walter

Abstract

We developed a new method of polarization analysis to reduce errors in determining dispersion characteristics of surface waves propagating along central California. We applied this method to Rayleigh and Love waves with periods between 20 and 150 s from a large earthquake south of Alaska that lies on the great circle path connecting the Terrascope station in Pasadena, California (PAS) with the Mount Hamilton station (MHC) at UC Berkeley; this path is in the vicinity of the San Andreas Fault System (SAFS). Results indicate that Rayleigh waves are strongly affected by low-velocity anomalies associated with the SAFS beneath central California, with ray paths bending eastward as waves traveling to the south. Love waves suffer much less deviation.

Objectives

Our goal was to use broadband surface-wave dispersion analysis to study Earth structure and anisotropy in California, specifically to improve our understanding of processes associated with the evolution of the Pacific–North American plate boundary. Surface wave velocities strongly correlate with the age of the oceanic lithosphere and asthenosphere, with velocities for a young ocean being significantly reduced. The methods currently used in surface-wave dispersion analysis are applicable to regions with smooth velocity variations but are inadequate for regions encompassing strong lateral heterogeneities. The crust and upper mantle beneath California is highly heterogeneous because it encompasses the active SAFS. Our objective is to develop new techniques for analyzing dispersion characteristics of waves propagating in laterally heterogeneous media. These techniques include a polarization analysis method and a high-resolution, two-station method of dispersion analysis.

Progress

Pure-state analysis. We developed a new technique for polarization analysis using formulas developed in time-series analysis for pure-state signals.¹ The polarization parameters calculated using this analytical method are consistent with and more reliable than several methods currently used in seismic data analysis in which numerical techniques are often used to solve an eigenvalue problem.²

Recent advances in understanding the effects of the laterally heterogeneous and anisotropic structure of the Earth on seismic-wave propagation have resulted in renewed attention to the polarization pattern of the particle motion trajectory, which is obtained from three-component displacement seismograms. In the laterally homogeneous structure, the particle motion of principal wave types (i.e., P, S, Rayleigh, and Love waves) are linearly or elliptically polarized. The effects of the heterogeneous structure involve interferences of direct, refracted, reflected, and scattered body and surface waves, which are characterized by unstable polarization patterns in both the time and frequency domains.

In the time-domain analysis, the time dependence of the polarization states is determined, which is useful for isolating waves with various group velocities. In this analysis, the observed polarization patterns are compared with those for

principal wave types (i.e., P, S, Rayleigh, and Love waves), which are linearly polarized for incident P, SH, and Love waves and elliptically polarized for incident SV and Rayleigh waves in the laterally homogeneous structure.

The nature of the seismic recording is usually much more complex than a pure-state process, defined by Samson¹ as an event that is followed by subsequent phases resulting in the shape and orientation of the ellipse varying with time and only for a short time interval the recorded motion is in the pure state. However, the formulas given by Samson for the pure-state process are useful for determining instantaneous ellipticity and polarization orientation of the ground motion for any given time. The polarization parameters calculated using these formulas are consistent with Vidale, in which the eigenvalue problem of a correlation matrix is solved and a numerical method is used to search for the direction of polarization.²

Our method of the pure-state polarization analysis has several advantages. First, it is evident that all polarization parameters are calculated analytically without solving eigenvalue problems and step-wise searching for appropriate parameters. Second, our method is particularly useful for determining the polarization characteristics of ground motion caused by waves with different group velocities. The transition between different polarization states can be well identified.

Polarization characteristics of surface-wave propagation in central

California. Figure 1 shows the polarization state vectors and incident azimuths of Rayleigh and Love waves at southern California station PAS. Here, r_{ij} denotes the j th component of the state vector r_i with the transverse, radial, and vertical components corresponding to indices j_1, j_2 , and j_3 , respectively; state vectors r_1 and r_2 are the major and minor axes of the polarization ellipse; and r_3 is their cross product.

Figure 1. (a) Polarization state vectors of ground displacements (filtered with the cutoff period of 20 s) obtained using seismograms (long-period channel) recorded at southern California station PAS from the September 4, 1989, South of Alaska earthquake. The units for various state vectors are $102 \mu\text{m}$ for r_{11} , r_{12} , and r_{13} and r_{21} , r_{22} , and r_{23} and $104 \mu\text{m}$ for r_{31} , r_{32} , and r_{33} . (b) Incident azimuths and corresponding instantaneous periods of surface waves at PAS. Azimuths are measured from a great circle (GC) and determined for Rayleigh waves (circles) and Love waves (squares) using state vectors of ground displacements; azimuths obtained using state vectors corrected for mode contamination are also shown for Rayleigh waves (solid line) and Love waves (dashed line).

These state vectors are determined from ground displacements using broadband seismograms and filtered with 20-s cutoff periods (Figure 1a). The Rayleigh wave arrival corresponds to the suddenly increased amplification of the major state vector r_1 on the vertical component and the minor state vector r_2 on all components. The minor axis r_2 for Rayleigh waves has a large component on the transverse direction, which corresponds to large values in r_{32} . This indicates that Rayleigh waves arrive in a direction significantly different from the great circle direction.

We determined incident azimuths of Rayleigh and Love waves as a function of instantaneous periods (Figure 1b). Mode contaminations are corrected with synthetic seismograms computed for the laterally homogeneous Earth model PREM using the procedure of normal mode summation of Gilbert and Dziewonski.³ For both Rayleigh and Love waves with periods between 20 and 150 s, the errors for the azimuths are generally less than 10 deg.

Data from the central California station MHC were also analyzed. For Rayleigh waves with a period of 20 s, the incident azimuth is about 15 deg less than the great circle azimuth at MHC and about 25 deg at PAS. Our results indicate that Rayleigh waves are strongly affected by low-velocity anomalies associated with the SAFS beneath central California, with ray paths bending eastward as waves travel to the south, while Love waves suffer much less deviation, adding observables to constrain the depth extent of the anomalies.

References

1. Samson, J. C. (1983), "Pure States, Polarized Waves, and Principal Components in the Spectra of Multiple, Geophysical Time-Series," *Geophys. J. R. Astron. Soc.* **72**, 647.
2. Vidale, J. E. (1986), "Complex Polarization Analysis of Particle Motion," *Bull. Seismol. Soc. Am.* **76**, 1393.
3. Gilbert, F., and A. M. Dziewonski (1975), "An Application of Normal Mode Theory to the Retrieval of Structure Parameters and Source Mechanisms from Seismic Spectra," *Philos. Trans. R. Soc. London, Ser. A.* **278**, 187.

Subsurface Crustal Imaging Using Seismic, Gravity, and Attenuation Data

Principal Investigator: Craig Nicholson (UC Santa Barbara)

LLNL Collaborator: Jay Zucca

Other Collaborator: Jonathan M. Lees (Yale University)

Abstract

We developed images of subsurface crustal structure in three dimensions (3D) using high-resolution tomographic inversion techniques and interactive computer color-graphic displays. Data examined included the 1986 and 1992 earthquake sequences in southern California. Joint tomographic inversions using both seismic and gravity data reveal significant correlations between velocity perturbations in 3D and rupture properties of recent major earthquakes. Large earthquakes tend to nucleate at or near regions of relatively high velocity and terminate in regions of low velocity. The strong correlation between earthquake rupture properties and subsurface velocity variations suggests that high-resolution 3D tomography may be a more effective means of mapping active fault segments at seismogenic depths than geologic mapping of the near-surface fault traces.

Objectives

Our objective was to use travel-time, spectral amplitude, and first-motion information from local microearthquakes to resolve detailed aspects of 3D velocity, attenuation, and subsurface fault structure. We can then use the 3D structure models to infer specific variations in subsurface material properties and patterns of active seismic strain.

Progress

The three major earthquakes that occurred during 1992 in southern California (magnitude M6.2 Joshua Tree, M7.4 Landers, and M6.5 Big Bear events) provided a unique seismic travel-time data set of unprecedented quality and quantity. We refocused our efforts to take advantage of this opportunity to investigate velocity and attenuation structures on a more regional scale.

Our first step was to perform a linear tomographic inversion of P-wave arrival times from the recent 1992 earthquakes to produce 3D images of subsurface velocity.^{1,2} The 1992 data set, augmented by arrival times from the 1986 M5.9 North Palm Springs sequence, consisted of 6458 high-quality events that ultimately provided 76,306 ray paths for inversion. The events were relocated relative to a standard one-dimensional (1D) model used in previous inversions at North Palm Springs.³ Station corrections were determined iteratively by manual inspection and relocation.

The target area consisted of a $104 \times 104 \times 32$ -km³ volume divided into $52 \times 52 \times 10$ -km³ rectilinear blocks. We applied Laplacian regularization, and the residual root-mean-square misfit was reduced by about 40%. We observed significant velocity perturbations that correlate with rupture properties of the recent major earthquakes. Our preliminary results indicate that a low-velocity anomaly separates the dynamic rupture of the M6.5 Big Bear event from the M7.4 Landers main shock; a similar low-velocity region along the Pinto Mountain Fault separates the M6.1 Joshua Tree sequence from the Landers rupture. In addition, high-velocity anomalies were observed at or near the nucleation sites of all four recent main shocks (North Palm Springs, Joshua Tree, Landers, and Big Bear). A high-velocity

anomaly is also present along the San Andreas Fault between 5- and 12-km depth through San Geronimo Pass. This high-velocity region may define an asperity where stress is currently concentrated and may represent a site of future dynamic rupture nucleation.

To test model reliability, we performed a joint inversion using both seismic and gravity data.² We can use gravity data by assuming a linear relation between density and velocity perturbations. Gravity may be important to resolving subsurface structure in this area because the M7.4 Landers earthquake follows a strong gradient in the local gravitational field. Gravity also helps constrain near-surface regions of the velocity model where incident rays are nearly vertical and seismic resolution is poor. The joint 3D model was required to fit both seismic data and isostatic gravity anomalies to a specified degree of misfit. The resulting joint tomographic inversion in which 40% of seismic data residual misfit and about 80% of the gravity anomalies are explained does not differ significantly from the previous 3D velocity models.

Once a preliminary velocity model was available, we analyzed aftershock recordings of the M6.2 Joshua Tree earthquake using tomographic methods to determine 3D variations of seismic attenuation or Q (Ref. 4). To evaluate the attenuation, the parameter t^* was used; t^* is the integral of $1/Qv$ along the travel path, where Q is the quality factor, and v is the velocity. The parameter t^* is determined from the Fourier amplitude spectra of the aftershock recordings by nonlinear least-squares best fits assuming an ω^2 -source model.⁵ To date, approximately 2500 P-wave t^* values were determined from the data set. The inversion for Q from the t^* values is computed using the previously derived 3D velocity model. Variations of Q may help us identify regional crustal structure and understand properties of the fault zone, such as pore-fluid pressure. In addition, several studies have found high-velocity anomalies near earthquake nucleation zones and low-velocity anomalies near termination zones.¹ For example, in the Loma Prieta region, there is a high Q_p/Q_s ratio in the vicinity of the main shock at depths where elevated velocities are observed.⁶ Attenuation anomalies may help determine the causes of these velocity anomalies and their relation to earthquake rupture dynamics.

References

1. Nicholson, C., and J. M. Lee (1992), "3D Tomographic Velocity Inversion of the 1992 Landers–Big Bear–Joshua Tree Sequence, Southern California," *EOS Trans. Am. Geophys. Union* **73**, 394.
2. Lees, J. M., and C. Nicholson (1993), "3D Tomography of the 1992 Southern California Sequence: Constraints on Dynamic Earthquake Rupture?" *Geology* **21**, 387.
3. Nicholson, C., and J. M. Lee (1992), "Travel-Time Tomography in the Northern Coachella Valley Using Aftershocks of the 1986 M_L 5.9 North Palm Springs Earthquake," *Geophys. Res. Lett.* **19**, 1.
4. Lees, J. M., and G. T. Lindley (in press), "3D Attenuation Tomography from Digital Recordings of Aftershocks of the 23 April 1992, Joshua Tree, California Earthquake," *EOS Trans. Am. Geophys. Union* **74**.
5. Lindley, G. T., and R. J. Archuleta (1992), "Earthquake Source Parameters and the Frequency Dependence of Attenuation at Coalinga, Mammoth Lakes, and the Santa Cruz Mountains, California," *J. Geophys. Res.* **97**, 14137.
6. Lees, J. M., and G. T. Lindley (1993), "3D Attenuation Tomography at Loma Prieta: Inversion of t^* for Q ," *J. Geophys. Res.* **98** (submitted).

The Inversion of Surface-Wave Phase-Velocity Measurements for Lithospheric Structure beneath the Western United States

Principal Investigator: Charles J. Ammon (UC Santa Cruz)

LLNL Collaborator: Howard Patton

Abstract

We have inverted an expanded seismic surface-wave phase-velocity data set for lateral variations in phase velocity beneath the western United States. Data coverage is good for both Love and Rayleigh waves between 10 and 50 s. For the nonlinear tomographic inversion, we incorporate geologic smoothness constraints and show that the data are for the most part consistent with a correlation in velocity within tectonic provinces. Within the largest tectonic province sampled, the Basin and Range, the data require lateral variations in shear velocity between the north-western, northeastern, and central regions.

Objectives

Using Rayleigh- and Love-wave phase-delay measurements from approximately 60 western U.S. earthquakes, we estimated the lateral phase-velocity structure of the region to a resolution on the order of 100 km. Surface-wave phase-velocity maps are useful for investigation of first-order geologic variations throughout the western United States and for direct application in near-real-time modeling of moderate-size earthquakes that occur within the region.

Progress

We have expanded a seismic surface-wave phase-velocity data set and estimated the lateral variations in phase velocity beneath the western United States. The expanded data contain more than double the previously available Love-wave measurements. In all, we have processed about 175 to 200 Rayleigh- and Love-wave paths and incorporated them into a nonlinear tomographic inversion for the lateral variations in phase velocity between the periods of 10 and 50 s.

The inversion technique has been modified to incorporate geologic smoothness constraints. This approach is a compromise between an unconstrained inversion and a rigid regionalized inversion approach. Velocities within each tectonic province are required to correlate over a specified distance (a few hundred kilometers), but velocities across tectonic boundaries are uncorrelated. With this a priori information incorporated in the inversion, the resulting model contains heterogeneities across tectonic boundaries that are directly constrained by the observations but are not simply a result of inadequate or anisotropic data coverage.

Figure 1 shows the results of a Rayleigh-wave inversion with strict province constraints (constant velocity in each province). Several interesting features are apparent. In particular, the southern Basin and Range is very fast, and the central Basin and Range is relatively slow at the longer periods, indicative of a slow region in the uppermost mantle. In general, structural differences between the northern, central, and southern Basin and Range are significant and indicative of different crustal and uppermost mantle structure in these regions.

Determination of Three-Dimensional Velocity Variations in the Crust and Upper Mantle beneath Costa Rica

Principal Investigator: Susan Y. Schwartz (UC Santa Cruz)

LLNL Collaborator: George Zandt

Student: Marino Protti (UC Santa Cruz)

Abstract

Subduction of the Cocos Plate beneath the Caribbean Plate along the Middle America Trench has produced an active volcanic chain and basaltic lava flows of late Tertiary age in northern and central Costa Rica and a trench-parallel elongated batholith in the south (Talamanca Cordillera). We have imaged the resulting complex crustal and upper mantle structure using P-wave arrival times from locally recorded earthquakes. Thurber's iterative inversion method is used to simultaneously determine velocities along a three-dimensional (3D) grid and hypocentral parameters of local earthquakes.¹ Our data consist of more than 12,000 arrival times from 1300 earthquakes recorded by stations of the permanent seismographic network in Costa Rica. We imaged low-velocity anomalies in the shallow crust beneath the active volcanoes that persist through to the lower crust (about 25 km), indicating the possible presence of deep magma reservoirs. The greatest Moho depths are found in these regions of deep low velocities. High-velocity anomalies are associated with the subducting Cocos Plate under Costa Rica, the Talamanca batholith, and basic Tertiary volcanic units.

Objectives

Our objective was to develop a 3D model of the P-wave velocity structure in the crust and upper mantle beneath Costa Rica. Images of the 3D velocity structure will improve determination of earthquake locations and focal mechanisms, helping us to understand the processes producing large earthquakes and the tectonics in Costa Rica and allowing us to address fundamental questions about magmatic processes.

Progress

We have used travel times of local earthquakes recorded at 46 stations in Costa Rica's permanent seismographic network to obtain the P-wave velocity structure in the crust and upper mantle beneath central Costa Rica. Costa Rica is located on the western margin of the Caribbean Plate, where the Cocos Plate subducts under the Middle American Trench, producing the Central American volcanic chain (Figure 1) and the Talamanca Cordillera, a batholith of intermediate composition.

We have used more than 12,000 travel times from 1300 local earthquakes to simultaneously invert for velocity at the nodes of a 3D grid and hypocentral parameters using the linearized inversion technique of Thurber.¹ We selected events based on their spatial distribution, number of arrivals, and network coverage; only events shallower than 70 km were used.

Prior to the simultaneous inversion, all events were relocated using hypoinverse and a one-dimensional velocity structure derived from combining several available models. We used this one-dimensional model as our starting model and performed the inversion using both a coarse (horizontal and vertical node spacing of 40 and 10 km, respectively) and a fine grid (horizontal and vertical node spacing of 20 and 10 km, respectively). Figure 1 shows the area of the coarse grid; both grids

had a maximum vertical dimension of 50 km. We performed the inversion procedure many times with different values of damping and chose the value that resulted in low model and data variance, high resolution, and a low standard error after convergence.

Analysis of one horizontal cut through our resulting velocity model at a depth of 30 km and two vertical cuts—one along the southwestern boundary of the grid and the other about 100 km from the northwestern boundary at the approximate location of the dashed line in Figure 1—display a number of interesting features. One feature apparent in these velocity sections is high velocities associated with subduction of the Cocos Plate seen in the long vertical cut paralleling the Middle American Trench. The disappearance of this anomaly to the southeast does not indicate cessation of subduction but corresponds to a large decrease in our model resolution.

High velocities are also apparent at the 30-km depth in the southeast corner of the grid, corresponding to the large Talamanca Cordillera intrusive complex. Low velocities are prominent in the shallow crust beneath all of the active volcanoes (Figure 1), and these low velocities persist to depths of at least 30 km below the southernmost group of active volcanoes, suggesting the presence of some deeper magma reservoirs. Our preliminary velocity images correlate well with published gravity maps for Costa Rica. Areas where we have imaged low velocities correspond to negative-gravity anomalies, and high velocities correspond to positive-gravity anomalies. Our future work involves refinement and interpretation of these preliminary velocity images.

Figure 1. Tectonic map of Costa Rica showing active volcanoes (black triangles) and slab contours in intervals of 10 km. The box indicates dimensions of the coarse grid used in the velocity inversion.

References

1. Thurber, C. H. (1983), "Earthquake Locations and Three-Dimensional Crustal Structure in the Coyote Lake Area, Central California," *J. Geophys. Res.* **88**, 8226.

High-Pressure Synthesis and Deformation of Alkali Halides

Principal Investigator: Jeff Wolfenstine (UC Irvine)

LLNL Collaborator: Mark Beeman

Students: Hiep Duong, Tom Wu, and Frank Shih (UC Irvine)

Abstract

We compared the creep behavior and dislocation substructure of polycrystalline KCl-RbCl and KCl-KBr solid-solution alloys to that exhibited by single-crystalline, solid-solution alloys of similar composition. Dense polycrystalline samples with grain sizes from 100 to 300 μm were prepared by hot-pressing spray-dried powders. The creep behavior of the polycrystalline pure components and alloys in both systems, KCl-RbCl and KCl-KBr, was similar to that exhibited by the pure and alloy single crystals in terms of the type of primary creep curve, stress dependence of the steady-state creep rate, activation energy for creep, creep transient after a stress reduction, relative creep between the alloys and pure components, and the dislocation substructure. The results suggest that the creep behavior of the coarse-grained alloys is governed by the same mechanism that controls the creep rate of the single crystals: a viscous dislocation glide process. The only difference between the coarse-grained and single-crystalline samples was in the length of the primary creep stage. The primary creep stage of the polycrystalline samples for both the pure components and alloys was reduced compared with that observed in the pure and alloy single crystals. In both the polycrystalline and single-crystal alloy samples, the dislocation substructure consisted of well-defined subgrains whose size varied inversely with stress.

Objectives

Naturally occurring rock salt and synthetic alkali halides have been extensively studied for both scientific and engineering reasons. Rock salt is of interest because of its relationship to oil-bearing rocks and its potential use as a waste-storage medium and a structural support in salt mines. Synthetic alkali halides have been studied because of their relatively simple ionic structure and the ease of producing high-purity single crystals and optical properties. Also, the same deformation mechanisms that operate in alkali halides also operate in more technologically important ceramics. Because alkali halides have relatively low melting points, many of the experimental problems associated with high-temperature testing of ceramics are avoided. One area that has received little attention is concerned with the creep behavior of alkali halide solid-solution alloys.

Our previous research on single crystalline KCl-RbCl and KCl-KBr solid-solution alloys, which exhibit complete solid solubility over the entire composition range, has shown the following:

- The primary creep stage is smaller than that for the pure components, and the stress exponent is close to 3. Also, the creep transient after a stress reduction for the alkali halide solid-solution alloys is in good agreement with creep behavior observed in class I metallic solid-solution alloys, where the creep rate is controlled by a viscous dislocation glide process.

- The creep resistance of the alloys is higher than that for the pure components at the same value of homologous or absolute temperature. The homologous temperature is the relative fraction of the actual temperature to the melting temperature.
- The dislocation substructure of the solid-solution alloys after deformation consisted of well-developed subgrains at large strains.

Our goal was to synthesize coarse-grained polycrystalline KCl-RbCl and KCl-KBr solid-solution alloys and compare their creep behavior and dislocation substructure to that exhibited by the single-crystalline samples.

Progress

Polycrystalline pure KCl, RbCl, KBr, KCl-RbCl, and KCl-KBr solid-solution alloys were fabricated at LLNL. The composition of the alloys was the same as that used in the single-crystal studies. To achieve homogeneous solid solutions, the alloy compositions were dissolved in water and then spray dried. The dried powders were hot-pressed at about 450°C under a stress of 300 MPa (3 kbar). The samples were then annealed at elevated temperatures (600–700°C) to increase the grain size.

After the annealing treatments, the samples had a relative density greater than 97% of crystal density, with an equiaxed grain morphology and linear-intercept grain sizes between 100 and 300 μm . Figure 1 shows an example of the microstructure of the KCl-20 mol% RbCl alloy after the annealing treatment. The linear-intercept grain size is about 150 μm . The creep behavior of the polycrystalline pure components and alloys in both systems, KCl-RbCl and KCl-KBr, was similar to that exhibited by the pure and alloy single crystals in terms of the type of primary creep curve, stress dependence of the steady-state creep rate, activation energy for creep, creep transient after a stress reduction, relative creep between the alloys and pure components, and dislocation substructure.

The creep behavior of polycrystalline pure KCl (grain size of about 200 μm) and the KCl-20 mol% RbCl alloy (grain size of about 150 μm) are compared with that for the single-crystalline materials of the same composition in Figure 2. The data in Figure 2 are plotted as steady-state creep rate vs applied stress on a logarithmic scale. Figure 2 reveals several important points. First, the creep rate for both the single and polycrystalline KCl-20 mol% RbCl alloy is lower than that for the pure polycrystalline and single-crystalline KCl. The homologous temperature T/T_m (where T is the absolute testing temperature, and T_m is the absolute melting temperature) for the pure component and alloy is about the same (0.86). Second, the stress

Figure 1.
Microstructure of
the hot-pressed
and annealed
polycrystalline
KCl-20 mol%
RbCl alloy.

exponent—the slope of the curves—is different for the alloy (both single and polycrystalline) vs the pure components (single and polycrystalline). The stress exponent for pure KCl is 4.4, whereas the stress exponent for the KCl-20 mol% RbCl alloy is about 3. Third, the single-crystal (both pure and alloy) creep data are in excellent agreement with the polycrystalline (pure and alloy) data.

The dislocation substructure of the polycrystalline alloys consisted of well-defined subgrains after large strains. This result is in agreement with that obtained for the single-crystalline alloys. The subgrain size of the alloys in both the polycrystalline and single-crystalline samples was larger than that for the pure components in both the polycrystalline and single-crystalline samples at the same value of normalized stress, and in all cases, it varied inversely with applied stress. The only difference between the coarse-grained and single crystals was in the length of the primary creep stage. The primary creep stage of the polycrystalline samples for both the pure components and alloys was smaller than that observed in the pure and alloy single crystals.

In addition, some fine-grained alloy samples (grain sizes of about 5 to 20 μm) were prepared and tested. Preliminary results on these materials suggest that they deform via a diffusional creep mechanism and that the stress exponent is close to unity with almost no primary creep stage, rather than the dislocation creep mechanism observed in the coarse-grained samples. No subgrains were observed in the fine-grained materials after testing. The fine-grained materials had creep rates that were a factor of 10 to 1000 times faster than the coarse-grained samples at the same value of testing temperature and applied stress.

We anticipate that the results for the alkali halide solid-solution alloys could be extrapolated to potential structural ceramic oxide solid solutions that are to be used in composite applications at elevated temperatures where creep resistance is critical. This work has been described in detail.¹⁻⁵

Figure 2. Comparison of the steady-state creep rate vs applied stress for the coarse-grained polycrystalline (closed) and single crystalline (open) KCl and KCl-20 mol% RbCl alloy materials.

References

1. Duong, H., M. Beeman, and J. Wolfenstine (1993), "Creep Behavior of Potassium Chloride–Rubidium Chloride Solid-Solution Alloys," *J. Am. Ceram. Soc.* **76**, 185.
2. Duong, H., M. Beeman, and J. Wolfenstine (1993), "Creep and Dislocation Substructure of KCl–KBr Solid-Solution Alloys," *Acta Metall. Mater.* (submitted).
3. Wolfenstine, J. (1993), "Creep and Dislocation Substructure Formation in Ceramic Solid-Solution Alloys," in *Creep and Fracture of Engineering Materials and Structures*, B. Wilshire and R. W. Evans, Eds. (London), p. 335.
4. Duong, H., M. Beeman, and J. Wolfenstine (1993), "Creep of KCl–RbCl Solid-Solution Alloys," invited talk, *45th Pacific Coast Regional Meeting of the American Ceramic Society* (San Francisco, November).
5. Wolfenstine, J. (1993), "Creep Behavior of Ceramic Solid-Solution Alloys," invited talk, University of Southern California.

Development of Anisotropy in Ice

Principal Investigator: Hans-Rudolf Wenk (UC Berkeley)

LLNL Collaborators: William B. Durham and Andrew J. Gratz

Other Collaborators: Stephen H. Kirby and Laura A. Stern (U.S. Geological Survey)

Student: Kristin Bennett (UC Berkeley)

Abstract

We developed a method to investigate the bulk textural development in deformed polycrystalline ice using neutron diffraction. Experimental pole figures on hexagonal ice I have shown that a weaker fabric develops with (001) poles parallel to the compression axis when ice is mixed with hard particulates than when samples of pure ice are deformed. However, when rhombohedral ice II is deformed, a strong texture maxima develops with (100) poles parallel to the direction of compression.

We used a high-pressure, low-temperature, triaxial gas apparatus unique to LLNL to deform several specimens of ice I, ice I plus hard particulates, ice I plus II, and ice II. The resulting textures produced from the uniaxial compression were measured with a four-circle goniometer equipped with a helium-gas cryostat using monochromatic neutrons at the National Institute of Standards and Technology (NIST) Research Reactor. Our investigations of texture provide the microstructural data for interpreting macroscopic flow laws in ice.

Objectives

For the past 13 years, the rheology of ice and of its high-pressure, low-temperature polymorphs has been studied extensively at LLNL. Creep experiments by Durham et al.^{1,2} have established flow parameters for many of the ices that divide the empirical flow laws by temperature, and presumably the divisions are accompanied by different textural microstructures and deformation mechanisms. Yet, the mechanical data have lacked bulk textural analysis of the samples. While the rheological experiments continue to become more complicated, such as studies with the addition of hard particulates,³ how the texture developments change and influence rheology should be defined to assist interpretation of macroscopic deformations.

Because a neutron has low absorption and penetrates deeply into a specimen, neutron radiation can provide information about the bulk microstructures of materials that cannot be obtained with ordinary x-ray diffraction techniques. Moreover, neutrons also penetrate sample containers and environmental cells that are needed to maintain low temperatures for texture measurements of ice. Our objective in this project was to develop a means for measuring texture (i.e., preferred crystallographic orientation) by neutron diffraction at low temperature in deformed polycrystalline ice I and in high-pressure polymorphs.

Progress

Because hydrogen scatters neutrons incoherently, we obtained coherent scattering from samples that were deuterated and remolded for the neutron experiments. Deformation experiments were reproduced, and samples were then transported to a neutron source. Following the work of Durham et al., we deformed a suite of deuterated ice samples at high pressure and low temperature within the ice I and ice II stability fields. We also deformed ice I mixed with both coarse-grained and fine-grained particulates.

We measured the texture of our samples at the NIST Research Reactor in Gaithersburg, Maryland, on the BT-6 four-circle goniometer adapted with a cryogenic core. We used a Soller slit collimation system and a copper monochromator crystal with a pyrolytic graphite filter and chose the 0.1512-nm wavelength from the (002) reflection. With this instrumental setup, beam flux at the sample was 3×10^6 neutrons $\cdot$ cm $^{-2}$ s $^{-1}$, and we could measure the density distribution of poles for a particular lattice plane (hkl) in approximately 10 h.

We invented aluminum containment fixtures for the ice specimens to attach to the end of a cold finger, with the sample axis of compression parallel to the cold-finger axis. By rotating the cold finger and sample assembly about the compression axis and on a perpendicular axis, we recorded the texture in a sample for a given Bragg reflection. At all orientations, the samples were fully immersed in the circular (6-cm-diam) neutron beam. The temperature at the end of the cold finger was controlled by a separate, closed-loop, helium-gas refrigerator that we modified to the goniometer cradle. This cryogenic setup can sustain a temperature range of 10 to 195 K at the sample; these temperatures were more than adequate for the ice I samples and were essential for the ice II specimens, which required a specific temperature of 77 K. When quenched to 77 K at high pressure, ice II is metastable and retains its deformation structures. Measurements at 77 K were a particularly noteworthy accomplishment because other metastable high-pressure ice polymorphs that need the same quenching procedure could be measured for texture.

We used a spectrum of Bragg reflections to identify the polycrystalline ice reflections. Figure 1 shows how we used the ice II diffraction patterns measured at two different orientations to identify and assess the presence of strong deformation textures in our samples. The ratio of the (110) to (012) peaks denoted by the shaded regions in the figure demonstrates a much higher ratio, a stronger preferred orientation, when the sample is parallel rather than perpendicular to the axis of compression. After we rotated the sample and recorded intensities at all the ϕ (0–360 deg) and χ (0–90 deg) rotations, we used pole figures in equal-area projection to describe the density distribution of the poles for the particular lattice plane. We measured pole figures for only those diffraction peaks that were sharp and well spaced without other overlapping peaks. Because the absorption for ice is negligible, we made no absorption correction, and diffracted intensities were only corrected for background.

Figure 1. Neutron diffraction spectra for ice II (a) parallel to compression and (b) perpendicular to compression. Ice II peaks are indexed based on a hexagonal cell. Al(111) peaks are reflections from the aluminum sample containers. These plots compare the ratio of (110) to (012) reflection at different orientations.

This method for texture analysis at low temperature has proven to be revealing and quantitative. Complete pole figures were measured for all deformed ice samples. The only restriction in our study now is the limited availability of neutrons. A neutron experimenter is usually allotted 3 to 4 days in a year for measurement, and we were fortunate to be given 18 days this year at NIST to measure 10 samples. Based on these experimental results, this technique should be applied to texture determinations of a large spectrum of experimentally deformed and naturally deformed ices and other polycrystalline materials that develop textures at low temperatures.

References

1. Durham, W. B., H. C. Heard, and S. H. Kirby (1983), "Experimental Deformation of Polycrystalline H₂O Ice at High Pressure and Low Temperature," *J. Geophys. Res.* **88**, B377; *Proc. 14th Lunar and Planetary Sciences Conferences, Part I*.
2. Durham, W. B., S. K. Kirby, H. C. Heard, and L. A. Stern (1987), "Inelastic Properties of Several High-Pressure Crystalline Phases of H₂O; Ices II, III, and V," *J. Phys.* **48**, 221.
3. Durham, W. B., S. K. Kirby, and L. A. Stern (1992), "Effects of Dispersed Particulates on the Rheology of Water Ice at Planetary Conditions," *J. Geophys. Res.* **97**, 20883.

Investigating Shock Effects in Porous Meteoritic and Terrestrial Materials

Principal Investigator: John T. Wasson (UC Los Angeles)

LLNL Collaborators: William J. Nellis and Andrew J. Gratz

Other Collaborator: Paul Warren (UC Los Angeles)

Student: Kurt Knesel (UC Los Angeles)

Abstract

We are conducting a series of shock-loading experiments to investigate the role of variable target characteristics, especially porosity, in impact metamorphism. The experimental targets include a variety of terrestrial and asteroidal materials and synthetic analogs. The most nearly complete phase of our study involves parallel sets of experiments using two different target materials, which were selected as likely candidates for the precursors of tektites: a loosely compacted dry loess and a siltstone that is similar in mineralogy, composition, and grain size to the loess but has lower porosity. In 20-GPa experiments, a large fraction of the loess was shock-melted, yet negligible melting occurred in the siltstone. These results and similar ones from higher shock pressures tend to support the hypothesis that only a particularly dry and porous variety of continental surface material is capable of spawning tektites. Two additional phases of our study, still in progress, will explore the shock and thermal histories of the CK group of carbonaceous chondrites and the potentially explosive role of carbon (graphite) during high-degree shock metamorphism of carbonaceous meteorites.

Objectives

Over the history of the solar system, impact-induced shock metamorphism has been an extremely important process. All of the terrestrial planets and at least most asteroids have been profoundly affected. Meteorites, which are fragments of collisionally disrupted asteroids, typically have been shocked to pressures on the order of 10 GPa and in many cases to more than 40 GPa (Ref. 1).

Our experiments are designed to study how shock effects may vary as a function of the preshock physical state (e.g., porosity and temperature) and the mineralogy (i.e., the petrology and chemistry) of the materials. We are conducting experiments using chondritic meteorites, synthetic analogs of chondrites and the enigmatic (e.g., carbon-rich yet igneously differentiated) ureilite meteorites, and selected terrestrial materials as sample targets. Most previous shock-loading experiments have investigated either pure minerals, igneous rocks, or lunar regolith. Relatively few have focused on chondritic meteorites, which have a distinctive mineralogy and moderately high porosity, and carbonaceous chondrites have been almost completely overlooked in this type of study.

We studied the shock and thermal histories of the CK group carbonaceous chondrites and the potentially explosive role of carbon (graphite) during high-degree shock metamorphism of carbonaceous meteorites, especially ureilites. Some of our experiments were directed at determining the origin of tektites. Tektites are homogeneous masses of pure SiO₂-rich impact glass, typically several centimeters in size, devoid of crystallites, and with very low contents of relict minerals and H₂O. They are concentrated in only four roughly continent-sized "strewnfields." Compositionally, tektites are uniformly close to shales, so the source craters must be in continental crust. Many aspects of tektite genesis are unclear.

We used a two-stage, light-gas gun at LLNL to accelerate projectiles to speeds of 0.1 to 4 km/s and impact them into fixed targets. In general, our samples are 11-mm-diam disks that are 1.2 to 1.4 mm thick. A variety of advanced recovery techniques can be used, including recovery of preheated or precooled samples, ejecta capture, inclined-target recovery, and use of impedance-matched sample holders. Using special alloys for both sample capsules and projectiles, we successfully deployed capsules with densities as low as 2.7 g/cm³, allowing good impedance matching of 33%-porosity silicate powder compacts. Thin sections of the recovered samples are being studied at UC Los Angeles, using mainly petrographic and binocular microscopes and an electron microprobe.

Progress

We conducted several experiments with shock pressures ranging from 7.9 to 43 GPa, in targets ranging from loess (eolian, very weakly coherent silt) to artificial blends of the major mineral constituents of ureilite meteorites to pieces of the Allende CV3 meteorite. Most of the work was completed for 20 experiments, which included obtaining suitable materials (e.g., Chinese loess, Colorado siltstone, pieces of the Allende meteorite, and pure olivine, orthopyroxene, graphite, and chromite), pulverizing and sieving rocks and minerals of synthetic analogs, preparing and loading the target containers, preparing and firing the gas gun, and recovering the samples from the impacted capsules. For six of the ureilite-related experiments, we fashioned containers with two narrow (790- μ m-diam) holes through the rear container wall to allow escape of CO and CO₂ gases generated by redox reactions in response to the shock.² Except for the highest pressure experiment (43 GPa) with an aluminum capsule, the capsules survived in good condition, and the sample was recovered nearly intact. For most of our experiments, petrographic investigation of thin sections produced from the experimental targets is still in progress.

We have essentially completed our studies of the targets from experiments aimed at determining tektite origins. Although there are only four tektite strewn-fields, nearly 100 craters have been produced in the past 40 million years that are large enough (diameters ≥ 10 km) and in regions with sufficiently thick sedimentary cover for one to expect that most of these craters have produced tektites. Apparently, a large crater in a thick pile of continental sediments is generally not sufficient to generate tektites. There must be some third requirement.

Wasson and Heins³ suggested that tektites form only if the crater is in a region covered by a dry, fine-grained, porous material—ideally loess. During shock alteration, dry porosity favors production of homogeneous, fully vitric masses because more of the impact energy is partitioned into shock and postshock heating. Where the target is porous but water-rich, vaporization of the water absorbs much of the available heat and causes high pore pressures, thus limiting the shock compression of the target.

We tested this model by shocking samples of loosely compacted loess from Shaanxi, China (sieved to <53 μ m and compacted to about 35% porosity). As an alternative tektite source material, compositionally similar (but wetter and less porous) samples of a siltstone from the State Bridge Formation of Colorado were also investigated. To optimize shock impedance matching, we built sample containers from aluminum in all but the highest-pressure experiment (43 GPa in stainless steel). For the loess powder, about one-third of the powder was melted in a 19.6-GPa experiment (Figure 1), the powder was more extensively melted in a 29-GPa experiment, and a preliminary study of a 42-GPa experiment indicates near-total melting. We also note that even in the 19.6-GPa experiment, some intriguing reduction of silicates occurred, including production of an iron silicide, perhaps

similar to the suessite found as a rare phase in ureilites or to iron silicides found in some fulgurites (products of lightning-strike fusion).⁴

In contrast, the siltstone yielded negligible melting at 20 GPa (Figure 2) and only minor (less than one-tenth) melting at 30 GPa. Preliminary characterization indicates that the siltstone still remained mostly unmelted even at 40 GPa. These results confirm that loess is an exceptionally favorable source material for tektites.⁵

Figure 1.
Backscattered electron image of a loess-powder sample shocked to 20 GPa. Note globules of impact melt, especially the large one in lower left. Bright crystals in melt globules are Fe_xSi phase. Black ovals in groundmass are vesicles. Dark gray crystals are quartz. Scale bar = 100 μm .

Figure 2.
Backscattered electron image of a siltstone sample shocked to 20 GPa. In contrast to the 20-GPa loess product (Figure 1), the texture here shows only mild brecciation, with negligible evidence of shock melting. Mineral phases are mainly quartz (medium gray) and alkali feldspar (light gray). Light rectangular crystal in center is calcium carbonate. Scale bar = 100 μm .

References

1. Stöffler, D., K. Keil, and E. R. D. Scott (1991), "Shock Metamorphism of Ordinary Chondrites," *Geochim. Cosmochim. Acta* **55**, 3845.
2. Kikuchi, M., Y. Syono, N. Kobayashi, T. Oku, E. Aoyagi, K. Hiraga, T. Atou, A. Tokiwa, and K. Fukuoka (1990), "Shock-Induced Superconductivity of $Tl_2Ba_2CuO_6$," *Appl. Phys. Lett.* **57**, 813.
3. Wasson, J. T., and W. A. Heins (1992), "Tektites and Climate," *J. Geophys. Res. (Planets)* **98**, 3043.
4. Essene, E. J., and D. C. Fisher (1986), "Lightning Strike Fusion: Extreme Reduction and Metal-Silicate Liquid Immiscibility," *Science* **234**, 189.
5. Warren, P. H., A. E. Rubin, J. T. Wasson, A. J. Gratz, W. J. Nellis, and N. H. Hinsey (1993), "Experimental Shock of Loess and a Compositionally Analogous Siltstone: Implications for the Origin of Tektites," *EOS Trans. Am. Geophys. Union* **74**, 390 (abstract).

Preparation and Characterization of Iron and Iron Alloy Thin Films on Diamond Substrates

Principal Investigator: David J. Webb (UC Davis)

LLNL Collaborators: Choong-Shik Yoo and Neil C. Holmes

Students: Christopher Pike and David Gettman (UC Davis)

Abstract

The temperature of the Earth's core is an important issue in deep Earth geophysics. To achieve the relevant high pressure and high temperature in the laboratory, iron films are shock-compressed. In this study, we made and characterized iron films for high-pressure shock experiments. We continued our study of the characteristics of thin films of iron on diamond and sapphire substrates and began a study of films of iron alloys on diamond substrates. The results of the first set of shock measurements of pure iron films on diamond led to an estimate of 6800 K (± 500 K) as an upper bound on the temperature of the boundary layer between the Earth's inner and outer cores. Regarding the alloy films, we found that films of $\text{Fe}_{100-x}\text{O}_x$ with varying x could be formed on diamond substrates by sputtering from two targets (one pure iron and the other pure Fe_2O_3).

Objectives

The melting temperature of iron at the Earth's core pressures is an upper bound on the temperature at the boundary of the Earth's inner core (pure iron) and outer core (iron alloy). A good estimate of the temperature at this boundary is necessary for a proper understanding of the energy balance and the resulting dynamics of the Earth; however, estimates of this melting point by various researchers differ by thousands of degrees. Our goal was to grow and characterize films of pure iron on sapphire and diamond substrates for use in shock measurements to estimate the melting point of iron at the pressure of the inner-core/outer-core boundary. Furthermore, to provide specimens for shock measurements to place a lower bound on the temperature of that boundary, we developed and tested techniques for producing films of iron alloys, such as $\text{Fe}_{100-x}\text{O}_x$. We also wanted to understand the magnetic properties of the thin granular films of pure iron that form on the sapphire substrates. These properties provide information on the nature of these films.

Progress

We found previously that deposition of the iron films onto diamond substrates by sputtering resulted in a film that had a very smooth surface, was within experimental uncertainty (about 1%) of bulk density, and had an interfacial width with the diamond substrate of about 5 nm. These results were within the limits necessary for the shock measurements. Indeed, the time-resolved data for the intensity and wavelength dependence of the light emitted from the hot iron during the shock measurement at LLNL were ideal in the sense that the intensity rose in a short time (about 2–4 ns) to a value that was then approximately constant for about 25 ns while the shock wave passed through the diamond substrate. The pressure–temperature states determined from these data have a well-defined knee, suggesting the melting point of iron is 6350 K at 235 GPa (2.35 Mbar) and 6720 K at 300 GPa. Extrapolation of these results yields a melting temperature of iron of about 6800 K (± 500 K) at the pressure of the Earth's inner-core/outer-core boundary.¹ This temperature is slightly lower but still consistent with previous shock measurements and some data extrapolated from static measurements,² but it is inconsistent with extrapolations of data from the static measurements of Boehler et al.³

Research was conducted at UC Davis in FY 1993 to characterize the growth of iron films and to optimize their fabrication. This work investigated the magnetization of the thin films of iron on sapphire. We had previously found that the iron initially forms islands on single-crystal sapphire when deposited on substrates held at 350°C. These islands do not merge to form a continuous film until the film is several tens of nanometers thick.

We have been studying the temperature dependence of the magnetic hysteresis loop and the relaxation of the magnetization near the coercive field for a range of film thicknesses and hence a range of iron island sizes. These iron islands were characterized by the temperature dependence of the magnetic relaxation. Two distinct behaviors of magnetization reversal are separated by a rather well-defined temperature near 50 K. The nucleation of reverse domains at low temperatures probably happens via tunneling, and we are attempting to understand the details of the change as we increase the temperature. Thus far, these results have not enabled us to improve our films for shock-temperature measurements.

The liquid outer core of the Earth is composed of an iron alloy with a density less than that of pure iron. A likely possibility is an iron-oxygen alloy because of the abundance of both elements. Therefore, we investigated making iron-oxygen films. Films of $\text{Fe}_{100-x}\text{O}_x$ were deposited by sputtering simultaneously from two sources onto diamond substrates. One of the sources used was pure iron, and one was an Fe_2O_3 target we manufactured by cold-pressing and sintering powder. We found that we could deposit smooth films onto substrates held at room temperature and that the films adhered to the substrate. The composition of the film was fixed simply by controlling the relative deposition rates of the two sources. These films have not yet been analyzed in detail for shock-temperature measurements.

1. Yoo, C. S., N. C. Holmes, M. Ross, D. J. Webb, and C. Pike (1993), "Shock Temperatures and Melting of Iron at Earth Core Conditions," *Phys. Rev. Lett.* **70**, 3931.
2. Williams, Q., R. Jeanloz, V. Bass, B. Svendsen, and T. J. Ahrens (1993), "The Melting Curve of Iron to 250 GPa: A Constraint on the Temperature at Earth's Center," *Science* **236**, 181.
3. Boehler, R., N. von Bargen, and A. Chopelas (1990), "Melting, Thermal Expansion, and Phase Transitions of Iron at High Pressures," *J. Geophys. Res.* **95**, 21731.

References

Shock Compaction of Ferromagnetic Nanoparticles

Principal Investigator: M. Brian Maple (UC San Diego)

LLNL Collaborator: William J. Nellis

Student: Ricky Chau (UC San Diego)

Abstract

We shock-compacted fine particles of SmCo_5 , a hard ferromagnetic material. Dynamic compaction of this brittle powder is a possible way to control the structure of a specimen to enhance its magnetic properties. We used the two-stage light-gas gun at LLNL to shock the samples at pressures of 60, 115, and 144 kbar. The magnetic properties of the shocked disks were measured at UC San Diego. In general, we found that the intrinsic coercivity and remanent magnetic field of the samples decreased monotonically with increasing shock pressures. The coercive force of a sample shock compacted at 60 kbar was larger than that of the reference sample, which indicates that lower shock pressures should be explored.

Objectives

The properties of permanent magnetic materials are a subject of great fundamental interest. Important desired properties are a high remanent magnetic field at zero applied field, a large magnetic reversal field needed to reduce magnetic values to zero, and a small volume of material required to produce a given magnetic field. The latter depends on the energy product BH , where B is the total magnetic field produced and H is the applied magnetic field. These properties are controlled by the saturation magnetization, magnetocrystalline anisotropy, and microstructure. In particular, the microstructure in the form of grain boundaries, defects, and precipitates determines the dominant magnetization reversal mechanism. The harder it is to reverse magnetism, the better the magnet.

Although great progress has been made in explaining magnetization reversal in these compounds, many important questions remain. Our goal is to resolve these questions by studying nanoparticles and shock-consolidated samples of brittle SmCo_5 . The novel properties of nanoparticles offer unique opportunities in controlling the microstructure of such small grains. Shock consolidation is a way to compact nanoparticles without the grains growing. Thus, we hope that in addition to answering fundamental questions about structure and properties, superior magnetic properties will emerge.

Progress

We have studied the effects of shock consolidation on microcrystalline particles of SmCo_5 . A sample of SmCo_5 powder was obtained from a commercial vendor because our anticipated supplier of smaller nanocrystalline powders was not yet able to produce the nanocrystalline ones that we expected. The rough powder was reduced in size mechanically because we wanted each particle to be a single magnetic domain. The particles had a distribution from 1 to 10 μm ; however, this is larger than the 1- μm size needed for SmCo_5 to be a single domain. The particles were loaded into a BeCu die, and the powder was aligned in a 1 T (10^4 Oe) field. The powder was then pressed at UC San Diego using a hydraulic press. The resulting disks were loaded into a copper fixture and shock-compacted with aluminum impactors using the 7-m light-gas gun at LLNL. Three disks were shocked using pressures of 60, 115, and 144 kbar.

The sample shocked at 60 kbar showed no visible cracks and seemed homogeneous. The 60-kbar experiment produced a single easily handled disk, but the other

two samples shocked at 115 and 144 kbar broke into several pieces as a result of their structural faults. The resulting shocked samples exhibited different characteristics at each shock pressure. The two higher pressures resulted in a lateral release, causing a circular crack in the disk-shape specimens. It was apparent optically that the density varied from the center to the edge of each disk.

We examined the microscopic structure of the shocked disks using x-ray diffraction (XRD) and scanning electron microscopy (SEM). Our attempt to use SEM was not successful because we were unable to focus at sufficiently high magnifications to reveal important features because of the strong magnetic fields of the sample. XRD showed that the high pressure experienced by the samples did not significantly change the atomic structure. More importantly, the shock compaction did not cause the SmCo_5 to decompose into the Sm_2Co_7 or $\text{Sm}_2\text{Co}_{17}$ phases. To the limit of our accuracy, we saw no significant change in the lattice parameters of the shocked samples.

For each sample, magnetic hysteresis loop measurements were made using a superconducting quantum interference device magnetometer at UC San Diego. From the hysteresis loops, the remanent field B_r (the residual magnetization when the applied field H is zero) and the intrinsic coercivity H_{ci} (the applied field needed to reduce B_r to zero) were obtained (Figures 1 and 2). Different parts of each sample were also measured individually as a function of radius. We found that both B_r and H_{ci} tended to decrease with increasing pressure. In addition, the inhomogeneities in each sample produced different results depending on whether the measured piece came from the center or rim of each disk. One particular measurement of H_{ci} resulted in a higher value than that found in an unshocked sample used as a control. This particular piece came from the 60-kbar sample, which suggests that using lower shock pressures would yield better results. Future experiments at lower pressures are planned to improve the magnetic properties of this brittle material.

Figure 1. A typical magnetization curve with the corresponding values of the remanent field B_r and the intrinsic coercivity H_{ci} .

Figure 2. Dependence of (a) H_{ci} and (b) B_r on shock pressure. Data were taken for four pieces at each pressure: two from near the center of a shock-consolidated disk and two from near the rim.

Dynamic Compaction of Alumina–Zirconia Ceramics

Principal Investigator: Joanna McKittrick (UC San Diego)

LLNL Collaborator: William J. Nellis

Student: John Freim (UC San Diego)

Abstract

We used shock compaction of fine powders to achieve high-density oxide ceramics. With shock compaction, it is possible to achieve a high density without grain growth by the fast (<1 ms) application of pressure. Shocked specimens have been recovered as one-piece, macroscopically crack-free, dense compacts at pressures ranging from 4 to 12 GPa. The high density facilitates interparticle bonding through a short post-shock anneal at elevated temperatures. The as-shocked and sintered samples possess higher bulk densities and superior physical properties than those reported in previous research on similar material.

Objectives

Alumina–zirconia ($\text{Al}_2\text{O}_3\text{--ZrO}_2$) ceramic composites possess desirable structural properties, which in turn can enhance physical properties. The hardness of a composite mixture, when fully dense, will approach that of a rule of mixtures for single-crystal specimens of each component using the Vickers indentation technique. Fracture toughness of the material, which measures the resistance to macrocracking under an applied stress, is enhanced by the martensitic-phase transformation from the tetragonal to monoclinic polymorph of zirconia. This tetragonal polymorph is metastable and under ambient conditions is observed only in small particles (<0.5 μm) or in particles where the transformation is constrained by a material with a higher elastic modulus, such as alumina. Conventional processing techniques are typically inadequate for producing bulk specimens with high densities accompanied by retention of the tetragonal phase.

Dynamic compaction of alumina–zirconia composites is a promising technique that can produce the high densities and metastable polymorphs that will result in bulk specimens with the desired structural and physical properties. The dynamic compaction process can produce heterogeneous frictional surface heating, quenching, and bonding along the particle surfaces, while maintaining relatively cool temperatures in the particle interiors.

The compaction process also results in particle fracture and plastic deformation of the particles. These properties should facilitate greater densification of the specimens through a short post-shock sintering process. The dynamic compaction process also induces the monoclinic to tetragonal phase transformation in zirconia that is necessary for enhanced fracture toughness. The ongoing experiments use prototypical research-size test materials (0.2 g per specimen) that are intended to demonstrate the effectiveness of the dynamic process.

Progress

Alumina–zirconia ceramic material prepared from commercial and rapidly solidified fine powders was shock-compacted in the 6.5-m-long, 20-mm-diam, two-stage gas-gun facility at LLNL. The starting materials were loaded into a stainless-steel capsule and subjected to pressures ranging from 4 to 41 GPa by impacting the capsule with projectiles traveling at approximately 1 km/s. For pressures ranging from about 4 to 12 GPa, single-piece, macroscopically crack-free specimens were produced.

These crack-free compacts have been recovered for rapidly solidified powders and mixtures of commercial powders. The coherent nature of the recovered specimens is significant because macrocracks in other ceramic systems were observed that are believed to be caused by the tensile stresses associated with decompression.

The as-shocked material was a specimen in the form of a disk 1 cm in diameter and approximately 1 mm thick. The as-shocked specimen, although relatively dense (75–80% of crystal density), was somewhat fragile and possessed a low mechanical strength relative to fully dense specimens. The compact was susceptible to cracking, delamination, and chipping if not handled with care. To facilitate the recovery and handling of the shock-compressed specimens, we placed paper shims on both sides of the powders as the capsule was loaded. The thin paper layers prevented the compacted powders from adhering to the metal capsule. After the powder was shocked and the specimen was recovered, these shims also protected the compact by preventing damage to the weakly bonded material. The shims were easily removed by heating the compact in an inert atmosphere at 750°C to minimize any exothermic reactions associated with combustion of the paper.

Micrographs of the as-shocked specimens reveal that the shock-compaction process enhanced the bulk density through particle rearrangement and plastic deformation. It did not, however, result in strong interparticle bonding, compared to that of sintered material, through the frictional melting and subsequent fusion of adjacent particles. The absence of strong bonding and the lack of achievement of an as-shocked density approaching that of a single crystal are presumed to result from the relatively high melting temperatures and low incidence of plastic deformation, which are present in ceramics. A high-temperature (1600°C) sintering step was used to fully densify and induce interparticle bonding in the specimens.

The densities and hardness measurements of the shock-compressed disks are higher than those of compacts that were cold-pressed at 350 MPa. Cold as-pressed densities ranged from 47 to 58% of theoretical maximum, while the as-shocked densities ranged from 76 to 79% of theoretical maximum. The recovered specimens were then sintered at 1600°C and the physical properties compared to those of the pressed samples. Again, the shock-compressed specimens possessed superior properties, particularly in the rapidly solidified starting material.

As-shocked sintered densities were approximately 95% of theoretical maximum, whereas the cold-pressed and sintered densities were significantly lower, ranging from 66 to 84% of theoretical maximum. The poor sintering characteristics of the cold-pressed, rapidly solidified specimen are attributed to the coarse and highly irregular morphology of the powder. Hardness measurements corroborated the density measurements. Cold-pressed samples had hardness values measuring approximately 10% of the shock-compacted samples. The hardness measurements of the sintered materials are approximately 90% of the theoretical value using the single-crystal rule of mixtures, which is significantly higher than cold-pressed specimens.

Our results suggest that the use of dynamic compaction can result in the production of single-piece, macroscopically crack-free ceramic disks in the alumina–zirconia eutectic, which provides an alternative to produce dense, fracture-tough materials. The determination of appropriate process conditions for compaction and the excellent mechanical properties associated with the material provide a baseline upon which further research can be conducted in developing this system.

Shock Synthesis of Amorphous Fayalite

Principal Investigator: Raymond Jeanloz (UC Berkeley)

LLNL Collaborators: Andrew J. Gratz and William J. Nellis

Student: A. Kavner (UC Berkeley)

Abstract

Amorphous specimens of the mineral fayalite (Fe_2SiO_4) made previously in a diamond anvil cell showed that these specimens are antiferromagnetic. This is a remarkable observation because no other material is known to have a well-ordered antiferromagnetic structure for magnetic moments sited on a disordered crystal lattice. It was not possible to measure the magnetic structure directly because the previous samples were made in a diamond anvil cell and are very small. Larger specimens of amorphous fayalite are needed. Because many minerals that amorphize in a diamond cell also amorphize at high shock pressures, a two-stage gun is being used to make larger specimens that are needed for direct measurement of the magnetic structure of fayalite.

Objectives

Our objective is to synthesize amorphous fayalite by shock compression. The motivation is twofold. First, fayalite has been amorphized under kinetically hindered, room-temperature, static compression. This result suggested that similar, metastable amorphous states might be produced under both static and dynamic loading. We wanted to test this hypothesis in the reverse direction for the first time, i.e., by determining whether fayalite amorphizes under shock loading, as observed in the static result.

Second, statically amorphized fayalite has unusual properties, notably an apparently unfrustrated antiferromagnetic ordering.¹ No other material is known to be an amorphous antiferromagnet. Previous static experiments, however, yielded too little material to carry out neutron scattering and other analyses required for detailed characterization of the magnetic structure of the amorphous specimens made previously in a diamond anvil cell. Our purpose is to use shock compression to produce relatively large specimens of amorphous fayalite to obtain the appropriate characterization data and compare them with results from the small specimens made previously with a diamond anvil cell. Therefore, there is a practical motivation for determining whether bulk quantities of pressure-amorphized fayalite can be produced under shock compression. Our goal is to determine the conditions required to make significant amounts of amorphous fayalite.

Progress

Single-crystal fayalite is the preferred form of the specimen to produce a uniform amorphous fayalite. However, fayalite crystals are rare, so we performed preliminary experiments with readily available, naturally occurring mineral powders. We hoped the results of these experiments would indicate the pressure rate required for our few small crystals. Four samples of fine-grained (15–20 μm) polycrystalline fayalite were shock-compressed to pressures of 35, 45, 55 and 75 GPa (Ref. 2). X-ray diffraction and optical microscopy of the shock-processed samples show that all contain crystalline fayalite. However, glass also appears to be present in both the 55- and 75-GPa samples. In particular, in the latter sample, brown-colored but otherwise optically isotropic and featureless zones of glass are intermixed with very fine micrometer-sized crystallites that appear to have formed on quenching

from the peak shock state. There is insufficient textural evidence to determine whether any of the specimen melted under shock loading or if all of the glass was produced by solid-state amorphization. The small crystallites could have formed either out of the melt, if such was present, or by thermal alteration of pressure-amorphized regions within the sample.

Attempts to examine the samples by transmission electron microscopy were not successful. The glass was extremely unstable under the electron beam, making it difficult to document the presence of anything but crystalline fayalite. The unstable nature of the glass supports our inference that recrystallization took place on quenching from the pressure-temperature states of the highest-pressure samples. We have succeeded, however, in characterizing our samples by microinfrared reflectance spectroscopy. We observed the characteristic infrared spectrum of amorphous fayalite in local regions of the 75-GPa sample intermixed with material having a crystalline spectrum. There is excellent correspondence with our optical determination of glassy regions within this sample. The infrared spectra also agree closely with corresponding spectra obtained from statically amorphized fayalite.

Because of the intrinsically heterogeneous nature of powder samples, local melting on particle surfaces is a distinct possibility during shock compression. Still, we considered it worth investigating powders because single-crystalline material is much more difficult to obtain, and there is special interest in amorphizing isotopically doped material that can only be obtained in powdered form. Once the amorphization conditions are known, both single-crystal and isotopically enriched samples can be efficiently converted to glass.

Our work shows that fayalite can be amorphized under shock compression, thus strongly reinforcing the hypothesis that dynamic and low-temperature static experiments yield similar results. Differences must exist in detail because of the differences in strain rate and thermal histories. Nevertheless, this work reinforces the idea that static and shock-wave methods are complementary, with each helping to reveal what happens when using the other.

Sample heterogeneity appears to be the greatest remaining problem in attempting to amorphize large quantities of fayalite. Therefore, follow-on work should concentrate on single-crystalline fayalite, shocked to peak pressures of 75 to 100 GPa. Because of the apparent instability of the amorphized material, it would also appear worthwhile to precool the sample. With these conditions, it should be possible to synthesize milligram quantities of amorphous fayalite, which is sufficient for a wide variety of characterizations of the structure and properties.

References

1. Kruger, M. B., R. Jeanloz, M. P. Pasternak, R. D. Taylor, B. S. Snyder, A. M. Stacy, and S. R. Bohlen (1992), "Antiferromagnetism in Pressure-Amorphized Fe_2SiO_4 ," *Science* **255**, 703.
2. Kavner, A., A. J. Gratz, W. J. Nellis, and R. Jeanloz (1993), "Shock Amorphization of Fe_2SiO_4 Fayalite," *EOS Trans. Am. Geophys. Union* **74**, 388.

Investigating the Shock Compaction of Powders

Principal Investigator: David J. Benson (UC San Diego)

LLNL Collaborator: William J. Nellis

Abstract

We predicted the morphology of a shock-compacted copper powder and the shock speed with a two-dimensional Eulerian hydrocode and compared these results with experiments performed with a two-stage gas gun at LLNL. We chose copper as a relatively simple test material because real-time data are available for copper powders, and copper powders are readily available to compare calculation and experiment after consolidation. The individual particles were modeled in a discrete manner so we could study their interactions in detail. The size distribution for the particles was measured experimentally, and the initial spatial distribution was generated with a computer program we developed. This method could be used to investigate other materials as well.

Objectives

The shock synthesis and compaction of powders of Earth materials and of advanced materials is an area of intense research. Shock loading can be obtained using gas guns, explosives, and lasers. Little numerical simulation has been performed on the micromechanical scale to characterize what happens to powders during shock compression. Our goal is to understand the shock-induced micro-mechanics of powders well enough so that the response to dynamic loading and pressure release of a variety of powders, including Earth materials, could be predicted computationally.

Progress

We chose copper as a test material because (1) copper is a relatively simple ductile material with an available material model at high shock pressures, (2) real-time shock compression data are available for porous copper for comparison with the calculations, and (3) copper powders are readily available for experiments to compare observed changes in particle shape with computational predictions.

An algorithm for calculating the initial size and spatial distribution of the powder particles was developed to simulate the process of loading the powder into a capsule for a gas gun experiment. The experimental procedure is to pour the powder into a capsule and then tap the capsule to settle the powder particles. Our algorithm uses a Monte Carlo method to "pour" and "tap" the powder into our specimen region one particle at a time. The algorithm is general and can handle a variety of simply connected polygons.

Figures 1 and 2 show the calculated initial and final states for a copper powder. These calculations were performed using RAVEN, an Eulerian code developed at UC San Diego, and agree well with the behavior observed in experiments (Figure 3). The lower boundary of Figure 1, which has a velocity of 0.20 km/s in the computation, acts as a rigid plate. Although all the particles are made of copper, each particle is assigned a material number that is different from the material numbers of particles surrounding it, so that the boundaries of particles can be tracked during the calculation.

In the calculation, the particles are subjected to only a single shock, while in the actual experiment, several waves pass through the sample because of the impedance mismatch between the powder and the surrounding solid capsule. However, most of the energy is deposited in the powder during transit of the first shock wave, so the

single-shock calculation is a reasonable approximation of the experiment. The agreement between the predicted and observed morphology of the particles is good at low velocities and pressure, but discrepancies appear at higher velocities. These are probably due to the approximation of the three-dimensional spherical particles as two-dimensional cylinders. The calculated shock velocity agrees to within 10% of the value obtained from published experimental data. Various aspects of the method have been described in detail elsewhere.¹⁻⁷

Figure 1. The initial configuration of the copper particles at 6.2 g/cm^3 . Each edge of the box is $160 \mu\text{m}$ wide and contains 100 zones.

Figure 2. Particle configuration calculated by moving the lower boundary upward at 0.20 km/s .

Figure 3. Particle configuration obtained experimentally by an initial velocity of the capsule wall of about 0.20 km/s. The region is 160 μm wide. Initial copper density was 6.2 g/cm³. The dynamic compaction pulse was generated by impact of a projectile accelerated by a two-stage gas gun.

1. Benson, D. J., and W. J. Nellis (1993), "Dynamic Compaction of Copper Powder: Computation and Experiment," *Appl. Phys. Lett.* (submitted).
2. Benson, D. J. (1993), "The Application of Eulerian Methods to the Micro-mechanical Analysis of Shock Compaction," in *Proc. IMM Workshop on Computational Modeling of Materials with Evolving Microstructures* (UC San Diego, April 19–21), p. 60.
3. Benson, D. J. (1993), "Application of Eulerian Finite-Element Method to Problems in Micromechanics," in *Proc. ASME Winter Annual Meeting, Symp. Advanced Computational Methods for Materials Modeling* (New Orleans, November 29–December 3), AMD-8.
4. Benson, J. D. (1993), "The Calculation of the Shock Velocity–Particle Velocity Relationship for a Copper Powder by Direct Numerical Simulation," *Wave Motion* (submitted).
5. Benson, J. D., and W. J. Nellis (1993), "Numerical Simulation of the Shock Compaction of Copper Powder," in *Proc. AIRAPT/APS High-Pressure Science and Technology Conf.* (Colorado Springs, June 28–July 2).
6. Meyers, M. A., D. J. Benson, and S. S. Shang (1993), "Energy Expenditure and Limitations in Shock Consolidation," in *Proc. AIRAPT/APS High-Pressure Science and Technology Conf.* (Colorado Springs, June 28–July 2).
7. Benson, D. J. (1993), "An Analysis by Direct Numerical Simulation of the Effects of Particle Morphology on the Shock Compaction of Copper Powder," *Model. Sim. Mater. Sci. Eng.* (submitted).

References

Bonding in SiO₂: First-Principles Calculations for Several Crystalline Configurations

Principal Investigator: Mark S. T. Bukowinski (UC Berkeley)

LLNL Collaborators: David B. Boercker and Lin H. Yang

Student: Huoyi Zhang (UC Berkeley)

Abstract

We used two ab initio approaches to generate ground-state energies for several crystallographic structures of SiO₂. The first method—which we call the modified variationally induced breathing (MVIB) model—approximates the total energy as a sum of pair potentials and atomic self-energies, both of which are computed from density-functional theory. The second method makes no such approximation; rather, it calculates the total energy within a nonlocal pseudopotential approach to the electronic structure of the material. The MVIB method proved accurate and allowed us to generate completely equilibrated structures for 20 different polymorphs of SiO₂, with as many as 48 atoms per unit cell. Within pressures relevant to the terrestrial planets, only a few of these phases are found to be likely candidates for the as yet unobserved poststishovite structure. We performed only preliminary calculations with the pseudopotential method. Energy curves for stishovite and coesite were generated, with structural parameters fixed to experimental values. We plan to use the MVIB structures of possible high-pressure phases as starting configurations for pseudopotential calculations. This approach will greatly decrease the computational effort required to perform the more rigorous electronic calculations needed to characterize covalent effects in SiO₂ phases.

Objectives

SiO₂ is a representative mineral of the Earth. Although it exists in many phases, it is often generally referred to as silica. Further progress in our understanding of silica could be greatly facilitated by a practical understanding of silicon–oxygen bonding in a variety of environments. Many ab initio calculations on crystal fragments exist; they have provided a wealth of insight into the nature of bonding and its relationship to observed structures.¹ Periodic Hartree–Fock calculations on silica and silicates have also been instructive;² however, there has been little systematic effort to collect sufficient theoretical results on crystal phases to constrain truly faithful and practical representation in terms of analytical potentials. By faithful, we mean accurate enough to reflect the observed correlations between bond lengths and angles¹ and between bond strength and bond order. Practical implies that it is simple enough to use in molecular dynamics simulations and other calculations in which simplifying symmetry is low or nonexistent.

There is also a need to explore possible high-pressure structures of silica that may be relevant to the physics of planetary interiors. These phases have proven difficult to identify experimentally. Our objective is to use ab initio techniques to examine the energetics of SiO₂ as a function of pressure and obtain insight into the relationship of bonding to structure at high pressures in the Earth. We also want to carry out an extensive ab initio effort to generate fully relaxed, high-pressure structures of a substantial number of SiO₂ polymorphs.

We developed the MVIB *ab initio* model and generated a Fortran code that optimizes the structure of crystals of arbitrary symmetry. The Hamiltonian operator includes atomic-ionic self-energies and pair interactions that arise from charge overlap and long-range Coulomb forces. The pair interactions and self-energies depend on the atomic arrangements through the response of the atomic-ionic charge densities to the crystal environment.³ We applied the method to some known crystals, such as corundum (Al_2O_3), and found it gave quite accurate equations of state and structures. Because it is far more efficient than band-structure methods, we used it to calculate the structures and energies of 20 polymorphs of silica, with an emphasis on potential high-pressure phases. Figure 1 shows selected phases.

The equilibrium phase at ambient conditions is α -quartz, which has the lowest energy. Detailed comparisons with data on stishovite suggest that some covalent interactions, which are not included in the MVIB model, are necessary to account for some structural details. It is possible that a few of the calculated relative energies are not sufficiently accurate to establish proper phase relationships. However, the method does give the correct relative energies of quartz, coesite, and stishovite, and it is consistent with the experimental suggestion that stishovite transforms to the CaCl_2 structure at pressures below 100 GPa (1 Mbar). The calculated energy curves are very close to those computed with accurate band-structure calculations based on density-functional theory and Hartree-Fock theory.^{5,6} We believe that the model's prediction that the $\alpha\text{-Pb}_2\text{O}_3$ and pyrite-like structures may become thermodynamically stable at lower mantle pressures must be considered seriously.

Figure 1. Energy vs volume curves for selected phases of SiO_2 .

We have also used ab initio pseudopotentials implemented with a plane-wave basis set. The calculations were performed within the framework of local density-functional theory. The pseudopotentials are ab initio, nonlocal, and norm-conserving but in separable form.⁷ To handle the large number of plane waves, we used a local optimization scheme of Teter et al.⁸ The computational effort required to fully optimize structures with many degrees of freedom is large. Hence, we have only performed nonoptimized structure calculations on a few silica phases. The energy curves thus generated appear to have minima at densities close to the observed ones, indicating that the calculated equilibrium structures would be very close to the experimental ones used in the computations.

Our next step is to combine the MVIB and pseudopotential calculations for those phases that have not been experimentally observed or whose structures have not been determined. The combined set of energy surfaces will then be modeled with pair-interaction models. Given our experience with the MVIB model, we believe that the most promising approach is to use the MVIB pair interactions as a first approximation to be augmented by parametric models of covalent interactions.

References

1. Gibbs, G. V. (1982), "Molecules as Models of Bonding in Silicates," *Am. Mineral.* **67**, 421.
2. Nada, R., C. R. A. Catlow, R. Dovesi, and C. Pisani (1990), "An Ab Initio Hartree-Fock Study of α -Quartz and Stishovite," *Phys. Chem. Minerals* **17**, 353.
3. Silvi, B., P. D'Arco, V. R. Saunders, and R. Dovesi (1991), "Periodic Hartree-Fock Study of Minerals: Tetracoordinated Silica Polymorphs," *Phys. Chem. Minerals* **17**, 674.
4. Zhang, H. (1993), *A Study of Lower Mantle Mineralogy by Ab Initio Potential Models*, Ph.D. thesis, UC Berkeley.
5. Sherman, D. M. (1993), "Equation of State and High-Pressure Phase Transitions of Stishovite: Ab Initio Results," *J. Geophys. Res.* **98**, 11865.
6. Cohen, R. E. (1991), "Bonding and Elasticity of Stishovite SiO_2 at High Pressure: Linearized Augmented Plane-Wave Calculations," *Am. Mineral.* **76**, 733.
7. Kleinman, L., and D. M. Bylander (1982), "Efficient Form for Model Pseudopotentials," *Phys. Rev. Lett.* **48**, 1425.
8. Teter, M. P., M. C. Payne, and D. C. Allan (1989), "Solution of Schrodinger's Equation for Large Systems," *Phys. Rev. B* **40**, 12255.

Astrophysics

Optical Properties of Nearby Radio Galaxies

Principal Investigator: Hyron Spinrad (UC Berkeley)

LLNL Collaborator: Wil J. M. van Breugel

Student: Arjun Dey (UC Berkeley)

Abstract

We have completed a continuum imaging survey of a well-defined sample of low-redshift powerful radio galaxies. Our survey was designed to search for extended ultraviolet (UV) continuum emission associated with the radio source, in order to study possible relations between the radio and optical properties of these radio galaxies. Approximately 30% of the galaxies in our sample show evidence for extranuclear continuum that is aligned with the major axis of the radio emission. Although the physical processes responsible for the UV emission in the low-redshift radio galaxies are varied, it appears that in most cases, the UV light is nonstellar. We discovered one case in which the UV emission is due to star formation and one in which it is due to synchrotron emission. We are undertaking a detailed analysis of the data and anticipate finishing this project in FY 1994.

Objectives

The question of how galaxies evolve is one of the fundamental problems in modern astronomy. Much of our present understanding of galaxy evolutionary history is based on the study of radio galaxies because these objects are relatively easy to identify at high redshift. However, there is evidence of a close relationship between (radio) galaxy activity and the global properties of the host galaxy. It is therefore essential that we understand this relationship to obtain a better understanding of galaxy evolution.

One of the most interesting discoveries in radio galaxy research in the last decade is that high-redshift ($z > 0.7$) radio galaxies show extended UV (and sometimes optical) continuum emission that is aligned with the nonthermal radio continuum emission. This alignment effect is generally attributed to star formation triggered by the passage of the radio lobes through a dense ambient medium. However, because of the difficulty involved in obtaining high signal-to-noise, moderate resolution spectra of the continuum light and in detecting optical polarization in some high-redshift radio galaxies, we find it difficult to rule out other physical processes, such as scattering, that may be responsible for the alignment of the optical and UV continua. A detailed study of the UV continuum in high-redshift radio galaxies is difficult to conduct since these radio galaxies are optically very faint. Therefore, we conducted a continuum imaging survey of a well-defined sample of nearby, bright radio galaxies with the aim of identifying aligned extranuclear UV continuum structures in these galaxies. These brighter objects can be studied in greater detail, and we hope to be able to identify the dominant physical process that may be responsible for the alignment effect seen in the high-redshift radio galaxies.

Progress

During FY 1993, we completed our ultraviolet- (U-) and red- (r'-) band filter imaging survey of low-redshift radio galaxies. The data were obtained using the 3-m Shane telescope at the Lick Observatory, the 1.5- and 4-m telescopes at the Cerro Tololo Inter-American Observatory (CTIO), the 2.1-m telescope at the Kitt

Peak National Observatory, and the 3.6-m telescope at the European Southern Observatory (ESO). Our sample consists of 44 radio galaxies selected from the 3CR and PKS radio catalogs on the basis of their redshifts ($0.079 < z < 0.2$ for 3CR; $0.1 < z < 0.2$ for PKS). We constructed special filters to image these galaxies in their continuum light in the near-UV and the red. We also designed the bandpasses of the filters to minimize contamination from strong emission lines.

We found spatially extended UV continuum emission distributed along the radio axis in about 30% of the radio galaxies in our sample. Figure 1 shows an example. In many cases, the UV continuum light has associated line emission with line ratios that are similar to low-ionization emission-line regions and probably indicative of photoionization by the active galactic nuclei (AGN). Since polarization observations may hold the key to understanding the processes responsible for the aligned UV continua, we have begun spectropolarimetry observations of the brightest UV continuum emitting regions. For these observations, we are working in collaboration with Robert Antonucci (UC Santa Barbara), using the Miller spectropolarimeter at the Lick 3-m telescope. Although we have discovered one case in which the extranuclear UV continuum emission is probably due to starlight,¹ a preliminary analysis of our data indicates that the aligned UV light in most of the low-redshift radio galaxies in our sample is probably nonstellar. Although a detailed study of the UV continuum emission in the low-redshift radio galaxies is still in progress, we have discovered one case of optical synchrotron emission associated with a radio knot in 3C346 (Ref. 2) and at least two possible cases of scattering.

One of the main results of our study is that the optical and UV properties of nearby radio galaxies are also affected by the presence of the radio source. The objects in our sample will be of importance in studying the interaction of the radio source with the ambient medium and as testing grounds for the AGN unification hypothesis. Our images will also be useful for studying the clustering environments of nearby radio sources. If scattering of light from an anisotropically radiating active nucleus is the main process responsible for the aligned UV light in most of the low-redshift radio galaxies, then a detailed study of the UV continuum may also probe the UV/optical properties of the nucleus, which is hidden from direct view in these radio galaxies.

These galaxies therefore provide good laboratories for studying the environmental impact of an active nucleus. In a related study, we are investigating the stellar and gaseous content of a sample of gas-rich galaxies that contain radio sources. The sample was defined by cross-correlating the Texas 365-MHz radio catalog with the Infrared Astronomy Satellite (IRAS) Faint Source Database. We have obtained optical broadband images and spectra of the galaxies in the sample at CTIO, ESO, and Lick and the radio images at the Very Large Array. The optical identification and spectroscopy of the sample are also nearly complete. This sample of gas-rich radio galaxies allows us to investigate the complex relationships between the ambient interstellar medium, the radio source, and the AGN.

We have discovered a class of gas-rich AGN at moderate redshifts ($z \geq 0.1$), whose properties suggest that this class may constitute the link between AGN and starbursts. The optical spectra of these sources show strong, broad (about 1000 km s^{-1}) emission lines with ratios characteristic of photoionization by an AGN in addition to strong Balmer absorption lines, which are generally interpreted as evidence for a recent episode of star formation. These objects also have large far-infrared luminosities, and their radio luminosities and far-infrared colors are intermediate between the IRAS ultraluminous starbursts and powerful quasars. This is further circumstantial evidence that the presence of an active nucleus is somehow related to the stellar evolutionary history of the galaxy. These objects are important for studying the starburst-AGN connection. In addition, our Texas-IRAS sample

AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 2

has yielded five new high-redshift ($z > 1.5$) IRAS quasars. These quasars have large far-infrared excesses, associated absorption, and asymmetric radio morphologies, all of which suggest the presence of large quantities of ambient gas. The broadband spectral energy distributions of these objects are similar to the dusty high-redshift IRAS galaxy F10214+4724 ($z = 2.286$), and they have comparable bolometric luminosity.

Figure 1. A low-redshift example of (a) U- and (b) r' -band images of 3C277.3, demonstrating the wavelength dependence of the alignment effect. Both images are free of strong line emission. Although the red continuum morphology of the galaxy is symmetric, the U-band continuum morphology is extended, clumpy, and aligned with the major axis of the radio emission.

1. van Breugel, W., and A. Dey (1993), "Induced Star Formation in a Radio Lobe of 3C 285?" *Astrophys. J.* **414**, 563.
2. Dey, A., and W. van Breugel (submitted), "Blue Optical Continuum Emission Associated with a Radio Knot in 3C34G."

References

High Angular Resolution Imaging in the Mid-Infrared

Principal Investigator: James R. Graham (UC Berkeley)

LLNL Collaborator: Christopher J. Skinner

Student: Matthew Richter (UC Berkeley)

Abstract

In FY 1993, we obtained mid-infrared (mid-IR) images of the nearby Seyfert nuclei NGC 1068 and NGC 4151, to study the spatial distribution of the emission. These observations help us distinguish between thermal and nonthermal emission mechanisms and thus determine the relative contribution of emission from dust in a molecular torus and the narrow line region.

We also obtained high angular resolution (1.2-arcsec), narrow-band ($\Delta\lambda/\lambda = 0.1$) images of the nucleus of NGC 253 at three wavelengths in the mid-infrared (8.5, 10.0, and 12.5 μm). We found that most of the mid-IR flux in the nucleus of NGC 253 derives from a very small region that is ≤ 120 pc in diameter. We also acquired useful, narrow-band images of dust nebulosities around several evolved stars.

Objectives

The objectives of this project were to use the mid-infrared camera at the UC Berkeley-IGPP Laboratory of Experimental Astrophysics, to obtain spatially resolved images of astronomical objects in the 10- and 20- μm atmospheric windows. The mid-IR array camera was designed and developed at the UC Berkeley Space Sciences Laboratory (SSL) and is operated jointly by SSL, IGPP-LLNL, and LLNL's Laboratory for Experimental Astrophysics.

Progress

In FY 1993, a new electronics and control system was built and tested. The electronics are based on and, in most respects, are identical to the electronics that were built for use on the long-wavelength camera at the Keck telescope. In previous systems, we used a 10- $\times$ 64-pixel Ga:Si array manufactured by Hughes Aerospace. In the new system, we are using a 20- $\times$ 64-pixel As:Si array, which has a considerably higher quantum efficiency than the older array and which extends the array's sensitivity through the 20- μm atmospheric window. The new array doubles the field of view and increases the quantum efficiency, to improve sensitivity over the old system by approximately a factor of 2.

We acquired filters and optics needed for imaging in the important 20- μm window. The sensitivity at 20 μm will be approximately a factor of 4 lower than that at 10 μm . (Because the sky noise is considerably higher at 20 μm , the camera is somewhat more sensitive at 20 than at 10 μm .)

The images at 8.5 and 12.5 μm both have a full width at half maximum (FWHM) of 1.3 arcsec and a very high signal-to-noise ratio (>300). When combined with an accurate measurement of the point spread function, these data permit us to constrain the subarcsecond structure of the emission. Although we have confirmed that the 10- μm emission of NGC 1068 is spatially extended in the north-south direction,¹ the new data show that the emission is very asymmetric. The emission consists of an unresolved point source, which accounts for about 40% of the flux, together with a jet-like extended component centered 0.3 arcsec farther north. The extended component has an FWHM of 0.88 arcsec in the north-south direction

(60 pc at a distance of 13 Mpc) and is unresolved (<0.1 arcsec) in the east–west direction. The extended component is almost certainly thermal emission from dust. However, since the dust is located about 20 pc from the nucleus, the emission is probably not due to dust that is in thermal equilibrium with the central engine. Rather, the emission is caused by dust that is heated locally in circumnuclear star-forming regions, by small dust grains that are stochastically heated, or by dust heated in the narrow line region by resonantly trapped Lyman- α photons.

Within this small nuclear region of NGC 253 are three spatially and spectrally distinct IR components: two bright compact sources and a surrounding envelope of low-level, diffuse emission. The mid-IR and 6-cm radio are loosely correlated in position but not in brightness. The implication is that the mid-IR–radio correlation may begin to break down on small spatial scales relevant to individual star-forming regions and large individual sources. These variations in the mid-IR spectra and in the radio–IR correlation imply that the nuclear emission is excited by more than one mechanism and source type.

The last stages of stellar evolution are determined by mass loss. For intermediate mass stars, the outer envelope is shedded and later forms a planetary nebula. The exact mechanism of this mass-loss process is poorly understood. For example, approximately 80% of planetary nebulae (PNe) have a bipolar or elliptical structure, while the mass-loss envelopes of OH/IR stars, the predecessors of PNe, have spherically symmetric envelopes. Furthermore, intermediate-mass stars are predicted to undergo a superwind phase near the end of their life on the asymptotic giant branch (AGB); however, little direct evidence is available for such a phase. Using the mid-IR camera to survey AGB stars, young PNe, and protoplanetary nebulae (PPNe), we found direct evidence for a superwind as well as a bipolar structure occurring at the “tip” of the AGB. Most convincing is an evolutionary sequence of carbon-rich PPNe and a young carbon-rich PNe, from which we can connect bipolarity in the carbon-rich dust shell from the PNe stage back to the G5Ia PPNe stage, less than 200 years from the AGB.

We also obtained 3.3-, 8.5-, 10.0-, 11.3-, and 12.5- μ m narrow-band ($\Delta\lambda/\lambda \approx 3$ to 10%) and K-band (2.2- μ m) high spatial resolution images of IRAS 21282+5050 and a 6-cm flux density measurement. The new infrared images reveal a toroidal dust nebula, 4.5×6 arcsec, with a position angle of 165 deg and two prominent emission peaks aligned almost east–west and separated by 1.7 to 2.1 arcsec—a remarkably similar structure to that observed in NGC 7027. From the 6-cm flux density and the dust nebula size, we derived an electron density of $3.6 \times 10^3 \text{ cm}^{-3}$ for the central ionized region. Comparison of these images with a published carbon monoxide map suggests that the structure of this dusty, ionization-bounded planetary nebula may reflect the density inhomogeneities of the progenitor’s wind. Only slight spatial differences are discernible when comparing the K-band and 10- μ m “dust” continuum images to the 3.3-, 11.3-, and 12.5- μ m unidentified infrared (UIR) emission-band images, which are attributed to polycyclic aromatic hydrocarbons (PAHs). This tight spatial correlation suggests that the K-band and 10- μ m emission also arises from PAHs.

1. Becklin et al. (1976), *Astrophys. J.* **186**, L69.

References

Extreme Ultraviolet Observations of Cataclysmic Variables with EUVE and ALEXIS

Principal Investigator: Oswald H. W. Siegmund (UC Berkeley)

LLNL Collaborators: Christopher W. Mauche and Howard A. Scott

Student: John Warren (UC Berkeley)

Abstract

In FY 1993, we obtained and analyzed data of cataclysmic variables from the Extreme Ultraviolet Explorer satellite. Two transient events occurred on the magnetic cataclysmic variable RE J1938-461, probably as a result of intermittent, clumpy accretion. The extreme ultraviolet bright spot on the magnetic cataclysmic variable UZ For may be bigger than previously thought, and we placed a constraint on the interstellar column to this object. The boundary layer of the dwarf nova VW Hyi is accreting at a much lower rate than expected by simple theory.

Objectives

Cataclysmic variables (CVs) are semi-detached interacting binaries consisting of a white-dwarf (WD) primary, a late-type secondary star, and typically, a luminous accretion disk. Theories predict that the radiation from both nonmagnetic and magnetic systems should peak in the extreme ultraviolet (EUV): from the accretion disk and the boundary layer between the disk and the WD in nonmagnetic systems, and from the reprocessing of hard x rays by the WD atmosphere in magnetic systems. Our goal in this research was to study CVs using data from two satellites, the Extreme Ultraviolet Explorer (EUVE)¹ and the Array of Low-Energy X-Ray Imaging Sensors (ALEXIS).²

During its sky-survey, EUVE mapped the sky in four broad EUV wavebands centered on 26, 34, 72, and 150 eV; in February 1993, it started its Guest Observer program of pointed EUV spectral observations. ALEXIS is an extreme ultraviolet monitor experiment that consists of six compact, normal-incidence, wide-field-of-view telescopes operating in narrow bands centered on 67, 70, and 93 eV. The boundary layers of all nonmagnetic CVs within 200 pc were predicted to be observable with the EUVE short-wavelength scanners and the ALEXIS 93-eV telescope. For the CVs found in both EUVE short-wavelength filters, the ratio of count rates in the two bandpasses allows us to place constraints on the temperature and luminosity of the boundary layer in nonmagnetic CVs and of the reprocessed radiation in magnetic CVs.

CVs with hydrogen column densities below $3 \times 10^{19} \text{ cm}^{-2}$ were also predicted to be observable with the ALEXIS 70-eV telescopes. For these CVs, similar temperature and luminosity analysis can be made using the ratio of count rates in the two ALEXIS bandpasses. The accretion disks of 1 to 3 CVs may also be visible to EUVE, allowing us to further constrain the accretion disk models. We expected about 10 magnetic systems to be seen by EUVE and none by ALEXIS. For the 16 dwarf novae observable in the ALEXIS 93-eV telescopes, simultaneous EUV and optical monitoring will shed light on the nature of the time lag between these wavebands and hence on the nature of the dwarf novae outburst.

Progress

The EUVE satellite, launched in June 1992, consists of four EUV telescopes, three of which conducted an all-sky survey in four photometric bands, from July 1992 to January 1993. These broad photometric bands are defined by the thin-film

filters placed above the detectors: The 150-eV bandpass has a Lexan/boron (Lex/B) filter, and the 72-eV bandpass has an aluminum/carbon (Al/C) filter. During the same time period as the sky survey, the fourth telescope conducted a deep survey along the ecliptic in two photometric bands. The instrument used in the deep survey has a bandpass centered on 150 eV (Lex/B filter) and the other centered on 72 eV (Al/C filter). The EUVE scientific instruments were designed, built, and calibrated at the UC Berkeley Space Sciences Laboratory.

EUVE detected the magnetic CV RE J1938-461 during its in-orbit calibration phase, which occurred immediately after launch. During about 40 hours of pointing for the deep survey, the instrument detected a pair of transient events in the Lex/B filter. Optical observations of this system around the time of the pointing showed that the system was in a low state, in which accretion onto the white dwarf is reduced dramatically. This was the first detection of a transient event during the low state of a magnetic CV. Warren et al.³ proposed that the transients were the result of dense filaments of matter falling onto the WD surface, heating it to EUV temperatures. They estimated a mass for these filaments of $\sim 10^{19}$ g, two orders of magnitude higher than masses deduced from transients occurring in other systems.

During the all-sky survey, EUVE detected 11 magnetic CVs, as expected. John Warren is analyzing the data for these systems. He presented preliminary results as poster papers at two conferences: the 182nd meeting of the American Astronomical Society in June 1993, and the 105th meeting of the American Society of Physics in July 1993. He also constructed and analyzed light curves for the two systems with the highest EUVE count rates: UZ For and AM Her. The light curves of magnetic CVs reveal elements of the system geometry, such as the size and location of the accretion spot.

In Figure 1a, we show the light curve of UZ For (binned somewhat), folded on its ephemeris of $\text{HJD} = (2445567.17622 \pm 0.00013) + (0.087865458 \pm 0.000000007)E$, where HJD is the heliospheric Julian day, and E is the cycle number. In this curve, we see two bright phase regions and two dim regions, consistent with earlier soft-x-ray data.⁴ However, our data show the rise to the bright phase occurring at $\phi = 0.58$, slightly earlier than observed with EXOSAT ($\phi = 0.60$) or ROSAT ($\phi = 0.61$). This difference indicates one or more of the following: (1) the EUV accretion spot is displaced in longitude and/or colatitude from the soft-x-ray spot; (2) the EUV spot is larger than the soft-x-ray spot; or (3) the orbital ephemeris needs adjustment.

The simultaneous detection of UZ For in two of the all-sky survey filters, Lex/B and Al/C, allows us to determine a filter ratio, which we can then use to place constraints on the temperature of the EUV-emitting area and on the column density of interstellar matter between Earth and the star. The filter ratio of the Al/C count rate over the Lex/B count rate for the whole observation was 0.041 ± 0.014 . In Figure 1b, we show that, given this constraint and the ROSAT result from a position-sensitive proportional counter of $19 \text{ eV} < kT_{\text{bb}} < 25 \text{ eV}$, then $N_{\text{H}} \geq 1.2 \times 10^{20} \text{ cm}^{-2}$, where T_{bb} is the brightness temperature, and N_{H} is the hydrogen column density.

The only nonmagnetic CV detected in the EUVE sky survey was the dwarf nova VW Hyi. It was detected in both Al/C and Lex/B, allowing us to determine filter ratios and place constraints on the temperature of the boundary layer and on the interstellar column. We concluded that the area of the boundary layer is a fraction of about 0.001 times the surface area of the white dwarf, and that the boundary layer is accreting at a rate of ≤ 0.001 times the value expected by simple theory.

More work remains to be done. At present, we are waiting to receive accretion disk models, which we will use to analyze the EUVE dwarf novae data on hand. Also, because of launch delays and postlaunch problems with ALEXIS, we will not receive data from this satellite until February 1994 at the earliest.

Figure 1. (a) Phase-folded light curve of UZ For. The data have been binned to $\Delta\phi = 0.0167$. (b) Expected filter ratios based on models of blackbody radiation attenuated by interstellar matter and folded through the Al/C and Lex/B response functions. The horizontal lines are the upper and lower limits to the filter ratio for UZ For. The vertical lines are the limits to the blackbody temperature determined by ROSAT.

References

1. Bowyer, S., and R. F. Malina (1991), in *Extreme Ultraviolet Astronomy*, R. F. Malina and C. S. Bowyer, Eds. (Pergamon Press, New York, NY), p. 397.
2. Priedhorsky, W. C., et al. (1991), in *Extreme Ultraviolet Astronomy*, R. F. Malina and C. S. Bowyer, Eds. (Pergamon Press, New York, NY), p. 464.
3. Warren, J. K., J. V. Vallerger, C. W. Mauche, K. Mukai, and O. H. Siegmund (1993), "EUVE Observations of the Magnetic Cataclysmic Variable RE 1938-461," *Astrophys. J.* **414**, L69.
4. Ramsay, G., S. R. Rosen, K. O. Mason, M. S. Cropper, and M. G. Watson (1993), "ROSAT Observations of UZ S or Evidence of a Structured X-Ray Emission Region," *Mon. Not. R. Astron. Soc.* **262**, 993.

The r-Process in Supernovae and Accretion-Induced Collapse

Principal Investigator: Stanford E. Woosley (UC Santa Cruz)

LLNL Collaborators: Grant J. Mathews and James R. Wilson

Other Collaborator: B. S. Meyer (Clemson University)

Student: Robert D. Hoffman (UC Santa Cruz)

Abstract

We have modeled the detailed nucleosynthesis arising from the neutron- and α -rich freeze-out of material initially in nuclear statistical equilibrium (NSE) that occurs within neutrino-driven winds during the first 10 to 20 s of a Type II or Ib supernova or during the accretion-induced collapse of a white dwarf to a neutron star. The conditions explored were taken directly from the latest 20- $M_{\odot}$ delayed explosion model of Wilson and Mayle.¹ Nucleosynthesis arising from the final $10^{-4} M_{\odot}$ of supernova ejecta is in very good agreement with the solar r-process, both isotopically and in the total mass of r-process elements ejected per event. However, the model suffers from a large overproduction of neutron-rich material during the first second of the explosion. This material is mostly composed of nuclei in the $N = 50$ closed neutron shell, and if ejected, it would overwhelm the successfully produced r-process isotopes made a few seconds later. Thus, substantial revisions of the supernova model are indicated.

Objectives

We proposed to provide a physical connection between the requisite (but highly parameterized) dynamics of the α -process and r-process² and the actual supernova models of Mayle and Wilson^{3,4} for Type II and Ib delayed explosions and of Woosley and Baron⁵ for accretion-induced collapse. The original motivation for our work was to determine the suitability of this environment for producing the r-process isotopes and a number of other species in the mass range of $60 \leq A \leq 100$. Toward that end, we improved the physical representation of the actual supernova model and the nuclear reaction network used to calculate the nucleosynthesis. In contrast to our previous efforts, we followed by interpolation the thermodynamic trajectories of many individual zones taken directly from a realistic delayed supernova explosion model.

We also proposed to study accretion-induced collapse, in which an accreting carbon–oxygen or neon–oxygen white dwarf collapses to form a neutron star. The goal here was to better understand the requisite conditions (especially central density at ignition) required for collapse and the nucleosynthesis that occurs in the $0.01 M_{\odot}$ of ejecta. The ignition conditions have now been determined by Timmes.^{6,7} Using these new results and the techniques developed to study the r-process, Hoffman and Woosley will further explore accretion-induced collapse nucleosynthesis in future work.

Progress

In FY 1993, we carried out detailed nucleosynthesis calculations of the α -process and r-process covering the first 18 s in a delayed explosion model of a 20- $M_{\odot}$ Type II supernova, provided by Jim Wilson at LLNL. From detailed time histories of temperature T , pressure p , entropy S , and electron fraction Y_e taken directly from the model, we calculated the freeze-out of material from NSE down to the point of charged-particle reaction freeze-out that occurred for 40 Lagrangian

mass points. For this calculation, we sampled the last $0.03 M_{\odot}$ of material ejected, using a mass grid that decreases smoothly and logarithmically down to $10^{-6} M_{\odot}$. This zoning (much finer in the actual model itself) allowed for adequate resolution in the continuum of conditions in T , p , S , and Y_e and in the expansion time scale within the ejecta.

Figure 1 shows the results of the complete survey and gives the production factor, defined as the final average mass fraction (after decay) of a given nucleus divided by its abundance in the Sun.⁸ The production factors were obtained from the individual mass fractions of all 40 trajectories, which were summed to form an average weighted by the mass of each trajectory.

From Figure 1, it is evident that the total yield is dominated by nuclei in the closed ($N = 50$) neutron shell, specifically ^{88}Sr , ^{90}Zr , ^{89}Y , ^{87}Rb , and ^{86}Kr , so much so that the model as it stands cannot produce anything other than these nuclei. Other nuclei with substantial abundance, ^{62}Ni , ^{66}Zn , ^{70}Ge , and $^{74,76}\text{Se}$, are expected to arise from the operation of the α -process, but here, the production is overwhelmed by the $N = 50$ nuclei. There is also a large production of ^{124}Sn and $^{126,128}\text{Te}$, but these are artificial, a result of material "piling up" at the end of our charged-particle reaction network. Such material will actually pass through this region to higher atomic numbers and produce the r -abundance distribution described later.

The large production factors for the $N = 50$ isotopes in Figure 1 occur because conditions that produce these nuclei are present in a large amount of the ejected

Figure 1. Production factors $X/X_{\odot}$ (formed from a mass-weighted average) vs atomic number for the $0.03 M_{\odot}$ of material studied in the delayed explosion of a $20 M_{\odot}$ Type II supernova.⁸ Overproduction of the isotopes in the $N = 50$ closed neutron shell, produced during the first second of the explosion, poses problems for the successful production of the r -process abundance and for stellar evolution in general. Solid lines connect isotopes of a given element. A white data point (whether a diamond or circle) indicates the most abundant isotope in the Sun for a given element. A diamond indicates production chiefly as a radioactive progenitor. A circle indicates the nuclei was made as itself.

mass. This material was ejected prior to the onset of any r-process when the supernova was only 1 s old. Matter with entropy near 50 and $Y_e \approx 0.46$, which comprises a large part of our $0.03\text{-}M_\odot$ sample, is especially efficient at producing these nuclei. The ratio of the mass fractions of these nuclei to their corresponding values in the Sun exceeds 10^7 in several thousandths of a solar mass of material. This large overproduction poses problems not only for making the r-process but also for stellar nucleosynthesis in general.

The overproduction of $N = 50$ isotopes may be due to several factors. The greatest uncertainty in the present model is the lack of a proper multidimensional treatment of the explosion mechanism during the period we studied. A one-dimensional calculation such as ours, even with mixing length convection theory, cannot give a reliable depiction of the mass separation during an epoch when non-radial motion is important.

Nevertheless, we find that the last $\sim 10^{-4} M_\odot$ ejected, especially the material that escapes more than 5 s after core collapse, has a composition that agrees remarkably well with the observed solar r-process abundance. Figure 2 shows the results of a mass-weighted average of the last 16 mass points to be ejected (solid line) compared to the solar r-process abundance. It also illustrates the excellent overall fit to the major abundance peaks at $A = 130$ and 195. This figure was obtained without variation of any "free" parameters and is compelling evidence that the r-process has indeed been synthesized as we have described here and elsewhere. Namely, the r-process nuclides (along with some helium) are formed in the neutron-rich material ejected by neutrino energy deposition in the atmosphere of a young neutron star experiencing its Kelvin–Helmholtz evolution.

Figure 2. Final abundance (formed from a mass-weighted average) arising from the r-process calculations for the last $10^{-4} M_\odot$ to be ejected from the explosion. An overall normalization has been applied to give the correct value at $A = 130$; otherwise, the results are from a model with no "free" parameters. The agreement with the solar r-process abundance from $120 \leq A \leq 200$ is excellent.

We examined aspects of accretion-induced collapse^{6,7} and considered in some detail the speed and stability of the nuclear combustion front that propagates through the star. We also determined the critical ignition densities above which collapse will ensue. The speed of the flame is severely restricted by the maximum wavelength of the Rayleigh–Taylor instability that can develop before it is suppressed by electron capture. In addition, we examined the continued collapse of a white dwarf to nuclear density and the subsequent neutrino-energized wind that blows from its surface. This wind obscures any potential burst of hard radiation that might have accompanied the collapse. The nucleosynthesis, however, placed severe constraints on the frequency with which such events may occur.

References

1. Wilson, J. R., and R. W. Mayle (1993), *Phys. Reports* **227**, 97.
2. Woosley, S. E., and R. D. Hoffman (1992), *Astrophys. J.* **395**, 202.
3. Mayle, R. W., and J. R. Wilson (1988), *Astrophys. J.* **334**, 909.
4. Mayle, R. W., and J. R. Wilson (1990), in *Supernovae*, S. E. Woosley, Ed. (Springer Verlag, New York, NY), p. 333.
4. Woosley, S. E., and E. Baron (1992), *Astrophys. J.* **391**, 228.
5. Meyer, B., G. Mathews, W. M. Howard, S. E. Woosley, and R. Hoffman (1992), *Astrophys. J.* **399**, 656.
6. Woosley, S. E., F. X. Timmes, and E. Baron (1992), “Accretion-Induced Collapse,” in *X-Ray Binaries and Recycled Pulsars*, E. P. J. Van den Heuvel and S. A. Rappaport, Eds. (Kluwer Academic Press).
7. Woosley, S. E., F. X. Timmes, and T. A. Weaver (1993), “Accretion-Induced Collapse,” *Astrophys. J.* (submitted).
8. Anders, E., and N. Grevesse (1989), *Geochim. Cosmochim. Acta* **53**, 197.

Design Study for a Survey for Earth-Crossing Asteroids

Principal Investigator: Christopher W. Stubbs (UC Santa Barbara)

LLNL Collaborator: Charles Alcock

Other Collaborators: Edward Bowell (Lowell Observatory) and Eugene Shoemaker (U.S. Geological Survey)

Student: John Angione (UC Santa Barbara)

In FY 1993, we evaluated various instrumental approaches for detecting Earth-crossing asteroids. In collaboration with Eugene Shoemaker of the U.S. Geological Survey (USGS), we have developed a conceptual design for an appropriate wide-field imaging system. This system is based in part on the camera system developed for our project to search for massive compact halo object (MACHOs). We also developed software that generates flexible-image transport system (FITS) image files from digital data that are read into a high-end personal computer (PC).

Abstract

Early detection of Earth-crossing asteroids is a topic of great interest. We have explored how our joint experience on the MACHO camera system can be used to help solve this problem.

Objectives

In FY 1993, we held extensive discussions with Eugene Shoemaker of USGS and Edward Bowell of the Lowell Observatory about upgrading their ongoing asteroid search, exploiting state-of-the-art charge-coupled device (CCD) technology. We also developed a conceptual camera design that meets the project objectives. Our design uses a drift-scanning CCD system that has a front end comprising a high-end PC tied into a network of UNIX workstations. We also developed the code needed to take raw digital data (at the pixel rate that the camera will produce) and generate FITS image files.

Progress

This collaborative effort is continuing, and in FY 1994, we plan to implement the camera design and build the system. As a result, funds have been allocated at LLNL to construct the CCD camera system and at the Lowell Observatory to construct a new telescope for use in surveying near-Earth asteroids.

Cosmic Microwave Background Constraints on Topological Defect Models of Cosmic Structure Formation

Principal Investigator: Philip Lubin (UC Santa Barbara)

LLNL Collaborator: David Bennett

Postdoctoral Fellows: Sun Hong Rhie (UC Santa Cruz) and Peter Meinhold (UC Santa Barbara)

Students: Todd Gaier and Jeff Gunderson (UC Santa Barbara) and Jeff Schuster (UC Berkeley)

Abstract

The origin of galaxies is a major unsolved problem in cosmology. Recent modeling indicates that a phase transition in the very early universe, in which a gauged or global symmetry is spontaneously broken, could create the primordial seed perturbations that are amplified by gravity and thus cause galaxies to form. Examples of such models include the cosmic string, texture, and global monopole models. We used numerical simulations of topological defect evolution in an expanding universe to calculate the microwave background anisotropies expected in these models. We found that the cosmic string model is compatible with recent data from the Cosmic Background Explorer-Diffuse Microwave Radiometer (COBE-DMR), while the texture and global monopole models are marginally compatible. We are continuing to study anisotropies at smaller angular scales to determine if the characteristic non-Gaussian features of these models might be detectable.

Objectives

Our research project was aimed at studying a class of models for generating the primordial density fluctuations that have grown by gravitational instability to form the galaxies and large-scale structure observed in the universe today. According to these models, the source of the fluctuations are topological defects, which are the remnants of a phase transition that occurred very early in the history of the universe when the temperature was about 10^{16} GeV. This phase transition led to the spontaneous breaking of a gauged or global symmetry, and the field that underwent the symmetry breaking can only begin to correlate itself on scales inside the horizon at subsequent times (barring a late round of inflationary expansion). Generically, however, the dynamics of this field will produce gravitational perturbations with roughly the right amplitude and power spectrum to induce galaxy and large-scale structure formation. The goal of our project is to compare the predictions of these topological defect models with the results from COBE and ground-based microwave background anisotropy experiments. We are particularly interested in finding ways to distinguish the characteristic non-Gaussian features of these models with real (noisy) data.

Progress

The study of theoretical models for cosmic structure formation was transformed by the discovery of anisotropies in the cosmic microwave background radiation announced by the COBE-DMR experiment in April 1992, shortly after our proposal was submitted. These anisotropies can be considered as a measure of primordial gravitational perturbations. They pin down the amplitude of the perturbations much better than measurements of galaxy distributions, which are muddled by uncertainties in the process of galaxy formation. The COBE detection put the anisotropies at

a level somewhat higher than predicted by the conventional models, in which the gravitational fluctuations are generated by inflation. This higher level is encouraging for proponents of topological defect models, which predict a higher ratio of microwave background fluctuations to density perturbations than does the inflation-based model.

Because of the COBE, we changed our research plan to concentrate initially on microwave background anisotropy on the large angular scales studied by COBE. We performed the first realistic all-sky calculations of microwave background anisotropies for any topological defect model with our calculation for the global monopole and texture models.¹ We found that these models were marginally consistent with the COBE data, whereas previous estimates² indicated anisotropies much larger than those seen by COBE. Figure 1 shows an all-sky map of global monopole-induced microwave background anisotropies. Eventually, our results were confirmed in independent simulations by Pen et al.³ One of us also participated in a somewhat less accurate calculation,⁴ which indicated that the cosmic string model was in good agreement with the COBE results.

Next, we turned our attention back to microwave background experiments at smaller angular scales. On these scales, some experiments give results that differ from each other by more than one might expect if a Gaussian temperature pattern is assumed. For example, the microwave anisotropy experiment (MAX)^{5,6} at UC Berkeley found significantly different levels of anisotropy when pointing at different directions in the sky. These results are quite difficult to reconcile with the Gaussian temperature patterns predicted by inflationary theories, but it may be possible to explain them in a topological defect model. We are investigating this possibility in the context of the cosmic string model, which seems to be the most promising topological defect model in light of the COBE results. To accomplish this, we generated more than 50 cosmic string-induced temperature maps and simulated the MAX and the South Pole experiment SP91^{7,8} experiments on our simulated maps. At present, we are investigating various techniques for extracting statistically significant signals of the non-Gaussian features that exist in these temperature maps.

Figure 1. Simulations of fluctuations observed in the microwave background radiation by the COBE satellite.

References

1. Bennett, D. P., and S. H. Rhie (1993), "COBE's Constraints on the Global Monopole and Texture Theories of Cosmic Structure Formation," *Astrophys. J.* **406**, L7.
2. Turok, N., and D. N. Spergel (1990), "Global Texture and the Microwave Background," *Phys. Rev. Lett.* **64**, 2736.
3. Pen, U., D. N. Spergel, and N. Turok (1994), "Cosmic Structure Formation and Microwave Anisotropies from Global Field Ordering," *Phys. Rev. D* **49**, 692.
4. Bennett, D. P., A. Stebbins, and F. R. Bouchet (1992), "The Implications of the COBE-DMR Results for Cosmic Strings," *Astrophys. J.* **399**, L5.
5. Gundersen, J. O., et al. (1993), "A Degree-Scale Anisotropy Measurement of the Cosmic Microwave Background near the Star Gamma Ursa Minoris," *Astrophys. J.* **413**, L1.
6. Meinhold, P. R. (1993), "Measurements of the Anisotropy of the Cosmic Background Radiation at 0.5-degree Scale near the Star Mu Pegasi," *Astrophys. J.* **409**, L1.
7. Gaier, T., et al. (1992), "A Degree-Scale Measurement of Anisotropy of the Cosmic Background Radiation," *Astrophys. J.* **398**, L1.
8. Schuster, J., et al. (1993), "Cosmic Background Radiation Anisotropy at Degree Angular Scales—Further Results from the South Pole," *Astrophys. J.* **412**, L47.

The Excitation of the Crab Nebula

Principal Investigator: Jonathan Arons (UC Berkeley)

LLNL Collaborator: A. Bruce Langdon

Postdoctoral Fellow: T.-Y. Brian Yang (UC Berkeley)

Student: Yves Gallant (UC Berkeley)

Abstract

We applied the results of previous particle-in-cell simulations of relativistic collisionless shocks, to predict the “nebular” synchrotron emission from the binary pulsar PSR 1957+20. We also used these results to develop a semi-analytical model of relativistic shock structure, which we then used to model the “wisps” in the synchrotron emission of the Crab Nebula. These surface brightness enhancements are the principal observational manifestation of the shock terminating the wind from the Crab pulsar. We found that the magnetic fields of millisecond pulsars are largely dipolar. We also studied one of the main processes governing pitch-angle scattering in a relativistic electron-positron plasma.

Objectives

The focus of our research is to understand the origin of nonthermal energy in astrophysical sources of synchrotron radiation. Our goal during FY 1993 was to study the application of the physics of relativistic shock waves to the origin of synchrotron emission in supernova remnants powered by pulsars, in particular to the Crab Nebula.

Progress

Theory of the wisps in the Crab Nebula. We have previously suggested that the wisps observed near the Crab pulsar are collisionless shocks in the magnetized relativistic plasma flowing out from the star. In FY 1993, we completed a semi-analytical theory of the shock structure, which allows us to model the spatial structure of the shock in such a way that we can then compare observations. The underlying motivation is the identification, described in Hoshino et al.,¹ of the compressions in the magnetic field and the pair plasma induced by the reflection of the heavy ions from the shock front, with the observed wisps in the Crab Nebula. These narrow bands of enhanced surface brightness are located spatially where the pulsar’s wind should terminate in a shock wave, as indicated by ideal flow solutions. The nature of the surface brightness enhancements has been a mystery for 70 years, since their discovery by Lampland in the 1920s. We adopted the outflow geometry shown in Figure 1, in which most of the energy lost from the pulsar is in the form of a magnetohydrodynamic wind confined to the pulsar’s rotational equator.

The basic theoretical idea is to represent the ions as a cold stream, reflected and gyrating in the increasing magnetic field of the shock front, and embedded in pairs already heated by the pure pair shock that lies at the leading edge of the structure. In essence, this is a solitary wave model, since ion dissipation is neglected. The model includes the effects of charge separation between the ions and the pairs as well as the spherical expansion. A solution is constructed by estimating the magnetic-field structure, integrating the ion orbit equations in that structure, then using the results to construct the ion-current and charge densities. These values are added to the current and charge densities of the pairs and treated as a small Larmor-radius fluid. The sources are then used in the Ampere and Coulomb equations to find a new iterate for the fields, and the procedure continues until convergence is achieved. Figure 2 shows an example of such a structure.

Figure 1. Geometry of equatorial out-flow from the pulsar in the Crab Nebula. The projected rotation axis of the pulsar lies along the northwest-south-east axis, and the plane of the equatorial wind is tipped at about 50 deg to the plane of the sky.

Figure 2. Magnetic field and radial electric field of the ion soliton model of shock structure as a function of radius from the pulsar, measured in units of r_l , the radius where the pairs are shock heated at the leading edge of the structure. The flow is assumed to be steady in the shock frame. Solid curve = transverse magnetic field, B_ϕ . The peaks occur at each turning point, where the gyrating ion stream reverses direction in the magnetic field. At these points, the transverse current density is large. Short-dash curve = transverse electric field, E_r . Long-dash curve = radial momentum of the ions, $p_r/\gamma_1 m_i c$, in units of the upstream 4-velocity. In this example, the ion Larmor radius based on upstream parameters is twice r_l .

We computed the synchrotron surface brightness implied by this model and compared it with the existing optical observations of the wisps. Figure 3 shows our results. One of the most intriguing results to emerge from this model is that the required ion flux needed to explain the magnitude of the surface brightness enhancements seen in the wisps is equal, within the uncertainties, to the electrical return current flux needed to prevent the neutron star from charging up.

The results of this research are described in an extended paper by Gallant and Arons, based on Gallant's Ph.D. dissertation.²

Nonthermal x-ray emission from binary pulsars. In FY 1993, we published the results of our application of the shock studies to predict x- and gamma-ray emission from millisecond pulsars in close binaries.³ Particular application was made to PSR 1957+20, a curious system in which the energy from the pulsar is causing the ordinary star to evaporate. In contrast to diffuse systems such as the Crab Nebula, the accelerated particles within the binary lose energy to synchrotron emission as fast as they gain it because a much stronger magnetic field is present within the binary's close quarters. We calculated the fluxes expected at Earth and showed that the Gamma-Ray Observatory might be able to detect this system, but only if unusually long observations are made. We also showed that the ROSAT observatory might be able to detect this system, and indeed, the x-ray flux was successfully observed at about the level we predicted.

Figure 3. Comparison of the predicted synchrotron surface brightness in the *I* band (750 nm) to observations. Solid curve = observations by van den Bergh and Pritchett. The central peak is the pulsar, and the first main peak to the right ($r = 1$ when radii are measured in units of this peak's distance from the pulsar) is the first main wisp northwest of the pulsar. The emissivity was assumed to be that of thermal synchrotron radiation, since the simulations¹ suggest that in the first region where the ions compress the plasma, the nonthermal acceleration has not had time to alter the particle distribution from that of the Maxwellian created by the leading edge shock in the pair plasma. The fit to the magnitude and shape of the wisp at $r = 1$, as well as the spacing between the first two wisps to the northwest, fully specifies the parameters of the model, which then correctly predicts the brightness and shape of the faint counterwisp to the southeast (and almost gets the position right). At larger radii, the model does not do as well because it does not include the breakdown in the coherence of the ion motion.

Magnetic topology of neutron stars. We also published the results of our study of the observational constraints on the morphology of pulsars' magnetic fields.⁴ We showed that the spin-up of millisecond pulsars can occur as observed only if the magnetic fields of such old pulsars are basically dipolar, with no more than 40% pollution by large-scale anomalies such as quadrupole fields.

Pitch-angle scattering in pair plasmas. We studied the physics of pitch-angle scattering in a magnetized, relativistic, electron–positron plasma. Our ultimate goal was to understand how pitch-angle scattering affects the acceleration of pairs in relativistic shocks and the beaming morphology of the radiation from the shock. The basic point is that the shocks accelerate particles primarily in the plane perpendicular to the magnetic field, so what one sees depends on how much pitch-angle scattering broadens the pairs' distribution functions.

We completed a detailed study of the linear theory of the Weibel instability, one of the principal mechanisms that can lead to pitch-angle scattering in a plasma whose particles are distributed anisotropically with respect to the magnetic field.⁵ Work is continuing (with support from the Plasma Physics Research Institute and from the National Science Foundation) on simulations of the instability and its implications for the nature of the flow in the relativistic plasmas emitted by pulsars.

References

1. Gallant, Y., M. Hoshino, A. B. Langdon, J. Arons, and C. E. Max (1992), "Relativistic, Perpendicular Shocks in Electron–Positron Plasmas," *Astrophys. J.* **391**, 73.
2. Gallant, Y. A., and J. Arons (in press), *Astrophys. J.*
3. Arons, J., and M. Tavani (1993), *Astrophys. J.* **403**, 249.
4. Arons, J. (1993), *Astrophys. J.* **408**, 106.
5. Yang, T.-Y. B., Y. A. Gallant, J. Arons, and A. B. Langdon (1993), *Phys. Fluids B* **5**, 3369.

The Relationship between Supernova Dynamics, Nucleosynthesis, and Closure Mass Neutrinos

Principal Investigator: George M. Fuller (UC San Diego)

LLNL Collaborators: Grant J. Mathews, James R. Wilson, and Ron Mayle

Students: Karsten Jedamzik and Yong-Zhong Qian (UC San Diego)

Abstract

In FY 1993, we used heavy-element nucleosynthesis (r-process) from supernovae to probe the mixing of ν_e with ν_τ (or ν_μ) neutrinos that possess cosmologically interesting masses (1 to 100 eV). We found that the vacuum mixing angle θ between these species must satisfy $\sin^2 2\theta < 10^{-5}$, to ensure that neutron-rich heavy elements can be produced in neutrino-heated supernova ejecta. Mixing at somewhat smaller angles may still produce interesting nucleosynthetic signatures of dark-matter neutrinos. We also investigated how neutrino flavor mixing in a galactic supernova event could be detected unambiguously in the next generation of water Cherenkov detectors.

Objectives

A light ν_τ (or ν_μ) neutrino remains one of the most attractive candidates for a component of dark matter. In fact, the recent results of the Cosmic Background Explorer mission indicate the need for an increase in amplitude over the standard Zeldovich spectrum for density fluctuations on the largest scales. These results suggest that some neutrino must have a vacuum mass between 5 and 15 eV. This neutrino must be either the ν_τ or ν_μ . Laboratory detection of such a neutrino mass is problematic, and neutrino oscillation experiments represent perhaps the best hope for detection. However, these experiments could be successful only for fairly large mixing between neutrino species.

We discovered, fortuitously, that supernova dynamics and nucleosynthesis can be very sensitive to the mixing of ν_e with ν_τ (or ν_μ) neutrinos that possess cosmologically interesting masses (1 to 100 eV). This sensitivity can be several orders of magnitude better than laboratory oscillation experiments. Our principal objective then became to characterize how supernova nucleosynthesis products would depend on neutrino mixing parameters (mass and vacuum mixing angle θ). We thus wanted to observe nucleosynthesis from supernovae to constrain these parameters.

Progress

In FY 1993, we accomplished the main part of our objective. Neutrino-heated supernova ejecta cannot produce the observed distribution of r-process neutron-rich nuclei with mass $A > 70$ if the vacuum mixing angle between ν_e and ν_τ (or ν_μ) neutrinos that possess cosmologically interesting masses (1 to 100 eV) exceeds $\sin^2 2\theta < 10^{-5}$. If Type II supernovae truly are the site of r-process nucleosynthesis, then our result represents a stringent new boundary on the flavor mixing of neutrinos with cosmologically significant masses. However, we cannot say that supernovae are the site of r-process nucleosynthesis with absolute certainty. If there are neutrinos having cosmologically important masses with mixing angles that exceed our limits, then we can conclude that the bulk of the r-process elements do not have their origin in neutrino-heated ejecta from Type II supernovae. They must then come from some other site. (For detailed results of this study, see Qian et al.¹) We also showed that the $^{16}\text{O}(\nu_e, e^-)^{16}\text{F}$ reaction in water Cherenkov detectors will allow an unambiguous signature for neutrino flavor transformation in the neutrino burst from a galactic

supernova explosion.² In FY 1994, we will continue to investigate neutrino mixing in supernovae.

Yong-Zhong Qian completed his doctoral work at UC San Diego under funding for this project and has assumed a postdoctoral position at the Institute for Nuclear Theory at the University of Washington.

References

1. Qian, Y.-Z., G. M. Fuller, G. J. Mathews, R. Mayle, J. R. Wilson, and S. E. Woosley (1993), "A Connection between Flavor-Mixing of Cosmologically Significant Neutrino and Heavy-Element Nucleosynthesis in Supernovae," *Phys. Rev. Lett.* **71**, 1965.
2. Qian, Y.-Z., and G. M. Fuller (in press), "Signature of Supernova Neutrino Flavor-Mixing in Water Cerenkov Detectors," *Phys. Rev. D*.

Atmospheric Characterization for Adaptive Optics

Principal Investigator: Stanley M. Flatte (UC Santa Cruz)

LLNL Collaborator: Claire E. Max

Student: L. William Bradford (UC Santa Cruz)

Abstract

In FY 1993, we continued investigations into the nature of the power spectrum of optical phase fluctuations caused by refractive-index variations arising from atmospheric turbulence. This work is directed at understanding how atmospheric turbulence will affect the performance of large optical telescopes and arrays of telescopes. In this study, we used the standard Kolmogorov model and an alternative "random-walk" model, combined with complex, measured profiles in altitude of turbulence strength, outer scale, and wind velocity. We have identified a single, measurable, optical parameter (the slope of the Allan variance at 60 s) as a measure that provides significant constraint on the behavior of large telescopes. Our calculations of this parameter show that it is most strongly dependent on the outer scale of turbulence. It is also dependent on the power-law index of the turbulent spectrum and on the magnitude of the wind velocity that is averaged over altitude by weighting with the turbulence strength. We compared our calculations with measurements from an infrared interferometer on Mount Wilson and showed that, without significant measurements of the profiles with altitude of turbulence strength and outer scale, the data cannot distinguish the power-law index of the spectrum.

Objectives

The objective of this investigation has been to model the effect of atmospheric turbulence on optical propagation without using the standard Kolmogorov model, which assumes that the turbulence is characterized by homogenous, isotropic, Kolmogorov turbulence.¹ During FY 1993, we used the methods of weak-fluctuation theory to develop closed-form solutions for our results, then we evaluated those solutions by numerical integration. A primary objective was to develop methods that can use measurements with small-diameter telescopes to predict the behavior of large-diameter telescopes. The usual parameter r_0 is not sensitive to the large-scale fluctuations that affect large-diameter telescopes. We have identified a parameter that can be measured in small-diameter telescopes and is affected by large-scale fluctuations: the slope of the Allan variance at large times.^{2,3}

A group from the Space Sciences Laboratory (SSL) at UC Berkeley measured the fluctuations in phase difference between two 1-m-diam telescopes operating at 2.2- μm wavelength.⁴ They also measured the slope of the Allan variance at 10 s. Our objective has been to find the variety of models of atmospheric refractive-index fluctuations that agree with the SSL measurements.⁴ We also want to identify any measurable parameter that would be a better discriminant between atmospheric models affecting a large-diameter telescope differently. In addition, we want to be able to use measured profiles of turbulence strength and wind velocity in our calculations.

Progress

For our measurements to be most sensitive to the large-scale fluctuations that affect large-diameter telescopes, we want to measure phase differences over large separations in space, large separations in time, or both. The SSL measurements use the phase difference between two 1-m-diam telescopes separated by 4 to 13 m, a reasonably large spatial separation. The Allan variance at a particular time separation looks at phase difference averaged over that time duration. Thus, fluctuations that occur over time scales shorter than the averaging time are suppressed.

With a 3-m/s wind, the Allan variance at 10 s favors scales of 30 m, while the Allan variance at 60 s favors scales of 180 m. These values fall within observed values of outer scale, which range from a few meters to some kilometers.⁵⁻⁶ It is the slope of the Allan variance β that allows extrapolation from one scale size to another. Thus, a simultaneous measurement of r_0 and β would significantly constrain the behavior of predicted phase fluctuations within a large-diameter optical system.

We used profiles of the atmospheric turbulence and the wind speed from various experiments. The different experiments are labeled as follows: A set of profiles denoted by MK is from the Mauna Kea site.⁸ The MKG profiles are the same as the MK profiles except that the ground-level v has been reduced from 3 to 1 m/s. The H-V profiles come from Hufnagel⁹ and Valley.¹⁰ The PdM profiles come from measurements on the Pic du Midi.¹¹ The Mauna Kea and Pic du Midi profiles were measured at night, and the Hufnagel-Valley model was scaled to be representative of good seeing conditions. None of the models is precisely representative of the conditions encountered at Mount Wilson; however, we hope that some verisimilitude is attained.

We summarize our results in Figure 1. Figure 1a shows the measurements of the SSL group for β at 10 s. Figures 1b and c show our results for β at two different times, as a function of outer scale L_0 . The model results at 10 s show that both Kolmogorov and random-walk models give acceptable values, provided that the profiles and outer scale are unknown. Even if the outer scale were known, different profiles create a substantial variation in β at 10 s for both types of spectrum.

Figure 1. Allan-variance slope β . (a) Measurements of the SSL group² using an infrared interferometer with baseline 4 m and time separations of about 10 s. (b) Model results at 10 s as a function of outer scale L_0 . (c) Model results at 60 s. Different symbols represent different sets of profiles (see text). In descending order at $L_0 = 100$ m: diamond = MKG; square = H-V; down-pointing triangle = PdMb; circle = MK; and up-pointing triangle = PdMa. Black data points = Kolmogorov model.¹ White data points = random-walk model.

On the other hand, at 60 s the values of β are much more definitive measures of the model characteristics. If the outer scale is 15 m, then extrapolating to large separations gives a plateau regardless of the power law in the small-scale region. As a result, the values of β cluster around -1 for all models. If the outer scale is 1000 m, then the power-law index largely determines β , and the Kolmogorov and random-walk models are clearly distinguished. At intermediate outer scales, the behavior for the two spectra is distinguishable for most profiles. It appears that if measurements of β could be made at 60 s, along with reasonable measurements of profiles, models could be usefully distinguished.

We have studied the differences in the 60-s β from the different profiles and have concluded that the differences can be attributed to differences in wind speed. Specifically, increasing wind speed decreases β and vice-versa. In complicated profiles, one must consider the weighted wind speed. For example, if the wind near the ground decreased while the wind at altitude increased, the effect will depend on the relative sizes of C_n^2 at the two altitudes.

We do find that a Kolmogorov model combined with some experimental profiles will produce values of β at time intervals of 10 s that are comparable with those measured by the SSL group. Measurements at 60 s would distinguish models more clearly and would place the effective spatial scales being measured closer to those of interest in large-diameter telescopes and interferometers. These measurements would be made significantly more useful for adaptive-optics system design, test, and evaluation if more simultaneous measurements of relevant atmospheric quantities were made, so that the profiles were not so uncertain.

References

1. Tatarskii, V. I. (1971), *The Effects of the Turbulent Atmosphere on Wave Propagation*, U.S. Department of Commerce, Washington, DC.
2. Bradford, L. W., S. M. Flatte, and C. E. Max (1993), "Modelling Atmospheric Turbulence Effects on Ground-Based Instruments," *Bull. Am. Astron. Soc.* **25**, 888.
3. Bradford, L. W., S. M. Flatte, and C. E. Max (1994), "Modelling Atmospheric Turbulence Effects on Ground-Based Telescope Systems," in *Adaptive Optics for Astronomy*, D. Alloin and J.-M. Mariotti, Eds. (Kluwer, Dordrecht, The Netherlands).
4. Bester, M., W. C. Danchi, C. G. Degiacomi, L. J. Greenhill, and C. H. Townes (1992), "Atmospheric Fluctuations—Empirical Structure Functions and Projected Performance of Future Instruments," *Astrophys. J.* **392**, 357.
5. Nightengale, N. S., and D. F. Buscher (1991), "Interferometric Seeing Measurements at the La Palma Observatory," *Mon. Not. R. Astron. Soc.* **251**, 155.
6. Coulman, C. E., and J. VERNIN (1991), "Significance of Anisotropy and the Outer Scale of Turbulence for Optical and Radio Seeing," *Appl. Opt.* **30**, 118.
7. Colavita, M. M., M. Shao, and D. H. Staelin (1987), "Atmospheric Phase Measurements with the Mark III Stellar Interferometer," *Appl. Opt.* **26**, 4106.
8. Olivier, S. S., C. E. Max, D. T. Gavel, and J. M. Brase (1993), "Resolution Limits for Ground-Based Astronomical Imaging Using Adaptive Optics," *Astrophys. J.* **407**, 428.
9. Hufnagel, R. E. (1974), "Variations of Atmospheric Turbulence," in *Digest of Technical Papers, Topical Meeting on Optical Propagation through Turbulence* (Optical Society of America, Washington, DC).
10. Valley, G. C. (1980), "Isoplanatic Degradation of Tilt Correction and Short-Term Imaging System," *Appl. Opt.* **19**, 574.
11. Hecquet, J., and V. Klaus (1989), "Comparison of Optical Measurements of Seeing and Calculations Based on Radiosonde Data," *Astron. Astrophys.* **225**, 585.

Hamilton Echelle Spectroscopy of Solar Flares

Principal Investigator: Gibor Basri (UC Berkeley)

LLNL Collaborator: Suzanne L. Hawley

Student: Christopher M. Johns (UC Berkeley)

Abstract

Flares are among the most energetic phenomena in the solar system, yet they remain relatively poorly understood. It is generally believed that solar (and stellar) flares result from the release of a tremendous amount of energy stored in the magnetic field of the corona. Exactly how this occurs and how it accounts for the various emissions (x-ray, microwave, ultraviolet, optical, lines, and continuum) remain outstanding questions in solar physics. Although this is a large subfield in the solar community, we have a unique capability to add an important component to the understanding of both solar and stellar flares. A powerful stellar spectrograph at the Lick Observatory can obtain for the first time the spectrum of a flare at high dispersion throughout the entire optical range. We have undertaken such observations on both the Sun and other stars to explore the response of the lower atmosphere to flares. We are analyzing the observations in conjunction with our theoretical effort to understand the energy deposition and dissipation during flares, using models already developed for solar and stellar flares. Here, we report on the progress made to date.

Objectives

The Sun offers many benefits in the study of flares because of its proximity, which allows both high spatial and spectral resolution observations. X-ray satellites such as Yohkoh and the Gamma-Ray Observatory (GRO) are continuously taking high-energy data, and magnetograms of the surface are routinely available. The wealth of simultaneous observations means that all levels of the atmosphere may be studied in the same flare. Although numerous solar-flare observations already exist, amazingly there are none of the type we have proposed: full-wavelength-coverage optical spectra with high spectral resolution and good time resolution. (One set of optical observations at high spectral resolution covers portions of the optical spectrum for a white light flare, which is a relatively rare flare event.¹) The design of solar spectrographs allows very high quality line profiles but usually with small wavelength coverage; the advantage of an echelle to get both of these has been largely employed in the stellar domain. The best high-resolution solar spectrograph with full spectral coverage is a Fourier transform spectrometer, which cannot observe time-variable phenomena over a large spectral range. Indeed, the Hamilton spectrograph at the Lick Observatory is unique even among stellar spectrographs in its ability to cover the entire optical wavelength range in one exposure with a resolution sufficient for good line profiles. This performance is possible because the Hamilton spectrograph uses prism cross-dispersers and a 2048- × 2048-pixel charge-coupled device (CCD) and because it is designed to give up a sky measurement between each order.

With full spectral coverage in the optical, we have many advantages. The greatest one is that the effect of the flare at all levels of the lower atmosphere can be determined simultaneously. The cores of the Ca lines and H α are formed in the upper chromosphere. The wings of these lines are formed successively lower, scanning through the temperature minimum and into the photosphere. The photospheric absorption lines are formed throughout the photosphere (the stronger ones higher up). The continuum itself is formed lowest. By looking at differential effects in various parts of the spectrum before and during a flare, one gets a direct measurement

of the heating effects as they propagate down into the atmosphere. The predicted response of the atmosphere to x-ray, extreme ultraviolet, or particle heating can be tested with such information, to determine which of these models is appropriate. Then the time scale and amount of heating at each level can be studied. Furthermore, with observations of several solar flares, we can test the prediction of Hawley and Pettersen² that long heating time scales and increased area coverage are responsible for big flares, instead of a different heating mechanism.

Solar observations of this type can be compared with stellar observations, which typically do cover a large amount of spectrum (although without such resolution). Such stellar diagnostics as the relative strengths of hydrogen Balmer and CaII emission at different times during the flare can for the first time be measured on the Sun, providing a direct test of the applicability of the solar analog to flares on other stars. In addition, we hope to use the Hamilton spectrograph on the Lick 3-m telescope to obtain flare spectra on a few stars, such as AD Leo, that flare quite frequently, so we can directly compare the line profile changes during flares.

Progress

We encountered tremendous difficulty in adapting the telescope and spectrograph system at the Lick Observatory to take spectra of a solar flare. We used the 0.6-m coudé auxiliary telescope (CAT) to feed the Hamilton spectrograph. By stopping down the primary to approximately 8 in. and placing a Mylar filter in front of the primary, we can take spectra of the solar disk without damaging any of the optics or filling the wells in the CCD. However, we need to guide on an H α image of the Sun to recognize and take spectra of a flare. Many experiments were performed to adapt a narrow-band H α filter to the guide camera that looks at the spectrograph slit. These all failed, and it became apparent that new reimaging optics were required to properly feed the H α filter and the guide camera.

We then tried a new approach. The CAT itself stays fixed in the observatory dome and is fed by a siderostat. Since we stop down the CAT aperture, there is plenty of beam from the siderostat that is not used. We mounted an 8-in. Meade telescope equipped with a Daystar 0.06-nm H α filter and a CCD camera in the siderostat beam. We were then able to use white light features (sunspots) to align the H α image with the image on the spectrograph slit and mark the position of the slit on the H α monitor. With this setup, we can take a spectrum spanning the range of 350 to 900 nm in a single exposure with a resolution $\lambda/\Delta\lambda \approx 48,000$ of any feature observed in H α .

On March 6, 1993, we observed a GOES M7.7 soft-x-ray classification solar flare. Figure 1 shows selected orders of the optical spectrum obtained during the flare. In addition to the high-resolution information shown in Figure 1, we can bin the echelle spectra to study the continuous spectrum of the flare. In Figure 2, we show some evidence for the continuous spectrum becoming bluer later in the flare. The observations and a preliminary analysis have been presented in Johns et al.,³ and a full analysis of these data is under way. We have compared the Balmer line profiles from this flare with the nonlocal thermodynamic equilibrium (non-LTE) model flare atmospheres calculated by Hawley and Fisher⁴ using the code MULTI. The observations are well bracketed by the range of models published. In the near future, we plan to actually fit the observed line profiles to better discriminate between the various models. This will be done for each flare spectrum so we can trace the temporal response of the solar chromosphere to the flare. We also observe changes in the line profiles of many strong FeI and FeII lines. Because these lines are formed deeper in the photosphere, we plan to use an LTE model atmosphere code along with the Harvard-Smithsonian reference atmosphere to determine the depth of heating reached by the flare as a function of time through the event.

Figure 1. Selected orders from the spectrum of the March 6, 1993, solar flare taken at 20:56 universal time. The spectrum is divided by a quiet Sun spectrum to enhance the line emission observed. Several line identifications are noted.

Figure 2. The full spectrum of the solar flare observed at two different times. The spectra are binned to approximately 6-nm resolution and have been divided by a quiet Sun spectrum. A possible blueing of the continuous spectrum occurs late in the flare. The two spectra are offset for clarity. UT = universal time.

In addition to solar flares, we have made efforts to obtain echelle spectra of stellar flares so we can compare them with solar flares. So far, we have caught only a small flare on the dMe star AD Leo during an observational campaign in support of directed observations with the Extreme Ultraviolet Explorer (EUVE) satellite, which have been reported in Cully et al.⁵ and Hawley et al.⁶ These observations were made with the CAT, and because of the relative weakness of the flare, they are not quite suitable for this study. Observations will continue.

-
1. Mauas, P. J. D. (1990), "The White Light Flare of 15 June 1982," *Astrophys. J.* **74**, 609.
 2. Hawley, S. L., and B. J. Pettersen (1991), "The Great Flare of 12 April 1985 on AD Leo," *Astrophys. J.* **378**, 725.
 3. Johns, C. M., G. Basri, and S. L. Hawley (1993), "Echelle Spectra of the 6 March 1993 Solar Flare," *Bull. Am. Astron. Soc.* **25**, 189 abs.
 4. Hawley, S. L., and G. H. Fisher (in press), "Solar Flare Model Atmospheres," *Astrophys. J.*
 5. Cully, S. L., O. H. W. Siegmund, G. Fisher, C. M. Johns, S. L. Hawley, and T. Simon (1993), "A CME Model for a Large EUV Flare on AU Mic," *Bull. Am. Astron. Soc.* **25**, 860.
 6. Hawley, S. L., S. E. Deustua, S. L. Cully, G. H. Fisher, C. M. Johns, T. Simon, V. V. Smith, and W. J. Spiesman (1993), "Simultaneous Optical EUVE Observations of a Flare on AD Leo," *Bull. Am. Astron. Soc.* **25**, 856 abs.

References

Center for Geosciences

Seminars

November 3, 1992

“Fractals in Geology and Geophysics”

Don Turcotte, Cornell University

November 5, 1992

“Hydrothermal Systems Associated with Stratovolcanoes”

Bob Criss, UC Davis

December 4, 1992

“What’s New at CHiPR?”

Alexandra Navrotsky, Princeton University

January 27, 1993

“Seismic Gaps”

David Jackson, UC Los Angeles

March 4, 1993

“Experimental Constraints on Subduction Zone Metasomatism”

Craig Manning, UC Los Angeles

May 6, 1993

“D/H Ratios of Hydrous Phases in SNC Meteorites: Implications for H₂O on Mars”

Laurie Watson, California Institute of Technology

May 11, 1993

“Ridge Forces, Absolute Plate Motions, and the Intraplate Stress Field”

George Zandt, LLNL

July 29, 1993

“Magma Mixing Revisited”

Charles Lesher, UC Davis

September 23, 1993

“Constraining Molecular Models of Ion Sorption Spectroscopy”

Peggy O’Day, UC Berkeley

Center for High-Pressure Sciences

Seminars

October 6, 1992

"Critical Phenomena in Metallic Liquids"

Sergei Stishov, Institute of Crystallography, Moscow

December 7, 1992

"Magnetic Instability Induced by Pressure in Cubic Ce Intermetallics"

Patrizia Monachesi, Università dell'Aquila, Italy

December 10, 1992

"Application of Synchrotron Radiation in High-Pressure Diamond Anvil Cell Research"

David Mao, Carnegie Institute of Washington

January 12, 1993

"Theoretical Calculations of the Structural Stability of Elemental Rare Earths and Actinides"

John Wills, Los Alamos National Laboratory, New Mexico

March 30, 1993

"From Quantum Mechanics to Atomistic Modeling Materials Science: A Challenge for Computer Simulations"

Roberto Car, University of Geneva and IRRMA, Lausanne, Switzerland

March 31, 1993

"Nonlinear Optics Probe of Electronic States of Alkali Halides at High Pressure"

William Daniels, University of Delaware

June 3, 1993

"Detonation of Condensed Explosives: Multiscale Approach"

Roger Cheret, Commissariat à l'Energie Atomique, Paris, Cedex, France

July 8, 1993

"Condensed Matter Problems in Stellar Astrophysics"

Gilles Chabrier, France

August 27, 1993

"A New Laser (16 to 18 μm) for Use in Photo-Induced Raman and Reflection Studies of High-Temperature Superconductors"

Eugene Kudriavtsev, Lebedev Physical Institute, Russian Academy of Sciences, Russia

Workshop

June 28, 1993

Joint AIRAPT/APS Topical Conference on High-Pressure Science and Technology, Iron Section

Astrophysics Research Center

Seminars

October 2, 1992

"Photodissociation Regions in Planetary Nebulae"

James Graham, UC Berkeley

October 9, 1992

"Collapse of Magnetized Clouds"

Daniele Galli, UC Berkeley

October 13, 1992

"Angular Momentum Transport Dynamo Activity in Thin Accretion Disks"

Pat Diamond, UC San Diego

October 16, 1992

"The Ultraviolet Spectra of Star-Forming Galaxies"

Anne Kinney, Space Telescope Science Institute

October 30, 1992

"Constraints on the s-Process in Stellar Models from Experimental Nuclear Measurements"

Franz Kappeler, Institut für Kernphysik, Karlsruhe, Germany

October 30, 1992

"Geminga: King of the Gamma-Ray Pulsars"

Jules Halpern, Columbia University

November 3, 1992

"Search for ^{138}La Isotopic Anomaly and the Nucleosynthetic Origin of ^{26}Al "

Typhoon Lee, UC Berkeley

November 6, 1992

"Cooling Flows and Clusters of Galaxies"

Richard Mushotzky, NASA, Goddard Space Flight Center

November 13, 1992

"Voyages to Giant Planet Magnetospheres"

Fran Bagenal, University of Colorado

November 20, 1992

"An Overview of Recent Results from the Ulysses X-Ray Experiment"

Kevin Hurley, UC Berkeley

November 23, 1992

"Isotopic Si Anomalies in SiC Meteoritic Grains"

Roberto Gallino, Istituto di Fisica Generale deli' Universita Torino

December 4, 1992

“Hard-X-Ray Spectra and Quasi-Periodic Oscillations of Black-Hole Candidates:
Recent Results from Granat and MIR”

Rashid Sunyaev, Space Research Institute of the Academy of Science, Moscow,
Russia

December 4, 1992

“Probing the Radial Age/Metallicity Degeneracy in Early-Type Galaxies”

David Silva, National Optical Astronomical Observatory

December 9, 1992

“Cosmological ‘Seed’ Magnetic Field from Inflation”

Bharat Ratra, Princeton University

December 10, 1992

“The Age Metallicity Relation of the LMC as Seen from Clusters and Field Stars”

Ed Olszewski, University of Arizona

December 18, 1992

“Large-Scale Dynamics from Peculiar Velocities”

Avishai Dekel, Hebrew University of Jerusalem, Israel

January 22, 1993

“Absolute Magnitudes of RR Lyrae Variables, H_0 and Ω ”

Allan Sandage, Observatories of the Carnegie Institute of Washington

January 29, 1993

“Physics and Astrophysics of Quark-Gluon Plasmas”

Charles Alcock, IGPP-LLNL

January 29, 1993

“Keck Telescope Status Report”

Claire Max, IGPP-LLNL

February 5, 1993

“Degree-Scale CXBR Anisotropy Studies: Results from the Comparisons between
MAX Measurements and UCSB South Pole HEMT Measurements”

Peter Meinhold, UC Santa Barbara

February 11, 1993

“Photoevaporating Clouds in Orion”

Peter McCullough, UC Berkeley

February 12, 1993

“Energetic Electrons in Jupiter’s Magnetosphere”

Imke de Pater, UC Berkeley

February 19, 1993

“Origin and Evolution of Comets”

Jane Luu, UC Berkeley

February 26, 1993

"The Nucleosynthesis History of ω Centauri"

George Wallerstein, University of Washington

March 4, 1993

"Radiative Transfer in Homogeneous Spherical Clouds"

Hendrik van de Hulst, Leiden University, The Netherlands

March 5, 1993

"Winds from Late-Type Stars"

Moshe Elitzur, University of Kentucky

March 9, 1993

"Far-Infrared Line Images of Galaxies"

Sue Madden, Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany

March 12, 1993

"Emission Line Nebulae in Cluster Cooling Flows"

Megan Donahue, Observatories of the Carnegie Institute of Washington

March 19, 1993

"A Baryonic Universe: What You See Is What There Is"

Jeremiah P. Ostriker, Princeton University

March 19, 1993

"The History of the Galactic Bulge"

Mike Rich, Columbia University

March 26, 1993

"First Observation of Extragalactic TeV Gamma Rays"

Carl Akerlof, University of Michigan, Center for Particle Astrophysics

April 2, 1993

"The First Data from the MACHO Project"

David Bennett, IGPP-LLNL

April 9, 1993

"The Emergence of Magnetic Flux through Stellar Interiors"

George Fisher, UC Berkeley, Space Sciences Laboratory

April 16, 1993

"New Constraints on the Evolution of Faint Blue Galaxies"

Matt Bershad, UC Santa Cruz

April 23, 1993

"Nucleosynthesis by Asymptotic Giant Branch Stars in the Small Magellanic Cloud"

David Lambert, University of Texas at Austin

April 30, 1993

"Recent Results from the Extreme Ultraviolet Explorer"

Stuart Bowyer, UC Berkeley, Center for EUV Astronomy

May 3, 1993

“High-Energy Variability in Active Galactic Nuclei”

Rick Edelson, NASA, Goddard Space Flight Center

May 7, 1993

“Galaxy Chemistry”

John Huchra, Harvard University

May 12, 1993

“New Telescope Optics: Large, Fast, and Adaptive”

Roger Angel, University of Arizona

May 21, 1993

“A New URCA Process”

Maurice Aufderheide, E Division, LLNL

May 25, 1993

“IR Spectra of Post-AGB Stars”

Kay Justtanont, Institut d’Astrophysique, Paris, France

May 28, 1993

“Gamma-Ray Jets”

Roger Blandford, California Institute of Technology

June 11, 1993

“X-Ray Spectroscopy with XSPECT/SODART Telescopes of Spectrum
X-Gamma”

Herb Schnopper, Danish Space Research Institute

June 18, 1993

“Interstellar PAHs and Interstellar Dust”

Alexander Tielens, NASA, Ames Research Center

June 25, 1993

“Spectral Evolution of Galaxies in Clusters”

Stephane Charlot, LLNL and UC Berkeley

July 2, 1993

“Globular Clusters in the Milky Way: Utopia or Post-Holocaust”

Steve Murray, UC Berkeley and LLNL

July 9, 1993

“The Difference between Globular Clusters and Elliptical Galaxies”

Michael Gregg, IGPP-LLNL

July 16, 1993

“The Thermal Structure of Outflows from Young Stellar Objects”

Pedro Safier, UC Berkeley

July 23, 1993

“Toward a Generic Big Bang: A New Direction in Numerical Relativity”

Beverly Berger, Oakland University

July 30, 1993

“Smooth Particle Hydrodynamics and Applications in Astrophysics”

Leigh Brookshaw, UC Davis

August 6, 1993

“Gamma Rays from Galactic Black Holes”

Edison Liang, Rice University

August 13, 1993

“X-Ray-Heated Winds from Accretion Disks”

Todd Woods, LLNL

August 20, 1993

“Geometrical Tests of Dark Matter in Clusters and Elliptical Galaxies from X-Ray Observations”

Claude Canizares, Massachusetts Institute of Technology

August 27, 1993

“Supernova Mechanisms and Equations of State”

Jerry Cooperstein, Oregon State University

August 31, 1993

“The Two Solar Neutrino Problems”

Sidney Bludman, University of Pennsylvania, Center for Particle Astrophysics

September 2, 1993

“The Sequencing of Long and Short Outbursts in Dwarf Novae—Clues to the Physics of Accretion Disks”

John Cannizzo, NASA, Goddard Space Flight Center

September 3, 1993

“Spectroscopy of Extragalactic Globular Clusters and Insights into Galaxy Formation”

Jean Brodie, UC Santa Cruz

September 10, 1993

“Clusters of Galaxies and the Mean Density of the Universe”

Douglas Richstone, University of Michigan

1993

- Alcock, C. R., C. W. Akerloff, R. A. Allsman, T. S. Axelrod, D. P. Bennett, S. Chan, K. H. Cook, K. C. Freeman, K. Griest, S. L. Marshall, H. S. Park, S. Perlmutter, B. A. Petreson, M. R. Pratt, P. J. Quinn, A. W. Rodgers, C. W. Stubbs, and W. Sutherland (1993), "Possible Gravitational Microlensing of a Star in the Large Magellanic Cloud," *Nature* **365**, 621.
- Akers, W. T., M. Grove, M. Harrison, and F. J. Ryerson (1993), "The Instability of Rhabdophane and Its Unimportance in Monazite Petrogenesis," *Chem. Geol.* (in press).
- Ammon, C., and G. Zandt (1993), "Receiver Structure beneath the Southern Mojave Block, California," *Bull. Seismol. Soc. Am.* **83**, 737.
- Anderson, O. (1993), *Physics of Iron*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-CONF-930676.
- Arons, J. (1993), "Magnetic Field Topology in Pulsars," *Astrophys. J.* **408**, 160.
- Arons, J., and I. R. King (1993), "A Reprocessing Model for the Ultraviolet and Optical Light from 4U 1820-30," *Astrophys. J.* **413**, L121.
- Arons, J., and M. Tavani (1993), "High-Energy Emission from the Eclipsing Millisecond Pulsar PSR 1957+20," *Astrophys. J.* **403**, 249.
- Aufderheide, M. (1993), "Convection and Neutrino Emission in the Late Stages of Massive Star Evolution," *Astrophys. J.* **411**, 813.
- Baker, G. E., L. J. Burdick, and J. B. Minster (1993), "Regional Broadband Waveforms: Individual Station and Three-Component Array Analysis of Nuclear Explosion Sources Crossing a Southern California Path," in *Proc. 15th Ann. Seis. Res. Symp.*
- Bazan, G., and J. C. Lattanzio (1993), "Energy Generation in Convective Shells of Low-Mass, Low-Metallicity Asymptotic Giant Branch Stars," *Astrophys. J.* **409**, 762.
- Bennett, D. P., and S. H. Rhie (1993), "COBE's Constraints on the Global Monopole and Texture Theories of Cosmic Structure Formation," *Astrophys. J.* **406**, L7.
- Benson, D. J. (1993), "An Analysis by Direct Numerical Simulation of the Effects of Particle Morphology on the Shock Compaction of Copper Powder," *Model. Sim. Mater. Sci. Eng.* (submitted).

- Benson, D. J. (1993), "The Calculation of the Shock Velocity-Velocity Relationship for a Copper Powder by Direct Numerical Simulation," *Wave Motion* (in press).
- Benson, D. J., and W. J. Nellis (1993), "Dynamic Compaction of Copper Powder: Computation and Experiment," *Appl. Phys. Lett.* (in press).
- Brookshaw, L., and M. Tavani (1993), "Wind-Driven Angular Momentum Loss in Binary Systems, I. Ballistic Case," *Astrophys. J.* **410**, 719.
- Carrigan, C. R. (1993), "Two-Component Magma Transport and the Origin of Composite Intrusions and Lava Flows," in *Magmatic Systems*, M. P. Ryan, Ed. (Academic Press).
- Charlot, S., and M. Fall (1993), "Lyman-Alpha Emission from Galaxies," *Astrophys. J.* **415**, 580.
- Charlot, S., F. Ferrari, G. Mathews, and J. Silk (1993), "Truncated Initial Mass Function in Starburst Galaxies," *Astrophys. J.* **419**, L57.
- Duba, A., and S. Constable (1993), "The Electrical Conductivity of Lherzolite," *J. Geophys. Res.* **98**, 11885.
- Duong, H., M. Beeman, and J. Wolfenstine (1993), "Creep and Dislocation Substructure of KCl-KBr Solid Solution Alloys," *Acta Metall. Mater.* (submitted).
- Duong, H., M. Beeman, and J. Wolfenstine (1993), "Creep Behavior of Potassium Chloride-Rubidium Chloride Solid Solution Alloys," *J. Am. Ceram. Soc.* **76**, 185.
- Field, G. B., and R. D. Rogers (1993), "Radiation from Magnetized Accretion Disks in Active Galactic Nuclei," *Astrophys. J.* **403**, 94.
- Flegal, A. R., H. Maring, and S. Niemeyer (1993), "Anthropogenic Lead in Antarctic Sea Water," *Nature* **365**, 242.
- Gentile, N., M. Aufderheide, G. Mathews, F. Swesty, and G. Fuller (1993), "The QCD Phase Transition and Supernova Core Collapse," *Astrophys. J.* **414**, 701.
- Graham, J. R., T. M. Herbst, K. Matthews, G. Neugebauer, and B. T. Soifer (1993), "H₂ Morphology of Young Planetary Nebulae," *Astron. J. Lett.* **408**, L105.
- Graham, J. R., E. Serabyn, T. M. Herbst, K. Matthews, G. Neugebauer, B. T. Soifer, T. D. Wilson, and S. Beckwith (1993), "A Spatially Resolved Photodissociation Region in the Planetary Nebula NGC 7027," *Astrophys. J.* **105**, 250.
- Gratz, A., W. Nellis, and N. Hinsey (1993), "Observations of High-Velocity, Weakly Shocked Ejecta from Experimental Impacts," *Nature* **363**, 522.
- Gurrola, H. G., E. Baker, and J. B. Minster (1993), "Simultaneous Time Domain Deconvolution with Application to Receiver Functions," *Geophys. J. Int.* (submitted).

- Hirsch, L. M., and T. J. Shankland (1993), "Quantitative Olivine-Defect Chemical Model: Insight on Electrical Conduction, Diffusion, and the Role of Fe Content," *Geophys. J. Int.* **114**, 21.
- Hirsch, L. M., T. J. Shankland, and A. G. Duba (1993), "Electrical Conduction and Polaron Mobility in Fe-Bearing Olivine," *Geophys. J. Int.* **114**, 36.
- Leloup, P. H., T. M. Harrison, F. J. Ryerson, C. Wenji, L. Qi, P. Tapponnier, and R. Lacassin (1993), "Structural, Petrological and Thermal Evolution of a Tertiary Ductile Strike-Slip Shear Zone, Diancang Shan, Yunnan," *J. Geophys. Res.* **98**, 6715.
- Keto, E., R. Ball, J. Arens, G. Jernigan, M. Meixner, C. Skinner, and J. Graham (1993), "The Mid-Infrared Radio Correction at High Angular Resolution: NGC 253," *Astrophys. J. Lett.* **413**, L23.
- Mangino, S. G., G. Zandt, and C. J. Ammon (1993), "The Receiver Structure beneath Mina, Nevada," *Bull. Seismol. Soc. Am.* **83**, 542.
- Mayle, R., M. Tavani, and J. Wilson (1993), "Pions, Supernovae, and the Supranuclear Matter Density Equation of State," *Astrophys. J.* **418**, 398.
- Meixner, M. (1993), *A Mid-IR Imaging and Millimeter Interferometer Study of Evolved Stars: Filling in the Missing Link of Planetary Nebula Formation*, Ph.D. thesis, University of California, Berkeley.
- Meixner, M., and A. G. G. M. Tielens (1993), "Models of Clumpy Photo-dissociation Regions," *Astrophys. J.* **405**, 216.
- Meixner, M., C. Skinner, P. Temi, D. Rank, J. Bregman, J. R. Ball, E. Keto, J. Arens, and J. G. Jernigan (1993), "2–12.5 Micron Imaging of IRAS 21282+5050: The Structure of a Young Planetary Nebula," *Astrophys. J.* **411**, 266.
- Nicol, M., T. F. Cooney, H. Cynn, A. Koumvakalis, S. K. Sharma, and J. Yen (1993), "Spectral, Chemical and Phase Changes at High P and T: Recent Results for $\text{NH}_3\text{H}_2\text{O}$, Ruby, and MgAl_2O_4 Spinel," in *Proc. 13th AIRAPT Conf. High Pressure Research and Technology*, A. K. Singh, Ed. (Oxford and IBH Publishing, New Delhi), p. 223.
- Nimz, G., K. Cameron, and S. Niemeyer (1993), "The La Olivina Pyroxenite Suite and the Isotopic Compositions of Mantle Basalts Parental to the Mid-Cenozoic Arc Volcanism of Northern Mexico," *J. Geophys. Res.* **98**, 6489.
- Olivier, S., C. E. Max, D. T. Gavel, and J. M. Brase (1993), "Tip-Tilt Compensation: Resolution Limits for Ground-Based Telescopes Using Laser Guide Star Adaptive Optics," *Astrophys. J.* **407**, 428.
- Olivier, S., J. Primack, G. Blumenthal, and A. Dekel (1993), "Significant Cluster Correlations at $30 \text{ h}^{-1} \text{ Mpc}$: Can Standard Models Be Ruled Out?" *Astrophys. J.* **408**, 17.

- hr/>
- Protti, M., S. Y. Schwartz, and G. Zandt (1993), "Simultaneous Inversion for Earthquake Locations and Velocity Structure under Central Costa Rica from Local Network Data," *Seismol. Res. Lett.* **64**, 14.
- Protti, M., S. Y. Schwartz, and G. Zandt (1993), "Subduction-Related High- and Low-Velocity Anomalies beneath Central Costa Rica: Results from Simultaneous Inversion for Earthquake Locations and Velocity Structure," *EOS Trans. Am. Geophys. Union* **74**, 420.
- Qian, Y.-Z., G. M. Fuller, G. J. Mathews, R. W. Mayle, J. R. Wilson, and S. E. Woosley (1993), "Connection between Flavor Mixing of Cosmologically Significant Neutrinos and Heavy-Element Nucleosynthesis in Supernovae," *Phys. Rev. Lett.* **71**, 1965.
- Rundle, J. (1993), "Magnitude-Frequency Relations for Earthquakes Using a Statistical Mechanical Approach," *J. Geophys. Res.* **98**, 21943.
- Schwartz, S., and T. Lay (1993), "Complete PP-Waveform Modeling for Determining Crust and Upper-Mantle Structure," *Geophys. J. Int.* **112**, 210.
- Seidl, M. A. (1993), *Form and Process in Channel Incision of Bedrock*, unpublished Ph.D. thesis, University of California, Berkeley.
- Smith, A. (1993), "Discrimination of Explosions from Simultaneous Mining Blasts," *Bull. Seismol. Soc. Am.* **83**, 160.
- Spinrad, H., A. Dey, M. Yates, M. Dickinson, and W. van Breugel (1993), "3C 364: A Steep-Spectrum Radio Galaxy at $z = 0.92$," *Astron. J.* **106**, 6.
- Steck, L., and W. Prothero, Jr. (1993), "Observations of Direct P-Wave Slowness and Azimuth Anomalies for Teleseisms Recorded in Long Valley Caldera, California," *Bull. Seismol. Soc. Am.* **83**, 1391.
- Tavani, M., and L. Brookshaw (1993), "Hidden Slow Pulsars in Binaries," *Astrophys. J.* **413**, L39.
- Tavani, M., and L. Brookshaw (1993), "Modeling Time Variable and Total Eclipses of the Millisecond Pulsar PSR 1744-24A," *Astron. Astrophys.* **261**, L1.
- Tavani, M., and R. London (1993), "Hydrodynamics of Winds from Irradiated Companion Stars in Low-Mass X-Ray Binaries," *Astrophys. J.* **410**, 281.
- Tunaboylu, B., J. McKittrick, and W. J. Nellis (1993), "Shock Compaction of Al_2O_3 - ZrO_2 Compositions," *J. Am. Ceram. Soc.* (in press).
- van Breugel, W., and A. Dey (1993), "Induced Star Formation in a Radio Lobe of 3C 285?," *Astrophys. J.* **414**, 563.
- Vidale, J., and S. Houston (1993), "The Depth Dependence of Earthquake Duration and Implications for Rupture Mechanisms," *Nature* **365**, 45.
- Warren, J. K., J. V. Vallerga, C. W. Mauche, K. Mukai, and O. H. W. Siegmund (1993), "EUVE Observations of UZ Fornacis and AM Herculis," in *Proc. 105th Meeting ASP* (in press).

-
- Warren, J. K., J. V. Vallerger, C. W. Mauche, K. Mukai, and O. H. W. Siegmund (1993), "Extreme Ultraviolet Explorer Observations of the Magnetic Cataclysmic Variable RE 1938-461," *Astrophys. J.* **414**, L69.
- White, R. L., A. L. Kinney, and R. H. Becker (1993), "New High Redshift Damped Lyman-Alpha Absorption Systems and the Redshift Evolution of Damped Absorbers," *Astrophys. J.* **407**, 456.
- Wolfenstine, J. (1993), "Creep and Dislocation Substructure Formation in Ceramic Solid-Solution Alloys," in *Creep and Fracture of Engineering Materials and Structures*, B. Wilshire and R. W. Evans, Eds. (Institute of Materials, London), p. 335.
- Yoo, C. S., N. C. Holmes, M. Ross, D. J. Webb, and C. Pike (1993), "Shock Temperatures and Melting of Iron at Earth Core Conditions," *Phys. Rev. Lett.* **70**, 3931.
-

1992

- Keto, E., R. Ball, J. Arens, G. Jernigan, and M. Meixner (1992), "Characterization of Solid-State Array Cameras for the Mid-IR," *Int. J. Infrared Millimeter Waves* **13**, 1709.
- Keto, E., R. Ball, J. Arens, G. Jernigan, and M. Meixner (1992), "Subarcsecond Midinfrared Imaging of the Nuclei of the Infrared Bright Galaxies NGC 1614 and NGC 7469," *Astrophys. J.* **389**, 223.
- McKittrick, J., B. Tunaboylu, J. D. Katz, and W. Nellis (1992), " Al_2O_3 - ZrO_2 Ceramics with Submicron Microstructures Obtained through Microwave Sintering, Plasma Sintering, and Shock Compaction," in *Proc. Mater. Res. Soc. Symp.* **274**, 149.
- Seidl, M. A., and W. E. Dietrich (1992), "The Problem of Channel Erosion into Bedrock," in *Functional Geomorphology Landform Analysis and Models, Catena Supplement*, K. H. Schmidt and J. de Ploey, Eds., vol. 23, p. 101.

Project No.	UC campus	Student investigators	LLNL investigators	Project title
GP94-02	Santa Cruz	Zhang	Walter	Shear Wave Velocity Structure beneath Central California from Surface-Wave Dispersion
GP94-03	San Diego	Morgan	Zandt	Modeling Small-Scale Asthenosphere Convection under California
GP94-04	San Diego	Shearer	Zandt	Imaging the 80-km Discontinuity with Shear-Coupled P Waves
GP94-05	Santa Cruz	Schwartz	Zandt	Investigation of the April 25, 1992, Cape Mendocino Aftershock Sequence
GP94-07	Berkeley	Romanowicz	Larsen	Continuous GPS Monitoring in Northern California
GP94-10	Santa Cruz	Ammon Ruppert	Zandt	Upper-Mantle P-Velocity Structure beneath Central and Northern California
GC94-11	Los Angeles	Harrison	Ryerson Yin	Crystal Thickening in Southern Tibet over the Last 27 Ma?: The Gangdese Thrust Revisited
GC94-12	San Diego	Constable	Duba	Point-Defect Diffusion and Intrinsic Oxygen Fugacity of Olivine Rock
GC94-13	Berkeley	Nishiizumi Caffee	Finkel ¹⁰ Be	Measurements of Muon-Induced and ²⁶ Al in Terrestrial Quartz
GC94-14	Davis	Criss	Kersting	Oxygen Isotope Values of Basalts and Associated Xenoliths from Quaternary Island-Arc Volcanoes
GC94-15	Santa Cruz	Williams	Ryerson	Actinide Element Partitioning between Coexisting Silicate Melts and Crystals: Constraints
GC94-18	Los Angeles	Harrison	Ryerson	Monazite as a Thermochronometer for Prograde Metamorphism
GC94-20	Los Angeles	Yin Harrison	Caffee Finkel Ryerson	Terrace Ages in Tian Shan Constrained by Cosmic-Ray Dating

Fiscal Year 1994 IGPP-LLNL University Collaborative Research Program

Project No.	UC campus	Student investigators	LLNL investigators	Project title
GC94-21	San Diego	Marti	Caffee Finkel	An Asteroid-Meteorite Link: High Resolution
GC94-48	San Diego	Lal	Caffee Finkel Southon	Studies of Soil Dynamics and Loess Paleoclimate Records Using Cosmogenic Nuclide ^{10}Be
AP94-22	Los Angeles	Morris	Castor	A Numerical Investigation of the Stability of the Gas-Dust Outflows from Cool Red Giant Stars
AP94-23	Davis	Becker	van Breugel Alcock	A VLA Survey of the Sky at 1400 MHz
AP94-25	Berkeley	Graham	Skinner	High-Resolution Mid-Infrared Polarimetric Imaging Observations of Ultracompact HII Regions
AP94-27	Santa Barbara	Stubbs	Alcock Cook	Analysis of Data from the MACHO Project
AP94-29	Santa Cruz	Woosley	Mathews Wilson	The r-Process in Supernovae and Parameterized Nucleosynthesis
AP94-30	San Diego	Fuller	Mathews Mayle	Dark Matter Neutrinos, Weak Interaction Physics, and Supernova Dynamics and Nucleosynthesis
AP94-32	Berkeley	McKee	Klein Bell	Numerical Studies of Fragmentation in Star-Formation Regions
AP94-33	Santa Cruz	Flatte	Max	Atmospheric Characterization for Adaptive Optics
HP94-38	Berkeley	Wenk	Durham	The Development of Preferred Orientation in Ice Investigated by Neutron Diffraction
HP94-40	Davis	Shelton	Radowsky	Semiconductors under High Pressure
HP94-41	San Diego	Maple	Nellis	Shock Compaction and Processing of Nanostructured Materials
HP94-43	Los Angeles	Wasson	Nellis	Experimental Investigation of Shock Effects in Porous Meteoritic and Terrestrial Materials
HP94-44	Berkeley	Jeanloz	Yoo	Melting of Ni and P^+ at Ultrahigh Pressure: A Unique Interlaboratory Comparison

Fiscal Year 1994 IGPP–LLNL University Collaborative Research Program

Project No.	UC campus	Student investigators	LLNL investigators	Project title
HP94-45	San Diego	McKittrick	Nellis	Shock Compaction of Nanocrystalline and Glassy Oxide Ceramics
HP94-47	Los Angeles	Ardell	Ryerson	Pressure-Induced Morphology and Spatial Correlations of (Ni ₃ X) Precipitates in Binary Ni-Based Alloys
HP94-49	Los Angeles	Anderson	Duba	Analysis of the Contradictions of Experiments and Theories Involved in the 1993 Phase Diagram of Iron

Total award: \$566,486

DATE

FILMED

10/6/94

END

[REDACTED]

1