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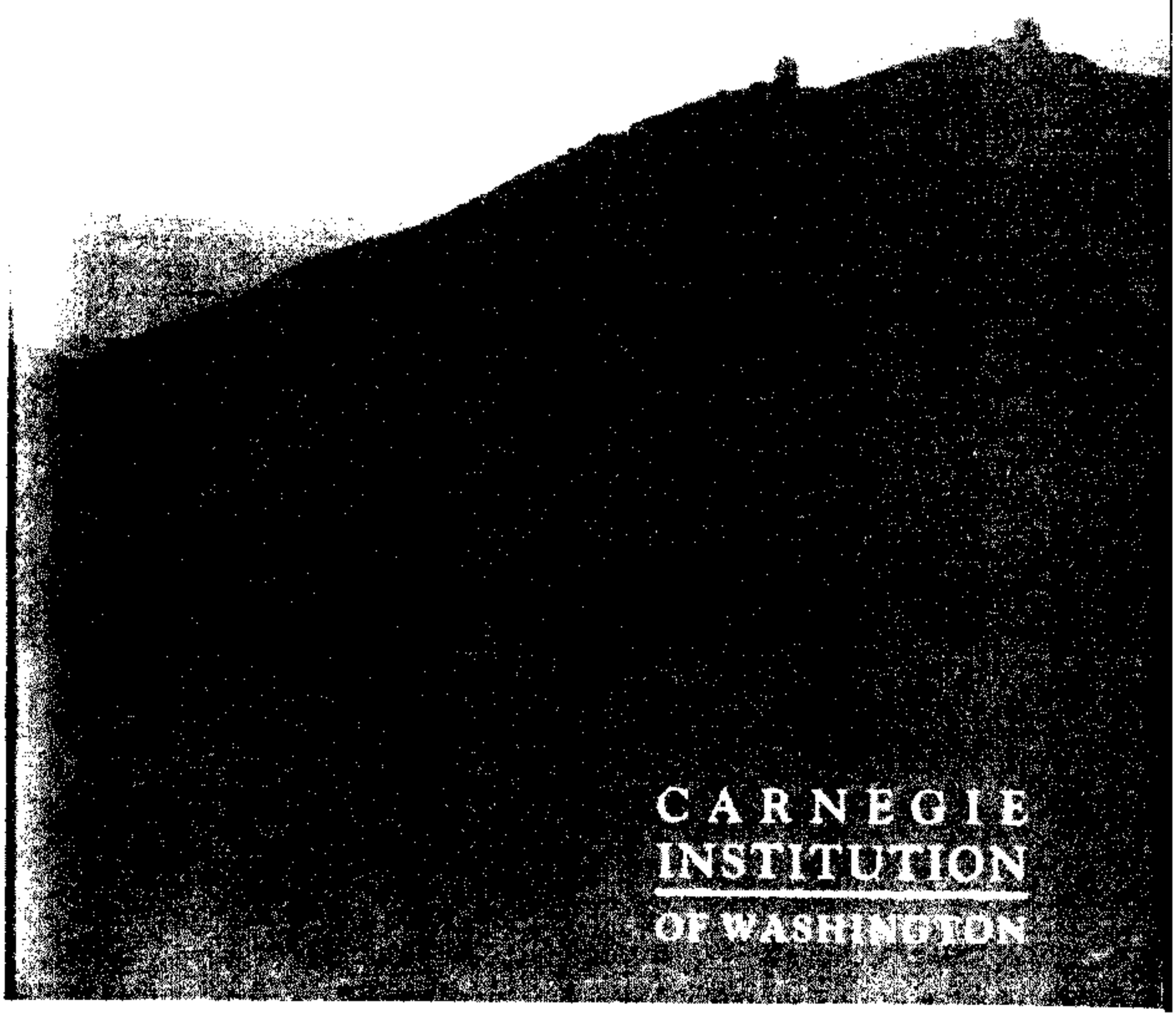
1995–1996

YEAR BOOK 95

The President's Report
July 1,1995-June 30, 1996



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President and Trustees

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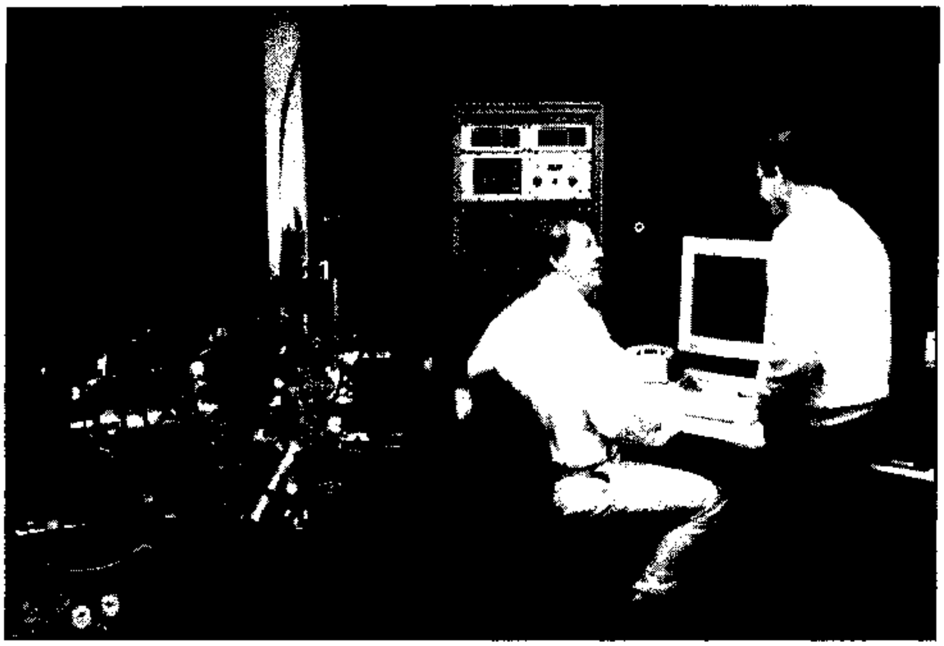
PRESIDENTS

TRUSTEES

The President's Commentary


Focused Images Photography

Carnegie president Maxine Singer



Department of Terrestrial Magnetism staff member Erik Hauri and visitor Vincent Salters from Florida State University with the Cameca IMS 6f ion microprobe at DTM. The instrument, which enables researchers to examine micro-scale variations in trace elements and isotopes by bombarding samples with beams of charged particles, is run as a regional facility, with approximately half the operating time reserved for scientists from other institutions. It was formally dedicated in June 1996. (Photo by Steve Shirey)

These are times of growing apprehension about how deeply the United States and several European countries are committed to the support of scientific research. Because the Carnegie Institution of Washington depends largely on an endowment for its annual operating funds, we feel less threatened by diminishing federal grants than other institutions. This circumstance is the consequence of decisions made decades ago by our trustees to eschew expansion on the basis of "soft" money. In exchange for our scientific independence, we have been somewhat limited in the scope and size of our research efforts. Consequently, our scientists have more freedom than many others to pursue long-term projects and risky new directions.

> *We see our own earth filled with abundance, hut we forget to consider how much of that abundance is owing to the scientific knowledge the vast machinery of the universe has* ***unfolded********
>
> *Thomas Paine*
> *The Age of Reason, Part I*
> 1794*

Besides being more independent in research, Carnegie scientists are relatively free from the academic resP^sibllities that burden their Peers in research universities. They have no formal requirements for teaching. The substantial time and effort they invest in graduate students and postdoctoral fellows rather reflect their recognition that teaching and research are interdependent endeavors. Committee work at Carnegie is generally rare and short-lived, unlike the time-consuming institutional committees that university faculty experience.

These considerations suggest an idyllic world in which Carnegie staff scientists can devote themselves entirely to thinking important thoughts and doing ground-breaking experiments. If there are any ivory towers left in the world, it would seem that Carnegie must be one of them. But it is not and it cannot be. There is no way in the contemporary world for an institution to be an ivory tower and maintain scientific excellence and leadership. Like all research institutions, Carnegie has a complex web of interactions with the larger scientific community and the public.

*I am **grateful** to Timothy Ferris, whose essay "A Message **from** Mars," in **the** *New Yorker* **magarine, August** 19, 1996, p. 4» introduced me to **Paine's** writing about science.

Institutional Review Mechanisms

Consider, for example, the mechanisms by which the Institution obtains peer opinions of its research. A department director reviews the work of each staff member every five years, with the help of evaluations from scientists outside the Institution. Similarly, the president evaluates the department directors' scientific and administrative activities every five years; opinions are sought from department members as well as external reviewers. In both cases, the results are shared, on a confidential basis, with the individuals being reviewed. In addition, each department is assessed by an Institution visiting committee approximately every three years; the committee members include experts from other institutions as well as several Carnegie trustees.

Trustee Gary Ernst (left) and other members of the Visiting Committee to the Geophysical Laboratory met with postdoctoral and predoctoral fellows in February 19%.

Typically, a visiting committee spends two days at a department, and the members have conversations with the president and director as well as the staff members and postdoctoral fellows. The committee can choose to address any topic, including excellence and originality of research, productivity, satisfaction among the staff and fellows, and adequacy of the facilities and resources. The visiting committees* reports are distributed to the trustees and the director, who may then share the evaluation with staff members. Beginning in 1996, the Board of Trustees' newly established Research Committee will review the available visiting committee reports each December. In addition, the newly expanded responsibilities of the Board's Employee Affairs Committee (previously the Employee Benefits Committee) include discussion of the visiting committees' comments on personnel matters, including salaries and benefits.*

Yet another opportunity to measure Carnegie science by external standards is provided by the formal systems that evaluate and rank federal grant applications- Federal grants account for about thirty percent of our annual operating budget and arc critical for the success of particular projects; they provide support for materials, travel, publications, stipends for postdoctoral fellows, and, in the shape of "indirect costs," funds for the infrastructure expenses associated with the related research.

*At its meeting on May 3, 1996, the Board of Trustees made several other changes to the Institution's Bylaws, thereby changing how the Board and its committees will function. The revised Bylaws require two regular meetings of the full Board annually, in May and [illegible]

None of these evaluation methods is perfect. Scientists, and even trustees, bring some biases to the processes. External experts are often longtime colleagues of the scientists being reviewed and may be loathe to be completely honest in their appraisals. Competition, academic politics, and even petty jealousies can influence the opinion of review panels. But together, the several approaches afford a reasonably reliable appraisal of Carnegie research.

The Community of Science

There are other important ways in which Carnegie scientists interact with the broader scientific community, and they provide compelling reasons why scientific research and an ivory tower mentality are no longer compatible. Foremost among them is the need for communication. The pace of research dictates that scientists be in constant touch with colleagues worldwide. Communication is provided at scientific meetings, and by Fax, phone, and email. The scientist who chooses not to be part of the "grapevine" runs a big risk of being left behind, or of missing some development that might advance a particular research project. Thus, it is not now possible, except in extraordinary circumstances, to do research in isolation and still be at the forefront of new knowledge.

The disappearance of the mirage of the ivory tower is, perhaps, most forcefully evident in the tremendous communal effort, often unseen by the public, that fuels and sustains the research enterprise. This effort consists of an active infrastructure of committees, commissions, workshops, and so on. It is based in institutions, in scientific societies, and in the federal government, and it works in both official and informal ways. Through it, the scientific community strives for excellence, establishes research priorities, influences the expenditure and distribution of federal and private funds, and dictates access to major public facilities like the Hubble Space Telescope. It becomes more vital and more complex as limited resources require that institutions share major, unique, and expensive instruments. Any institution whose scientists fail to participate stands a good chance of becoming marginal, no matter how good its own resources and research. This means that citizenship in the scientific community is an ongoing and ever increasing responsibility. It demands time, study, writing, and extensive travel. It requires the nonscientific skills of negotiation and diplomacy. It also holds rewards. It ensures that the views of individual scientists and their institutions are heard. And for the individuals who participate, it avails important contacts and a degree of prestige. Rarely are there financial incentives for individuals and institutions in these efforts. Indeed, it is more likely that there will be extra costs either for the scientist or for her or his home institution. Such costs are willingly assumed as part of regular operations, given the importance of the effort. But it is worth noting that the expenditures are not recognized as "cost-sharing*' in the formulas that federal agencies use to determine institutional contributions to research grants.

The only way *to* convey the full sweep of Carnegie participation in this broad scientific infrastructure is to describe individual efforts. A full accounting makes for an informative but rather boring catalog, and therefore what follows is a very selective summary.

Participation in Scientific Societies

Scientific societies play a major role in the publication of scientific journals. The societies' publication committees set policy for their publications and editorial boards. The boards are then responsible for the review of submitted papers and decisions regarding publication. At stake are the integrity of the published body of scientific knowledge and the reputations and careers of the contributing scientists. Even the direction of research in particular subfields is strongly influenced by the interests and tastes of editors. Thus, editorial board membership is a serious undertaking and can involve many hours of work each week.

DTM's Alan Boss (right) at the 58th Meteoritical Society Meeting in September 1995.

David James and Steve Shirey at the Department of Terrestrial Magnetism (DTM) have assumed such responsibilities for the *Journal of Geophysical Research* and *Geochemkal News*, respectively. At the Geophysical Laboratory, Ron Cohen and Marilyn Fogel serve as editors *of American Mineralogist* and *Ancient Biomokcuks*, respectively. Arthur Grossman at the Department of Plant Biology is an editor of the *Journal of Biological Chemistry,* and Chris Field is a senior editor of Global *Change Biobgy.*

Besides the journals that publish individual reports of new research, there are many review journals where experts annually survey entire fields. One important series of reviews is published by Annual Reviews, Inc., an organization started years ago by scientists. Winslow Briggs, director emeritus of Plant Biology, is on the board of directors of this organization after serving for many years as an editor of the *Annual Review of Plant Physiology and Mokcuhr Biology.* This position is now held by the Department's current director, Christopher Somerville. Somerville is also an editor of several primary journals in plant biology and, interestingly, is a member of the Electronic Publishing Committee of the American Society of Plant Physiologists. George Wetherill, director emeritus of DTM, is an editor of the *Annual Review of Earth and Planetary Sciences,* while DTM's current director, Sean Solomon, serves on the editorial committee that plans the yearly content for these volumes.

Joseph Gall at the Department of Embryology has what must be the most pleasurable of the editorial positions. He is the Art and History Editor of Molecular Biiil(i0 *of the Cell* Each nionth he chooses an historically important illustration for the cover of the journal, and he writes a brief, erudite, and usually charming essay tt) explain the picture.

Scientific societies also organize scientific meetings on local, national, and international scales. Society members are engaged in a variety of related activities. They choose appropriate meeting sites, plan programs, invite speakers, and act as hosts for distinguished participants. Alan Boss at DTM has served over the past few years on committees organizing conferences on subjects ranging from Stardust to protoplanetary disks to the origin of the solar system.

Of course, the societies themselves have governing structures that keep their activities going. Election to a society office is an honor, a sign of great recognition. It can also be a major burden, albeit for a limited term of office. This year, Sean Solomon has the honor and the challenge of the presidency of the American Geophysical Union.

Doing for Others What We Ask Them to Do *for Us*

Just as we ask experts from other institutions to participate in visiting committees to our departments, or to evaluate our staff members, so Carnegie scientists return the favor. A small measure of such activities is apparent in Carnegie's intellectual contributions to Harvard University. Carnegie staff scientists serve on visiting committees in the Departments of Astronomy (DTM's Vera Rubin), Earth and Planetary Sciences (Solomon), Organismal and Environmental Biology (Briggs and Field), and in the Center for Astrophysics (The Observatories' Wendy Freedman). Some visiting committees require long travel to, for example, Australia (Somerville), Japan (Geophysical Lab's Charles Prewitt), Israel (Plant Biology's Joseph Berry), and Taiwan (Geophysical Lab's Ho-kwang Mao). Other visiting committees, functioning as scientific advisory groups, may be established by pure research organizations (exemplified by my service to the Weizmann Institute of Science in Israel), by corporate entities (Somerville's service to the Monsanto Company), or by foundations (Somerville's service to the Noble Foundation).

Federal agencies and their offshoots spend billions of dollars on research each year. Much of this money is given out to research institutions, like Carnegie, in the form of grants and contracts for specific, investigator-initiated research proposals. The peer-review process used by most agencies involves hundreds of committees and thousands of scientists, Carnegie people among them. Federal agencies also use committees to advise them on future initiatives. The Associated Universities for Research in Astronomy (AURA), which runs the Hubble Space Telescope (HST) for NASA, also advises the National Science Foundation (NSF) on the National Observatories at Cerro Tololo, Chile, and Kitt Peak, Arizona, and on the Gemini Project, where two eight-meter national telescopes are planned, one in Chile, the other in Hawaii. Vera Rubin serves on the AURA board, and the Observatories' Alan Dressier serves on the Gemini board. Dressier and Wendy Freedman recently completed work on an AURA committee called HST and Beyond, which was asked to consider the next generation of space telescopes. Dressier chaired this very important committee and served as editor of its published report.

There are also individuals who initiate efforts to fill a perceived need.

Embryology's Don Brown, who has served on the governing council of the National Academy of Sciences and has been president of the American Society for Cell Biology, founded, years ago, the Life Sciences Research Foundation (LSRF). He is still its guiding spirit. The LSRF solicits fellowship support from science-based industry and then dispenses the postdoctoral fellowships to worthy candidates chosen in a highly rigorous and competitive process. Over the years, the LSRF has supported some of the brightest young people in the life sciences.

Research Consortia

In today's world, major research facilities are frequently operated by consortia of institutions, including the federal agencies that provide essential funds. These consortia plan and develop instrumentation and review applications for access to the facilities. The Hubble Space Telescope is an important example; Carnegie astronomers from the Observatories and DTM are active participants in decisions about HST access. Paul Silver and Sean Solomon contribute efforts to IRIS (Incorporated Research Institutions for Seismology), which makes seismic instruments available for a variety of projects. Charles Prewitt has taken a leading role in helping the earth science community access synchrotron radiation sources, in particular, the new Advanced Photon Source at the Argonne National Laboratory. And Prewitt along with Ho-kwang Mao and Russell Hemley spend substantial time with their Princeton and Stony Brook colleagues in planning and managing the NSF-sponsored Center for High Pressure Research. At DTM, Erik Hauri manages access to the department's new ion microprobe. And, not the least, the vitality and accessibility of the data banks for the genomes of the fruit fly Draso *phila* and the experimental plant *Arabidopsis thaliana* owe a great deal to the dedication of Allan Spradling (Department of Embryology) and Christopher Somerville, respectively.

During the past year, Harvard University, the Massachusetts Institute of Technology, and the University of Michigan joined Carnegie and the University of Arizona *in* the Magellan Telescope Project. Consequently, there will be not one but two 6.5-meter telescopes at our Las Campanas Observatory in Chile. This expanded consortium must work out agreements for construction and operation of the telescopes in a way that satisfies the scientific and administrative interests of all the institutions, a formidable task. Leonard Searle, who stepped down as the Crawford H. Greenewalt Director of the Observatories early in 1996 just as the commitments were received from the three new consortium members, worked hard at ensuring the success of this exciting development. Carnegie was very fortunate to recruit Professor Augustus (Gus) Oemler away from Yale to replace Searle in this distinguished Chair. Besides his outstanding accomplishments in astronomical research, Oemler is experienced in the negotiation of telescope consortia agreements, a skill he began immediately to apply to the challenge of the Magellan Project.

Observations

I hope this catalog has conveyed the sheer magnitude of the contributions to the scientific enterprise made by Carnegie scientists over and above their highly productive research. Even more important, it should convey some sense of what it is like to be a scientist in a nation with a vast, vital, and exciting scientific enterprise. Consider, for example, just one person—Christopher Somerville, director of the Department of Plant Biology. His name recurs frequently in this essay not because he does so many more things than anyone else, but to emphasize what all this activity means on a personal level. He, like everyone else, reviews other people's grant applications, referees other people's papers, and writes evaluation letters for proposed appointment and promotions in other institutions; he says that he generally reviews one grant application or manuscript, or writes an evaluation letter, every day, and his estimate (and mine) is that each such task requires, on average, two hours. He frequently talks to colleagues all over the world, he organizes meetings, writes research papers and books, plans for broad access to accumulating data, considers the future directions for his field, talks with the postdoctoral fellows in his lab, worries about appointments, facilities, and instruments in his department, answers the requests of the president and trustees, and, of course, thinks about, plans, and carries out experiments. He even found time this year to contribute his "way cool science" to Bill Nye the Science Guy's children's television program. A day in the life of a scientist in this last decade of the century requires stamina and dedication. Yet most of us cannot imagine a more wonderful existence; the lure of new knowledge is what carries the day.

Plant Biology director Chris SomerviSIe and former postdoctoral associate Christiane Nawrath examine *Arabidopsis* plants.

The ramifications of the scientific enterprise are rarely evident to the larger community. The general public sometimes expresses a sense that the scientific community is disconnected from the nation and its goals and aspirations. In reality, the scientific infrastructure is a critical aspect of the nation's well-being. Carnegie scientists are not unique in their commitment to this effort; a similar story could be told about every significant research institution in the country. The scientific enterprise, like all important human endeavors, is a complex mix of personal interest, individual curiosity, and dedication to the general welfare.

Jerome A. Kristian
(1933-1996)

Losses

We are saddened to report the loss of Jerry Kristian, a staff member of the Carnegie Observatories since 1968 (and a fellow, 1966-1968). Jerry died when his small plane crashed into the Santa Clara River on June 22, 1996. Trained as a theoretician in astrophysics at the University of Chicago (Ph.D., 1963), he became an accomplished observer during his tenure at Carnegie. His work focused on quasar identifications, pulsar timing, gravitational lenses, galaxy imaging at remote look-back times, and the form of the Hubble diagram for the expansion of the universe. Personally, he was a source of quiet inspiration to the staff, giving help to all who asked. He will be sorely missed.

Cyril Grivet
(1947-1996)

We will also miss Cyril Grivet, a technician at the Department of Plant Biology for nine years, who died July 17 when the TWA flight 800 he boarded in New York crashed in the ocean nearby. Holding two master's degree and a doctorate (all from Stanford), Cyril was a master technician in Joe Berry's lab, helping Joe solve intricate math problems to simulate global change.

Oscar Torreson, a DTM staff member from 1923 until 1951, died on December 15, 1995, at the age of 97. He served in a variety of capacities, working at the magnetic observatories in Australia and Peru, and on the *Carnegie* research vessel as navigator and executive officer.

Winslow Briggs
(retired)

George Tunell, Jr., a staff member at the Geophysical Laboratory from 1924 until 1945, died on July 4, 1996, at the age of 96. Tunell came to Carnegie after receiving his doctorate in geology at Harvard. Among his honors was the Mineralogical Society's Roebling Medal in 1973.

Mack Ferguson, custodian and mechanics helper at the GL (1948-1981), died November 25, 1996.

William Quails, custodian/chauffeur at the Observatories (1978-1986), died November 3, 1995.

Leonard Searle
(retired)

Carl Rinehart, instrument maker at DTM from 1964 until his retirement in 1982, died March 21, 1996.

Bessie Smith, laboratory helper at the Department of Embryology (1965-1979), died October 28, 1996.

Felice Woodworth, draftsperson at the Observatories (1965-1978), died April H, 1996.

Retiring. • •

Three longtime Carnegie scientists retired on June 30, 1996: Winslow Briggs, Leonard Searle, and Francis R. Boyd.

Winslow Briggs served as director of the Department of Plant Biology from 1973 until 1993, at which time he stepped down to resume research full time. He plans to continue his research program in photomorphogenesis as a scientific consultant.

Leonard Searle has spent 28 years at Carnegie, serving as Observatories' director from 1990 until June 1996. His research interests include Galactic nuclei and stellar content, Galactic chemical composition, and the evolution of galaxies. He will maintain his office at the Observatories as a staff member emeritus.

Francis R. (Joe) Boyd, a staff member for 43 years, also plans to continue his research at Carnegie, as a consultant. His interests include the composition and history of the Earth's upper mantle, xenoliths of mantle rocks, and high-pressure and high-temperature phase studies.

Ray Bowers, the Institution's editor and publications officer, retired May 31, 1996, after nineteen years of service.

Joe Boyd
(retired)

Ray Bowers
(retired)

• *Qains* •

We welcome new staff members Yingwei Fei and Yixian Zheng.

Yingwei Fei became a staff member at the Geophysical Laboratory on July 1, 1996. He grew up in China and received his Ph.D. in 1989 from City University of New York. He was a predoctoral and then associate staff member at the Laboratory and NSF Center for High Pressure Research, 1988—1996. Among his interests are element partitioning and phase relations in systems related to the Earth's interior, and physical properties of mantle/core material.

Yixian Zheng joined the Department of Embryology in September 1996. She received her B.S. in biology from Sichuan University, China, and her Ph.D. (1992) in molecular biology from Ohio State University. Before coming to Carnegie, she was a postdoctoral fellow at the University of California, San Francisco (1992-1996). Her interests include the arrangement and reorganization of cellular interiors and the control of microtubule nucleation.

Patricia Knesek (Ph.D., University of Massachusetts) joined the Las Campanas Observatory as a resident scientist in October 1995. She studies the morphology, content, and evolution of galaxies.

Patricia Craig was appointed editor and publications officer in June 1996.

New staff member
Yixian Zheng

New staff member
Yingwei Fei

Staff member Alan Dressier

Director Christopher Somerville

Director Sean Solomon

Staff member Vera Rubin

• Honors •

National and International Awards and Honors

The Observatories' Alan Dressier and Plant Biology director Christopher Somerville were elected to the National Academy of Sciences in April 1996.

DTM director Sean Solomon was elected a fellow of the American Association for the Advancement of Science in September 1995.

Joseph Gall of the Department of Embryology was selected to receive a 1996 AAAS Mentor Lifetime Achievement Award.

DTM's Vera Rubin was elected to the National Science Board by President Clinton in July 1996. Rubin was also appointed to the Pontifical Academy of Sciences in October 1996.

Geophysical Laboratory's Ho-kwang Mao was elected a foreign member of the Chinese Academy of Science in June 1996.

Professional Society Awards

Vera Rubin received the Gold Medal of the Royal Astronomical Society (London) during the Society's November 1996 meeting.

Donald Brown was selected to receive the 1996 E. B. Wilson Award from the American Society for Cell Biology.

Former DTM staff member Albrecht Hofmann received the V. M. Goldschmidt Award of the Geochemical Society.

The Geophysical Laboratory's Ho-kwang Mao was selected as a 1996 Geochemistry Fellow of the Geochemical Society and the European Association for Geochemistry,

Former DTM and Geophysical Lab staff members Ikuo Kushiro, George Tilton, Stanley Hart, and former DTM fellow William White were also named Geochemistry Fellows.

Geophysical Lab postdoctoral fellow Tahar Hammouda was awarded the Prix Lacroix from the Société Frangaise de Minéralogie et Cristallographie for his Ph.D. thesis.

Geophysical Lab postdoctoral fellow Pamela Conrad received the Award for Outstanding Student Paper in the Tectonophysics Section of the American Geophysical Union at AGU's 1995 December meeting.

Foundation Awards

Embryology staff member Chen-Ming Fan received a John Merck Fund Scholarship.

The Geophysical Lab's Larry Finger received a Humboldt Award for U.S. Scientists, presented by the Alexander von Humboldt Foundation, Bonn, Germany.

Staff member
Donald Brown

Academic and Institution Awards and Lectureships

Carnegie president Maxine Singer received an honorary degree from the Weizmann Institute of Science in November 1995. On October 26, 1995, she was honored by the Washington Committee for the Weizmann Institute at the Weizmann Founder's Day Event in honor of her longtime service. She received the Mendel Medal at Villanova University on November 20, 1995.

Postdoctoral fellow
Tahar Hammouda

Vera Rubin was awarded the 1996 Weizmann Women & Science Award on June 5 by the American Committee for the Weizmann Institute of Science. She was elected to the first group of Fellows of the Association for Women in Science. She delivered the commencement address to physics and astronomy graduates at the University of California, Berkeley, on May 17, 1996.

Sean Solomon delivered the annual S. Thomas Crough Memorial Lecture at Purdue University in April 1996.

Postdoctoral fellow
Pamela Conrad

Russell Hemley and Ho-kwang Mao of the Geophysical Laboratory were coauthors of a paper, "Vibron excitations in solid hydrogen: a generalized binary random alloy problem" *(Phys. Rev. Lett. 74)*, that won an Alan Berman Award from the Naval Research Laboratory. Visiting investigators J. H. Eggert (Pomona College) and Joseph Feldman (NRL) were also coauthors.

Embryology director Allan Spradling delivered the Larry Sandier Memorial Lecture at the University of Washington on May 6, 1996.

Alan Dressier was the Grubb Parsons Lecturer at the University of Durham, U.K.

Robert Hazen of the Geophysical Lab was the 1996 Dibner Lecturer at the Smithsonian Institution.

Embryology research assistant Tammy Wu and predoctoral fellow Jessica Blumstein won 1996 William D. McElroy Awards for Excellence in Undergraduate Research at Johns Hopkins University. Martha Kimos, a high-school laboratory[7] helper at Embryology, won the Grand Prize at the 44th Annual Baltimore Science Fair for her project mapping a zebrafish mutation.

Staff member
Ho-kwang Mao

Research assistant
Tammy Wu

Geophysical Lab high school intern Amanda Mortl won the Washington regional competition of the 1996 Junior Science and Humanities Symposium, held in January 1996, at Georgetown University. Her paper was about how the amino acid racemization of ostrich eggshells can help scientists track the origins of modern humans.

Allison Macfarlane, visiting investigator at DTM and the Geophysical Lab from George Mason University, received a Bunting Science Fellowship and a John E Kennedy School Fellowship to explore issues of high-level nuclear waste disposal during the 1996-1997 academic year at Harvard University.

High school intern
Amanda MartI

And our trustees • • •

Philip Abelson received the Vannevar Bush Medal from the National Science Foundation Board on May 8.

James Ebert was elected an honorary foreign member of the Korean Academy of Science and Technology on December 9, 1995,

Sandra Faber was appointed University Professor, the highest honor the University of California bestows on its faculty.

William Golden received the 1996 Public Welfare Medal, the highest honor awarded by the National Academy of Sciences, in April 1996.

Trustee Philip Abelson

William Hewlett and David Packard jointly received the Computer Enterprise Award from the IEEE Computer Society on December 7, 1995. Hewlett and his wife, Rosemary, received honorary fellowships at Harris-Manchester College, Oxford University.

Frank Press received the Doctor Honoris Causa degree of the Institut de Physique du Globe de Paris in June 1996.

William Rutter received the 1995 Heinz Award for Technology and the Economy on November 20, 1995.

Trustee emeritus Robert Seamans, Jr. received the 1995 Daniel Guggenheim Medal Award from the American Institute of Aeronautics and Astronautics on May 2, 1996.

Charles Townes received the 1996 Frederick Ives Medal, the highest honor of the Optical Society of America, on October 22, 1996.

Trustee William Golden

Contributions, Gifts, and Private Grants

• TOWARD TOMORROW'S DISCOVERIES •

The Carnegie Institution has received gifts and grants from the following individuals, foundations, corporations > and government agencies during the period from July 1,1995 to June 30, 1996.

FOUNDATIONS AND CORPORATIONS

$100,00041 million

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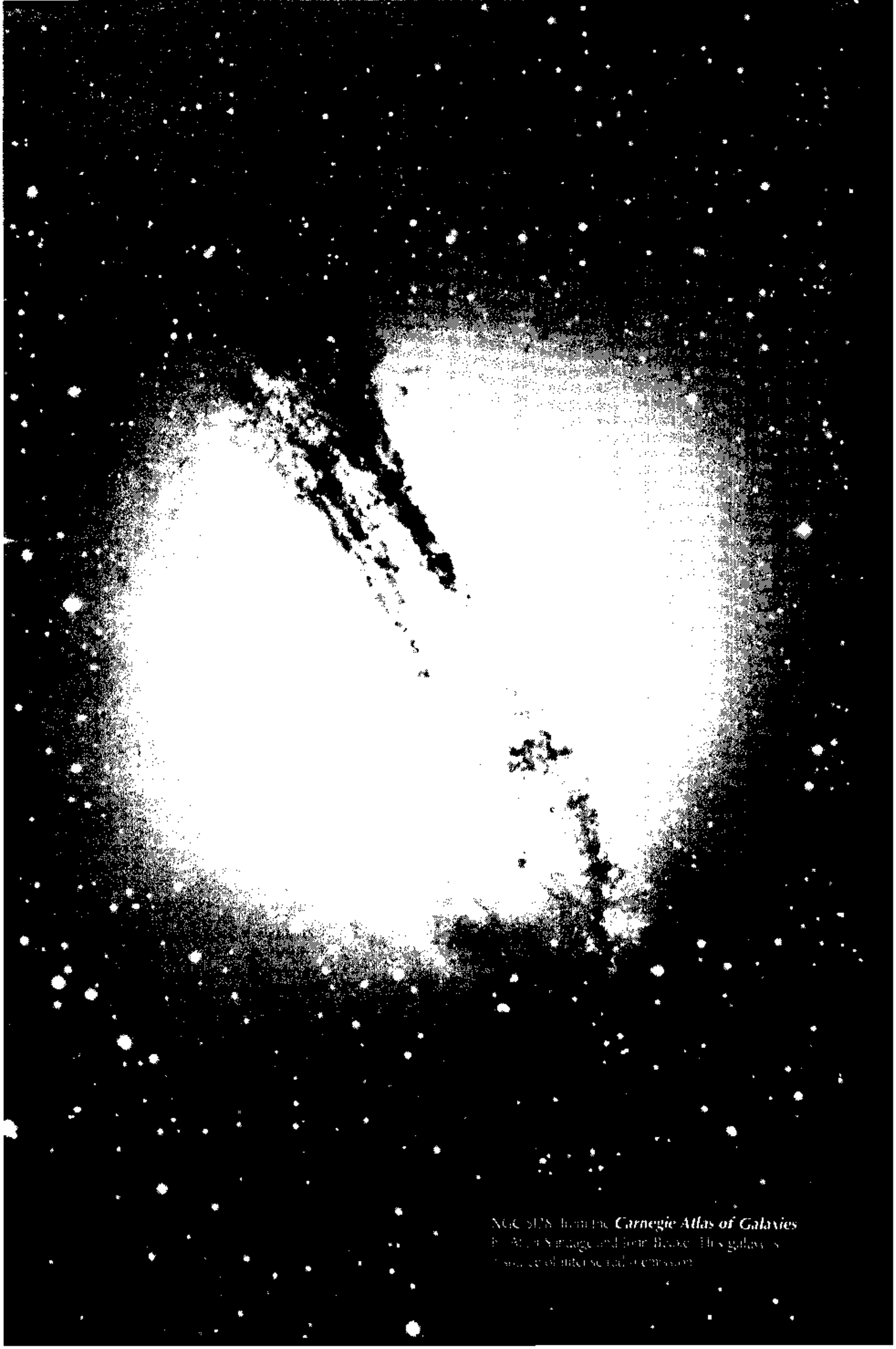
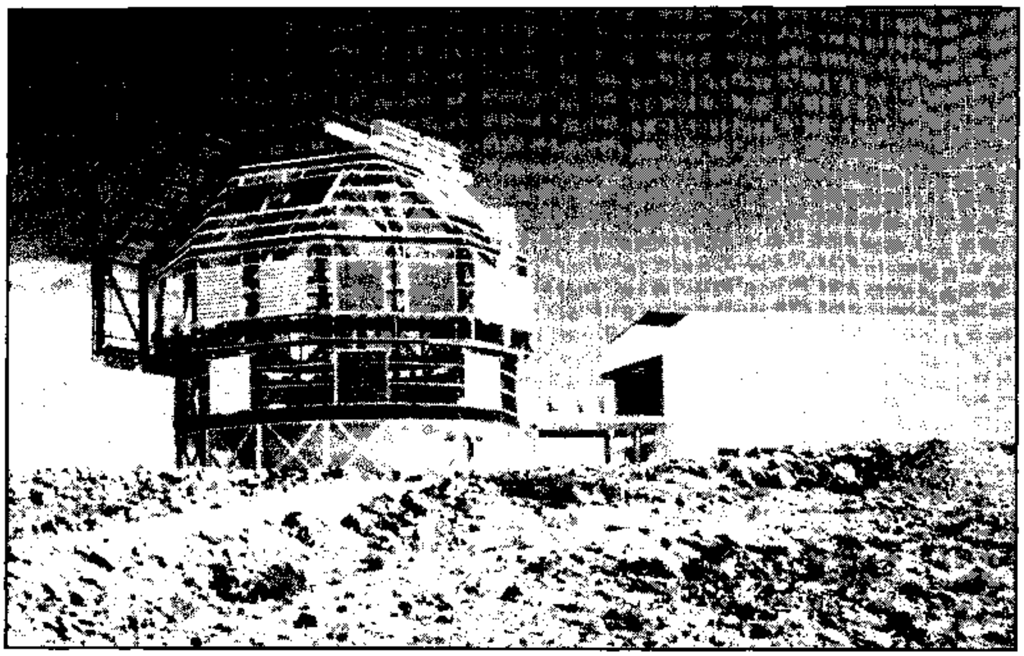


NGC 5128 from the *Carnegie Atlas of Galaxies* by Allan Sandage and John Bedke. This galaxy is a source of intense radio emission.

The Observatories

Morning tea at 813 Santa Barbara Street



Progress continues on the Magellan I telescope at Las Campanas. This photo, taken in August 1996. shows ventilation louvers on the telescope enclosure. First light is expected in 1999. (Photo by Frank Perez.)

Director's Introduction

This has been a landmark year for the Observatories. With the addition of three new members—Harvard University, the University of Michigan, and MIT—the Magellan Consortium is now complete, and the project to construct two 6.5 meter telescopes on Las Campanas is a reality. Carnegie will have a 50% share of the project, Harvard a 20% share, and the University of Arizona, the University of Michigan, and MIT will have about 10% each. This is a very happy combination of strong, like-minded astronomy programs, and we are looking forward to the intellectual partnership with as much expectation as we are to the completion of the telescopes. The first Magellan Project telescope continues to make good progress. As of this writing, the enclosure nears completion at Las Campanas, and the telescope mount is being assembled at L&F Industries. A year from now, the telescope should be installed in the dome, awaiting only the arrival of the primary mirror. First light for Magellan I is anticipated in 1999, with Magellan II following about four years later.

"• • .*JYOYltieTS Lie* ITl *tTUXTty divectiotlSt the faitltest*, *the TtlOSt* ***distant, the earliest,*** *the* ***SmttOest....***"

Completion of the Magellan Project should occur very near the 100th anniversary of the founding of the Observatories. It will mark the end of a century of unsurpassed brilliance for an astronomical institution. Indeed, the history of 20th century astronomy was in large part written by Carnegie Institution astronomers, and at Carnegie Institution telescopes. The challenge before us is to make the Observatories' second century as brilliant as its first. Even if we thought ourselves the equals of George Ellery Hale, Edwin Hubble, and Walter Baade, that would be a very daunting charge, because Hale's task, though no easier, was in many ways simpler than ours. George Ellery Hale stood at the dawn of modern astronomy and astrophysics, which he helped create. Before him lay limitless unanswered questions about the universe; all he had to do was build the biggest telescopes and find the best people to start using them.

Astronomy today is a much more mature field, and the practice of astronomy a much larger enterprise. Entire areas*—stellar evolution, galactic structure—have been developed, if not to completion, at least to the point of diminishing returns* Hordes of astronomers pursue the most fashionable and exciting topics; scarcely an intellectual niche is unfilled by at least a few researchers. Great sums of money are spent by both government and private groups to build new facilities. In 1926, there were 480 members of the American Astronomical Society, of whom 30 worked at the Mount Wilson Observatory. Today, the AAS has 6500 members, and still 30 work at the Carnegie Observatories. In such an environment it is much harder to tower over the field in the way that the Mount Wilson Observatory did in Hale's and Walter Adams's times.

How, then, can the Observatories make a contribution to the astronomy of the 21st century that is worthy of its history? Clearly, by the route that the Carnegie Institution has always followed: finding the great scientists and providing them with the support they need to do great science. Thanks to Magellan, the Observatories will be able to provide its scientists with access to telescopes which is second to none, in an environment for work which no other institution can even approach. What those scientists will be doing—working at the frontiers of our knowledge—is also clear, but where those frontiers will be is today totally obscure. Sometimes those frontiers move quickly. For example, there has been an explosion in our knowledge of the early history of galaxies in the past few years. Sometimes they move painfully slowly. Hobble's program of determining the two fundamental cosmological parameters is still incomplete. It is futile for a scientific institution to try too hard to predict the important problems of even the near future and direct its efforts in those directions. The wise course is, rather, to find the most nimble minds who will head for the frontier wherever it may appear.

Those frontiers lie in many directions: the faintest, the most distant, the earliest, the smallest. The two essays which follow describe two such directions in which Carnegie astronomers now work. Staff member Patrick McCarthy studies high-redshift radio galaxies. These galaxies are among the most distant in space, and therefore distant in time, of any astronomical objects. They provide one of the most effective probes of the early formation history of galaxies. That history, completely unobserved a decade ago, is now being vigorously explored with the Hubble Space Telescope and the new generation of large ground-based telescopes of which Magellan will soon be a member. Hubble Fellow Julianne Dalcanton describes a subtler, and less appreciated, frontier—that of detectability. The very-low-surface-brightness galaxies which she studies are just barely visible above the night sky's glow. Completely ignored until recently, they may represent an important constituent of the universe, and may, like radio galaxies, provide an important handle on the processes of galaxy formation.

—Augustus Oemler, Jr.
Crawford H. *Greenewalt Chair*

The *Sky at Meter Wavelengths*

byPatrick].McCarthy

Before the invention of electric lighting and all of the technological marvels that followed, gazing at the star-filled sky was one of our primary forms of nighttime entertainment. Our eyes, however, give us a limited taste of the wonders of the sky, as they are sensitive to only a thin slice of the electromagnetic spectrum. (See Fig. 1.) If, for example, our eyes were sensitive to the far infrared (where wavelengths are roughly 100 microns, or one tenth of a millimeter), we would see the sky filled with clouds of dust with temperatures of 200 degrees below zero centigrade. Two bright bands would cut across the sky, revealing disks of dust both in the plane of the Milky Way and in the solar system.

Radio galaxies are powerful tools for probing the evolution of the early universe Patrick McCarthy explores the unique characteristics of these giant objects.*

At the long-wavelength end of the spectrum, in the realm of radio astronomy, electromagnetic waves can be as long as a kilometer across. If our eyes were sensitive to radio waves (putting aside the fact that at these wavelengths our one-cm diameter eyes could not resolve even the largest objects in the sky), the Sun would still be the brightest object in the sky. However, the daytime sky would be nearly as dark as the night sky The Milky Way would cut a beautiful swath across the sky, but the light would come not from the stars but from synchrotron radiation, released as cosmic rays travel through the magnetic field of our Galaxy.

At radio wavelengths, we would see virtually no bright stars, but embedded in the plane of the Milky Way would be shells of light with diameters many times that of the full Moon. These are the remnants of supernovae, stars in our Galaxy

Before becoming a staff member in 1993, Patrick McCarthy was a Carnegie Fellow, then a Hobble Fellow, at the Observatories. He received 'both his M.S.. and his Ph.D. (in astronomy) from the University of 'California at Berkeley. Concurrent with his interest in radio .astirofiomy* •he studies galaxy formation and evotucioxi*

The Very Large Array Radio Telescope at the National Radio Astronomy Observatory, Socorro. New Mexico. Courtesy, NRAO.

that exploded hundreds or thousands of years ago. The radio sky contains many other objects that appear unresolved at the resolution of our eyes (which is about one arc minute at visible wavelengths). Most of these sources are radio galaxies and quasars, which are some of the most intrinsically luminous objects in the universe. Radio sources appear bright even though they are among the most distant objects known, lying as much as 15 billion light years away. This is in dramatic contrast to the relatively nearby (only a few tens of thousands *of* light years distant) stars that populate the visible sky. Radio stwrces span a much larger range of intrinsic luminosity than either stars or visible galaxies, so the lists of the apparently brightest radio sources also contain many of the intrinsically most luminous sources at distances comparable to the dimensions of the universe itself.

Since many radio sources are extremely distant, they are particularly well suited for studying how the universe has evolved over time. In particular, we can use radio sources to infer the density and pressure of gas present in the neighborhood of very distant, and hence young, galaxies. For the past few years, I and my colleagues Vijay Kapahi, director of the National Centre for Radio Astrophysics in India, and Eric Persson, Observatories' staff member, have undertaken a large-scale census of the radio sky. Highlighted here, our work illustrates the power of radio astronomy to probe the evolution of the early universe.

A *Southern Hemisphere Radio Survey*

In 1988 we cataloged 543 radio sources above a well-defined brightness limit in a strip of sky that passes nearly overhead at Carnegie's Las Campanas Observatory in Chile. Because the positions of our radio sources were not precisely known, we then traveled to the high planes of New Mexico, where we observed them with the National Radio Astronomy Observatory's Very[7] Large Array. This is a telescope composed of 21 dishes whose combined signals are used to produce images with a resolution equal to that of a single telescope with a diameter of roughly 30 km. Finally, we went to Las Campanas to use the du Pont Telescope, identifying at visible wavelengths each of the radio galaxies and quasars that were the sources of the radio emission detected in our initial radio survey.

Before we could answer any astrophysical questions, we needed to know the distances to each radio source in our sample. Distance is determined from the redshift and the Hubble constant, which is the quantity relating the distance of an object to its redshift. (The redshift is a measure of the recession velocity of an object.) A redshift of 1, for example, means that the wavelengths of light have been increased by 100%, and corresponds to a distance of roughly half the size of the universe. A redshift of 2 corresponds to 75% of the way back, while a redshift of 1000 would probe the universe when it was only 100,000 years old.

We measured the redshifts of many of our objects using the spectrographs on the 2.5-meter du Pont Telescope. The most distant radio galaxies in our sample are too faint for the du Pont Telescope; these we measured with the 4.0-meter telescope at Cerro Tololo, located 70 miles south of Las Campanas. Remarkably, more than 50% of our 543 radio sources lie at distances that are at least half way across the visible universe, and 8% lie more than 80% of the way.

The Evolution of Radio Source Sizes

Wavelengths in the radio portion of the spectrum range from millimeter to kilometer length. Most extragalactic radio astronomy is focused on the portion ranging from roughly 20 millimeters to 3 meters, corresponding to frequencies from as large as 15,000 MHz down to the top of the FM radio band at 100 MHz. The low-frequency portions of this window are increasingly impacted by man-made sources of interference.

Although all galaxies emit some radio waves, most produce very few, emitting at radio frequencies only a tiny fraction of the total energy their constituent stars produce at visible and ultraviolet wavelengths. Radio galaxies, on the other hand, are the small fraction (roughly 1%) of large galaxies that radiate a large amount of their total luminosity in the radio portion of the spectrum. The radio waves emitted by radio galaxies and quasars arise from charged particles, most likely electrons, moving through a magnetic field at speeds very close to the speed of light. The magnetic field effectively puts the brakes on these speeding electrons, and as they slow down they give up their energy as radio-wavelength photons.

Most radio galaxies and quasars eject

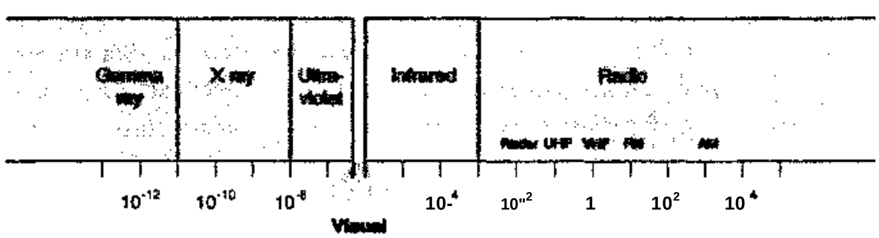


figure I. Electromagnetic spectrum (wavelengths in meters).

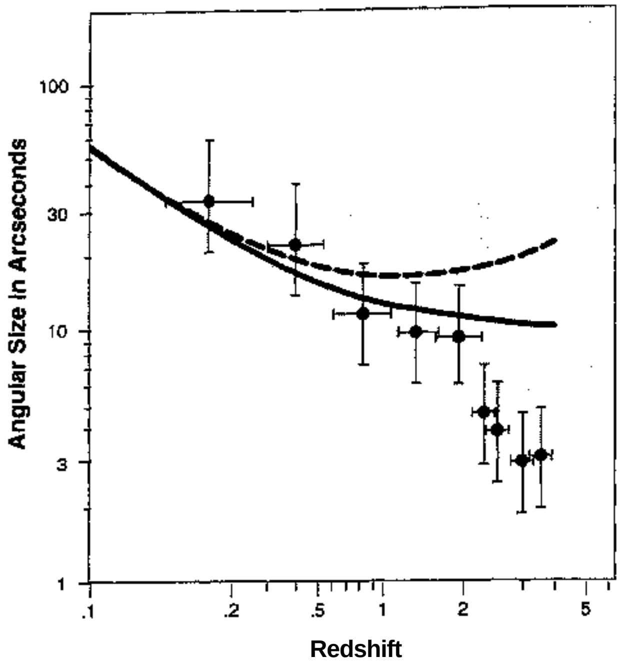


Figure 2: The angular sizes of radio sources from our survey. Each point is the median size in seconds of arc for 15-30 galaxies in the redshift range indicated by the horizontal error bars. The vertical error bars show the typical range of sizes found at each redshift. The curves are the expected angular size of a radio source of constant linear size in two different cosmologies. The solid line corresponds to an empty universe; the dashed line is for a universe with just enough matter to eventually halt, but not reverse, the expansion (a critical universe).

their high-energy electrons in the form of streams, or jets, having high internal pressure. While we usually think of the space between the stars as being empty, it actually contains gas with densities of one or so atoms per cubic centimeter. The ionized gas, or plasma, that produces radio emissions has an even lower density, even though the pressure in the radio-emitting material is very high.

As the radio jets push on the gas in the surrounding medium, they expand at speeds typically 5% of the speed of light. Like a jet of high-pressure air expanding into a body of water, a radio jet creates an interface between the nearly evacuated region it defines and the *>unrounding medium. The size of the evacuated region tells one about both the power of the jet and the density of the surrounding medium. The largest radio sources span nearly 10 million hyht ye;*r», making them the largest individual object* in the universe.

One of the simplest questions we can ask about the evolution of radio sources is whether they were the same size in the past as they are now. Figure 2 shows a plot of the apparent angular sizes (the angle they subtend from the Earth) of radio sources in our survey. The plotted points are the median sizes at nine different redshifts; each point contains data for 15-30 objects. The superposed smooth curves show the apparent angular size of an object of constant physical size for two different model universes. The solid line is for an empty, and hence open, universe (one which would expand forever), while the dotted line *is* the prediction for a universe on the dividing line between open and closed, with just enough gravity to eventually halt, but not reverse, its expansion. (The curves deviate from the straight-line expectation in a Euclidean universe because the curvature of space bends the light from distant objects and magnifies these sources, essentially acting like a lens).

As seen in Figure 2, for redshifts less than 2, which correspond to distances between 8 and 12 billion light-years, the radio sources in our sample have a roughly constant physical size. More distant sources, those with redshifts beyond 2, show a marked decrease in their angular sizes, suggesting that they are physically smaller. We calculate that they are two and a half times smaller than the radio sources at intermediate redshifts. Coupling this data with our estimates of the power of the radio jets leads us to conclude that the sources in the early universe were smaller than present-day radio galaxies because they were born in higher-pressure environments. Thus, complete samples of sources, like ours, provide us with a probe of the conditions in the universe when it was only 10-20% its current age.

Ultraviolet Emission From Radio *Sources*

Radio galaxies and quasars produce copious amounts of ultraviolet radiation (wavelengths from 0.03 to 0.3 microns; see Fig. 1). This radiation is seen directly in the quasars, which appear as unresolved points of light with colors indicative of a strong ultraviolet component that does not arise from stars. When first discovered, radio galaxies appeared to be normal in all respects (other than being roughly a million times more luminous at radio frequencies than the average galaxy is at visible wavelengths). However, in the mid-1980s, large optical telescopes with modern digital detectors obtained the first detailed images of radio galaxies. The images revealed complex structures unlike those seen in normal galaxies. In 1987, my colleagues and I at the University of California discovered that the spatially resolved ultraviolet light in radio galaxies is found only along the pathway of the expanding radio jets. This so-called "alignment effect" is illustrated in Figure 3, which shows images of the radio galaxy MRC 0406-244, found in our survey. The radio emission appears as contours of constant brightness; the ultraviolet emission appears as a gray scale. The correlation between the ultraviolet continuum radiation (right panel) and the light from glowing hydrogen gas (left panel) with regions of bright radio emission illustrates the alignment effect.

Although the alignment effect was discovered nearly a decade ago, it still remains largely unexplained. Two competing models exist. One hypothesizes that hot massive stars are formed by the passage of the high-pressure jets through dense gas lying near galaxies in the early universe. Thus, the ultraviolet continuum seen along the radio jets would reveal regions of stimulated star formation. The other theory postulates that radio galaxies harbor powerful sources of ultraviolet light that are enshrouded by dust and are thus hidden from Earth-bound observers. In this way, clouds of ionized gas or dust that hover above the central source of the UV light would act like a mirror and reflect a small fraction of the light towards the Earth, producing the regions of ultraviolet light found along the radio jet's path. The high degree of linear polarization (approximately 10%) seen in several distant radio galaxies lends strong support to this

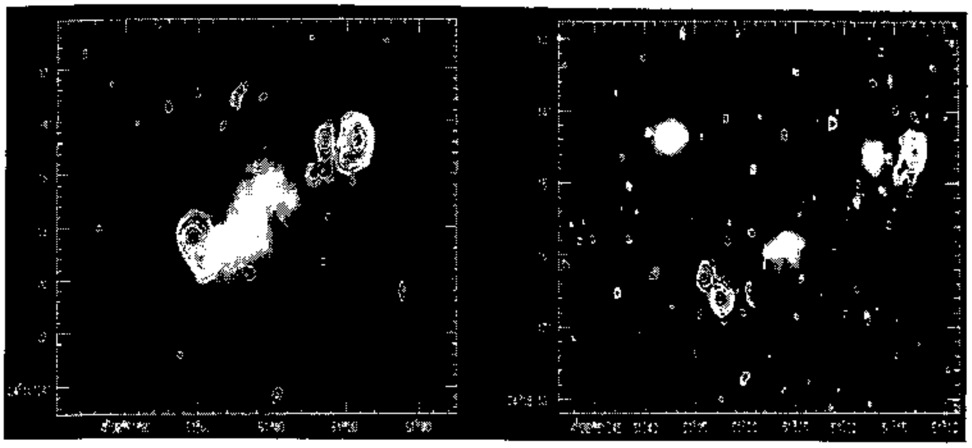


Figure 3: Two images of the radio galaxy MRC 0406-244. The right panel shows an image in the ultraviolet continuum obtained with the Hubble Space Telescope. The left panel shows an image taken in the light of ionized hydrogen, obtained with the du Pont Telescope at Las Campanas. In both images, the radio emission corresponds to the contour lines, and the ultraviolet emission corresponds to the bright regions. These images were prepared by postdoctoral associate Brian Rush.

theory, since reflection naturally produces a high degree of polarization.

Recent improvements in near-infrared imaging detectors and the refurbishment of the Hubble Space Telescope offer new tools that we can apply to this problem. Together with Observatories' postdoctoral research associate Brian Rush, I have analyzed deep Hubble Space Telescope images of the radio galaxy MRC 0406-244 in an effort to understand the alignment effect. We are considering two possible sources for the extended ultraviolet emission: scattering of the UV light by dust grains, and scattering by free electrons (Thompson scattering).

The cloud of ionized gas associated with MRC 0406-244 is roughly 100,000 light years across and contains a mass of gas equivalent to 100 million Suns. While the cloud appears to be fairly smooth and uniformly filled, it actually contains tens of billions of individual clouds with densities of approximately 100 atoms per cubic centimeter. The gas in these clouds has a temperature of 10,000 Kelvins, and the clouds are embedded in a very tenuous atmosphere with temperatures of from 10 to 100 million K. This hot medium confines the dense clouds and prevents them from dissipating on time scales of a few million years.

The galaxy's central nucleus emits roughly 10^{55} far-ultraviolet photons each second. These photons travel distances of 50,000 to 100,000 light years along the path cleared in the wake of the radio jet, until they encounter clouds of dense gas. When they do, each photon ionizes a hydrogen atom within the cloud. Then, after being absorbed and re-emitted several times, it is transformed into a Ly-α photon with a wavelength of 0.1216 microns, at which point it escapes the nebula. When the hydrogen gas is

Facing page: Patrick McCarthy (right) and postdoctoral associate Brian Rush al Santa Barbara Street.

ionized, it releases electrons that can reflect, or scatter, a fraction of the incident ultraviolet light away from the nucleus and toward the Earth. Whether the electrons can reflect enough of it to produce the observed luminosity of the UV light seen in the alignment effect is unclear. Calculating the reflective power of these electrons (which is possible with a modest degree of accuracy, using the properties of the ionized gas), Rush and I found that the reflectivity of the electron plasma in MRC 0406-244 ranges roughly 1-5% in different parts of the cloud. This is within a factor of three to five of the amount needed to explain the observed ultraviolet continuum light.

Dust grains (roughly 1 micron in diameter) also reflect ultraviolet light, but they do so more effectively than electrons, being 10,000 times more efficient per unit mass. If the dust in MRC 0406-244 makes up roughly 1/2% of the total mass of gas (as it approximately does in dense clouds in our own Galaxy), *it* would provide a reflectivity of roughly 30%, enough to produce the ultraviolet light seen along the radio jets. However, the dust content of distant galaxies may not be the same as that in the Milky Way. Distant galaxies seen shadowed against bright quasars, for example, have dust contents suppressed by a factor of ten or more. This leads us to believe that dust scattering *in* radio galaxies might not be effective enough to produce the ultraviolet emission we see.

Reflection by dust has a spectral signature very different from reflection caused by electrons. Electrons reflect visible and ultraviolet light equally, while dust reflectivity depends on wavelength to the inverse fourth power, and hence is much more efficient in the ultraviolet, where the wavelengths of light are small compared to the size of the dust grains. Deep near-infrared observations should help us resolve this issue. If electrons are the scattering medium, near-infrared images should reveal structures similar to those seen in the ultraviolet. If, on the other hand, dust is the scattering medium, the signal in the near-infrared will be roughly 100 times fainter.

Unfortunately, our deepest images with the near-infrared camera on the du Pont do not reach the sensitivity level needed to settle this issue. At the moment, we are unable to conclude with certainty whether electron or dust scattering is the dominant mechanism. The Magellan telescope, and the next generation near-infrared instrument set to be deployed on the Hubble Space Telescope in early 1997, will be able to detect the signature of electron scattering in the near-infrared unequivocally.

Radio surveys like ours, and similar programs going on in the UK and The Netherlands, have revealed to us a population of massive galaxies at large redshifts. These giant radio sources display a wealth of astrophysical phenomena, many of which are not evident in our view of the local universe. At the same time, they serve as tools, allowing us to study the universe when it was only 10-20% its current age. As the Magellan telescopes and other large telescopes around the world come into operation, they will allow us unprecedented views of one of nature's grandest creations.

Lurking Qalaxies

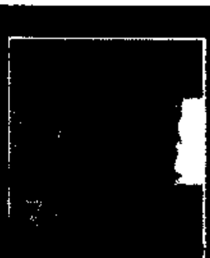
hy JulianneJ. Dalcanton

Anybody who has seen a science fiction movie or an astronomy special on public television has a reasonable idea of what a galaxy looks like. The backgrounds behind spaceships and the posters on undergraduate dormitory walls are filled with pictures of huge swirling galaxies with stars tracing enormous arms spiraling out of the center of a thin disk of gas, dust, and multi-colored stars. The images of these galaxies are dramatic and compelling, but they are also somewhat misleading.

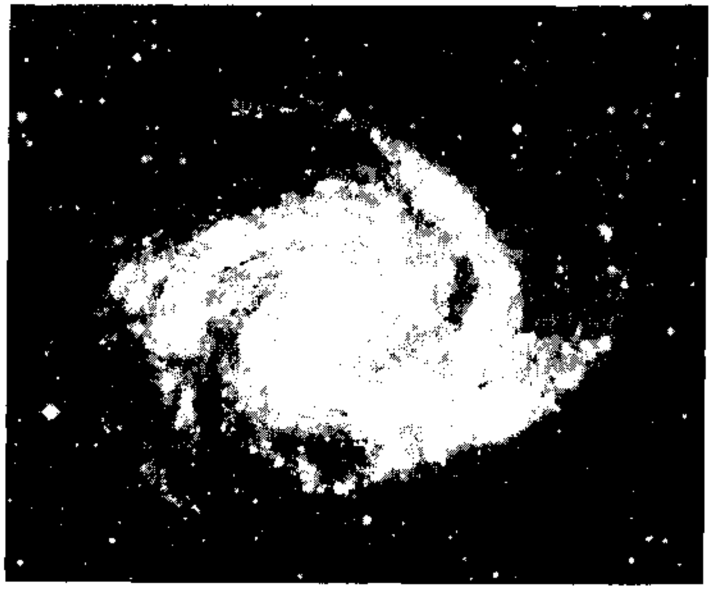
Although we happen to live in the disk of a spiral galaxy, these galaxies are by no means the norm. Perhaps more representative of the population of galaxies in the universe are the two faint smudges in the southern sky—the Small and Large Magellanic Clouds. These two small galaxies are actually tiny companions to our own large Milky Way. While they are far from impressive, being almost factors of 50 less massive than our own galaxy and having diameters five times smaller, the Magellanic Clouds are among a sample of galaxies far more numerous than the giant spirals and ellipticals which even astronomers refer to as normal.

It *may be that galaxies of low surface brightness, often overlooked by astronomers, are the most numerous galaxies in the universe. Besides helping explain some of the universe's missing mass, they offer clues about galaxy formation.*

The Magellanic Clouds show us something very fundamental about the universe—that galaxies are formed at many different scales. There are giant galaxies factors of ten larger than our own, and there are tenuous, diffuse "dwarf' galaxies a factor of 100 smaller than the Magellanic Clouds. The Magellanic Clouds also show us another important way in which galaxies are astoundingly diverse—in



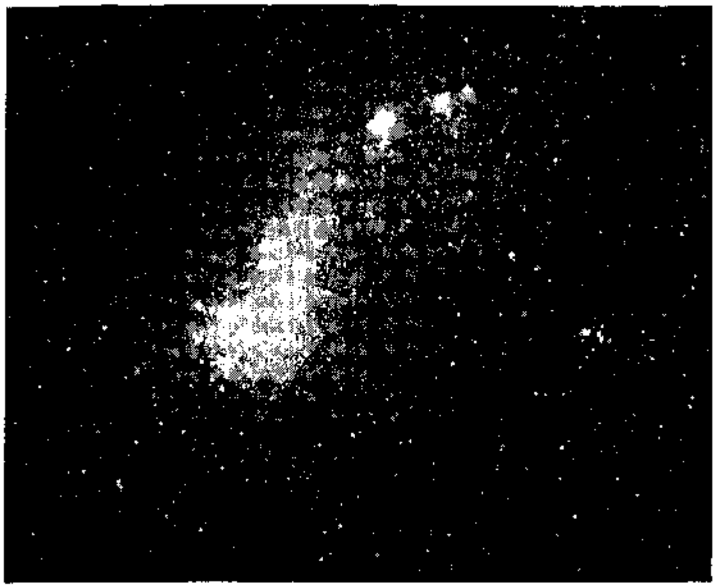
The Hubble Postdoctoral Fellowship *is* a prestigious,- nationwide award bestowed only to- a handful of individuals each year. **Juiianne** Dalcanton came to the 'Observatories as a Hubble Fellow in 1995. She received tier B«S- from **MIX** artd her **Ph.0«** *{in* astrophysics) **from** Princeton **University*** their surface brightness. The Las Campanas Observatory is blessed with one of the darkest skies in the world, but when you go outside at night and look towards the sky, you can barely see the Clouds. What the poet considers to be the blackest velvet of midnight, the astronomer actually sees as annoyingly bright. For the atmosphere glows faintly even at night, far from the lights of any major city, with the emission of atoms and molecules far above the surface of the planet. Against this bright background, the diffuse light created by the stars in the Clouds is so low that it is difficult to see them with the unaided eye. In fact, even the disks of bright galaxies like the Milky Way are actually fainter than the night sky itself!



The spiral galaxy NGC 2997, above, is what most people think of as a "normal" galaxy. Far more numerous, however, are galaxies like the Small Magellanic Cloud, on facing page, whose surface brightness is orders of magnitude smaller. (The diameter of the SMC is about ten times smaller than NGC 2997.) Photos from the *Carnegie Atlas of Galaxies,* by Allan Sandage and John Bedke.

Finding low-contrast galaxies against the bright background of the night sky is a problem not just for the casual stargazer, but for the astronomer using the largest telescopes and the most sensitive detectors. In the same way that the Magellanic Clouds are close to the limiting surface brightness the eye can detect, there are galaxies whose surface brightnesses are at the limit of what a large telescope can detect. This raises a very interesting, though perhaps obvious, point: Astronomers can only study the properties of galaxies which fall above the limiting surface brightness of their observations.

A limit to the observable surface brightness can lead to strong but erroneous correlations in the properties of galaxies, which reflect more about the way the observations are made than about the intrinsic nature of what is being studied. This problem, which astronomers refer to as a "selection effect," can be illustrated by making an analogy to a census of U.S. citizens. Suppose a naive polltaker questioned people who live only in Beverly Hills, and used the data to draw conclusions about the population of the United States as a whole. The polltaker would erroneously find that most everyone in the United States is incredibly wealthy. Likewise, an astronomer taking a census of galaxy populations could conclude



forces that shape galaxies. By attempting to make sense of the physics driving galaxy formation without complete knowledge of the entire galaxy population, astronomers are akin to unfortunate sociologists using the Beverly Hills census to build elaborate models explaining why the United States is so prosperous.

The last five years have seen a particularly dramatic improvement in our understanding of the low-surface-brightness universe. Two new, large catalogs of low-surface-brightness galaxies have appeared, one created by James Schombert (NASA), Greg Bothun (University of Oregon), and DTM postdoctoral fellow Stacy McGaugh; the other by Chris Impey (University of Arizona), David Sprayberry (University of Groningen, The Netherlands), and Mike Irwin (Institute of Astronomy, Cambridge). The new observations have surface brightness limits roughly a factor of ten fainter than the workhorse galactic censuses on which most astronomer rely, and they have revealed a universe of unusual, diffuse galaxies. Smaller surveys, which push the limiting surface brightness another factor of ten lower, both in clusters (gravitationally bound collections of galaxies) and in the smoother background of galaxies known as the field, have also appeared.

that all galaxies have a characteristic surface brightness suspiciously similar to the limiting surface brightness. This, in fact, happened in the early 1970s with the "discovery" of Freeman's Law, which stated that all galaxy disks have a characteristic surface brightness.

Fortunately, since the 1970s there has been a growing appreciation of the role that our biases against low-surface-brightness galaxies have played in shaping past knowledge of galaxy populations. With this has come a drive to understand and quantify selection effects in existing censuses of galaxies and, more importantly, to design new, less-biased galaxy surveys which will open a window onto a wider view of the true galaxy population. Because there are possibly unknown galaxies as close as our own Galactic backyard with surface brightnesses so faint that they have never been seen, we have an extremely incomplete understanding of the universe. It is vital that we open our eyes onto this previously hidden world if we are ever to understand the

1 myself have done this latter survey, and I am currently collaborating with former Carnegie fellow Dennis Zaritsky (now at the University of California, Santa Cruz) to expand it.

Several astronomers, including Stacy McGaugh, David Sprayberry, and me, have shown that this previously hidden population of low-surface-brightness galaxies is not a negligible dusting of unimpressive galaxies sprinkled throughout the skies, but is a very important contributor to the universe. Low-surface-brightness galaxies may, in fact, be the most numerous type *of* galaxy in the universe. If all these galaxies were added together, the total mass might well be as much as the combined weight of all other previously known galaxies. Current low-surface-brightness surveys are not quite sufficient to place tight numerical constraints on the degree to which these galaxies contribute to the number and mass density of the universe. But they have already provided a crucial puzzle piece for understanding the problem of galaxy formation. For they show us that many, if not most, galaxies have low surface brightness.

Despite their dramatically different surface brightness, low-surface-brightness galaxies have some surprising similarities to normal galaxies. Like the dramatic high-surface-brightness spirals, they tend to be rotating disks of gas and stars, with a circularly symmetric light profile which fades exponentially from the center outwards. Even more surprising, galaxies over the entire range of surface brightness tend to share the same relationship between the speed of their outer-disk rotation and the brightness of their disk. While the laws of physics suggest that the shape of the relationship should be the same for all galaxies regardless of their surface brightness, the only way for galaxies to fall on the exact same curve is if physics had conspired to accompany any decrease in the surface brightness of the disk with a precise increase in the amount of mass encompassed by the disk.

In addition to the broad similarities, there are also some systematic differences (besides the obvious change in surface brightness). For example, the low-surface-brightness galaxies tend to spin more slowly in their centers than their brighter counterparts, even though the two types spin equally fast in their outer regions. The disks of low-surface-brightness galaxies also tend to be more spread out than those of normal galaxies.

This intriguing collection of differences and similarities raises a very interesting question. How did nature produce such a wide variety of galaxies while preserving so many similarities from galaxy to galaxy? I believe the answer to this question can be found in the process of galaxy formation. When the universe was very young, space was filled with a mixture of hot gas and the mysterious dark matter, which, although it has not been observed directly, can be inferred to exist from the motions of stars and gas. While this early cosmic soup was extremely smooth, there were almost certainly the tiniest of ripples within it, so that some parts of the soup were denser than others, if only by the slightest amount. As the universe aged, the excess gravity in these overdense regions helped pull nearby matter into them, shaping the lumps into continuously denser and more massive protogalaxies. Eventually, the hot gas in these protogalaxies became dense enough to interact with itself, and began to cool and contract even further inwards into the center of the protogalaxy. This collapse proceeded until either all the gas was turned into stars (which cannot cool), or some other physical process took over and stopped the collapse.

During the formation of disk galaxies, that other process is thought to be the spin which the gas acquired while it was still a young, puffy protogalaxy. The lumps in the early universe were not alone, and they tugged on one another as they were forming. The small gravitational nudges caused most of the lumps to begin whirling slightly. As the barely rotating gas in the young galaxy cooled and collapsed into the center of a halo of dark matter, the gas spun even faster, speeding up like a person pulling in his or her arms while spinning in a desk chair. However, the gas can't fall all the way into the center, because it spins too fast.

Anyone who has been to an amusement park knows the experience of being thrown outwards by a rapidly rotating ride. Galaxy disks experience similar forces, except that gravity, not walls or seatbelts, prevents the gas from being flung outwards. The gas settles to a place where the restraining force of gravity exactly balances the flinging force of the rotation. In a rapidly rotating disk, the gas settles in to a larger radius than it would in a slowly rotating disk. It does so because it needs a larger restraining force to hold it together. The gas's orbit encloses more of the mass of the dark matter, which provides more gravity to hold the gas in. Therefore, a rapidly spinning protogalaxy will eventually form a very large disk, with the gas spread out over a larger area than in a disk which forms from a slowly spinning protogalaxy.

Stars are born from the gas only after it settles into the disk, so if the gas is very spread out, the stars which form from the gas will be spread out as well All the light we see from galaxies comes from the stars, so a rapidly spinning galaxy, with its widely spread stars, will appear to have low surface brightness. (It will also encompass a wider area than a slowly spinning galaxy of the same mass.) Because the restraining force of gravity is vital in shaping the galaxy, the shape and size of a disk also depends on how much mass is in it. Lower-mass galaxies thus form disks of low surface brightness just as rapid rotation does, although the lower-mass disks are smaller.

My collaborators David Spergel and Frank Summers and I believe that this general picture leads naturally to galaxies with the range of properties we see, while preserving the general features shared by all galaxy disks. Because the structure of a galaxy disk depends upon both the mass and the spin of the protogalaxy from which it formed, any variation in the masses and spins of protogalaxies will automatically produce wide variations in surface brightness and disk size. Astronomers can calculate the expected distribution of both the masses and spins of primordial galaxies from theories of the origin of the initial ripples in the cosmic soup. We have transformed these theoretical expectations into a prediction for the observable properties of galaxies today,

Observatory domes dot the Las Campanas landscape when viewed from Mount ManQiii, the site of the future Magellan telescopes. Left to right: the 1-meter Swope telescope, the University of Toronto's 24-inch telescope, the 10-inch astrograph, the 1.3-meter Warsaw telescope, and the 2.5-meter du Pont reflector.

and find that our calculations yield a remarkably good fit. They explain the large disks and the slow inner rotation of the low-surface-brightness galaxies, and they explain the properties these galaxies share with normal galaxies, including the relationship between brightness and rotation speed. More importantly, for the first time we can explain why galaxies form with an incredible range of sizes and surface brightnesses. We can even predict what we might see when we begin *to* observe the universe at even lower surface brightness.

It seems, from our calculations, that we truly have seen only the tip of the proverbial iceberg, and that there is a whole universe of lurking galaxies waiting *to* be discovered and studied. We believe that the light hidden by these low-Hirtace-hritfhtness galaxies may be more than twice what we can currently detect. We also believe that some galaxies may be hiding for entirely different reasons; our calculations suggest that many galaxies may be so small that they are mistaken for nearby stars!

It seems clear that discoveries are waiting for us in the hidden world, some perhaps as close as our own Galactic neighborhood. To see one's neighborhood, astronomers must observe huge areas of the sky in every direction. Modern ground-based telescopes can do this. All of the telescopes at Las Campanas, including the upcoming Magellan telescopes, are like wide-angle lenses that include reasonably large patches of sky in a single shot. This makes them perfect tools for the hard but exciting work ahead.

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[1] Died June 22, 1996
[2] From February 1, 1996
[3] Retired June io, 1996
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[5] From March I, 1996
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[18] To January M, 1996
[19] From November 2, 1995
[20] From November 15, i«
[21] Retired January M, 1996

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Department of Terrestrial Magnetism

DTM staff on the front steps [illegible] building, Broad Branch Road campus, autumn [illegible]. First row (left to right): Frank Press, Fouad [illegible], [illegible], Herald Butner, Jtanhua Wang, Richard Carlson, Andrew Menzies, [illegible] Silver, [illegible], François [illegible]. N'tison McWhorter. Second row: [illegible], Alan [illegible], [illegible] Bukcr, David Kutnt/, Cone! Alexander, F.nk Haurj, John Lassiter, Alan Boss, [illegible], [illegible] Rur^pker, Da\d fames, John Graham, John Almquist, [illegible], [illegible], Sartira [illegible], Wdio Ron. [illegible] row Akin Brandon, Terry Stahl, [illegible], [illegible] Sacks, Prudence Foster, Stacy [illegible], [illegible], ynd Mar> Coder.

Director's Introduction

The last twelve months have been an extraordinary year for planetary science. In December 1995, the NASA Galileo spacecraft arrived at Jupiter and began a series of novel observations of that planet and its moons, an ordered set of satellites having many parallels to a planetary system. In February, NASA launched what is destined, in several years, to be the first spacecraft to orbit an asteroid. This August, a team of scientists from NASA Johnson Space Center and several universities announced the discovery, in a meteorite thought to come from Mars, of organic compounds and microstructures which they suggest may be the fossil remains of ancient martian lifeforms. And not the least of the notable milestones of the past year for planetary science were the astronomical detections of planets around other stars broadly similar to our Sun. As elated as the poet Keats on reading a particularly fine translation of Homer, planetary scientists have seen new examples of extrasolar planets "swim into [their] ken" at a breathtaking pace.

Then I felt like some watcher of the skies
When a new planet swims into his ken;
Or like stout Cortez when with eagle eyes
He star'd at the Pacific-and all his men
Look'd at each other with a wild surmise-
Silent, upon a peak in Darien.

John Keats[1]

In November 1995, Michel Mayor and Didier Queloz of the Geneva Observatory in Switzerland published observations of periodic variations in the velocity of the star 51 Pegasi. These variations indicate the presence of a large planet, at least half the mass of Jupiter, with the surprisingly short orbital period of slightly more than four days. Within three months, Geoffrey Marcy and Paul Butler of San Francisco State University had confirmed the discovery and announced a new one of their own: a planet at least twice the mass of Jupiter in a three-year orbit about the star 47 Ursae Majoris. Since then, further announced discoveries of extrasolar Jupiter-mass planets have come at the rate of nearly one per month. The promise

[1] From his sonnet "On First Looking into Chapman's Homer," published in 1817.

that full-fledged planetary systems are within reach of detection no longer seems improbable. Already there are strong suggestions of at least two planets in orbit about the star 55 Cancri, on the basis of velocity measurements reported by Marcy and Butler, and the star Lalande 21185, on the basis of astrometric observations by George Gatewood of the Allegheny Observatory in Pittsburgh.

While the news media, and some scientists, have seized upon the discovery of extrasolar planets as fuel for speculations on the prospects for life outside our solar system, we should recognize that the importance of these discoveries for planetary science is enormous. Just as one cannot deduce the laws of probability from only one coin toss, or unravel the rules of genetics from studies of only one generation, it has been difficult to claim a full understanding of how planets form as long as our observations have been restricted to our own planetary system. As the characteristics of other planetary systems are discerned, planetary scientists will have both the opportunity and the responsibility to test and to generalize their understanding against this new information.

At the same time, it is worth remembering that the scientific interpretation $ if the properties ot planets around other star* will bin Id on several decades of *whit* *v* h;ne learned about stellar evolution anJ aKwt our *own* solar sWeni. The formation anJ evolution of planet* and *ur* has lort^ been a fiicus i>t reHMtth *M* DTM The firki is marked *bx A* heahhy balance between fheoHii-cal developments and insightful observations. Because of rhe complexity of the processes governing planet formation, theoretical advances now require sophisticated computer modeling efforts. Two examples of this class of work are well described in previous Year Book essays by Alan Boss, on the collapse of dense interstellar clouds to form young stars surrounded by orbiting disks of gas and dust (Year Book 92, pp. 111-120), and by George Wetherill, on the formation within the disk *of* planetesimals that grow by gravitational interactions to planetary embryos and eventually to planets *(Year Book 88,* pp. 101—111). Essential complements to numerical modeling are thoughtful programs *o{* new observations, which can provide stimulus and check to theory. Two such programs are described in the essays that follow.

In the first, John Graham summarizes some of his recent astronomical observations of young stellar objects, thought to be promising candidates for sites of ongoing planet formation. Such objects, marked by large quantities of surrounding gas and light-obscuring dust, are best studied by imaging at infrared and millimeter, as well as visible, wavelengths. There is a richness and complexity to the early evolution of stars like our Sun. Graham describes the large-scale geometry of the circumstellar disks around two young stellar objects, His observations point *to* mass election occurring at the stellar poles, consistent with current theory, as well as smaller-scale luminous knots of i»as and time variations in the distribution of Just indicating clumping on a scale similar to that thought to be important for planet formation. Strwny variability in the inures nf one of the objects nver a tune -pan ot sTiiy a *k-w* years points in energetic and even explosive activity, Graham also describes infrared spectroscopic identification of ices of water, carbon monoxide, and carbon dioxide on dust grains surrounding young stellar objects. Because the formation of such ices early in the history of our solar system is thought to have been necessary to seed the formation of the giant planets, documenting their distribution around other young stars at different stages of development will be an important task.

The second essay, by Conel Alexander, reviews work at DTM and elsewhere on presolar grains isolated from meteorites. These tiny grains of diamond, graphite, and other compounds have been identified as predate ing the formation of the solar system on the basis of their highly anomalous relative abundances of isotopes of carbon, oxygen, nitrogen, and other elements. Their presence in certain types of meteorites indicates that the disk of dust and gas from which the planets and meteorite parent bodies formed was never fully vaporized or thoroughly mixed. Most classes of grains can he linked to mass-ejection phenomena in supernovae and red giant stars. Thus the astrophysical processes that led to the collapse of the molecular cloud out of which our Sun and planets formed can be studied in the laboratory by means of chemical and isotopic analysis of these grains. Because of the tiny dimensions of the grains, typically micrometers or smaller, the analytical tool best suited for the identification and characterization of presolar grains is the ion microprobe. Alexander's essay describes how the newly acquired DTM ion probe is being adapted to this promising avenue of research.

As these essays document, further progress in our understanding of planetary systems will require that the new results from astronomy, cosmochemistry, and solar system science be integrated into the steadily improving theoretical models for star and planet formation and evolution. With expertise spanning the full sweep of these disciplines, DTM staff members are particularly well positioned to continue to make substantive contributions to this rapidly growing research area. A sense of the "wild surmise" that Keats imagined was experienced by the first Europeans to glimpse the Pacific can likely be shared by all who follow the findings from planetary science over the next few years.

—*Sean* C. Solomon

Time Scales and Stellar Evolution

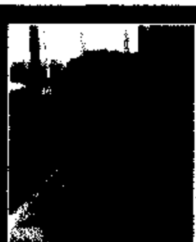
by John A. Graham

We are easily made aware of the immense range of distances encountered in modern astronomy by just looking up at the sky on a dark, clear night. But we find it hard to comprehend the similar range of time scales which apply to the stars and galaxies we see out there. For example, a star like the Sun, now 4½ billion years old, requires about 10 billion years to traverse its lifetime. Smaller stars evolve more slowly. Some of them seem to be almost as old as the universe itself. At the other end of the scale, the core of a supernova like SN1987A in the Large Magellanic Cloud undergoes terminal collapse in less than a second before exploding. The waste nuclear material ejected by these stars are remnants of a short lifetime—no more than a few million years—of extravagant energy generation.

> *There is plenty of action in a stellar nursery, where stars are born and evolve in ever-changing patterns.*

With the exception of the hydrogen and helium produced in the early universe, most chemical elements can be manufactured only in the hot interiors of stars. Supernova explosions are one way of distributing the elements widely to seed future star-forming events. Our own physical and chemical makeup, as well as that of our surroundings, thus depends on a vast interlocking of different processes operating on different time scales over a whole galaxy and its history.

As we look back over the 20th century, one of the most impressive achievements in astrophysics has been in our understanding of how stars shine. A star is bound together by gravity. As it contracts (collapsing under its own weight), a part of the gravitational potential energy is converted into heat, which is radiated away. In the middle of the 19th century, scientists believed that this was how our



A native Australian, John Graham holds a B.Sc. from the University of Sydney, and a Ph.D. (1964) from the Australian National University. Graham's research focuses on star formation, structure and evolution of galaxies, and variable stars. He has been a DTM staff member since 1985.

Sun generated its luminosity. However, it was already becoming clear that the Sun didn't have enough potential energy to maintain its output of heat and light over geological time. Some other mechanism of solar energy was needed.

In the 1920s, Sir Arthur Eddington, one of the early champions of Einstein's theory of relativity, knew that energy and mass were equivalent. He also knew that a helium atom is slightly lighter than four hydrogen atoms. If hydrogen could be turned into helium, he suggested, an enormous amount of energy could be produced out of the mass deficit. It was not clear that stars contain sufficient hydrogen until a few years later, when Cecilia Payne-Gaposhkin used the results of stellar spectroscopy to show that the stars were, in fact, made almost entirely of hydrogen. Later studies by George Gamow, Hans Bethe, and others showed quantitatively how nuclear reactions in the center of a star, blanketed to very high temperatures by an extensive outer atmosphere, could provide a stable energy source which would support the star against collapse and provide radiant heat to its surroundings. But what would happen after the star burned up its available supply of hydrogen? In the 1940s, astrophysicists such as Sir Fred Hoyle and Martin Schwarzchild showed that the star would go on burning, generating heavier elements starting from helium and proceeding all the way to iron. A key result of this work was that a star's luminosity and lifetime depend largely on its mass, and that this mass changes very little during a star's evolution.

Exploring *a Stellar Nursery*

At DTM we are particularly interested in the state of a star shortly after its birth. In *Year Book 92* (pp. 111-120), Alan Boss discussed his theoretical studies exploring how a new star emerges from the collapse of dense clouds of dust and gas. Observationally, it is difficult to detect newborn stars. Visible light cannot penetrate the obscuring dust within the parent cloud. However, longer wavelength radiation *can* get out. Infrared and millimeter-wave instrumentation, developed over the past two decades, now allows us to see right into the core of the dusty cloud where all the action is. And there is plenty. Even while the star is still growing by accumulation, strong out-flowing winds are forming. They sweep almost all excess material from the surroundings, eventually to reveal the star as one of the millions we can observe on a starry night. Our solar system was made from the little gas and dust left over from such a clearing process.

Time scales are fairly critical here. Collapse to form a solar-mass star probably takes a few hundred thousand years. But clearing of the gas and dust cannot be too quick if planets are to form. It is necessary for the residual material to stay around for a few million years in order to form gas-rich planets like Jupiter and kilometer-size planetesimals, which can then grow to form rocky planets like the Earth. Our Sun may be disconcertingly active now, but at the time *oi* its formation it must have been a thousandfold more so. We know that magnetic fields play a verv important pan in present-dav solar activity, and we Mirnuse that magnetic activ·lty

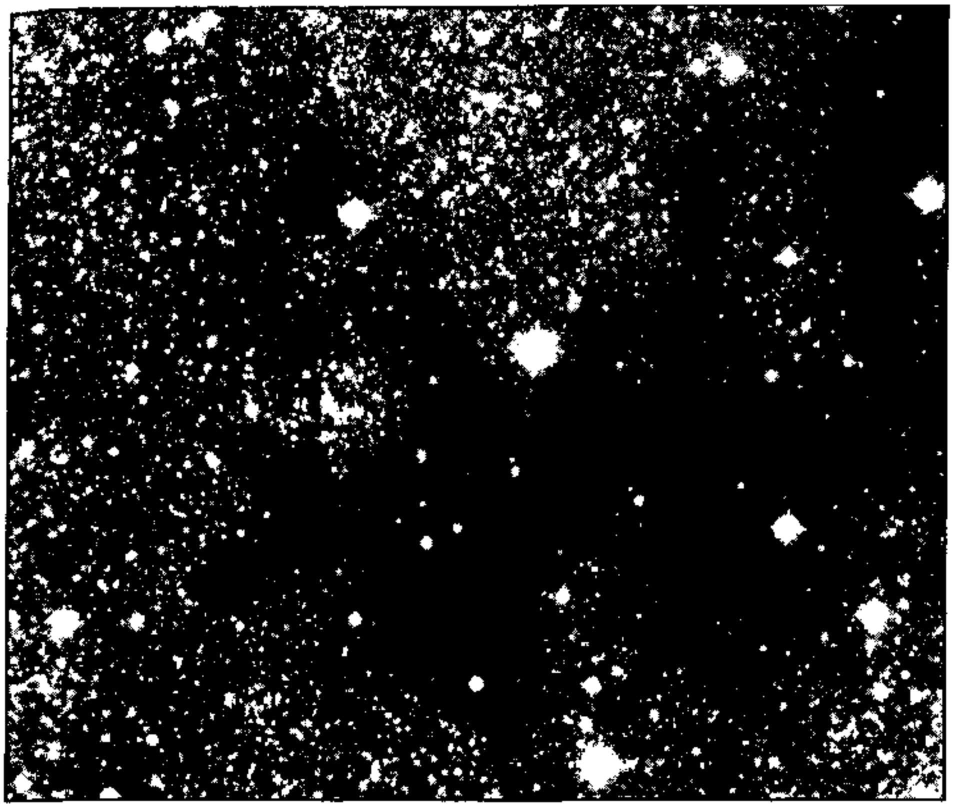


Figure I. A dust cloud in the southern constellation Norma. This image was taken in visual light in May 1995 with the 2.5-m du Pont Telescope at Las Campanas Observatory.

was much stronger when the Sun was young. Infalling material appears to be channeled into flows, which impact the stellar surface and produce extended high-temperature regions. It is possible that the outflowing winds, too, have a magnetic origin. Not surprisingly, irregular light variability is the rule rather than the exception in young stars as they strive towards some sort of mature stability.

Many stars form in groups. It can be hard, thus, to study the interaction of a newly born star with its surroundings amid all the other activity in a stellar nursery. There is good reason to pay special attention to those rarer cases where single star formation apparently proceeds in isolation. The example 1 ^ive hm\ though not quite achieving the ideal state of isolation, deals with two wiJelv separated \ouni* stellar iifyects which have recently formed within a dark dust cloud in the southern constellation Norma. Both appear to be of about the same mass as the Sun but at slightly different points on their evolutionary paths.

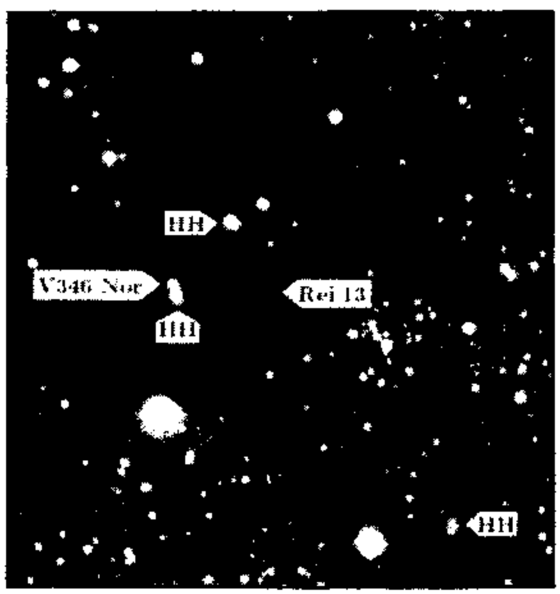
Figure 1 sets the stage. This is an image of a section of the Milky Way taken in visual light with the Las Campanas 2.5-meter du Pont Telescope. The dark dust cloud is not visible directly but we know it is there because its silhouette is outlined against a multitude of faint background stars. In its dense parts, the cloud is quite opaque. We can estimate its distance by comparing distances of occasional superposed foreground .stars with those of a selection of background stars. Thus we find that the cloud is about 2,000 light years from us. In a dark interstellar cloud like this one, there is a continuing tug-of-war going on. Gravitation tries to collapse the cloud while internal pressure, rotation, and magnetic fields and tides from neighboring clouds all work to tear the cloud apart. Almost always, gravity loses, and the cloud disperses back into interstellar space to reform again at a later time, rather in the manner of terrestrial clouds. But on this particular occasion, gravity won, and stars, and perhaps planets, have been able to form.

The two young stellar objects observed in this cloud are identified in Figure 2. Close-up views are shown in Figure 3. The first star, with the cataloged variable star name V 346 Normae, has cleared away enough material to be dimly visible through the dust. The second cannot be seen optically. But it does register its presence indirectly. Its light is scattered by the enveloping dust and illuminates a faint luminous patch at the outer boundary of the dust cloud. This patch has been catalogued as Reipurth 13 and is marked as Rei 13 in Figure 2. The two stars are separated by about 36,000 astronomical units, or half a light year.[1] (The astronomical unit is the distance from Earth to the Sun).

While obscured in visible light, Rei 13 can be detected in infrared light. Figure 4 reproduces an image taken at 2 microns with the NICMOS 2 array on the du Pont Telescope at Las Campanas Observatory in 1991. The central stellar image of Rei 13 illuminates a curved tail, which is probably part of a complete cone structure hollowed out *ot"* the Just by the outflowing wind. Most of the remnant material is arranged around the star in the form of a thick disk, which rotates on the same axis as the star. (There is now strong evidence that such disks surround about half of the observed youngest stars. Some have been imaged directly from observations made at millimeter wavelengths by specially designed radio telescopes.) Rei 13's outflowing wind escapes along the path of least resistance (i.e., perpendicular to the rotating disk). In doing so, it carves out a cone which broadens with time. V346 Normae also displays a faint cone-like nebulae. Such conical cavities are known to be associated with many young stars, one on either side of a star's disk. The one *on* the far side is almost always hidden from view by the thick disk.

A young star's clearing wind can be detected in another way. Small knots of gas, often no more than several Earth masses in size, find themselves in the

Figure 2. A more detailed view of the star-forming region in the Norma cloud. This image is a combination of two made in hydrogen and sulfur light in April 1991 with the 1.0-meter Swope Telescope at Las Campanas. The locations of the two embedded stars are marked. Herbig-Haro objects recognized in the area are flagged HH.



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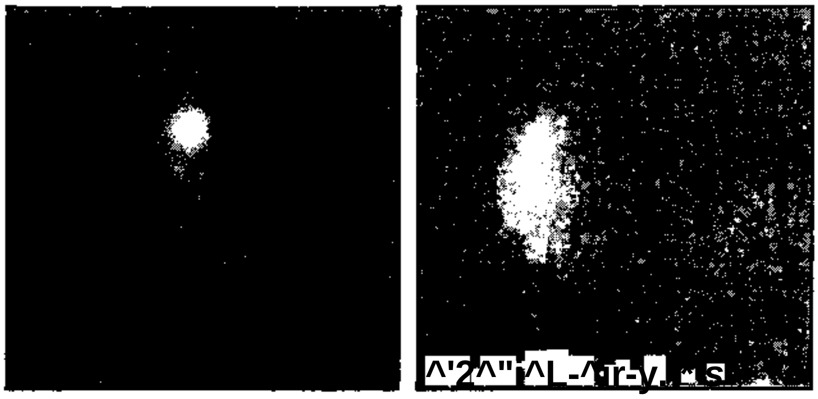

Figure 3. Details from the image in Fig. I showing the surroundings of the two embedded young stars in visual light. Each image is 21 arc seconds on the side (corresponding to approximately 15.000 astronomical units). The left image shows V346 Normae illuminating its surrounding dust. The right image is of the nebulous patch Reipurth 13. It is illuminated by scattered light from dust surrounding the embedded star, which is not visible directly at optical wavelengths.

central, most energetic part of the outflow, known as the jet. When shocked into visibility, these knots reveal themselves as luminous wisps known as Herbig-Haro objects. Their velocities can be measured and then used to probe properties of the outflow material (e.g., its extent, orientation, velocity, and age). Neighboring material from the cloud itself is also swept up and contributes a slower, more massive component to the outflow, which can be detected with millimeter wave telescopes. Herbig-Haro objects radiate especially strongly in the light of hydrogen and sulfur, and can be most easily detected by comparing images taken through filter pairs which pass or block a particular emission line. (Stars radiate at all wavelengths and register with both filters.) Herbig-Haro objects are associated with both of the young stellar objects described in this essay. They are marked on Figure 2, an image taken in hydrogen and sulfur light. (See also illustration on p. 56.)

Not much is known about the central star in Rei 13; no infrared spectra have been taken. However, the scattered light from the nebula Rei 13 has been analyzed. The spectrum shows strong emission lines of hydrogen and ionized calcium which are characteristic of the active outer atmosphere of young stars. Compared to other stars at this stage of their evolution, the level of activity is low. V 346 Normae is much more active. No star was known in its position until 1983, when it was seen for the first time at Cerro Tololo Observatory in Chile. Examination of earlier photographs showed that it had flared up by at least a factor of 100 in the previous two years. V 346 Normae is shown in Figure 3 along with its Herbig-Haro object. The Herbig Haro object (the fainter of the two objects) was discovered several years before the 1983 outburst. This leads us to believe that the present flare-up *is* only the most recent of many. There are several other stars with properties similar to this one. They are grouped together as "FU Orionis" stars. All appear to be accreting matter from their surroundings at a very fast rate. For reasons not yet understood, they have a need to radically readjust themselves every thousand years or so by the flaring and throwing off of a material shell of gas with a velocity of 300-500 km/sec. The 1983 outburst is but the latest of these episodes.

The infrared radiation from FU Orionis stars is very strong, indicating that local dust is being heated to high temperatures. Both the ejected shell and the intense local heating must be playing very active roles in dispersing and modifying the material left over from star formation. When one looks at the statistics, it seems possible that all young stars go through this mildly explosive stage, with long periods of quiescence in between. Thus, although the star at the center of Rei 13 may appear dull now, it probably had a more active past, and more excitement may yet be ahead. Change, when it happens, takes place on a time scale of years.

The *Nature of Dust Clouds*

Locating the dust in FU Orionis stars is difficult. Infrared observations indicate that dust clouds around the star are being heated at different times. In addition, the dust appears to he distributed quite unevenly. V346 Normae's appearance, for example, has changed over the last ten years, indicating a redistribution of obscuring dark matter. These observations suggest that the distribution of dust and gas around these stars is rather clumpy. The gas is easy to detect because of sharp absorption features seen against the radiating star. But dust particles, made up mostly of carbon or silicates, are large and complex structures. They do not impress such simple absorption features on light passing through them. At infrared wavelengths, however, dust has many broad absorption bands, and they give us intriguing information about its state and composition.

The field of infrared spectroseopy is going through an exciting phase. Because of heavy, irregular absorption in mi our atmosphere, and strong, variable fhenna! background from the land-

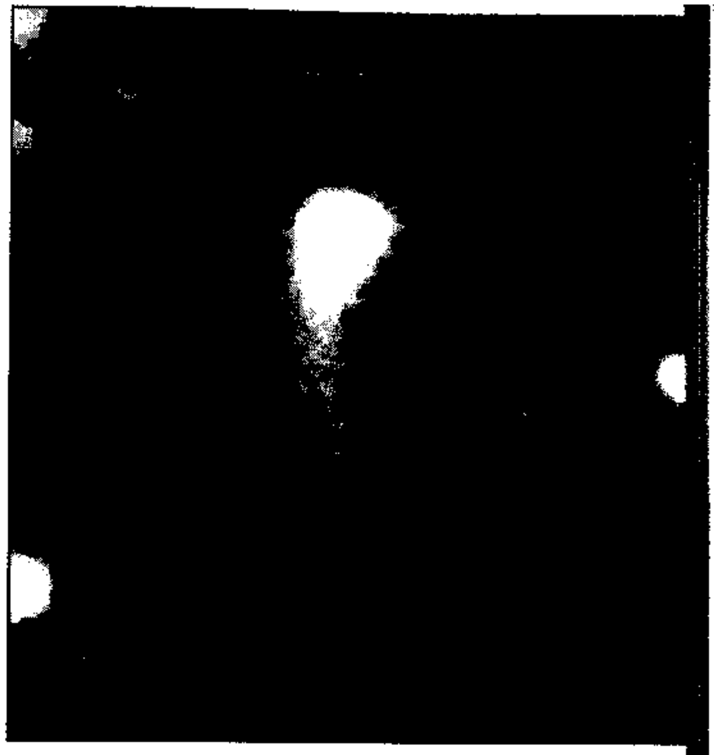

Figure 4. The Reipurth 13 ncbuia imaged at *2.2* micron*. At infrared wavelengths, radiation from the embedded star penetrates the dust (compare Figure 3, right). The star illuminates a cone-shaped scattered-light nebula which is partly visible in this image taken in April 1991 with the NICMOS 2 infrared array on the du Pont 2.5-m Telescope. This image extends *28* arc seconds on the side. Note the several background stars which are detectable in the infrared because of the lower opacity of the dust at 2 microns.

based telescope environment, much of the important work has been done airborne. Early data came from the Kuiper Airborne Observatory, which operated from a Lockheed C-141 jet aircraft flying above most of the Earth's atmosphere. The latest data are comim* from the Infrared Space Observatory, which was launched in November 1995.

The Infrared Space Observatory has detected a multitude of features within dense dust clouds. Water, carbon monoxide, and carbon dioxide ices all appear to be forming on the dust particles. Ices are fragile molecules and are quickly destroyed in the har4i environment of interstellar sp*icc, Thev can \inly survive when the Just yraniN on which they form are well protected

Hubble Space Telescope view of the Herbig-Haro objects HH46 (right) and HH47 (left) in the Gum nebula, another nearby region of star formation. HH47, at the head of a jet of nebulosity, is moving away from the associated protostar. which is embedded in the bottom right-hand edge of HH46. (Photo by). Morse. STScl, and NASA) Compare this view with the ground-based views of this newly born star and its surroundings published in Carnegie Year Book *87* (pp. 136-137) to realize the abundant new detail revealed by the Hubble Telescope.

within dense, opaque clouds like the one in constellation Norma. V 346 Normae is now a bright infrared source and emits radiation characteristic of dust heated to 2000°C. Its spectrum shows a strong water-ice feature. But ice clearly cannot survive temperatures as high as 2000°C. Ice grains close to the star must therefore have been destroyed, leaving only cooler material more distant from the star. Thus, grain evolution must be going on as a consequence of the 1983 outburst.

Along with the simplest ices, the Infrared Space Observatory is also detecting increasing detail about distinctly organic chemical reactions in newborn stars. The products of such reactions must be passed to any planets evolving around the star. Thus, some first steps towards the formation and evolution of biogenic molecules, and perhaps pointing to early life, may be taking place at this very early stage of stellar and planetary evolution. Closer to home, bright comets which swing into our neighborhood from the outskirts of the solar system may be present-day remnants of the Sun's primitive circumstellar ices.

Both young stellar objects discussed in this essay have almost the same age, Although it is possible they grew from the condensation of a single dense dust cloud, deep infrared images of the area show that the cloud is fragmented into cores, with scales of the order of 7000 astronomical units, smaller by a factor of five or more than the distance between the two stars. Young as they are, both stars contain chemical elements which are the products of many previous generations of stars. It may be that the collapse of the two cloud cores were induced nearly simultaneously by an expanding shockwave from a nearby older star nearing the end of its life. Alan Boss and postdoctoral fellow Prudence Foster are now exploring this scenario at DTM. If a supernova is indeed responsible, then the explosive collapse of a massive star occurring in less than a second could have triggered the formation of two stars which will resemble our own Sun in $4^1/^2$ billion years time. Our Sun will then be entering its own old age and, after an initial brightening, will move steadily towards its extinction. Such are the superpositions of time scales that we encounter among the ever-changing yet ever-regenerating patterns of dust, gas, and stars which we perceive in our view of the cosmos.

Stardust in the Laboratory

by Conel Alexander

Nine years ago, researchers isolated from a primitive meteorite the first grains of material believed to have formed around stars before the birth of the solar system. Since then, the study of presolar grains, part of a field informally called laboratory astronomy, has evolved into a truly dynamic, multidisciplinary endeavor, bringing together meteoriticists, chemists, astrono mers, and astrophysicists.

> *Cast off of dying stars before our own solar system formed, presolar grains provide astronomers with some novel challenges.*

The search for presolar material in meteorites actually began in earnest in the 1950s. It was then that scientists realized that the interstellar dust from which the solar system formed—if it survived in primitive, chondritic meteorites—would have a wide and unique variety of isotopic compositions. Fortuitously, the 1950s also saw the advent of high-precision mass spectrometry, which allowed scientists to study the isotopic compositions of meteorites and their inclusions in unprecedented detail. Early hopes of discovering presolar material were dashed, however, when it was found that the isotopic compositions of most elements in large samples of chondritic meteorites were identical to those of the Earth. This observation helped formulate the idea that early in its history, the inner solar system went through a high-temperature phase that vaporized most or all of the original solid material and hoEiogenized the isotopic compositions of the elements.

The first hint that presolar material survives in meteorites came in 1964, when researchers discovered that trace amounts of the noble gas xenon (Xe), having a

Conel Alexander's meteotiticai studies are part of a larger effort to understand! hew the-solar system was .formed. A. native of. England* he 'received, his Pti»D« from the Univer^ sity of Essex in 1987* la 1,994# alter .several'years WOCK* • lag. at Waslilftgioii: Uiiiv€rsif f -St. Louis,, be accepted a staff |icislt:Ic» at 0TM* unique isotopic composition, are released over a narrow temperature interval during progressive heating of very primitive meteorites. At first, the Xe was thought to be the fission product of a new, superheavy element. This idea soon proved untenable. The discovery of several other highly unusual trace noble gas components followed, but, despite some attention from astrophysicists, they remained little more than curiosities.

The first actual presolar grains were isolated by Edward Anders and colleagues in 1987 at the University of Chicago. The grains turned out to be tiny diamonds, only a few nanometers (10^{-9} m) across. The diamonds contain the Xe component (now called Xe-HL) discovered more than twenty years earlier, and Anders and colleagues developed a technique for isolating them by using the Xe-HL as a tracer. (The technique necessitates the chemical destruction of more than 99.9% of the host meteorite, a procedure that Anders likens to burning down a haystack to find the needle.) The discovery of the nanodiamonds was rapidly followed by the isolation of several other types of presolar grains. (See Fig. 1 and Table.)

The ability to analyze presolar grains in the laboratory provides an enormous advantage. The isotopic compositions of the grains mirror those of the stars from which they came, but they can be measured with far greater precision and for a wider range of elements than is possible astronomically. For instance, the grains of silicon carbide (SiC) have been isotopically analyzed for the elements carbon, nitrogen, silicon, magnesium, calcium, titanium, strontium, barium, samarium, neodymium, helium, neon, argon, xenon, and krypton. Of these, typically only carbon and nitrogen are accessible to an astronomer's spectrograph. The isotopic information has implications for a diverse range of fields, and it presents astronomers and astrophysicists with some novel challenges.

Figure I, Scanning electron microscope pictures of flop) a presolar SiC grain, and (bottom) a graphite grain isolated from the Murchison meteorite. Each is approximately 5 microns in diameter, (Courtesy of Dr. S. Amari, Washington University.)

Nanodiamonds: a Major Form of Carbon in the Qalaxy?

Although they were the first presolar grains to be isolated, the nanodiamonds remain, in many ways, the most enigmatic. The isotopic composition of

Type	Size	[illegible]	Sources
Diamond	1-5nm	"lOOOppm	Supernovae and ?
SiC	0.1-10jim	10ppm	C-rich AGB stars and supernovae
Graphite	1-1OjJ.m	≤2ppm	Supernovae and C-rich AGB stars (?)
Al_2O_3	1-5µm	≤0.1ppm	O-rich AGB stars
$MgAl_2O_4$	-mm	~2ppb	O-rich AGB stars
Si_3N_4	~1µm	~2ppb	Supernovae

Table I. Summary of the types, size range, concentrations, and identified sources of presolar grains so far isolated from meteorites. The concentrations are very variable. Those listed here are the highest encountered, (ppm and ppb are parts per million and parts per billion, respectively.)

the Xe-HL they contain is best explained by nucleosynthesis during the supernova explosion of a massive star. But the Xe-HL would have to have formed deep inside the supernova, and diamonds could not have grown in this region. The best place for the diamonds to have formed is in an outer carbon-rich region, and they could only have formed after the explosion, as the supernova expanded and cooled. There is evidence that the Xe-HL was implanted into the diamonds, so the Xe-HL must have been entrained in an energetic wind that overtook the diamonds. A recent study suggests that all this happened within hours of the supernova explosion, a remarkably short time given the violence of a supernova, and considerably shorter than astronomical observations have previously suggested for time scales of dust formation in supernova remnants.

Tii compound the mystery, the average carhon isotopic composition of the diamonds is very close to solar, which is not what would he expected for supernova products. The diamond carhon isotopes are actually more consistent with those in molecular clouds (the hotbeds of star formation), whose compositions are close to solar. In fact, astronomers have recently interpreted a molecular cloud infrared absorption feature as possible evidence that 5-20% of all carbon in the dust of molecular clouds may be in the form of nanodiamonds. Because the fraction of dust in the Galaxy produced by supernovae is estimated to be only 2-8%, and most of this dust is oxygen- and not carbon-rich, supernovae are unlikely sources for most of the nanodiamonds.

How can these observations—that the Xe-HL is best explained by formation in a supernova while the carbon isotopes and Galactic diamond abundances seem inconsistent with a supernova origin—be reconciled? Not all diamonds contain Xe-HL; in fact, most are so small, typically a few hundred to a few thousand atoms, and the concentrations of Xe-HL so low, that on average less than one in a million of the diamonds contains a single Xe atom. It is possible that the nanodiamonds come from a diverge, *but* so far unidentified, rantje of sources and that their uurrvn isotope* are > mean of man> types of JiK producers in the Galaxy. In thi-u.iv, if nn >t:<? the

sources produced Xe-free diamonds, the Xe-HL signature of the supernova-derived grains would still be detectable. The challenge to astronomers and astrophysicists is not only to explain how the Xe-HL-bearing nanodiamonds formed but also to identify the other sources of what may be one of the more abundant forms of dust in the Galaxy.

Qrains from Red Qiant Stars and Evidence of Qalactic Chemical Evolution

SiC is probably the best-studied type of presolar grain. Ion microprobe analyses of individual 1-10 |im SiC grains, primarily by Ernst Zinner and colleagues at Washington University, have revealed a remarkable diversity of isotopic compositions. For instance, the carbon isotope ($^{12}C/^{13}C$) ratios of the grains range from 2 to 7000 (Fig. 2). This compares with a range in natural terrestrial materials of approximately 88-90. Comparing the isotopic compositions of SiC grains with astronomical observations and theoretical calculations, one finds that most SiC grains come from carbon stars, presumably from many different stars with a range of masses and ages.

Carbon stars are some of the main dust producers in the Galaxy. As early as the mid-1970s, astronomers observed SiC signatures in the infrared spectra of carbon stars. In retrospect, better communication between astronomers and meteoriticists might have led to the isolation of the presolar SiC a decade earlier, though the meteoritic grains are typically much bigger than astronomers anticipated.

Carbon stars are low-mass stars (approximately one to four solar masses), approaching the ends of their lives. They are in their second giant, or asymptotic giant branch (AGB), phase, and they have enormously extended but relatively cool atmospheres. At the beginning of the AGB phase, freshly synthesized, carbon-rich material is dredged up from the stellar interior and mixed into the outer envelope of the star. As soon as this happens, the C/O ratio of the initially oxygen-rich envelope increases rapidly. Once it exceeds one, SiC can begin to form. It is thought that the SiC grains form near the stellar surface and are subse-

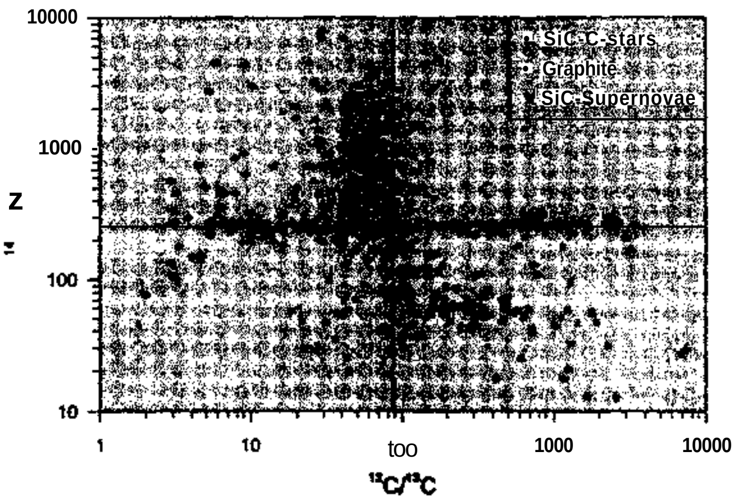

Figure 2. The range of carbon and nitrogen isotopic compositions in presoiar SiC and graphite grains. The SiC grains are divided into those most likely to have come from carbon stars and those *dtrlwa* from supernovae. The range of compositions exhibited by the presoiar grains far exceeds those encountered or. Earth Koiid lines). For e\3!Tiple. $^{12}C/^{13}C$ ratios in terrestrial materials range *horn* about *SS* to 90.

quently expelled in the massive winds these dying stars produce. It may only take a few years for a grain to form and then be expelled from a star, which is very short compared to the evolutionary time scale of the star. Consequently, each grain provides a snapshot of the isotopic composition of the star's atmosphere as it evolves.

The carbon-rich material dredged up from an AGB star's interior includes a wide range of newly synthesized elements, including Si. Theoretical expectations were that the Si isotopes in the SiC would be dominated by the signature of the dredged-up material, and thus contain a record of the star's internal nucleosynthetic processes. However, while the isotopic composition of many elements in the SiC grains do conform to theoretical expectations, the Si isotopes do not (see Fig. 3). What the Si isotopes appear to be recording instead is the chemical evolution of the entire Galaxy. The composition of our Galaxy has evolved over time, and the elements, built up from primordial H and He by succeeding generations of stars, have become progressively enriched. Not all isotopes of an element are produced at the same rate, so the isotopic composition of an element like Si has also evolved with time. The stars around which the SiC grains grew formed at different times and places and therefore inherited a variety of elemental and isotopic compositions. It is these initial variations in the compositions of the stars due to Galactic evolution that the Si isotopes are reflecting. Some of the Ti isotopes in the SiC grains also appear to record Galactic chemical evolution instead of stellar nucleosynthesis. Neither Si isotopes nor Ti isotopes can be measured astronomically and, along with astronomical observations of elemental abundance evolution, they provide stringent constraints for modelers of Galactic chemical evolution.

SiC grains are produced at the end of a star's AGB phase, when the star is enriched with carbon. But there is significant mass lost earlier in the AGB phase, when the envelope and the grains that condense from it are oxygen-rich. The major condensates

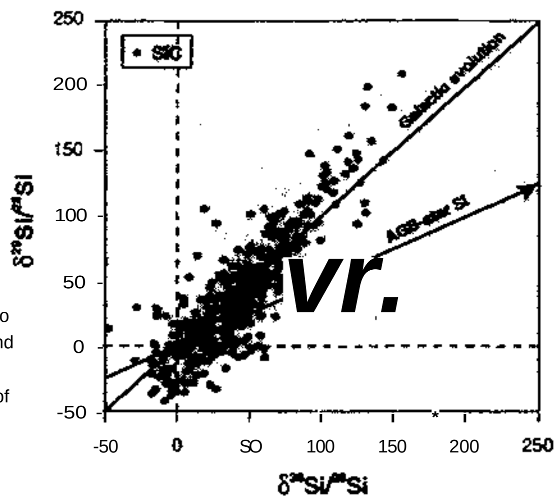

Figure 3. The Si Jsotoplc compositions of the SIC grains thought to have come from carbon stars. The compositions are expressed as the deviation, in parts per thousand, from the solar ratios. These SiC grains are believed to have formed around stars with masses of one to four times that of the Sun during their final asymptotic giant branch phase. During this phase, carbon-rich material from the star's interior is mixed into the star's initially oxygen-rich envelope, ultimately producing a star from which the SiC an form. The SI Isotopes were expected to be Influenced by this process and to plot along a line with a **slope** of' between 0.2 and 0.5. In fact, the SiC grains form a trend with a much steeper slope, consistent with estimates of the change in Si 'tsotopfc composition during Gabcttc evolution. Evidently, the SiC grains come *kom* numerous stars with different **ages.**

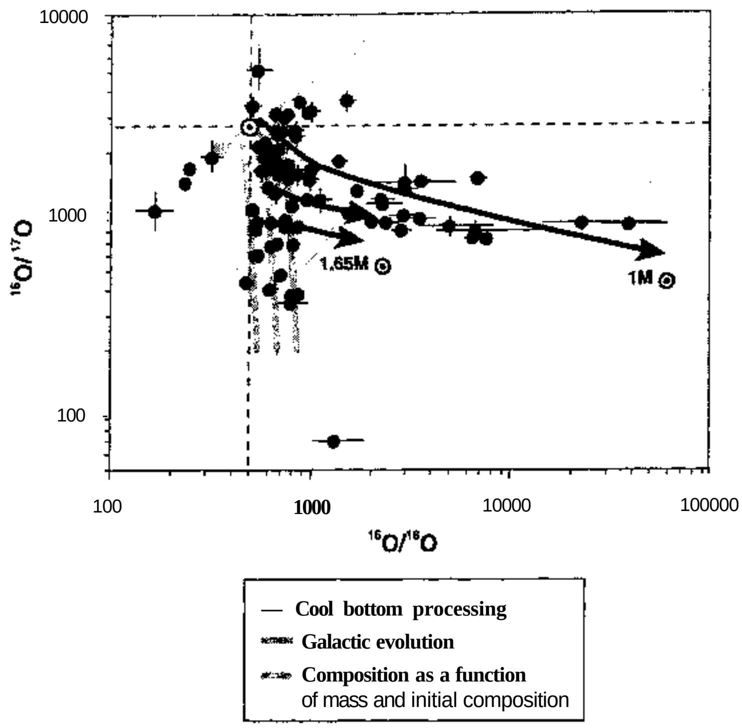

Figure 4. The oxygen isotopic compositions of presolar oxide grains (solid circles). Most of the grains fail within the field of the isotopic compositions observed in oxygen-rich red giant stars (gray-shaded field), though the size of the stellar field may be somewhat exaggerated because of the large errors in the astronomical data. Much of the variation in these "star-like" grains is due to variations in initial mass of the parent stars and initial composition of the star as determined by Galactic chemical evolution. This is illustrated by the three vertical curves. Each curve shows the predicted oxygen isotopes as a function of mass (1-3 solar masses) of the stars but for three different initial compositions. Those grains to the right of the plot with no stellar counterparts have large, and often extreme. ^{18}O depletions (high $^{16}O/^{18}O$ ratios). Theorists have suggested a new process to explain these grains, called cool-bottom processing (see text). This process appears to occur significantly only in stars with solar masses below 2.

under these conditions are silicon oxide-bearing (silicate) minerals. Unfortunately; meteorites are dominated by silicates which formed in the solar system. Since there is no simple physical or chemical way of concentrating presolar silicates relative to those from the solar system, it is extremely difficult to find the minor amounts of tiny presolar silicates that must he in meteorites To date, the only presolar oxygen-containing minerals to have been found are corundum (Al_2O_3) and spinel ($MgAl_2O_4$). These oxide grains exhibit a far larger range of oxygen isotope compositions than has been observed astronomically (Fig. 4).

Like the SiC, most or all of the oxide grains are thought to have come from AGB stars. The composition of the oxygen isotopes in AGB stars are largely determined by two dredge-up events that occur prior to the beginning of the AGB phase. The final oxygen isotopic composition of a star depends on the depth of the two dredge-up episodes, which in turn depends on the mass of the star. However, the range of oxygen isotopic compositions exhibited by the grains are too large to be explained by the dredge ups. As with the Si in the SiC grains, Galactic chemical evolution appears to have been an important influence in producing the oxygen isotopes in these oxide grains. But even Galactic evolution cannot explain the isotopic compositions of some grains. To explain the j$roup of grains that fall to the far right in Figure 4, for example, rheintsts have proposed a new process, called cool-bottom processing, in which small amounts of a star's envelope cycle through the hotter, deeper regions of the star where nucleosynthesis takes place and where the oxygen isotope ^{18}O is depleted.

Qrains from Type II *Supernovae*

Although most SiC grains originate in carbon stars, about 1% appear to come from supernovae. These supernova-derived grains are characterized by large and highly variable isotopic compositions. For instance, their carbon isotope ratios range from 50 to 4000 (Fig. 2). The grains also appear to have once contained several short-lived radionuclides with half-lives as short as 45 days. This implies that the grains formed, at most, a few years after the supernova explosion. The silicon nitride (Si_3N_4) grains and a subset of the graphite grains also appear to have come from supernovae. Their Si, N, and C isotopic compositions, for example, are very similar to those of the supernova-derived SiC grains. So far, the only grains without a subset suspected to have a supernova origin are the oxide grains. None exhibit the isotopic characteristics expected of supernova material, despite the fact that most supernova material should be oxygen rich.

While the SiC, Si,N_4, and graphite grains have many of the characteristics expected of supernova material, explaining *all* their isotopic compositions has proved problematic. The classical picture of a typical supernova is i if an onion-shell structure in which each shell has a distinct chemical and isotopic character. The best, though by no means perfect, fit to the grain compositions appears to require mixing of non-adjacent shells with little contribution from the intervening material This apparent paradox may have been partially solved in recent numerical simulations showing that instabilities develop during a supernova explosion, causing fingers of material *to* punch up through overlying shells (see Fig. 5). If these fingers can locally mix with the surrounding shell, it may be possible to produce the grain compositions we see. At present, the grids sn the simulations are too coarse to *test* this theory; and the grains remain a considerable challenge to theorists.

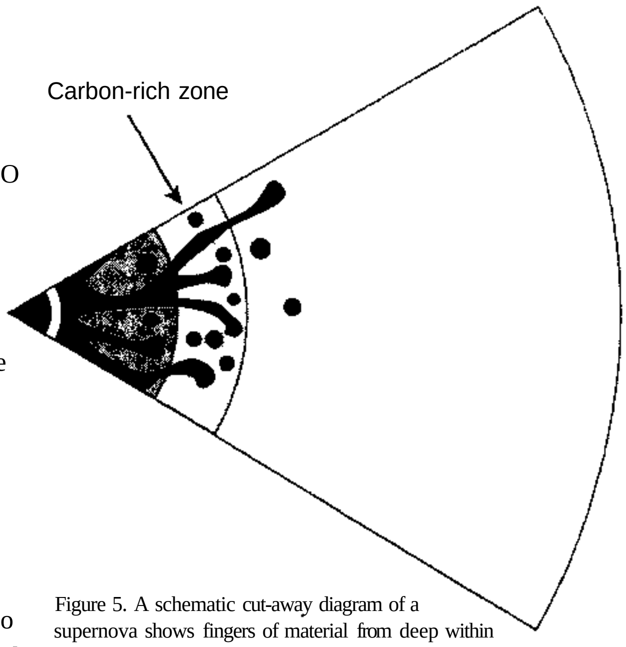

Figure 5. A schematic cut-away diagram of a supernova shows fingers of material from deep within the star punching up through overlying shells. This material may mix with carbon in the carbon-rich zone to eventually form SiC and graphite grains with uniQue isotopic compositions.

New Developments at Canwgie

The brief description ah»\e highlights just some of the implication* that prcsoLir grains have 4or :HTOPJ *UU JFJ astrophysics. Scientists studying the presolar grains are also using them to elucidate the processes of grain formation around stars and to understand how the grains are able to survive for up to several hundred million years in the interstellar medium, where they are subject to several destructive mechanisms. Astronomers are able to use the grains to augment and constrain their models, and even to place limits on the age of the universe. In studies of our solar system, the grains are challenging the theory that all material was vaporized and homogenized prior to planet formation. It could be that the presolar grains simply represent a small amount of material that entered the inner solar system after the high-temperature period. If not, they may spark a new understanding of how the inner solar system evolved.

Fairly extensive surveys have been conducted on the known presolar grain types, and new subtypes are continually being discovered and identified. Rare subtypes, however, often remain poorly studied. The oxide grains have proven particularly difficult to find; even in the purest residues, 99% of the grains are solar system in origin. To help locate presolar oxide grains and some rare subtypes of SiC, groups at Washington University and the University of Bern have developed a successful semi-automated isotope-mapping technique for use with their ion microprobes. All but six of the 88 known presolar oxide grains have been found in this way. However, the technique can only detect the more anomalous grains. It thus misses about 50% of the presolar oxides in the samples, and it is unable to distinguish many of the SiC subtypes from the main SiC population.

At DTM, we are developing a new, highly automated mapping technique to search for and analyze (among other things) the sought-after presolar silicates. Our efforts take advantage of the enhanced capabilities of DTM's recently purchased ion microprobe. Larry Nittler, who helped develop the mapping technique at Washington University, will be joining us in the fall of 1996 as a Carnegie postdoctoral fellow to work on this project. The technique aims to rapidly but precisely analyze every grain in a sample. This will enable us to collect an unbiased sample of presolar oxide compositions, survey large numbers of SiC and graphite grains to locate significant numbers of known subtypes, and search for new ones. To date, only a small fraction of the possible types of stellar condensates have been isolated, and grains from several important dust producers have yet to be identified. With these new approaches made possible by our new ion microprobe, we will be at the forefront of this young, exciting, and rapidly evolving field.

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Department of Embryology

Drosophila eye

Members of the Department of Embryology, summer 1996: First row (left to right): Earl Potts, Bill Kelly. Bill Kupiec, Doug Koshland, Brian Harfe. Horacio Frydman, Kim Dej, Maggie de Cuevas. Amy Rubinstein. Second row (kneeling): Jia Jia Mai, Melissa Pepling, Kornelia Szabo, Chris Murphy. Eileen Hogan, Pam Meluh, Kathleen Wilsbach, Allison Pinder. Third row (standing): Pat Cammon, Tammy Wu, Amy Rizzitello, Marnie Halpern, Aléjandro Sánchez, Valarie Miller, Mei Hsu, Dianne Stewart. Mary Lilly. Irene Orlov, Sue Dymecki. Dianne Stern. Fourth row: Allan Spradling. Andy Fire. Chen-Ming Fan. Wye Cheatham. Noah May, Ting Xie, Jennifer Kalish. Jenny Hsieh, David Furlow, Marija Tadin, Catherine Lee, Paul Megee, Jessica Pamment, Jeff Kingsbury, Tony Mahowald, Michel Bellini, Jennifer Abbott, Vinny Guacci, Joe Gall. Deborah Berry. Haochu Huang, Ben Remo, Si-Qun Xu, Steve Farber. Zheng-an Wu. Steve Kostas.

Director's *Introduction*

Biologists today confront an ironic situation. Individual productivity is at a level undreamed of only twenty years ago. Solutions to the great questions underlying cell function and organismal development, many posed in previous centuries, are unfolding before our eyes. The theory and practice of medicine is being transformed, as we almost weekly witness the detailed explication of yet another cancer or inherited malady. A biotechnology industry, spawned by the biological revolution, bolsters the economy. Most significantly in the long term, a deep understanding of biology seems certain to shed new light on pressing medical, environmental, and social problems, and to create unique new approaches for their amelioration.

Despite these extraordinary accomplishments, biologists feel less appreciated and less secure than at any time in the recent past. The principles articulated 50 years ago by Vannevar Bush, guiding the growth of research and making the biological revolution possible are now viewed in some quarters as indefensibly self-serving. Research funds are slated to be reduced and focused more heavily on short-term goals selected by nonscientists. Career prospects for young scientists, now declining toward pre-World War II levels, are expected to sink even further. In response to these changes, competition for shrinking funds and a declining number of positions have reached new heights. Increasingly, biologists and other scientists feel their experiments must produce results quickly and predictably.

> « ^n *interesting measure* ***of a*** ^**ogy** de|)artment *is the* ***fraction of its research that leads to improvements in experimental methods.... I believe Our department would*** ^ *extremely well in this* **regard.**

The pressure for rapid, metered productivity cannot fail to impact a crucial aspect of biological research—the development of new techniques. Biology has always been driven by experiment, to a far greater extent than in the physical sciences. The biological revolution was made possible by a series of synergistic advances in the experimental technology of biochemistry and genetics* However, the development of new techniques is inherently risky and unpredictable. Unless a significant advance is achieved there may be little to show for substantial expenditures of time and effort. Moreover, a new technique is often valued only after it has been successfully applied *to* a significant problem and come into wide use, ensuring further delays in documented productivity. These factors contribute to an increasing focus on short-term projects in established areas, and they discourage work on techniques and other areas with long-term payoffs.

An interesting measure of a biology department is the fraction of its research that leads to improvements in experimental methods. I believe that over the last twenty or thirty years our department would fare extremely well in this regard. Nearly every member *of* the faculty has developed new techniques while working here. Furthermore, it is heartening to note that enthusiasm remains high for the initiation of such projects. It is particularly significant that staff associates, the young faculty members most susceptible to the trends noted above, are active in developing new methods. Two such projects described this year, by staff associates Susan Dymecki and Pernille R0rth, hold great potential

Susan Dymecki has perfected a method for altering the genetic constitution of small groups of cells within developing mice. Most genes function at diverse times and places during embryonic development. When a gene cannot function due to mutation, the affected embryo usually becomes abnormal. Because the abnormality begins when the gene is first used, the embryo may not survive to reach the stage an experimenter wishes to study. If the embryo does survive, it may become so deranged that the direct effects of the mutation become obscured. Dymecki's technique, using what is called FLP recombinase, targets mutations to specific groups of cells at specific times, greatly extending the power of genetic analysis. Moreover, her method has a variety of other uses. For example, it can genetically mark small groups of cells so that their movement within the embryo can be followed during development.

Pernille R0rth has also extended classical genetic methods. Two out of every three genes in the fruit fly *Drosophila* (and likely most higher organisms) can be destroyed by mutation without producing effects detect-

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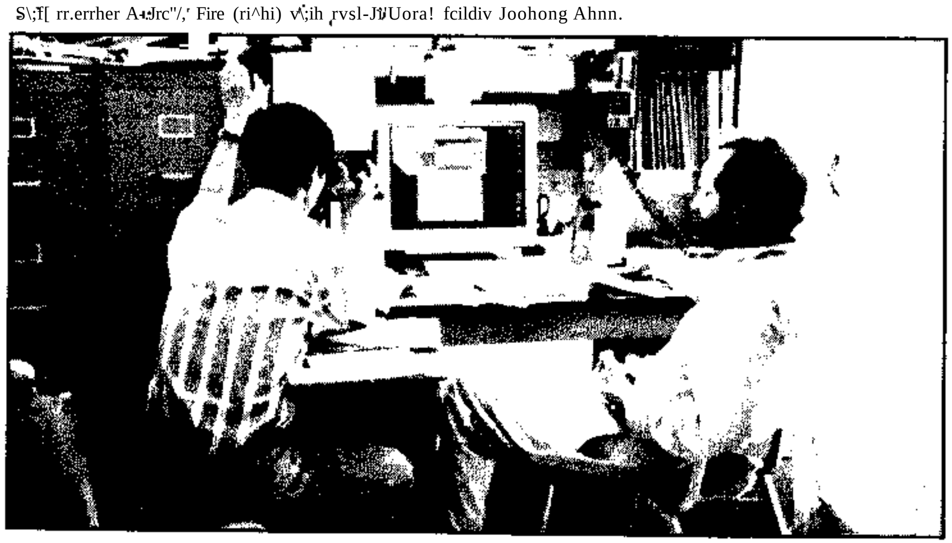


able in a laboratory setting. These genes probably have subtle influences on behavior, disease resistance, or other properties that cannot be easily studied outside of an organism's normal habitat. Experience with bacteria and yeast has shown that much can still be learned about the probable function of such genes. When produced in excess or in the wrong situation, many genes will disturb cell function in highly informative ways. R0rth's method is extremely versatile since it allows essentially random *Drosophila* genes to be mis-expressed at a time and in a tissue selected by the researcher. Those genes whose mis-expression has a desired effect can be identified and cloned.

Chen-Ming Fan

"NewsoftheDepartment

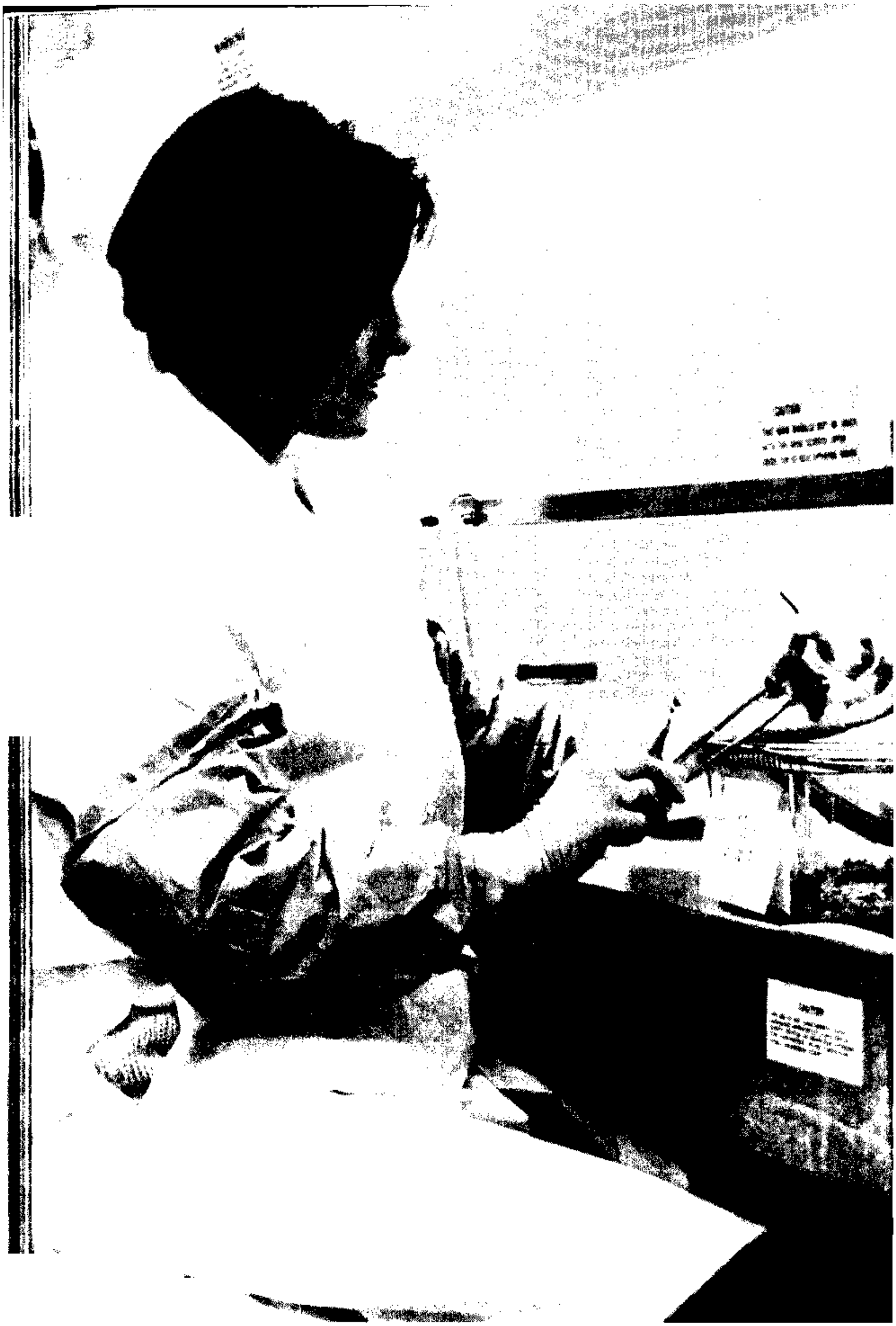
This year the department welcomed staff member Chen-Ming Fan. Fan studies the early development of mouse embryos. One of his interests, shared with several other staff members, is in learning how structures that repeat along the anterior-posterior body axis, such as muscles, nerves, and ribs, are patterned in the early embryo. Another of Fan's interests is to determine the role in brain development played by the mouse genes Sim I and *Sim2.*

Our seminar program was highlighted this year by the Nineteenth Annual Minisymposium, "Chromosome Organization." Carl Wu (NIH), Mitzi Kuroda (Baylor College), William Earnshaw (Johns Hopkins Medical School), Susan Gasser (Swiss Institute for Experimental Cancer Research), Scott Hawley (University of California, Davis), and Bruce Nicklas (Duke University) presented one-hour talks.

Support of research in the Department comes from a variety of sources besides the Institution. I and various members of my lab are employees of the Howard Hughes Medical Institute. Others are grateful recipients of individual grants from the National Institutes of Health, the John Merck Fund, the G. Harold & Leila Y. Mathers Charitable Foundation, the American Cancer Society, the Jane Coffin Childs Memorial Fund, the Helen Hay Whitney Foundation, the Damon Runyon-Walter Winchell Cancer Fund, the Pew Scholars Program, the Rita Allen Foundation, and the Human Frontier Science Program. We remain indebted to the Lucille P. Markey Charitable Trust for its support.

•—*Allan* C. *SpradMng*

Photo, next page; Staff associate Susan pymccki in the W. M. Keck Foundation Laboratory for Vertebrate Development,



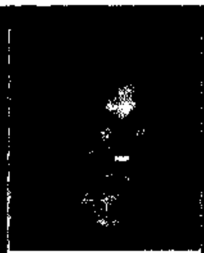
Mice Flip Over New *Qenetic Techniques*

by Susan Dymecki

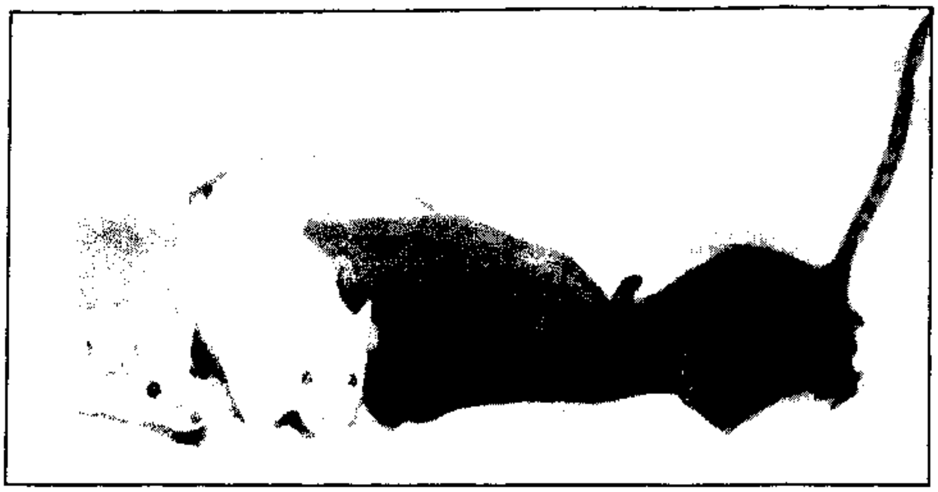
Since the early 1900s, the house mouse M. *musculus* has served as an exceptional model animal for studies of nearly all aspects of mammalian, including human, genetics. The remarkable utility of this organism is a direct result of the many sophisticated tools developed to manipulate and study its genes. The first and one of the most important of these tools was generated by Carnegie research associates William Ernest Castle and Clarence Little. While a member of the Castle group at Cold Spring Harbor in 1909, Little set up the first matings to produce inbred, genetically homogeneous lines of mice. This was a significant advance. For the first time scientists worldwide were able to experiment on the same genetic material and make meaningful comparisons. Deriving these strains was quite an undertaking. Not only did it require great resolve to maintain the necessary brother-to-sister matings, it took intellectual mettle as well Little's work successfully challenged the view that, because of the presence of recessive lethal mutations in the founding pairs, inbreeding to homozygosity was impossible. Through his tenacity, Little generated some of the most widely used mouse strains today, including DBA, B6, and BALB/c.

All cells *contain virtually the same number and kinds of genes. Susan Dymecki describes a way to "erase" genes in specific cells at specific times during mouse development.*

Mouse geneticists continue to develop new technology as driven by experimental need. My own lab is interested in developing new tools to dissect the processes that transform the homogeneous cells of early embryos into the complex highly patterned tissues of a newborn. Our work rests on the strong foundation of



Susan Oyniecki teceiivedl both a B.S.E-"afi4 an M»S*E. from the. University of Pennsylvania. la 1984'. Sfie went *mi* ta -earn aa M-.-D./Ph-0* •from Johns Hopkins Utiiveiv sity 'School ®i Mecflcitte la 1992^-She joined Carnegie's IJcpartiiieai of Bt&btyotogy 10 1993' as a'staff associate. "There she studies ejartbryonEic- pattcttting' in tfefc ttiouse,. •



manipulative genetics established in the mouse over the last two decades.

Increasingly powerful methods have been developed to manipulate mouse genes. It is now standard, for example, to transfer genetic material ("transgenes") into the mouse from any source. The vast majority of transgenic mice are generated using a technique developed at Yale University by Jon Gordon and Frank Ruddle. In this procedure, transgene DNA is injected into the nuclei of fertilized eggs, where it becomes incorporated into the mouse genome and eventually expressed in various tissues. By analyzing any abnormalities associated with transgene expression, it is then possible to infer aspects of normal gene function.

Another revolutionizing technique was the isolation and genetic manipulation of embryonic stem ct4ls. Though this technique is the cumulative effort of many labs, the pivotal advance came in 1986 from work by Elizabeth Robertson and colleagues while at the University of Cambridge, and Achim *iltn^htet id,* of the Max*P!anck Institute. Robertson andCiossler independently developed a method to culture genetically modified embryonic stem cells so that they would differentiate into germ cells when put back into the mouse embryo. This meant that genetic alterations engineered in petri dishes could be studied through many generations in the mouse. This far-reaching achievement has led to the generation of hundreds of mutant mouse strains, many of which are invaluable to the study of human genetic disease.

Despite the success of these transgenic and mutagenic techniques, the genes and biological processes they open for study are limited. Both methods yield mice which carry a transgene or engineered mutation in every cell. If the gene is one required for viability, its loss can be lethal to the early embryo, precluding further analysis. To increase the number of genes and developmental processes accessible to study, geneticists have been working to develop methods to modify genes only in *specific* tissues. This new type of genetic manipulation exploits a class of molecules called site-spec if it rea unhinases.

Erasing a Qene

Site-specific recombinases are enzymes which catalyze recombination between specific DNA sequences. The two best-studied recombinases are Flp, from the yeast *Saccharomyces cerevisiae,* and Cre, from the bacteriophage PL Each recombinase recognizes and recombines a distinct sequence of DNA called a recombination target site. When these target sites are oriented head-to-tail on the same DNA molecule, the recombinase excises the DNA lying between them, joining the sequences on either side with base-pair precision. This is illustrated schematically in Figure 1. Although both recombinases are derived from much simpler organisms, they seem to function quite well in a wide variety of environments, including mammalian cells. As a result, many researchers—tantalized by the prospect of being able to control precisely when and where genes are deleted—have begun testing these enzymes in mice.

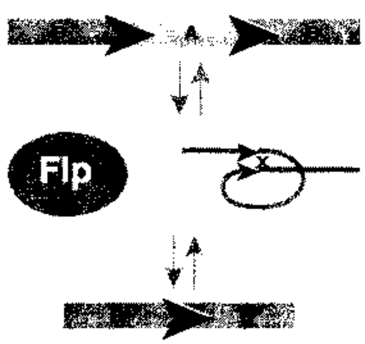


Figure I. Schematic of Fip~mediated recombination reaction. Flp recombinase target sites are depicted as black triangles oriented head-to-tail on a DNA molecule. In this configuration, Flp recombinase excises the DNA lying between the two target sites and joins the sequences on either side. This reaction can be used to delete hypothetical gene "A" lying between the target sites, or to activate a marker transgene "B" by excising previously Inserted DNA,

In theory, it is possible to flank a gene with recombinase targets, add recombinase, and delete the gene (Fig. 1). In this way, a gene can be erased only in those cells to which recombinase has been added, and the effect can be analyzed without compromising the organism. This has been called "conditional mutagenesis." Alternatively, a recombinase can be used to activate a marker transgene ('B' in Fig. 1) by excising previously inserted DNA. Elegant studies in the fruit fly have shown how the latter strategy can be used to mark and study specific populations of cells during fly development. Flp recombinase is now being used successfully by many *Droso*phila* geneticists, and results using Cre in mice look very promising. My own laboratory has been working to establish Flp as a tool for studying embryonic patterning in mice.

Stephen O'Gorman and Geoffrey Wahl of the Salk Institute were the first to show that Flp can efficiently catalyze site-specific recombination in mammalian cell culture. Building on this work, my lab has demonstrated that Flp is both necessary and sufficient to recombine and delete genes in the mouse. I began these studies by first assessing whether Flp expression alone would have any adverse affects; if high levels of illegitimate recombination were to occur as a result of Flp expression, the resulting embryo would be highly abnormal and the technique would be useless. This was not my experience, however. The mice I generated expressed Flp in nearly all tissues yet never showed any associated abnormalities. Encouraged by these results, I

Figure 2. The transgenic mouse embryos shown here have been engineered to express Flp using control elements from a gene (Wnt-I) normally expressed in the dorsal aspect of the developing central nervous system. Dark staining reflects Flp mRNA.

went on to test whether Flp could be used to delete genes *in vivo.* I tested two different types of DNA substrates, an introduced transgene and an endogenous gene, each flanked by Flp recombination target sites. After crossing to the Flp-producing mice and analyzing the offspring, I observed that both the transgene and the endogenous gene were deleted in a wide variety of tissues.

So far so good. But would brief expression of Flp in the mouse embryo be sufficient to delete genes during development? By using regulatory DNA sequences from a gene called *Wnt*l,* which is normally expressed only in the dorsal aspect of the embryonic central nervous system (see Fig. 2), I limited where and how long Flp would be present in the embryo. Subsequent molecular analyses showed that deletion of the target gene occurred in the embryo, and was restricted, as I desired, to neural tube-containing tissue. These results provided the first demonstration that regulated gene deletion could be achieved in the embryo, and has established Flp as a tool for genetic manipulations in mice.

'New Aspects of Development

I have since used Flp to follow the fate of neural cells during development. By tracking the adult fate of cells marked by gene deletion in the embryo, I have uncovered an interesting aspect of mammalian brain development: cells which transiently expressed *WntA* in the embryonic neural tube do survive and eventually populate the adult tectum, cerebellum, brainstem, and spinal cord. Given the great diversity of neuronal cell types in each of these adult brain tissues, it is now critical that I determine exactly which neurons in each tissue are marked, and therefore come from *Wnt-l*-expressing cells in the embryo. This type of analysis will define some of the principles that control diversification and patterning of the nervous system, and will likely reveal new insights into the genetic mechanisms underlying various human brain defects.

In addition to using site-specific recombination to study nervous system development, I have also initiated genetic experiments to uncover more general determinants of tissue patterning. One such interesting class of regulatory factors is the transforming growth factor (3 family (TGFp) of secreted molecules. These small signaling molecules have been shown to play a role in the development of nearly all mammalian organs, including the nervous system. Although many TGFp-like molecules have been

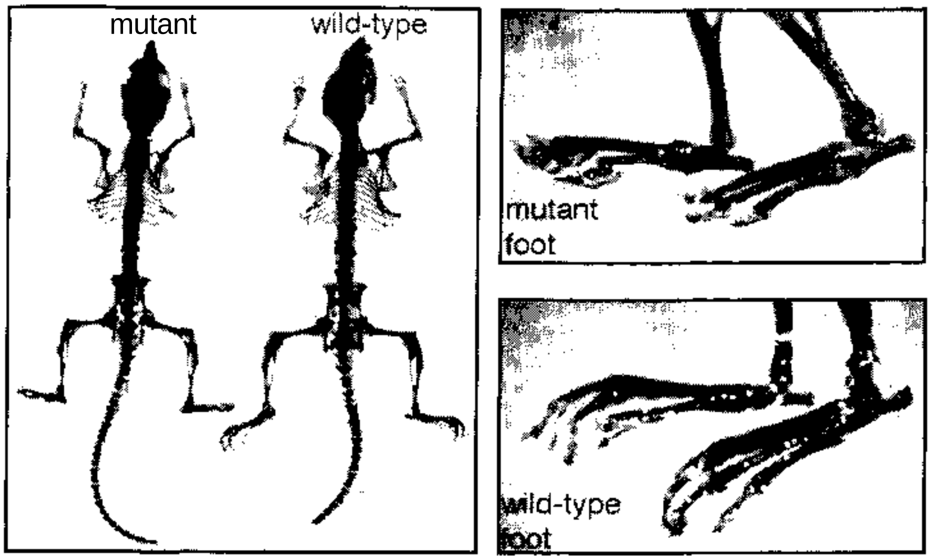


Figure 3. New mouse mutant with skeletal defect. Alizarin red skeletal preparations from a representative homozygous mutant mouse is shown with an age-matched wild-type mouse. Most prominent is the loss of phalangeal bones in the digits.

identified, a remaining challenge is to identify other components in their signaling pathways. I have recently obtained a potential handle on one of these molecules.

I identified a transgene insertional mutation that exhibits skeletal defects analogous to a known TGF(3-family mutation. In these mutant mice, the length and numbers of bones in the limbs are reduced. Most noticeable is the loss of bones comprising the digits; the proximal and medial phalanges are either absent or are significantly reduced in size and fused as a single bone (Fig. 3). Because our genetic analyses indicate a novel mutation, I am currently in the process of identifying the affected gene. Whether the mutation be in a new TGF(3 family member, its receptor, a downstream transducer, or in an alternative pathway, it will be exciting to unravel how this molecule organizes embryonic tissues.

The cumulative work of mouse geneticists over the last century has provided many tools to study genetic aspects of mammalian development and human disease. The ability to manipulate genes with increasing precision and specificity should enable us to learn still more about the dance between our genes, our environment, and ourselves. "Mousers" will surely be kept busy well into the next century.

Modern Qeneticst A Modular Mis-expression Screen in Drosophila

by Pernille R0rth

Genetic screens are powerful tools for biological research. They enable researchers to identify genes which control a particular biological process, and, at the same time, learn a lot about that process. Experimental organisms like *Drosophila melanogaster,* whose genetics have been well characterized over the past century, make efficient screens possible.

The first step of a genetic screen is to make a large number of random mutations (alterations) in the genome. A single mutation, inactivating a single gene, can manifest itself by a specific change in appearance or behavior. In a traditional *Drosophila* screen, genes are disrupted at random by the chemical mutagenesis of the sperm of adult males. The second step of a genetic screen is to examine the mutagenized flies' progeny (or later generations) for specific defects. If one wishes to study eye development, for example, one would look for flies with abnormal eye morphology or impaired vision. Once an interesting mutant strain is identified, the gene affected by the mutation can be cloned and analyzed.

Pernille R0rth describes a novel way to identify and analyze the function of genes in the fruit fly.

Genetic screens can allow geneticists to deduce some of the fundamental principles underlying a process even before the genes involved are molecularly identified. A good example of this are the screens performed by Christiane Nusslein-Volhard and Eric Wieschaus, who wanted to understand how the basic body plan of *Drosophila* embryos was determined. In their screens, they looked at the cuticle, the outside surface of the fully developed embryo. They realized that

PetitiHe R0rth, a native of Denmark, has been a staff associate In the Department of Embryology since 1994* Before joining Carnegie-, she earned a Cand. Scient. in biology in 1990 followed: by a Pli.0. in molecular biology in .1993* *both*, from the University of Copenhagen.•

The fruit fly *Drosophila melanogaster,* used for nearly a century *by* geneticists and developmental biologists.

the precise pattern of the cuticle (the number of subdivisions and appearance of body hairs) was a good indicator for the underlying early patterning events. They also realized that the way mutations changed this pattern reflected how the early patterning was controlled- For this work, they (with Edward Lewis) were awarded a 1995 Nobel Prize.

A sophisticated type of genetic screen, called a genetic interaction screen, can be used to identify gene products that work together in a biological pathway. The starting point for an interaction screen is a mild mutation affecting a known component in the pathway of interest. Mutant animals are then screened for secondary mutations that either correct for the original mild defect or make it significantly worse. If the secondary mutation has such a specific effect, its disrupted gene is probably also involved in the pathway. Genetic interaction screens have been used successfully to study cellular signaling pathways in *Drosophila** Because molecular pathways in flies and mammals are similar, results with *Drosophila* can be directly related to the signaling that controls growth and differentiation in mammals. This is convenient, because it is very costly and time-consuming to do genetic screens in mammals.

Although traditional genetic screens are wonderful tools for biology, they do have limitations. For one, even when an interesting mutant is identified, the chemical mutagen used to make the mutation often makes it hard to identify which gene is actually disrupted. Also, many genes do not cause detectable defects when disrupted; sometimes other genes mask the defect by assuming the mutated gene's function. And finally, interaction screens only work well if the starting mild mutation is reliable,, easy to analyze, and exquisitely sensitive. Such mutations are hard to find.

Fortunately, there are other ways to learn about genes and gene function in a living organism. Instead of studying what happens when a gene is absent, we can study what happens when it is expressed at a higher than normal level (over*expres*»ion) or in the wrong cell (mis-expression). Many informative biological changes are caused by mis-expression of genes. For example, striking transformations of *Drosophila* body segments, such as the appearance of legs instead of antenna, are caused by mis-expression of so-called homeotic genes. Homeotic genes are now known to be important for regional patterning in many animals. Also, the original identification of myogenic (muscle-forming) factors in mice was based on the observation that mis-expressed factors can convert other, nonmuscle cells into muscle. Finally, the initial molecular understanding of cell growth and cancer was greatly aided by finding that certain genes cause benign or malignant tumors when over- or mis-expressed.

I decided it would be useful to have a genetic screen based on mis-expression in *Drosophila.* I wanted the screen to identify genes which, when over- or mis-expressed in a tissue and at a time of choice, give a specific phenotype or modify an existing mutant phenotype (i.e., a genetic interaction). In yeast, over-expression screens have helped uncover the functions and interactions of many genes. But no one had tried this type of screen in a multicellular eukaryote, so I set out to develop the methodology.

Before I continue, I should point out that some geneticists maintain that the only acceptable way of doing a genetic screen is the traditional way, despite the examples given above. The key thing to remember is that over- or mis-expression experiments provide information about what a gene *can* do. This is not necessarily the same thing as what a gene *does* do under normal circumstances. It is important to address the specificity of a mis-expression phenotype (i.e., is it a defined change or is everything messed up?). It is also useful to compare the mis-expression phenotype with the phenotype that emerges when the gene is disrupted. (One would expect over-expression and disruption of a gene to have opposite genetic interactions.) The system I have developed, called the modular mis-expression screen, provides efficient ways to deal with both these issues. Furthermore, the results I have obtained with my mis-expression screen fit very well with expectations from traditional screens. Thus it seems clear that this novel method can, indeed, uncover biologically relevant effects.

Testing the Screen

In designing the modular mis-expression screen, I took advantage of two very useful techniques in *Drosophila:* single P-element mutagenesis, developed by Allan Spradling, Gerald Rubin, and others; and the GaH system, developed by Andrea Brand and Norbert Perrimon (Harvard Medical School). P elements are small, movable bits of DNA which when injected into *Drosophila* embryos can insert into the genome. A P element can mutate a gene simply by inserting into or next to it. Because the sequence of the P element is already known, it tags the insertion spot, and the mutated gene (or any nearby gene) can easily be recovered. GaH is a transcriptional activator protein. It can bind to a known DNA sequence (a GaH binding site) and activate a nearby promoter, turning on the gene regulated by that

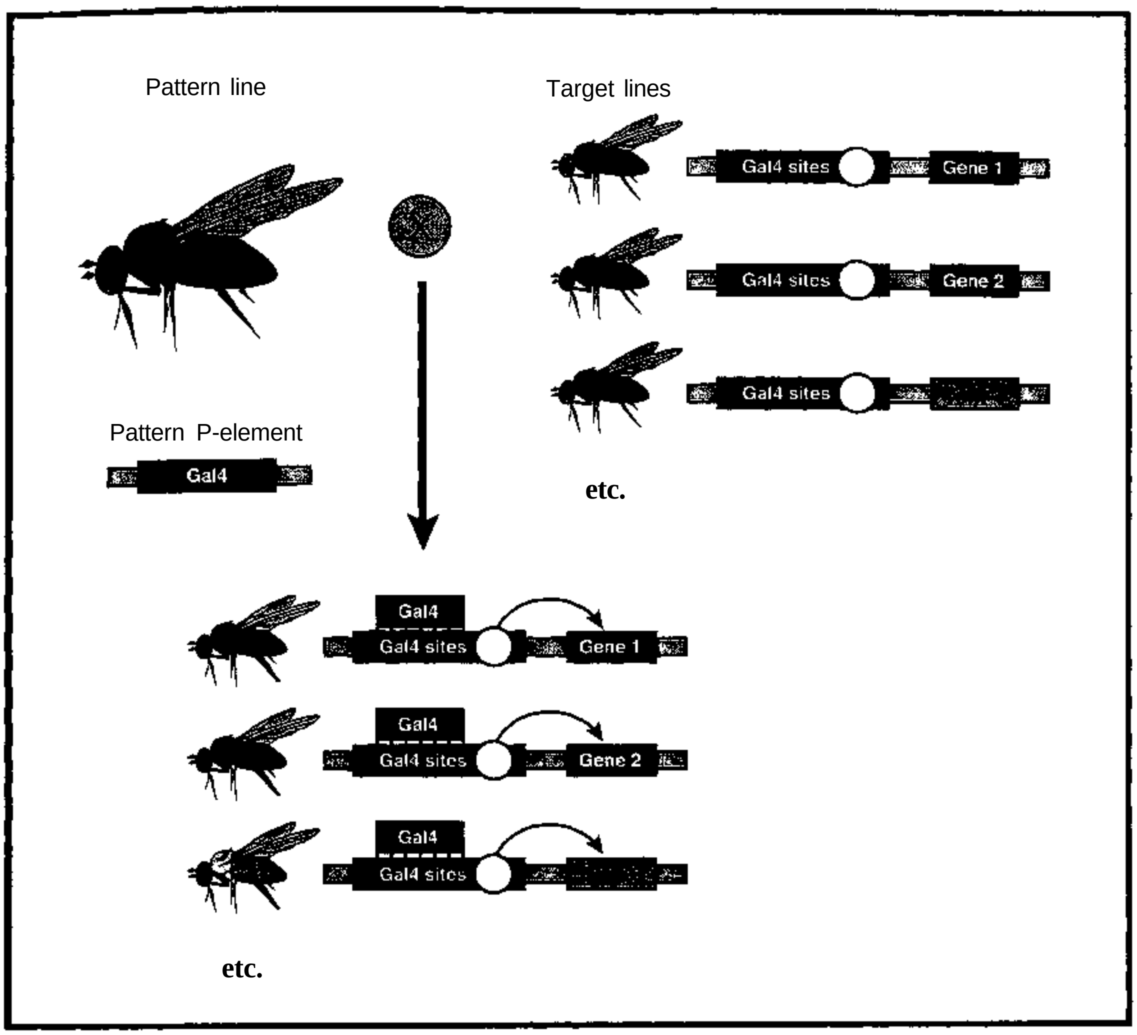


Figure 1. Outline of the modular mis-expression screen. Flies from the pattern line (top left) carry a pattern element and therefore have Gal4 expressed in a specific tissue, for example in the developing eye. The target flies (top right) each contain a single target element at an unknown position in the genome, often right next to an endogenous gene. (Fortunately, P elements have a tendency to insert adjacent to genes.) When pattern and target flies are mated, their progeny will contain both elements. Gal4 binds to its binding sites within the target element, stimulates the promoter (arrow), and thus induces expression of whatever gene is adjacent to the target element. If the phenotypic effect of this expression is interesting, the endogenous gene responsible for It can easily be cloned and analyzed.

promoter. Gal4 protein and Gal4 binding sites are not normally present in *Drosophila* but will function if artificially introduced.

The mis-expression screen has two parts, or modules: "pattern" flies and "target" flies (Figure 1). Each of the pattern flies contains a P element bearing the gene that codes for GaH protein and regulatory sequences that control which tissue Gal4 is produced in. Adult flies carrying this GaH pattern element are crossed to a large population of target flies. Each target fly carries a single target P element at some random place in its genome. The target P element contains binding sites for the GaH protein and a promoter at one of its ends*

The target and pattern elements are inactive on their own. When pattern and target flies are mated, however,

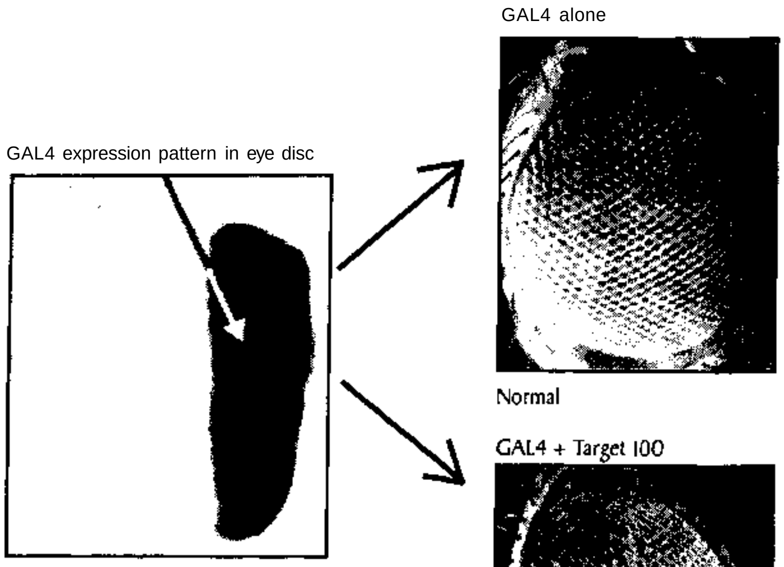


Figure 2. Looking for genes that affect eye development. The left panel shows an eye disk (the structure that will become the eye) of a larva from a particular pattern line expressing Gal4. The cells that express Gal4 are darkly stained. Over time, most cells in the eye disc will express Gal4. As shown on the top right panel, Ga!4 expression alone does no harm: the eye looks normal. Flies that also contain a particular target insert (#100) have abnormal, rough eyes (bottom right panel). Thus, mis-expression of the endogenous gene adjacent to target insert #100 affects eye development.

their progeny will contain both elements. This results in over- or mis-expression of an endogenous *Drosophila* gene in the following manner: In cells producing Gal4 protein, Gal4 will bind to its binding sites on the target P element and activate the target's promoter (see Fig. 1), The promoter then turns on whatever gene happens to be adjacent to the target element. If interesting phenotypes result from this over- or mis-expression, the endogenous gene can be recovered and analyzed.

The insertion site of the target clement determines which endogenous «ene will he activated. The target P element is thus *the* "mutagen" in this type 4jf screen. The fact that the target element *is* a randomly transposing P element makes it possible to generate many different target flies each having a different insertion site. It also facilitates the cloning of the mutated (adjacent) gene. The modular design makes the screen flexible: genes can be induced in any spatial or temporal pattern by simply using pattern lines with different GaH expression patterns. Finally, by keeping the pattern and target elements apart and inactive until mating them in the test cross, one can recover target inserts that are lethal or sterile when activated.

To test the method, I performed a simple screen, focusing on the eye. Perturbation of eye development in *Drosophila* leads to a rough-eye **phenotype,** which is clearly visible in a dissecting **microscope** (Fig. 2)* **Because** a number of genes important for eye development have already been identified, I knew what to expect (or rather hope for). After I optimized components of the method, the screen was successful. I crossed a pattern line expressing GaH in the developing eye to 163 target lines. Six (4%) of the target lines gave distinct dominant phenotypes (i.e., rough eyes) in the progeny when, and only when, the Gal4 pattern element was present. (See example in Fig. 2.) Molecular analyses confirmed that genes adjacent to target elements were being over- or mis-expressed by Gal4 activation.

Taking advantage of the system's modularity, I looked for effects in other tissues by crossing my six target lines to other Gal4 pattern lines. Three of the target elements only affected eye development, three had effects in other tissues as well. When I cloned the DNA adjacent to those target elements affecting only eye development, I got a very pleasant surprise. One element had inserted right next to the gene encoding GTPase-activating protein (GAP). This was a nice result because it agreed with previous traditional genetic experiments showing that GAP expression was critical for correct eye development. GAP converts the active form of a protein called Ras to an inactive form (see Fig. 3A).

To confirm that increased GAP was causing the rough-eye phenotype by decreasing Ras activity, I tested the effect of reducing Ras activity even further by introducing a mutation in Ras itself. As expected, this made the rough-eye phenotype much more severe (compare Fig. 3D to Figs. 3B and 3C). Finding the insertion in GAP and showing how it interacts with Ras proved that the method can identify biologically relevant effects and genetic interactions, as it was designed to do.

Future Directions

Having shown that the mis-expres-

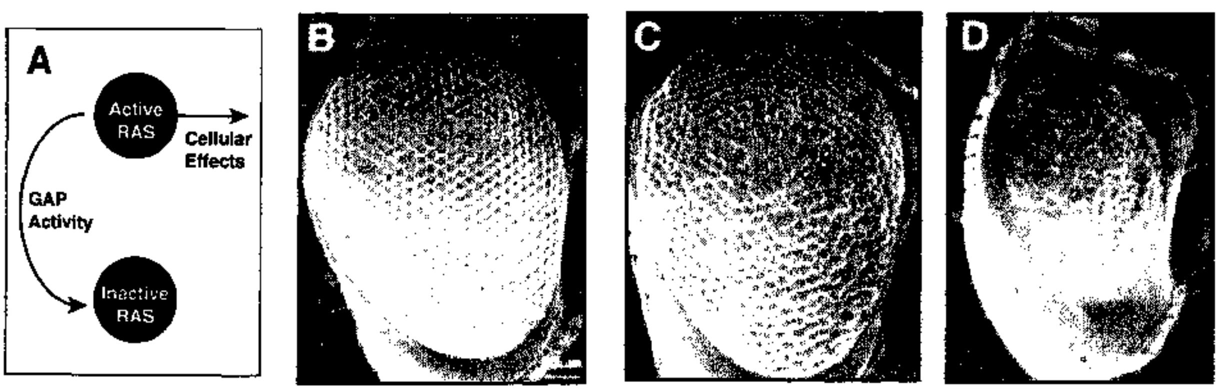


Figure 3. Consequences of altering Ras activity in the eye, A certain amount of active Ras Is reopired for correct eye development. Too much or too little distorts the process. Panel A: GAP protein converts active Ras to the inactive form. (Another protein converts inactive Ras to the active form, tot Is omitted for clarity. J Panel 8: This eye has lower than normal levels of Ras protein, bui there is still enough active 'Ras to give a normal-looking eye. Panel C: GAP is over-expressed in this eye. As a result, too much Ras protein is inactivated and the eye is abnormal (i.e.. rough). Panel D: GAP is being over-expressed, but new there ts too little Ras protein to begin with (as the eye In B). The result Is an even further reduction in the level oi active Ras, causing the eye to be severely deformed. This is an example of a genetic Interaction, showing that Ras and GAP at! together.

sion screen works, we are now set to carry out a large-scale screen. With support from the Berkeley *Drosophila* Genome Project, we are generating about 2,000 target lines, each potentially mutating a different endogenous gene. The target inserts are made by allowing a target element to transpose (jump around) in the genome in a controlled fashion. Because the target lines have no inherent tissue specificity (this is provided by the pattern line), they can be used by anyone who wants to do a screen of this type. We plan to make the lines available to all *Drosophila* researchers, and hope they will be used to address many different biological problems.

I, myself, am interested in using the screen to study mechanisms of cell-type specific gene expression. Imagine two cells with different identities in the same organism, say a muscle cell and a skin cell. These cells have the same genomic DNA, yet express different genes. How is this achieved? We know some of the regulators (transcription factors) that recognize specific DNA sequences and turn genes on and off. Surprisingly, some factors can recognize and regulate different genes in different cell types. I have been studying one such factor, called C/EBP, which performs several essential roles during fly development. Based on a detailed analysis of the C/EBP protein in transgenic flies, I concluded that the genomic DNA itself may be imposing cell-type specificity *on* C/EBP.

This is not as strange as it sounds, for although the DNA is the same in each cell of ;m organism, the chromatin into which it is Kumd is not. (There is no "naked" DNA in a cell; it is all hound into a highly complex protein-DNA lattice called chromatin). Intriguingly, it appears that chromatin's structure can reflect earlier decisions of cell identity and thus serve as a memory of these events. Perhaps it is this memory, in the local structure of a cell's chromatin, that directs the action of a transcription factor like C/EBP on the DNA. I will use the modular misexpression screen to look for proteins that affect C/EBP's function or chromatin function in general, in order to gain a detailed understanding of how C/EBP interacts with chromatin.

In conclusion, the modular misexpression screen identifies genes which when over- or mis-expressed in a pattern of interest give a specific phenotype or modify an existing mutant phenotype. This is a novel way of finding genes with specific functions in higher eukaryotes, and it is likely to uncover new information. The modular design makes the screen simple to use and applicable to the study of many developmental processes. Many useful Gal4 pattern lines are already available. Target lines are easy to generate and can be used repeatedly, and mutated genes can be readily identified. The fact that the screen has uncovered genetic interactions which agree with more traditional genetic analyses is strong support for its usefulness and relevance in studying biological processes in *Drosophila.* By using other transposable elements or retroviruses as indue ible mutagens, it is likely that similar approaches may eventually be developed for other organisms.

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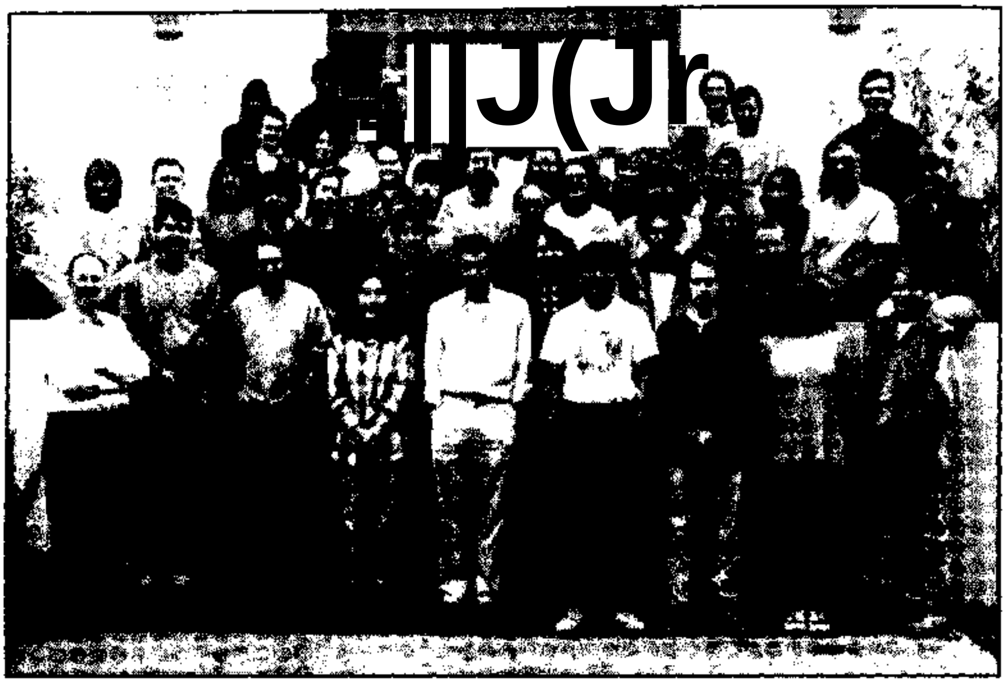

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Director's Introduction

In order to understand a biological phenomena, it is frequently useful to first identify a suitable model. This concept is among the most important of experimental biology. It explains why populations of mice, flies, and other organisms inhabit the laboratories of molecular biologists. One of those organisms, the single-celled yeast *Saccharomyces cerevisae,* has proved to be an exceptional model for modern biology. This organism is particularly valuable in studies identifying the proteins and corresponding genes that control ubiquitous cellular processes. *Saccharomyces* has all of the basic machinery of a typical eukaryotic cell, as well as properties that facilitate the analysis of gene structure and function. It is easy to maintain in the laboratory, and easy to manipulate. Indeed, the value of this organism for eukaryotic biology has been so profound that several years ago a consortium of scientists from around the world undertook to sequence its entire genome. In April of this year, they announced the project s compie-tion. As described in a recent review article in *Current Biology* (Vol. 6, pp. 500-503), the roughly 15,000,000 base pairs of DNA in *Saccharomyces* encode approximately 6,000 genes. Surprisingly, despite the intensive genetic analysis this organism has undergone over the past twenty years, less than half of its genes had previously been identified by mutations. In some cases, the presence of two functionally redundant genes may have masked the effects of a mutation in one of the genes. In the majority of cases, however, the newly discovered genes are simply of unknown function. A new international collaboration is now underway to systematically mutate all of the genes in yeast in order to assign function to each one. In preliminary experiments, many such mutations have no apparent phenotype in laboratory conditions, i.e., they cause no change in the organism's appearance or behavior. Thus, it seems likely that much of the yeast genome is not required for cell viability but rather is used for adaptive responses to changing environmental conditions.

"The potential utility of easily cultivated single-celled Organisms has not been hst on plant biologists...."

The potential utility of easily cultivated single-celled organisms has not been lost on plant biologists. The green alga *Chhmydinnonas reinhardtii,* for example, has been used as an important model for studying aspects of plant biology, including photosynthesis, for more than thirty years. Early work by Paul Levine and colleagues at Harvard University showed that it was possible to isolate and grow large numbers of *Chlarnydomonas* mutants unable to carry out photosynthesis simply by providing an alternate carbon source, such as acetate. Such mutants were essential tools in dissecting the series of steps involved in photosynthetic electron transport. Unfortunately, *Chhmydorno" nas* proved to be recalcitrant to genetic transformation with exogenous DNA (i.e., it was not possible to introduce genes), and the early plant molecular biologists frequently bypassed it in favor of other organisms that could be transformed. However, a few researchers. Including CamegieV Art Grossman, persevered. Several years ago, the transformation problem was resolved, and if is now routinely possible to introduce exogenous DNA into the *Chlamy&ommas* genome at random sites. Because *CMamydanumas k* normally haploid* the insertion of exogenous DNA frequently disrupts a ^ene. By transforming *with* a well* JeftneJ source of DNA, such as a small bacterial plasmid, disrupted genes can easily be found (and later cloned) by virtue of their association with the plasmid.

Chlamydomonas

In their essay on p. 99, Kris Niyogi, Art Grossman, and Olle Björkman explain how *Chlarnydomonas* mutants are providing new insights into a problem of long-standing interest to the Björkman laboratory—the dissipation of excess energy as heat. Over the past decade, Olle and others have accumulated abundant physiological evidence suggesting that pigments called xanthophylls play a key role in dissipating the excess energy produced by light absorption during photosynthesis. However, much of the evidence implicating the xanthophyll cycle has been indirect. Furthermore, it was unclear what other processes, if any, contributed to the energy dissipation process. By screening for insertional *Cbkmydommas* mutants that are defective in photochemical quenching (which provides a measure of the amount of energy dissipated as heat), Kris, Art, and Olle are dissecting the process with unprecedented detail

The genetic approach will events ally reveal the different kinds and amounts of gene products involved in the overall process. Since the disrupted genes can be cloned, and, in many cases, identification of the gene product deduced by sequencing, it should be possible to define the precise function of each component. Although much remains to be done, the initial isolation and characterization of *Chlamydomonas* mutants has demonstrated that addi' tional mechanisms, besides the xantho phyll cycle, contribute to the dissipation of excess light energy. Considering that plants cannot control the amount of sunlight they receive, it is hardly surprising that they have developed distinct processes with redundant functions to cope with the potentially lethal effects of too much light.

Looking back, we may envision the first moment several decades ago when Olle Björkman stood in Death Valley and was struck with the question of how plants were able to survive the blazing sun. Much can be learned about the nature of biological research—and the use of model systems—by considering the path that led from that first moment of curiosity to the current work on gene identification in *Chlamydomonas.*

The importance of models is also evident in Chris Field's essay explaining how increasing atmospheric CO_2 concentration is likely to affect natural ecosystems. Because of the high cost of long-term CO_2 enrichment experiments, it is necessary to expose plants to CO_2 in relatively small enclosed areas. The complexity of the responses observed in Chris's model containment system reveals some of the principles that will guide current and future thinking about the consequences of increased CO_2 concentration.

Chris's results show that in addition to changes caused by the climatic effects of increased CO_2, we may expect accompanying changes in the species composition of natural ecosystems. These changes result from direct and indirect biological effects of increased CO_2 on water use efficiency and photosynthesis. I consider the results obtained by Chris and colleagues to be alarming. As we continue to make massive alterations to the ecosystem (by our land and water use practices), it seems we will face as yet unknown alterations in the species balance of the remaining undisturbed areas. It appears unlikely that we will be able to curb CO_2 emissions in the foreseeable future. Indeed, it is very hard to imagine that anything can be done on a large enough scale to have a remedial effect. Perhaps our best hope is that our increasingly sophisticated ability to manipulate plants genetically will eventually permit us to develop plants with much higher rates of CO_2 assimilation.

— *Christopher Somervilk*

Photo, next page: *Carnegie^ gigantea* cacti near the site of Carnegie's former Desert laboratory in Tycson, Arizona. How these ami other plants avoid damage to their photosjethetlc apparati in high light remains an active area of research at the Department of Plant Biology.

How Plants Protect Themselves from Damage by Excessive Sunlight

by Krishna Niyogi, Arthur Grossman, and Oik Björkman

Over the course of days and seasons, plants experience large variations in the amount of sunlight they receive. Much of the radiant energy is absorbed by light-harvesting complexes in the photosynthetic (or thylakoid) membranes of the chloroplasts. The light-harvesting complexes are composed of a family of proteins bound to chlorophyll and the carotenoids (accessory orange and yellow pigments such as lutein, zeaxanthin, and (3-carotene). The energy absorbed by the pigment-protein complexes drives photosynthetic electron transport, which converts light energy into chemical energy in the form of ATP and NADPH; these molecules are required to fix atmospheric CO_2 into sugars and other organic molecules upon which the plant's life—and ultimately our own lives—depends.

Plants *dissipate much of their excess energy as heat. Insights from molecular biology are helping scientists learn details of this photoprotective process.*

For the past several years, research in the Björkman laboratory has focused on questions relating to how environmental parameters, such as light intensity, alter the way in which a plant uses incident light energy. Regulation of light energy is critical for balancing the production and metabolic consumption (by photosynthesis) of chemical energy. In low light, plants increase their capacity for light harvesting by making larger light-harvesting complexes, allowing them to maximize photosynthetic efficiency- As the intensity of light increases, however, the rate of capture of radiant energy exceeds the capacity for which it can be used; photosynthesis becomes saturated not because of a limitation in light absorption but because of a limitation in light energy utilization. The level of light intensity at which photosynthesis reaches a maximum is influenced by such factors as

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temperature, salinity, and water availability. Under unfavorable growth conditions, the plant will experience excessive light even at relatively low intensities.

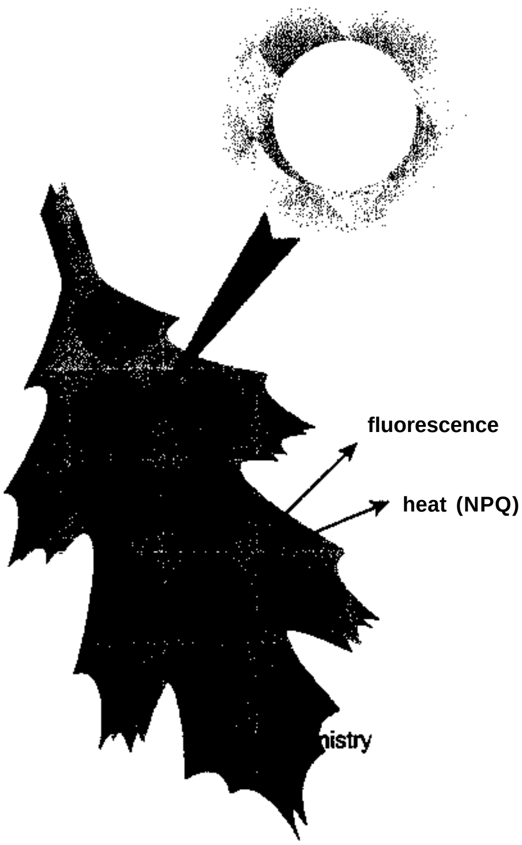
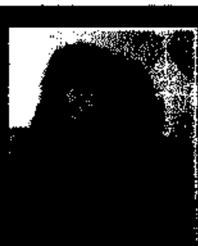


Figure 1. Pathways for dissipation of light energy absorbed by chlorophyll. Absorption of sunlight causes chlorophyll (Chi) to enter the singlet excited state (Chi*), It then releases that energy In one of foor ways: through photochemistry, NPQ, fluorescence, or by generating the toxic singlet

Dissipating Energy as Heat

When the input of radiant energy exceeds a plant's capacity to use it, the photosynthetic apparatus may be damaged. Excess light may lead to the production of dangerous pigment and oxygen species that can react promiscuously with numerous chloroplast components. For example, when excitation energy accumulates in the light-harvesting complexes, triplet chlorophyll may form. This molecule reacts with molecular oxygen to generate highly reactive singlet oxygen, a toxic radical. Although plants have some capacity to cope with oxidative damage, they are generally able to dissipate much of the excess light energy safely as heat before toxic radicals form.

Plants dissipate heat through a mechanism called nonphotochemical quenching (NPQ). When a chlorophyll in the light-harvesting complexes absorbs a photon of light, an electron becomes excited, and the chlorophyll enters the energized singlet excited state. It can return to the ground state by one of the four routes depicted in Figure L It can transfer its excitation energy to another chlorophyll molecule and ultimately to the photosynthetic reaction centers to drive photochemistry (1). The chlorophyll can dissipate its excitation energy as heat through



Arthur R* Grossman eatwtee! an M.*8* and a PiuD. from .-Indiana Uaivtwity and Jcwied Carnegie In 1982* one of the first stall' ntcmiiers to *he* mtilectttarly ©iicistccL His **major** Jiifcrtst **lies** is **leatttittg** itiiw pluitosvntlictic offpitiistiis sense **and** respond to changes- in, •apvirciciniettfal **conditions*** iiiili';its li|hflaiefisif:f •tin! ^ittilti^ IIIKI **nutrient availability***

NPQ (2). It can release the energy as fluorescence (light energy of a longer wavelength) (3). Or, the singlet excited chlorophyll may drop to the triplet excited state, which then can return to the ground state after interacting with oxygen to generate the toxic singlet oxygen molecule (4). The first route provides energy for photosynthetic electron transport and the generation of sugars. The second and third pathways are harmless dissipative processes. The last pathway has the potential to damage the photosynthetic reaction centers and destroy many molecules in the cell.

NPQ is photoprotective in part because it provides an effective alternative to the de-excitation of chlorophyll via the hazardous triplet pathway. However, NPQ also competes with photochemistry, so it must be strictly controlled to minimize any loss in photosynthetic efficiency at subsaturating light intensities. We are interested in determining the mechanisms which trigger NPQ, and identifying the molecules critical for the process.

We can determine NPQ by measuring changes in chlorophyll fluorescence. Although the amount of energy emitted as fluorescence is generally small (at most 3-4% of the absorbed energy), fluorescence provides a convenient visual indicator of the energy dissipated as heat, which can be very significant—up to two-thirds of the absorbed light energy. When heat dissipation increases, chlorophyll fluorescence decreases, i.e., it is quenched, hence the origin of the term nonphotochemical quenching.

Numerous biochemical and physiological studies suggest that the pH within the aqueous lumenal space of the thylakoid membranes plays a key role in establishing NPQ. Photosynthetic electron transport is accompanied by the movement of protons (hydrogen ions, H^+) across the thylakoid membranes, which generates a different pH on either side. This proton gradient, or ApH, is the stored energy that is harnessed (by the enzyme ATP synthase) to make ATP. In the process of forming ATP, the gradient is dissipated. However, when light harvesting and electron transport exceed the capacity of CO_2 fixation and other energy-assimilating reactions, ATP is not consumed fast enough to liberate ADP (the precursor to ATP) for the ATP synthase. As a result, the magnitude of the ApH increases, and the lumen becomes more acidic. This change in pH serves as an indicator of excessive light and triggers NPQ.

Several years ago, workers elsewhere noted that changes in NPQ were accompanied by changes in the concentrations of particular carotenoid

Born and educated in Sweden (where he earned his doctor' ate at the University of Uppsala), Olle Bjdrfcman lias been with Carnegie since 1964- His biochemical studies on plant adaptation, have taken him to environments- ranging *from* Death 'Valley to the tropical irotsties of Australia.

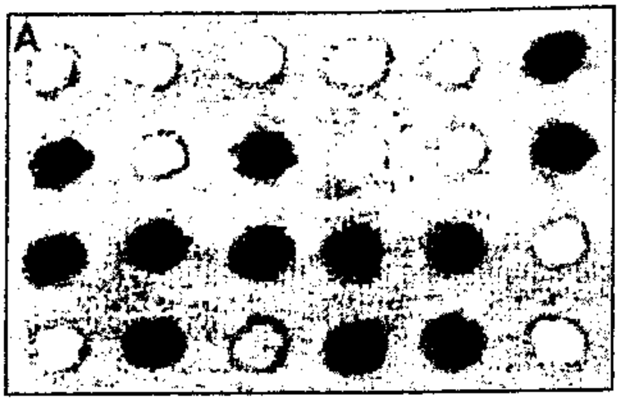


Figure 2. Fluorescence imaging of *Chlamydomonas* colonies. NPQ. mutants are shown among progeny of a genetic cross between the mutant and the wild type. Mutant colonies with reduced NPQ.appear black, whereas wild-type colonies appear white. The mutant phenotype segregates 2:2 in each tetrad (column of four colonies) *produced* by meiosis, indicating that ihe phenotype is due to a single Mendelian mutation.

pigments called xanthophylls. These molecules, integral to the photosynthetic membranes, are derived from P-carotene and a-carotene. The key xanthophylls thought to be involved in NTQ—zeaxanthin (Z), antheraxanthin (A), and violaxanthin (V)—are derived from P-carotene. The forward and reverse interconversion of Z, A, and V is called the xanthophyll cycle. V is converted to A and Z when the *ApH i4* the thylakoid membranes reaches a critical magnitude, i.e., when the plants are exposed to too much htfht.

Subsequent work *in* the Björkman lab has contributed to what is now a large Kdy of evidence demonstrating a strong; correlation between the concenrratit^n of Z and A :ind the extent *of* NPQ. In particular, inhibitors of Z and A formation can greatly decrease NPQ. Recent work from the laboratories of Thnnu* iVtvens (Cornell University) ·md H;ur\' Frank tL'nsverMtv i**f Con-** *iKxtKiit* \ h_t* ^hnun that Z, and perhaps *A\M** A, are theoretically capable of directly de-exciting singlet excited chlorophyll, providing a biophysical basis for NPQ.

Clues from Molecular Biology

A couple of years ago, we in the Björkman lab began a collaboration with the Grossman lab, exploring how genetic and molecular biological approaches might help us understand the mechanisms that contribute to NPQ. For this work, we are using the single-celled green alga *Chlamydomonas reinhardtii. Chlamydomonas* performs photosynthesis in a manner essentially identical to that of vascular plants, but unlike vascular plants, *Chlamydomonas* is able to grow without photosynthesis. It can use acetate as its sole carbon source. This characteristic makes *Chlamydomonas* an advantageous experimental subject, since mutants that are unable to carry out photosynthesis can be maintained on acetate-containing medium. *(Chlamydomonas* mutants of this type were used over three decades ago to define the pathway of photosynthetic electron transport.) In addition, *Chlamydomonas* is an excellent organism for genetic studies; it has a well-defined sexual cycle, a predominant haploid generation that facilitates the isolation of recessive mutations, and it is readily transformed with exogenous DNA.

Kris Niyogi has isolated and characterized several mutants defective in NPQ, using a mutagenesis technique in which a piece of DNA of known sequence is inserted into a genome. The mutant organisms were then grown as colonies in petri dishes. When they reached sufficient numbers, they were exposed simultaneously to excessive light for a ten-minute period. (This allowed us to determine which of the colonies were deficient in NPQ.) We captured fluorescence images by video camera, digitized the images with a computer, and calculated the extent of NPQ. As seen in Figure 2, the dark colonies had higher fluorescence and thus reduced NPQ, while the light colonies had normal NPQ.

To determine how NPQ and the xanthophyll cycle were related in the NPQ-deficient mutants, we measured levels of chlorophyll, carotene, and xanthophyll after again exposing the mutants to high light (Fig. 3). The wild-type strain (upper left) showed the normal complement of xanthophylls, including Z and A produced from V via the xanthophyll cycle. (The other components of the "pie" are identified in the legend.) The strain designated *npql* (bottom left), one of the most interesting mutants we isolated, was unable to convert V to Z and A upon exposure to excessive light. (Likely, *npql* is defective in the enzyme that catalyzes this reaction.)

That the *npql* mutant was unable to produce Z and A confirmed suggestions from earlier experiments that Z and A are involved in NPQ. However, a significant amount of NPQ—about

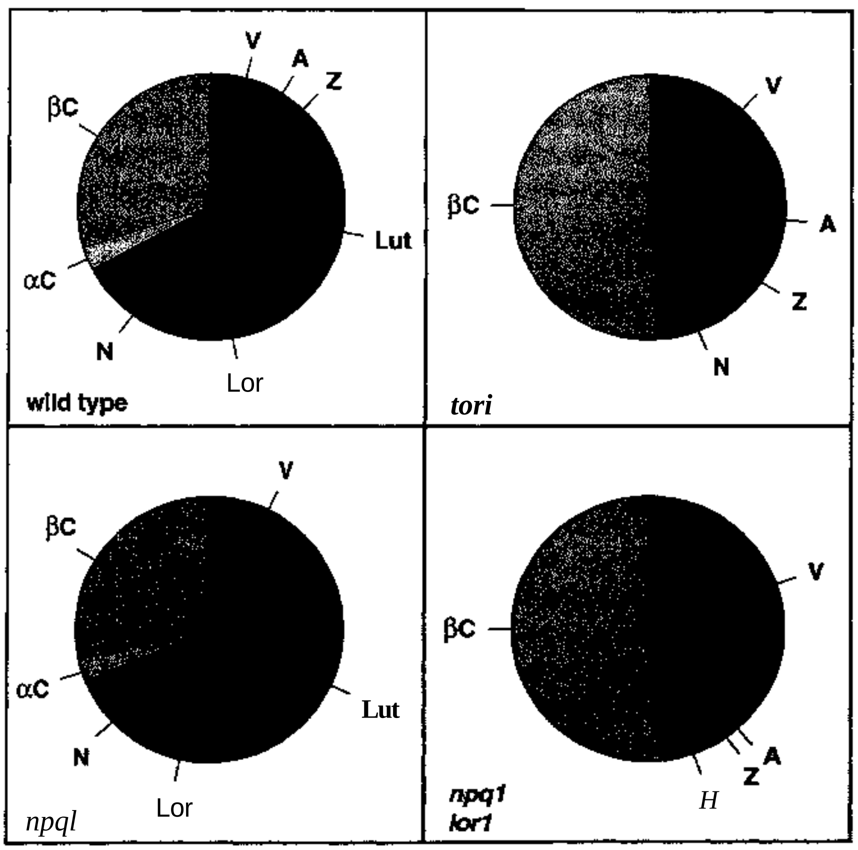


Figure 3. Pigment composition of wild type (upper left) and three mytants of *Chlamydornonas*. All cyltores were exposed for 40 minytes to a light intensity equivalent to 25% of full sunlight Nxneaxanthin, Vavfolaxanthin, A«antheraxanthln, Z^zeaxanthin. Lut«lutein. Lor»toroxanthm. aC and pC * oc-carotenc and p-carotcne, respectively. |See text for explanation.)

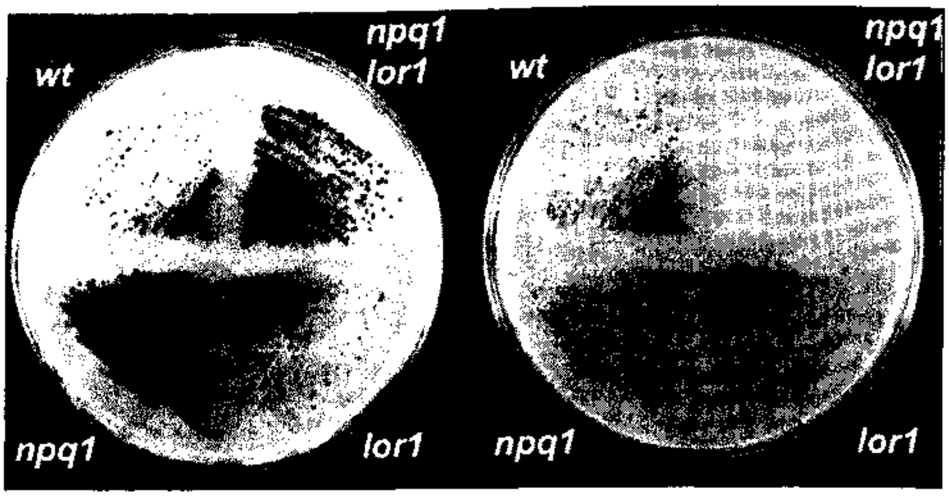


Figure 4. Growth of wild type and three mutants of *Chlamydomonas* under a light intensity eauivalent to 5% (left) and 25% (right) of full sunlight.

two-thirds of that in the wild-type—was still observed in the mutant. This seemed inconsistent with the premise that Z and/or A are absolutely required for NPQ. Furthermore, we were surprised to find that the *npql* mutant experienced no more sustained photodamage than wild-type *Chlamy* dumonas* upon short-term exposure to high light. In long-term growth experiments, too, *npql* seemed to have no growth defect in high light compared with wild type (Fig. 4), despite the fact that the regulatory process of NPQ was perturbed. One possible explanation for these results is that a remaining capacity for NPQ in the *npql* mutant is sufficient to permit normal growth in excessive light. This implies that there is mure than one way to generate NPQ, which is not surprising given its ecological importance. It also implies that there are components in the light* harvesting complex other than A and Z that are critical fur the normal operation of NPQ in high light.

We hypothesized that other xanthophylls pren.*nt in the photosynthetic memhrime* ot *Chkmydomnnas,* besides V_T A. and Z, might hv re*»pomable for the NPQ observed in the *npq!* mutant. In particular, we suspected that the xanthophylls lutein (Lut) and loroxanthin (Lor), both derived from a-carotene, were likely candidates, as both are similar structurally to Z and A. In addition, the available information concerning the energetic properties of Lut and Lor suggested that one or both, like Z and A, have the potential to quench excitation energy in the light-harvesting complexes by direct interactions with chlorophyll.

We tested this hypothesis by again using genetics, taking advantage of an existing mutant of *Chlamydomonas,* called lorJ, that is unable to make a-carotene, Lut, and Lor, but can synthesize large amounts of Z and A via the xanthophyll cycle (Fig. 3C). Upon exposure to high light, the *lor1* mutant exhibited substantially less NPQ than wild type, but like the *npql* mutant, *hrrl* was able to grow in high light (Fig. 4, lower left). A very exciting result was obtained when we crossed the lorI and *npql* mutants to generate the double mutant. This strain has no cc-carotene, Lnt» or Lor, and only small amounts of Z ;tnd A (Fig. 3D). Because of a severe Jefect in NPQ, it is unable to survive in high light, whereas growth in low light (subsaturating with respect to photosynthetic electron transport) is normal (Fig. 4).

Future Studies

These genetic experiments using *Chlamydomonas* have provided the first evidence that xanthophylls derived from both p-carotene *and* oocarotene play critical roles in establishing NPQ and in controlling the use of light energy. They also strongly suggest that there is some functional redundancy in photoprotection; that is, the (3- and a-carotene derivatives seem able, at least partially, to substitute for one another. Future studies will address several remaining questions. For example, are the xanthophylls acting directly or indirectly to facilitate dissipation of excitation energy as heat? It seems possible that the lack of particular xanthophylls in our mutant strains was the result of an indirect effect, perhaps a structural perturbation of the light-harvesting complexes. Examination of light-harvesting complex assembly and structure in the mutants will address this point.

Another question involves location. Where in the light-harvesting complexes are the xanthophylls located, and what are precise functional interactions among xanthophylls, chlorophylls, and the light-harvesting proteins? Characterizing NPQ mutants that exhibit normal xanthophyll composition, i.e., those with mutations in some other part of the energy-dissipation process, and isolating the genes affected in these strains may provide us with some answers.

A final question relates to the generality of our results. To what extent are experiments with the unicellular green alga *Chlamydomonas* applicable to the process of NPQ in vascular plants? We have recently initiated mutant analyses with the vascular plant *Arabidopsis thaliana,* which is currently the most popular and powerful model plant system. Like *Chlamydomonas, Arabidopsis* possesses numerous characteristics that make it an excellent genetic organism; it has a small nuclear genome with few repetitive DNA sequences, a dense genetic map and a developing physical map of the genome, a database containing many thousands of expressed sequence tags, and the likelihood that the complete sequence of the genome will be available in just a few years. In preliminary experiments, we used our fluorescence video system to isolate *Arabidopsis* mutants with reduced NPQ (Fig. 5). Two of these mutants are unable to make Z and A during exposure to high light. During the next year we plan to undertake detailed characterizations of these mutants to gain further insights into the mechanisms that allow photo* synthetic organisms to survive a constantly changing light environment.

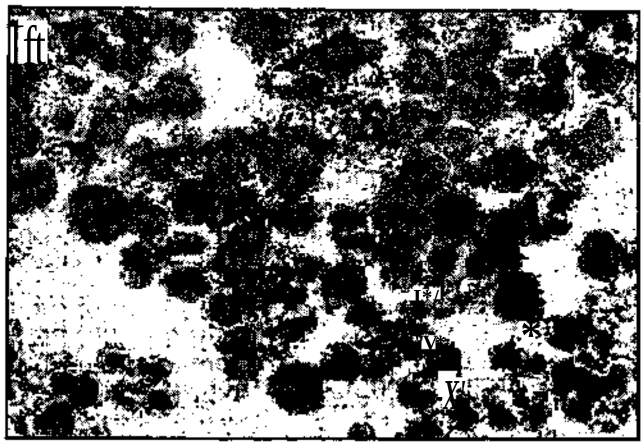


Figure 5. Screening for NPCImutants in *Arabidopsis.* A mutant appears black among a large number of non-mutant plants (light gray).

The *Changing Carbon Cycle, from the Leaf to the Qlobe*

by Christopher Field

Much of the discussion concerning carbon dioxide (CO_2) and global change has focused on CO_2 and climate. Yet, CO_2 has important direct effects on plants. At least in the short term, increased CO_2 leads to increased photosynthesis and decreased water loss (through small pores, or stomata, on the surface of the leaves). If these effects persist after long-term exposure to increased CO_2, and if they are not suppressed by other factors at the ecosystem scale, they could have dramatic consequences. Plants could grow bigger, faster, and use less water, leading to increased production of food, fuel, and fiber, and increased farming of arid lands. Increased CO_2 uptake by plants could also remove some of the carbon injected into the atmosphere by human activities, especially fossil fuel combustion. Should this occur, the rate of increase in CO_2 concentration in the atmosphere may slow down, decreasing the need for costly societal changes to reduce CO_2 emissions.

What happens when plants are exposed to excess carbon dioxide? Department of Plant Biology workers find that the availability of water is a critical factor.

However, this bright picture darkens significantly when one considers that CO_2 atmospheric concentration has already increased by over 25% since the beginning of the industrial era. Strong evidence suggests that terrestrial ecosystems currently sequester 20—30% of the carbon released by human activities. Will plants and soils reach a saturation point where they can store no more carbon I

Global change is subject to large unknowns. The seemingly positive, direct

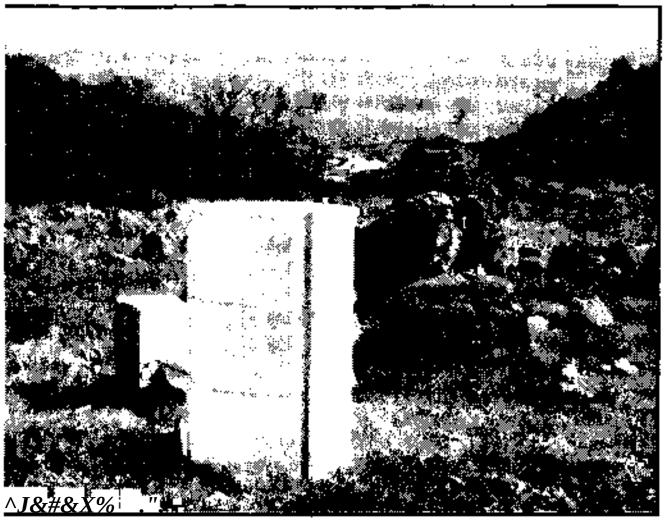
Chris Pieicl .earned his B.S* *si* Harvard and *his* Pli.P* at Stanfo&d* 1:0: 1:984, after teaching at the University of •Utah for several years* lie came &> the Department of Pifiit Biology .as a staff inenibet*, There, lie participates in sfudBes exploring biodiversity and evolution* and effects of elevated CO_2 are complicated by a host of indirect effects. Some of these indirect effects amplify the direct effects, but others may suppress them. In addition, effects that are beneficial from one perspective may be detrimental from another. For example, a CO_2-stimulated increase in plant growth could be a benefit if the stimulated species were economically or ecologically valuable. But it could be a serious problem if the stimulated species were weeds. Overall, our understanding is increasing rapidly, but it is still too incomplete to support accurate predictions across a broad range of ecosystems and over the whole suite of direct and indirect mechanisms.

My lab is exploring these issues at a number of scales, ranging from single plants, through whole-ecosystem experiments, to global models. The objective of all these studies is to identify mechanisms that have not been fully explored, quantify their impacts, and clarify their interactions. We are striving for an understanding general enough to be relevant to all the world's ecosystems, across tremendous variation in climate, soils, and species characteristics. We still have a long way to go, but more and more of the pieces are in place.

Ecosystem-Scale Responses to Increased CO_2

The literature on plant responses to elevated CO_2 contains thousands of papers. Most of these concern agricultural species grown as individuals in pots, with abundant light, water, and mineral nutrients. For the goat of developing a general understanding, these studies are of limited use. The plant species studied are too similar in their growth characteristics and climate requirements. Each experiment is too alike to assign causality for the differences among results. And relatively few studies address mechanisms at levels above the scale of the individual plant.

A relatively small fraction of the CO_2 literature concerns wild plants, and an even smaller fraction concerns whole ecosystems. Yet, several processes at the ecosystem level have the potential to dominate the responses of the terrestrial biosphere to increasing CO_2. Some of these involve species effects. In mixed communities, for example, species that are more CO_2 sensitive may be more successful in a CO_2-enriched environment and become dominant, creating a total response greater than that averaged across species. Other processes concern environmental factors limiting plant growth. It isn't clear if nutrient or water limitation would restrict the actual growth responses to increased CO_2, or if elevated CO_2 would allow plants to cope more successfully with stressful habitats. And some of the most interesting processes involve interactions among aspects of the CO_2 response. For example, extra carbon in the soil (as plant litter) could stimulate microbial activity, which could release more nitrogen from decaying plant material. On the other hand, litter from plants grown at high CO_2 may be more resistant to microbial decay, slowing nitrogen release. Experimental access to this kind of ecosystem-scale process is critical in evaluating the relative importance of mechanisms with very different outcomes.



One of the open-top chambers of the Jasper Ridge CO_2 experiment with the Stanford campus in the background. During the spring, this grassland is a rich carpet of blooming wildflowers.

In 1992, my lab started ecosystem-scale CO_2 experiments on Stanford University's Jasper Ridge Biological Preserve, about five miles from the Department of Plant Biology. These experiments are a collaboration with groups from Stanford, the University of California at Berkeley, and the National Center for Atmospheric Research, with inputs from researchers at a number of other institutions. The idea is to use an annual grassland ecosystem as a model for probing ecosystem-scale CO_2 responses. Our working hypothesis is that the underlying principles we uncover by studying and manipulating this ecosystem will provide a sound basis for predicting the response of other ecosystems to increasing atmospheric CO_2.

Just as a biological model like *Arahidopsis* provides unique opportunities in plant genetics and molecular biology, annual grasslands provide unique opportunities in ecology. Like other model systems, the Jasper Ridge grasslands operate with very general mechanisms, and experiments based on them are efficient in terms of space, time, and expense. Key advantages of these grasslands are the annual habit (allowing us to study entire generations), the small size of individual plants (allowing us to study a reasonably complete ecosystem in a small space), and the high species diversity. Also, the close juxtaposition of grasslands on very infertile and moderately fertile soils at Jasper Ridge helps insure that we are not confusing ecosystem-specific patterns with general patterns.

The leaf-level responses to doubled CO_2 we observe in our Jasper Ridge experiments are typical of many plants. When the soil is moist, elevated CO_2 leads to a 30-70% decrease in plant water use and a 20-40% increase in net photosynthesis. As the soil dries at the end of California's winter-spring rainy season, the differences are even greater, with net photosynthesis in the elevated-CO_2 plots up to twice as high as it is in the low-CO_2 plots. This is because soil moisture reserves are higher in the elevated-CO_2 plots.

To understand this effect, Chris Lund, a Stanford Ph.D. student in my lab, has conducted careful studies of CO_2 effects on the water budget of the plants. He finds that doubled CO_2 increases by up to 100 mm the water stored in the soil. The extra water allows some plant species to extend their growing season by several weeks. The effect is greatest in experiments with relatively fertile soil, where transpiration from leaves (and not evaporation from the soil) controls water loss.

Increased soil moisture in the high-CO_2 plots at the end of the growing season has a number of important consequences. Only some of the Jasper Ridge annuals are physiologically capable of using the extra water reserves. Most of the species follow a developmental schedule strongly regulated by daylength. By flowering and setting seed before the soil drought becomes too severe, these species can minimize the probability of a catastrophic failure to reproduce. However, they miss the opportunity to use the extra water resources. The species that *are* physiologically competent to use the extra water resources include two important groups. One group that takes dramatic advantage of the extra water is the native, nitrogen-fixing annual legume *Lotus wrangelianus.* Because *Lotus* grows much bigger, it fixes much more nitrogen under increased CO_2. Concentrations of ^{15}N in tissues of *Lotus* and other species suggest that at least some of this extra nitrogen becomes available to other species, providing an indirect benefit from the increased CO_2.

Another group of plants that responds positively to the extra moisture at the end of the growing season are the long-lived annuals, which reproduce during the summer or autumn, after living for up to a year. Most important among them are the native tarweeds, which are sticky, coarse, almost woody plants. Their dominance under elevated atmospheric CO_2 conditions suggests that the character of the Jasper Ridge ecosystem might change dramatically in such an environment, from grasslands and wildflower fields to something more like a weed patch in a vacant lot.

The results also suggest some general trends that may be broadly important, and that we are now preparing to test. One is that increased CO_2 may generally favor the invasion into grasslands of deeply rooted species able to capitalize on the increased soil moisture. In general, moisture availability is a critical controller, along with fire and grazing, of the boundaries between grasslands and shrublands or forests. If increased CO_2 favors woody vegetation, fundamental changes may occur over vast areas, eventually leading to a severe decrease in grassland ecosystems. Another possible trend is suggested by the success of *Lotus* under doubled CO_2. A number of simulation models indicate that long-term ecosystem CO_2 response is very sensitive to changes in the total nitrogen. If nitrogen-fixers in general are more stimulated by CO_2,

Former Carnegie Ph.D. student Missy Holbrook (now on the faculty at Harvard University) measures plant water stress as a test for effects of elevated CO_2 soil moisture.

Former research assistant Julie des Rosiers (right) and research associate Susan Thayer record the abundance of late annuals during the California summer.

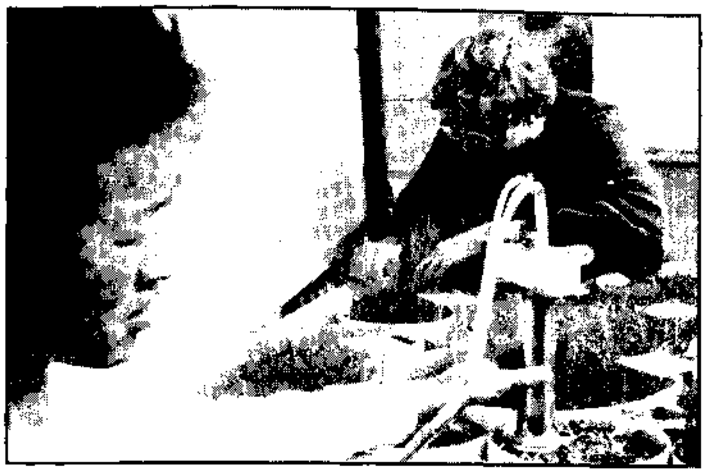
then limits on plant growth from nitrogen availability may be much less important than we currently estimate.

Microbial processes are also very sensitive to CO_2-induced changes in soil moisture. Work by Bruce Hungate (who worked on the Jasper Ridge CO_2 experiment as a Ph.D. student at the University of California, Berkeley) suggests that doubled CO_2 leads to an increase in the rate at which microbes release nitrogen into the soil, and a concomitant increase in plant nitrogen uptake. The latter result was a surprise, because microbial biomass also increases, and microbes often outcompete plants for nitrogen. The explanation may lie in how CO_2 affects the composition of the microbial community. It appears that elevated soil moisture under doubled CO_2 allows an increase in the number of protozoans, which prey on the bacteria that would normally compete with the plants for available nitrogen. Whether or not this response is general, it clearly highlights the potential importance of species interactions, and of ecosystem players beyond the dominant plants.

The Jasper Ridge CO_2 experiments [illegible] identify water, and how plants respond to water, as a critical component of the large-scale, long-term response to increased CO_2. Other components, including species characteristics and soil fertility, are important as well. Across the world's grassland ecosystems, species composition and changes in nutrient cycling will most likely control the major responses.

CO_2 Responses at the Global Scale

Most studies on the effects of CO_2 and climate use general-circulation models to evaluate the consequences of CO_2 as a greenhouse gas. (A greenhouse gas traps solar energy and prevents it from being radiated to space; as a consequence, the atmosphere is heated and radiates back to Earth.) Building from our experience at Jasper Ridge, where effects of doubled CO_2 on the water budget loomed so large, my collaborators and I decided to explore the climate implications of decreased water loss (through stomatal conductance) induced by elevated CO_2. In experiments with increased CO_2, leaf temperatures are often elevated, sometimes by a degree or more, as partial stomatal closure forces a decrease in the amount of energy used to



Postdoctoral fellow Yioj tuo (left) measures soil respiration on an experimental ecosystem growing under elevated CO_2 conditions, as Ph.D. student Jim Randerson records plant density.

evaporate water. Because the canopy must dissipate as much energy as it absorbs, it compensates for the decrease in evaporation by transferring more heat to the air. As a result, canopy temperatures increase.

Is this effect important at the global scale? We are exploring this question using a model of the terrestrial biosphere developed by Piers Sellers (NASA's Goddard Space Flight Center) and others, including Plant Biology staff member Joe Berry. (Sellers has since become an astronaut in training.) Coupling Sellers' model to an atmospheric general-circulation model developed by Dave Randall and colleagues at Colorado State University, we examined changes in surface temperatures with greenhouse warming and stomatal warming resulting from doubled CO_2. Our simulations suggested a substantial magnitude for stomatal warming, more than 1° in mid-continental locations (Fig. 1). While smaller than the greenhouse warming, the stomatal effect will increase the overall impact of elevated CCX on climate.

With these simulations, we started with an experimental observation at the local scale, tested its implications with a sophisticated model, and are now returning to experiments for a clearer picture of the effects that need to go into the model. Hopefully, a continuing dialog between local-scale experiments, local-scale models, and global-scale models can provide a foundation for narrowing the uncertainty about future global changes.

Biological Interactions and Increased CO_2

A few experimental studies with elevated CO_2 have examined how CO_2 might affect interactions between plants and their predators. Others have explored how CO_2 might affect the success of an invading plant species. But most studies, even those at the ecosystem level, exclude such potentially important biological interactions. Carolyn Malmstrom, a Stanford Ph.D. student in my lab, recently undertook some of the first studies on a set of biological interactions involving plants and their pathogens.

Carolyn studied how increased CO_2 might afteet the impact of Barley Yellow Dwarf Virus (RYDV) on oats *Arena SUUWL* Since RYDV is transmitted only through aphid infestations, and is not carried in the germ line, Carolyn could regulate infection by controlling aphid treatments, and she could confirm the infection immunologically. (Because an aphid infestation has effects beyond transmitting the virus, Carolyn assessed the impacts of viral infection by comparing her plants to those briefly infested with non-BYDV-infected aphids.)

BYDV is generally nonfatal, but it decreases plant growth by disrupting the movement of carbohydrate out of leaves through the phloem. This is a potentially large problem, because carbohydrate export is the fuel for producing other plant parts, including grain. Two possible scenarios exist for interactions between BYDV and elevated CO_2. Under increased CO_2, BYDV infection could disrupt the mechanisms by which the leaves distribute carbohydrate even more, and thus have a larger negative impact on the growth and grain production. Or, the increased carbohydrate from the elevated CO_2 could essentially overpower the BYDV blockade.

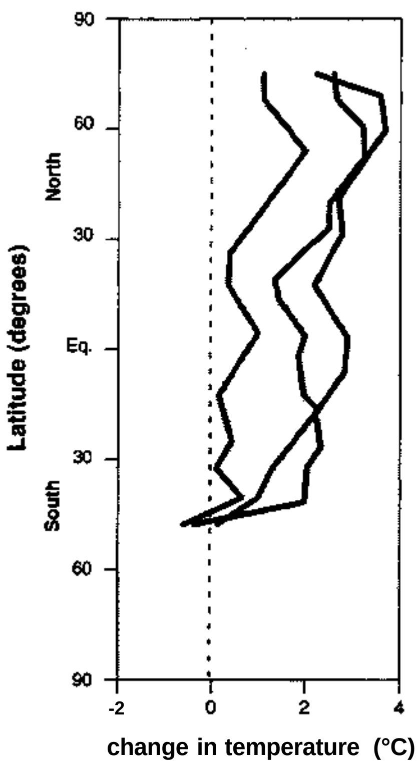


Figure I. Simulated changes in surface temperature as a function of latitude for the world's land points in |ujy, plotted relative to model simulations with ambient CO_2 (dotted line). Effects of greenhouse warming are shown as the solid purple line, stomatal warming (with a relatively large effect of CO_2 on conductance) as the dashed purple line, and the combination of both mechanisms as the black line. {Redrawn from Sellers et al. *Science* 271, 1402-1405.)

In Carolyn's experiments, doubled CO_2 led to greater growth in both virus-infected and uninfected oats, but the relative stimulation was greater in the virus-infected plants. The virus-infected plants responded to increased levels of leaf carbohydrate with increased transport. In this way, increased CO_2 helped infected plants tolerate their infection, which would lead to decreased overall yield losses. At the same time, increased CO_2 might increase the number of infected plants by providing the aphids with larger targets for infection- While we have yet to quantify the balance between these two components, it is clear that CO_2-pathogen interactions can have major impacts on ecosystem function. Our predictive models will be incomplete until they account for these interactions.

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'From December 11, 1995 to April 11, 1996
-To September 16, 1995
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Outside the seminar room on the department's grounds.

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Geophysical Laboratory

High school student Alex Feldman, drilling wood to obtain samples for a long-term decomposition study.

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Director's Introduction

International visitors to the Geophysical Laboratory are often surprised at the small size of its staff, given the Lab's enormous influence on the earth and materials sciences. Much of the Lab's reputation is based on broad studies of physical and chemical studies of inorganic rock-forming minerals, i.e., oxides, silicates, and sulfides, and the roles these minerals play in igneous and metamorphic processes. The accompanying three articles illustrate other dimensions in earth science research at the Lab, all extending substantially beyond what many consider to be its central research theme. In the first article, Marilyn Fogel and Beverly Johnson describe their investigations of the carbon and nitrogen isotope variation in modem and ancient emu eggshells collected from the Great Australian Desert. Their study seeks to answer whether the Australian continent was once more heavily forested than it is today, and whether the ancient aboriginal people were responsible for the deforestation through their large-scale burning practice—global change caused by anthropogenic intervention!

> ***"There IS every indication that...research in the interface between organic and inorganic geochemistry will continue to flourish and expand..."***

The other two articles describe research that has benefited enormously by the availability of new technology. In one, George Cody describes how a unique x-ray microscope at the National Synchrotron Light Source enables him to obtain detailed images of a variety of ancient organic materials, ranging from fossil kerogen to coal. These images provide organic structural information unavailable by any other method, and will undoubtedly help in understanding how coal and petroleum deposits are formed.

In the third article, Douglas Rumble describes an exciting new discovery in rocks from China showing that the rocks were subducted deep into Earth's upper mantle and then transported back to the surface with little alteration of their isotopic signatures. In this work, he uses a new laser fluorination technique he developed that allows him to analyze oxygen isotopes on very small areas **(~10firn)** of the minerals of interest. This provides detailed mapping of the isotopic variation across and between the mineral grains. The results suggest that the climate was very cold in the area where the original rocks were formed more than 200 million years ago.

Together, these essays show the broad but also closely-linked research of three collaborating staff members, covering global change on different spatial and time scales, using different techniques, and combining field work in widely separated areas of the world. There is every indication that the Geophysical Laboratory's research in the interface between organic and inorganic geochemistry will continue to flourish and expand in the future.

—*Charles* T. *Prewitt*

Beverly Johnson and Marilyn Fogel began their journey through the Australian Outback in the desolate Lake Eyre Basin, above. (See map on p. 123.) Photo by Chris Swarth.

Isotopic Tracers of Climatic Change in the Australian Outback

by Marilyn L. Vogel and Beverly]. Johnson

The geological record shows that major changes in the climate of the Australian Outback have occurred over the past 150,000 years. Most of these climate shifts are related to Milankovitch sunspot cycles, which affect the intensity of the Asian monsoon and thus impact the area's rainfall. Milankovitch cycles, however, can not explain the most recent shift, from wet to dry climate, that has occurred in the Australian interior over the last 20,000 years. We hypothesize that humans, through their practice of frequent, large-scale landscape burning, may have been responsible for the changes in vegetation that forced this climate shift.

Researchers are learning why the Australian Outback became the desert it is today through an unlikely source— the emu, a large, flightless bird native to the "down under' continent.*

Humans came to the Australian continent about 60,000 years ago. These hunter-gatherers used fire to hunt, promote the growth of certain plants, send signals, and in religious ceremonies. Over the long term, frequent burning alters the landscape dramatically; only plants able to tolerate burning more often than every 20 years survive in large numbers. In addition, burning alters soil fertility, producing soils with very low nitrogen, phosphorus, and organic matter contents. As a result, plants and soils sequester less moisture, and monsoon rainfall entering Australia from the north can't easily transfer moisture into the continent's interior.

Marilyn **Fogel** lias been exploring the **inter**faces.**fjet^** [illegible] **biology** .mod the -earth sciences since |aiiilag Cariic|iie%,.' Geophysical Laboratory in 1977. She earned a B.S. in biology fri»t PciwiSflvtiiiiii. .S^e-lliiiv«*^ty/siiid.it:?li*I)*:. In bcifSfiT fiiiarifte :§€§eiice} frwii'-ilb^IJ^[illegible] of Texas.

Establishing the Climate Connection

The first step in our effort to understand how humans may have influenced the Australian Outback was to establish a means to assess the climate changes that have occurred over the last 50,000 years. Towards this end, we (with our U.S. and Australian collaborators) have been studying the geochemistry and geology of the Lake Eyre Basin. Our tools include the stable (i.e., nondecaying) isotopes of carbon and nitrogen in modern and fossil emu shells. Previous work by Beverly Johnson demonstrated that the isotopic signals of the eggshell of a related bird, the ostrich, are stable over geological time and that they record information on the animal's diet. Because this information can be linked to patterns of rainfall, temperature, and vegetation when the animal was still alive, the fossil ostrich eggshells can be used as climate indicators. We are applying the same principles to emu eggshell.

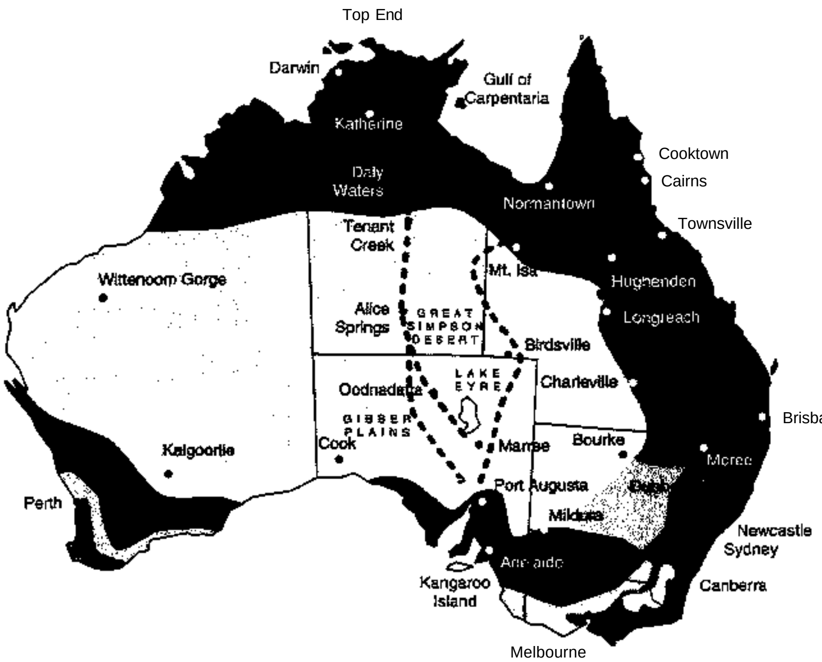
Chris Swarth

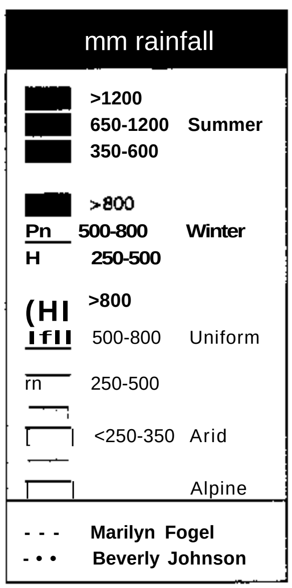
Marilyn Fogel gathering plant samples.

The basic hypotheses of our study are the following: (1) The carbon and nitrogen isotopic compositions of plants reflect the climate and the environment in which they grow. (2) Animals feeding on these plants incorporate the plant's isotopic tracers into their own tissues and into those of their predators, passing the signatures up the food chain. (3) Fossilized remains of animals, such as bones and shells, retain these isotopic signatures, and thus provide a record of changes in ancient climates and environments.

During July and August of 1994, we collected samples of modern vegetation, soils, and emu eggshell along a 3,500-km transect across the interior of Australia. (See map, next page.) (Our track was very similar to that of a 1930s DTM magnetic expedition.) To verify the links between diet, vegetation, and climate, we collected samples over a range of climatic conditions, from the

From 1991 until 1993, Beverly Johnson was a predoctora! fellow at the Geophysical Laboratory, where she did research leading to a Ph.D. She received her degree' in 1995 from the University of Colorado and since then has been working with. Marilyn Foget as a, postdoctoral fellow.

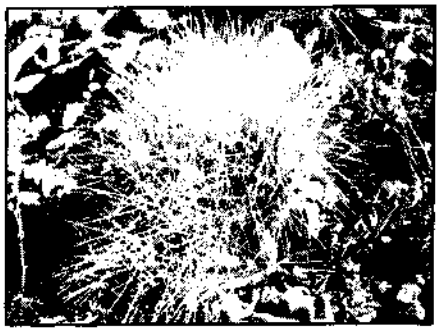




very dry Lake Eyre Basin (1.50 mm rainfall per year) to tropical locations at the Top End outside of Kakadu National Park (1,100 mm rainfall per year).

Sampling the vegetation of such a vast and diverse continent as Australia was a daunting proposition. Our strategy was to collect representative species of the principal components of the vegetation—and the soils associated with them—seven different locations along the transect. This included species with known fire sensitivity or tolerance. Some species, for example *Macropteranthes keckvueckii* (also known as bulwoody), dominated the north-central regions of Australia 10,000 years ago. Today, bulwoody occurs only in small patches with a very narrow range near the town of Daly Waters. This plant and others like it are unable to withstand fires more frequently than about every 50 years. Other plants, such as the prickly spinifex grasses, *Triodia* sp$_{M}$ require fire to give them a competitive edge. Almost all of the north-central area of Australia is now covered with spinifex grasses.

To understand haw emu diet is linked to climate, we also gathered remains of emus and the plants and



Chris Swarth

Spinifcx grass, a common inhabitant of north-central Australia.

insects they commonly eat. (We collected one unfortunate emu from a roadside accident.) Emus mostly eat seeds, small shoots of grasses and herbs, flowers, and fruits, but they have been observed eating insects, including grasshoppers, caterpillars, and other larvae. The insects we collected came from one location in the middle of the Gibber Plains region, where we observed a flock of emus eating grasshoppers.

Measuring *Isotopes in Plants and Soils*

Since our 1994 expedition, we have measured the carbon ($8^{H}C$) and nitrogen ($8^{15}N$) isotope ratios of over 200 species of plants. The ratios of ^{B}C to ^{12}C, and ^{15}N to ^{14}N, both expressed in parts per thousand (‰), show up in every tissue of every plant.[1]

Depending on how plants initially process their incoming carbon dioxide, they arc categorized as either C, or C_4. Most tropical grasses and other plants adapted to hot, dry climates are C_4 plants. Shrubs and trees tend to use the C_p pathway. We found that the C_3 plants we collected varied in their carbon isotope ratios from -25‰ at Lake Eyre to almost -30‰ at the Top End. This variation accurately reflected the region's mean annual precipitation, which affects the water-use efficiency of the plants. (The more water available to the plants, the more open are the stomates—the tiny pores on the plant's surface. This allows more CO_2 to diffuse in and out, ultimately affecting the ratio of the carbon isotopes.) The grasses and other C_4 plants we collected had isotopic ratios that were essentially the same over the precipitation spectrum ($S^{13}C$ = -13 ± 2‰). However, average $S^{n}C$ values from the seven sampling stations, including both C_3 and C_4 plants, clearly revealed the effect of climate on the overall vegetation. (In drier regions, C_4 grasses constituted a greater proportion of the vegetation and so the effect of precipitation on $8^{13}C$ of all plants was slightly greater.)

The $8^{15}N$ we measured in the plants was, like the $S^{n}C$, strongly correlated to mean annual precipitation, though the presence of *Acacia* shrubs, which fix atmospheric nitrogen gas via bacteria in their roots, slightly dampened the trend. The median centered around +5‰, with a range of from -3 to +15‰. Nitrogen-fixing shrubs had an average value of about +1‰. Plants incorporate nitrogen typically from a pool of oxidized or reduced forms of nitrogen in their soils. To learn how the plant and soil reservoirs were related in our samples, we measured the isotopic compositions and concentrations of

[illegible] up the [illegible] chain, *so* that an animal contains practically the same carbon [illegible] Nitrogen, though, becomes slightly enriched in ^{15}N as one proceeds up the chain.

ammonium and nitrate in many of the soils we collected. All our soil samples contained only a fraction of the soluble nitrogen (and phosphorus) found in the rich soils of the United States. But while there was greater variation of the 8^{I5}N in the plants than there was in the soils, the relationship between precipitation and soil nitrogen isotopic composition was strong. The plants had thus incorporated the nitrogen isotopes almost directly from the soil.

While we found a strong plant-soil connection for nitrogen, the carbon isotopic composition of the soils had very little relationship to the carbon isotopes of the plants. Soil collected directly under a C_4 spinifex grass (S^{13}C = -13), for example, had an isotopic composition enriched in ^{12}C to -18‰, but it still varied by 5-6‰ from the S^{n}C of the grass itself. Organic matter in soils generally contains plant fragments mixed with a pool of biologically unreactive carbon that can be several thousands of years old. Indeed, organic matter in paleosoiis has the potential for retaining its isotopic signature over geological time. It can therefore contain a record of the S^{B}C of ancient vegetation. But our results indicate that these modern soils, like most of the soils in Australia, have either been burned or are heavily weathered. Either way, they contain very little organic matter.

Analyzing the Eggshells

Once we finished analyzing our plant and soil samples, we were ready to measure the isotopes in emu eggshell. The modern emu eggshell we collected came from a slightly different transect than the one yielding soils and vegetation, but it extended through similar climatic regimes. The task of searching for emu eggshells is similar to the job of a fireman—a lot of tedious boredom punctuated by moments of excitement. Beverly Johnson was able to gather eggshells from as far south as Kangaroo Island and as far north as the Gulf of Carpenteria. She obtained specimens from station holders, who found them on their ranches, and from museum collections. She also discovered several nests with broken or whole eggshells in desolate parts of the Great Simpson Desert.

Organic matter in eggshell consists primarily of proteins with some attached carbohydrates. The stable isotopic composition of this organic

Chris Swarth

From Simpson's Gap, the rugged landscape of MacDonnell's Range stretches to the horizon matter is directly related to the diet of the emu just before she lays her eggs. In essence, it records the emu's previous few weeks of meals. The stable nitrogen isotopic ratios we measured in the shells indicate that the shells' organic matter *does* reflect mean annual precipitation, that is, the isotopic signal was passed from soil to plant to emu. However, a complication arose. In the very arid regions surrounding Lake Eyre, the $\delta^{15}N$ of the emu was greater than one would have predicted based on prior animal measurements. Ordinarily, the $\delta^{15}N$ of an animal is 2-5‰ more positive than that of its diet. In controlled feeding situations with captive birds, the difference in $\delta^{15}N$ between diet and eggshell is typically 3‰. Eggshell from Lake Eyre, however, was enriched by at least 6‰ relative to coexisting vegetation. It is known that emus can survive on a diet with very low nitrogen content, as they are able to retain and recycle nitrogen rather than excrete it. The increased isotopic fractionation we observed could thus result from greater nitrogen retention. Alternatively, it could be caused by omnivorous feeding practices, i.e., by the presence of insects in the emu diet.


An emu roams the desolate landscape.

The grasshoppers we collected had extraordinarily enriched $\delta^{15}N$ values (+15‰) relative to that of emu feather ($\delta^{15}N$ = +12). The plants eaten by the emus, in contrast, had an average $\delta^{15}N$ of approximately +7‰. Mass balance calculations indicate that about 25% of the emu's nitrogen could thus be originating from insects. Because plants generally have very little nitrogen relative to protein-rich insects, complications of omnivory must therefore be addressed when assessing fossil eggshell fragments.

Most of the fossil eggshell samples we analyzed were collected by Gifford Miller of the University of Colorado. Miller is a former predoctoral and postdoctoral fellow with Geophysical Laboratory staff member Ed Hare. (He was also Johnson's dissertation advisor,) He has been gathering small, one-cm fragments of ratite eggshell from the scorched shores of Lake Eyre since 1990. In areas where the stratigraphy of the sediments has been preserved, he can place the eggshell accurately in geological context. Where wind has deflated the sediments, he can also find eggshell fragments on the ground. Fogel spent several days (and Johnson several weeks) with Miller during the 1994 field expedition walking slowly around the shoreline of Lake Eyre looking for glimpses of shell fragments. Miller has a trained eye, and can easily tell the difference between emu eggshell and that *of Genyornis*, an even larger ratite that went extinct about 30,000 years ago. The fossil eggshells are rich with geochemical information. The shell's carbonate can be radiocarbon dated; amino acids in the organic residues can be tested for alloisoleucine-to-isoleucine ratios, which give relative ages; and the isotopic compositions of the carbonate and organic fraction record dietary and climatic information. All of these analyses can be performed on a one-cm-square bit of shell.

As part of her dissertation, Beverly Johnson developed the protocol for analyzing the isotopic compositions in modern and fossil ostrich eggshells. (She performed this work as a predoctoral fellow at the Laboratory from 1991-1994.) She used the same techniques to analyze some 450 radiocarbon-dated emu eggshells from the Lake Eyre basin, encompassing a range in age from 0 to 150,000 years.

Her data clearly reveals changes in isotopic composition as a function of time. Both the nitrogen and the carbon isotope records indicate that the emu diet changed sometime around 10,000 years ago. The animals began to eat plants with isotopes mirroring a more arid environment. Interpretations beyond this must be made very carefully. We are well aware of the complications in tracing backwards the complex environmental, vegetational, and dietary isotope signatures of fossil samples, especially considering the variability in the diet of modem emu. To convince us that isotopic trends are, indeed, indicative of long-term climatic change, we realize that we must analyze many more fossil samples.

The remaining challenge is twofold. Miller and his Australian colleagues are actively seeking a fossil locality with a continuous sedimentary record in a region north of Lake Eyre. The addition of a second site would allow us to compare dates and isotopic swings, and verify that we are recording continental and not regional climate. Meanwhile, Johnson will be starting an NSF International Fellowship at the University of Woolangong in late 1996. She will be searching for vegetational tracers in the $5^{13}C$ of isolated lipids from terrestrial plants preserved in sediments in the Gulf of Carpenteria. She hopes the marine sediments hold terrestrial climate signals.

Our second challenge involves the link of climate to human activity, especially to the practice of burning. Archaeological remains in the area are sparse and difficult to obtain. Charcoal fragments and organic products from burning, such as polycyclic aromatic hydrocarbons (PAHs), may hold further clues.

Because our task is not yet finished, our conclusions are tentative. We are confident that the isotopic compositions of plants and soils in central Australia change as a function of mean annual precipitation, and that the organic matter of modern emu eggshell mirror these isotopic signals. But because of complications arising from the animal's diet and physiology, we only cautiously interpret that fossil emu eggshells are an accurate barometer *of* the changes in vegetation and mean annual precipitation over the last 10-15*000 years.

Ancient Structures: Probing the Chemistry of Organic Matter Diagenesis

by George D. Cody

Organic geochemists like myself are interested in understanding what happens over time to organic matter trapped within sedimentary rocks. When subjected to high temperatures and pressures over long periods of time, this material, called kerogen, undergoes a process of alteration we call diagenesis. In some cases, the reactions which occur during diagenesis lead to the formation of oil, gases, and tars. Kerogen's fate is coupled directly to the tectonic and geochemical evolution of the sedimentary basins that contain it. The cumulative, regional-scale changes in temperature, pressure, and pore-fluid chemical history of these basins are mirrored in kerogen's complex, macromolecular structure. Our challenge is to extract this information using the tools of organic geochemistry.

Is carbohydrate lost to the environment during diagenesis of organic matter, or is it transformed into something else? The answer may impact our understanding of the Earth's carbon budget.

It seems a simple task. Given sufficient information on the chemical structure of kerogen, one should be able to establish fairly easily the temperature and chemical history of the surrounding rock (provided that one can determine the reactions operating on the organic system). The problem is that the chemical structure of kerogen is very difficult *to* characterize. To he sure, significant technical strides in analytical instrumentation over the past couple of decades have greatly improved our

.George, D* Cody is the newest staff member at the Geophysical Laboratory* He came to Carnegie in 1.995., following a postdoctoral fellowship at Argonne National I^bos#t<jcy. He received Iris Ph.D. in 1992 at Pennsyl- **%stM** Slate Ofilvcrsitf, **where** tie **first** became interested ia keffTOtti's macrcwicileetilar stnicttice*

understanding. Pyrolytic-gas chromatographic techniques, for example, when coupled with mass spectrometry, enable us to obtain information about the discrete molecular "building blocks" of the bio/geopolymer. And ^{n}C solid-state nuclear magnetic resonance (NMR) spectroscopy can give us detailed information on kerogen's specific organic functional groups. Both techniques thus reveal considerable detail about kerogen. However, neither technique yields representative information on *all* of kerogen's carbonaceous material. As well, both techniques average all spatial chemical heterogeneity which exists within kerogen at the sub-microscopic scale. Such limitations clearly compromise our capabilities to identify specific reaction pathways that modify kerogen during diagenesis.

Applying Synchrotron-Based Instrumentation

The microheterogeneity of kerogen has long been a challenge to organic geochemists. Recent technology, however, has begun to meet that challenge. For example, a unique scanning soft x-ray microscope (STXM) and spectrometer now enables geochemists to explore the detailed organic structure of kerogen, and other organics, in the sub-micron range. Located at the National Synchrotron Light Source at the Brookhaven National Laboratory, this instrument is capable of resolving physical structure down to 50 nanometer spatial resolution, with an energy (or frequency) resolution of 03 eV. (A nanometer is a billionth of a meter) It operates Kith as a microscope, recording images with the photon energy fixed to a selected value, and as a microspectrophotometer. As such, it is able to differentiate structure within discrete regions of heterogeneous material by detecting their characteristic x-ray absorption spectra. The instrument is a major achievement in microanalytical science, and reflects the vision and capabilities of its creator, Janos Kirz, and his colleagues at SUNY Stony Brook's Department of Physics.

Near-Edge *Absorption Fine Structure Spectroscopy*

Over the past several years, I have been involved in applying the STXM to a number of fundamental problems in organic geochemistry, probing spatial and chemical variations of such elements as carbon, oxygen, calcium, potassium, and chlorine. The spectroscopy I employ is commonly referred to as Near Edge X-ray Absorption Fine Structure Spectroscopy (NEXAFS).

The physics of NEXAFS is straightforward. The absorption of a photon of light in the soft x-ray region promotes core-level electrons to higher-energy, unoccupied electronic states. A photon is absorbed when its energy equals the energy difference between an electron in its electronic ground state and that electron in an excited state. The magnitude of this energy "gap" changes with differences in nearest-neighbor electronic interactions, i.e., chemical bonding. Thus, a NEXAFS spectrum provides information on the distribution of different chemical bonds within a sample. In general, the intensify *oi* absorption scales linearly with the concentration *oi* a yiven atomic species in a given electronic environment; however, there is a proportionality constant intrinsic to each transition, and this constant can vary substantially from one electronic environment to another- It is thus a great challenge to obtain truly quantitative data. One must determine independently the magnitude of the proportionality constant so that the intrinsic oscillator strength of a given core-level electronic transition can be ascertained. I typically use synthetic or well-characterized natural standards, as well as other spectroscopic methods (e.g., nuclear magnetic resonance spectroscopy), to determine the oscillator strengths of given transitions. Once I've obtained these, I am able to quantify the NEXAFS spectra in terms of the abundances of different bonding environments, for example carbon in kerogen's various organic functional groups.

Tracing the Fate of Polysaccharides in Ancient Wood

Kerogen is generally thought to be the product of selective preservation of resistant, chemically stable biomacromolecules that survive early diagenesis. By far the most abundant biomacromolecular component in plants are the carbohydrates, prince pally cellulose. (Carbohydrates are molecules constructed from carbon, hydrogen, and oxygen; cellulose, a polymer of glucose, provides the main structural support of plant cell walls, and is probably the most common carbohydrate on Earth.) Recently, I have been exploring the fate of carbohydrates in wood and woody tissue-derived organics which have undergone chemical structural evolution during various stages of diagenesis.

Numerous studies on recent and ancient organic-rich sediments have suggested that carbohydrates disappear from the organic assemblage early during diagenesis. For example, in studies where pyrolysis-gas chromatography-mass spectrometry is employed, one observes a progressive reduction in the concentration of polysaccharide-derived pentose and hexose sugars from samples corresponding to positions along the diagenetic pathway of increasing temperature, pressure, and time. Using ^{13}C solid-state NMR, one observes a reduction in absorption intensity at ~75 and 100 ppm, corresponding to the secondary alcohol and anomeric carbon present in polysaccharides. (ppm refers to a shift in resonant frequency relative to a standard frequency.) The lost carbohydrates supposedly are recycled back into the environment, presumably as carbon dioxide and water. This interpretation—that the carbon associated with carbohydrate is lost during diagenesis—underlies the principal assumption regarding the mass balance between sedimentary organic carbon which is recycled and that which is retained in the sedimentary record.

To gain a better understanding of the fate of carbohydrates during diagenesis, I have been studying the kerogen derived from ancient wood, using the STXM technology at Brookhaven. Here I highlight two particularly interesting and illuminating examples. The first is an Eocene metasequoia wood some 40 million years old from a Canadian Arctic fossil forest on

Ellesmere Island, north of the Arctic Circle. The second is a considerably older, Cretaceous sample of wood (some 90 million years old) from coal-bearing strata in the western United States.

To determine the overall chemistry of each sample, and to obtain quantitative organic functional group information, I used ^{13}C solid-state NMR. Figure 1 (top) presents the NMR spectrum of the Eocene wood. The relatively complex resonance structure reveals carbon distributed in a variety of electronic environments, consistent with the presence of polysaccharides and lignin. Lignin is the principal chemically resistant biopolymer in woody tissue, and so one would expect progressively older samples to be increasingly lignin-enriched. The resonances at 150, 135, 120, and 50 ppm correspond to the carbon in lignin, while resonances at 105 and 75 ppm reveal the carbon in carbohydrate. Approximately 50% of the carbon is associated with carbohydrate, and 50% with lignin. In contrast, 70% of the carbon in fresh wood is in the form of carbohydrates. Thus, the Eocene wood has been diagenetically altered along the path leading to a loss in carbohydrate.

The chemical structure of the Cretaceous wood is considerably more diagenetically evolved than that of the Eocene wood. As evident in its NMR spectrum (Fig. 1, bottom), the Cretaceous sample lacks absorption intensity in the regions corresponding to carbohydrate. Even the resistant lignin has been significantly modified (as seen by losses in resonance intensity at 150 and 50 ppm). The reasonable conclusion from these data is that the carbohydrate

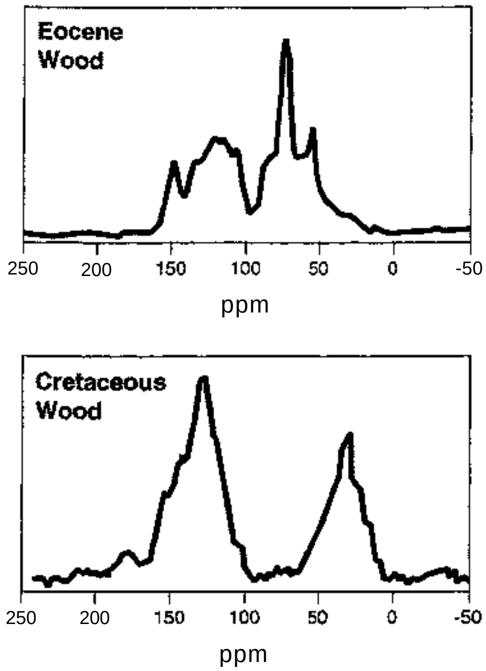


Figure I. ^{13}C NMR solid-state spectra of Eocene wood (top) and Cretaceous wood (below). Resonances at 150, S35, 120. and 50 ppm correspond to the carbon in lignin; resonances at 105 and 75 ppm reveal the carbon in carbohydrate.

is lost from the system, leading to a selective enrichment of lignin along the diagenetic pathway. This would require that 70-90% of the carbon initially present in the wood be recycled back into the environment.

A different picture emerges when analyzing these same samples with the STXM, focusing on core-level electronic transitions associated with carbon. The high-resolution image in Figure 2 reveals the microstructure of the Eocene wood. The image acquired, at 285 eV, reveals a spectacular tapestry of collapsed cell structure. Although only cell-wall material is preserved, the cell wall is. clearly chemically differentiated, just as *it h* in living tissue* The striking contrasts are based on variations in the absorption features of carbohydrate and lignin. The dark areas, i.e., regions with strong ahsorp-

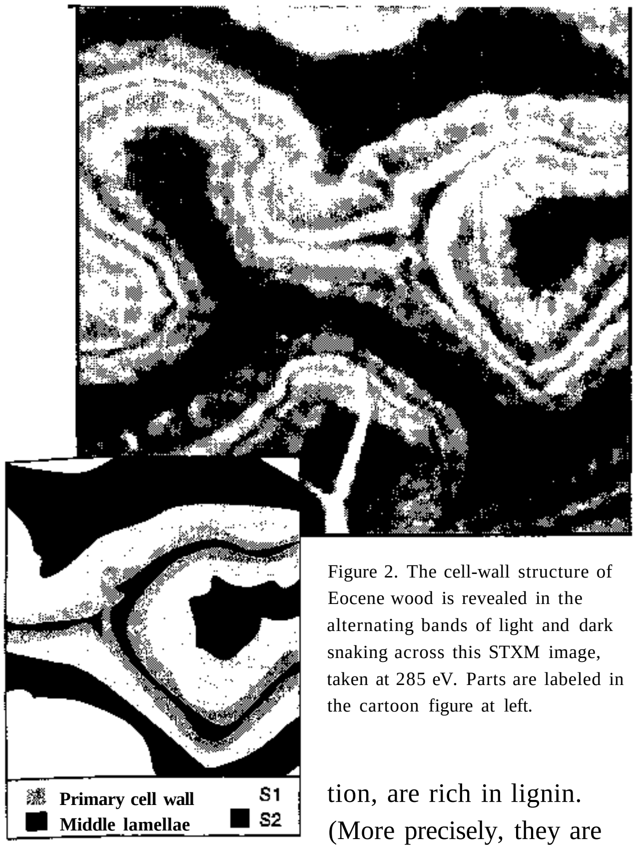


Figure 2. The cell-wall structure of Eocene wood is revealed in the alternating bands of light and dark snaking across this STXM image, taken at 285 eV. Parts are labeled in the cartoon figure at left.

tion, are rich in lignin. (More precisely, they are rich in aromatic carbon, and only lignin contains aromatic carbon.) The light areas of the image, in contrast, are rich in carbohydrate.

At the center of each cell wall lies the thin middle lamellae (approximately 50 nm thick). The middle lamellae exhibits intense absorption consistent with a lignin-rich composition. On either side of the middle lamellae lies the primary cell wall, rich in carbohydrate (as evident by the low absorption). Beyond this lies the secondary cell wall, which includes two regions—SI and S2. The SI region, immediately adjacent to the primary cell wall, is depleted in lignin. The S2 region, however, is clearly lignin rich.

To show that the contrast in Figure 2 is not biased by simple variations in carbon density, I acquired a second image, with the monochromator tuned to 289.5 eV (Fig. 3). This energy corresponds to an absorption band diagnostic of carbon in carbohydrates.

Figure 3. The same STXM image as Fig. 2. but taken with the monochromater tuned to an energy band (289.5 eV) associated with carbohydrate. The dark and light areas are thus reversed. See text.

(The secondary alcohol carbon in carbohydrates has a strong absorption band at 289.5 eV.) The image clearly shows that carbohydrate is concentrated in the primary cell wall. The basis of contrast is, therefore, due to true variations in the distribution of lignin and cellulose within the different regions of the cell wall, and not merely to variations in carbon density.

Analysis of the discrete ONEXAFS spectra (Fig. 4) obtained from the different regions of the cell wall reveals the full variation in carbon chemistry within each region. It is noteworthy that each region exhibits absorption intensity associated both with lignin (actually, with aromatic carbon, E = 285 eV), and with carbohydrate (that is, with carbohydrate's secondary alcohol carbons, E = 289.5 eV, which is a hydroxylated aliphatic carbon.) This doubly confirms that the contrast observed in Figure 2 is due to local variations in the abundance of carbohydrate and lignin.

A second subtle, but important, point must be highlighted regarding the absorption bands at 287.2 eV in Figure

4. The Eocene wood is related to a conifer, a gymnosperm (as opposed to flowering plants, the angiosperms). Hence its lignin is formed exclusively from conferyl alcohol, an aromatic molecule with two hydroxyls (OH) per ring. The peaks at 287-2 eV in each of the spectra of Figure 4 indicates the presence of aromatic carbon bonded to a hydroxyl (OH). One would expect the ratio of the intensities at 285 and 287.2 eV to remain constant. However, this is not the case. It is clear that the degree of hydroxylation of the aromatic carbon in the primary cell wall is greater than that of the middle lamellae or S2 region, even though the overall aromatic content is less. Assuming that all aromatic carbon is derived from lignin, it would, appear, therefore, that the lignin chemistry varies across the cell wall. This conclusion is counter to what we know regarding the chemistry of lignin.

Before considering the potential implications of these results, let us turn to the older sample, the Cretaceous wood. The ^{B}C NMR of this sample reveals no carbon associated with the carbohydrate. Yet an STXM image with the monochromator tuned to 285 eV (Fig. 5) clearly reveals cell-wall structure. Although there is less contrast (and hence less differentiation) in the Cretaceous wood than there is in the Eocene wood, the Cretaceous wood still evidences the primary cell wall, as well as the SI and S2 regions of the secondary cell wall Clearly the primary cell wall contains less aromatic carbon than the secondary cell wall, even though the difference *in* concentration between the two regions is considerably less than it is in the Eocene WCHK!

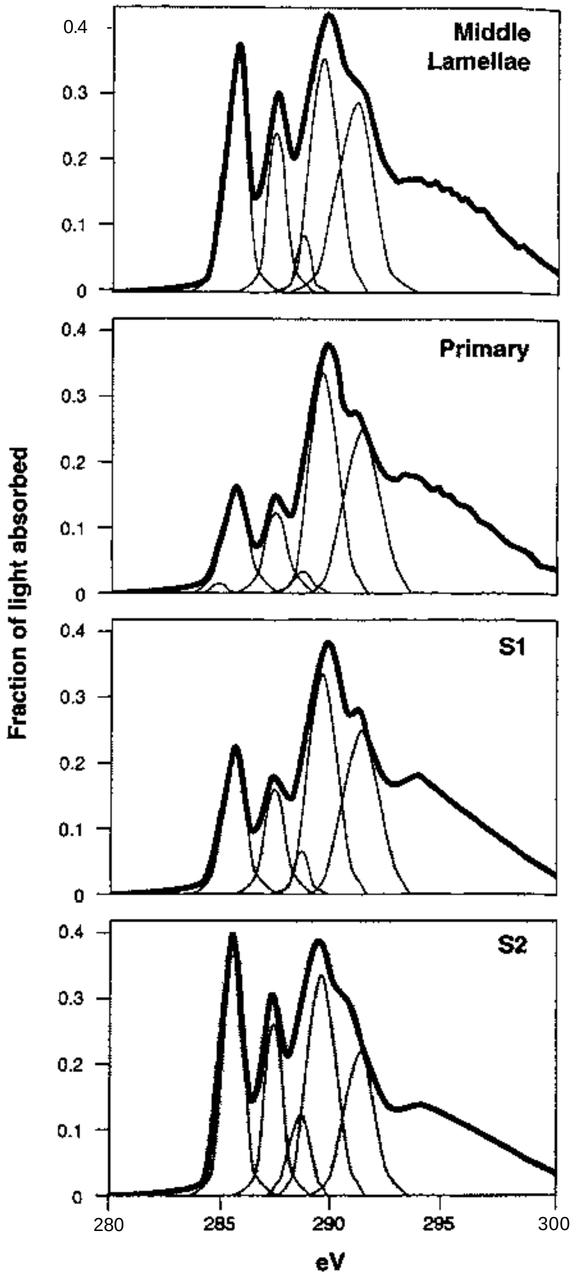


Figure 4. C-NEXAFS spectra of discrete regions within the Eocene wood's cell walls: middle lamellae, primary cell wall, SI region, and S2 region. See text for explanation.

C-NEXAFS spectra of individual regions within the Cretaceous sample (Fig. 6) reveal that the chemistry of the wood-derived kerogen differs considerably from that of the Eocene wind. In

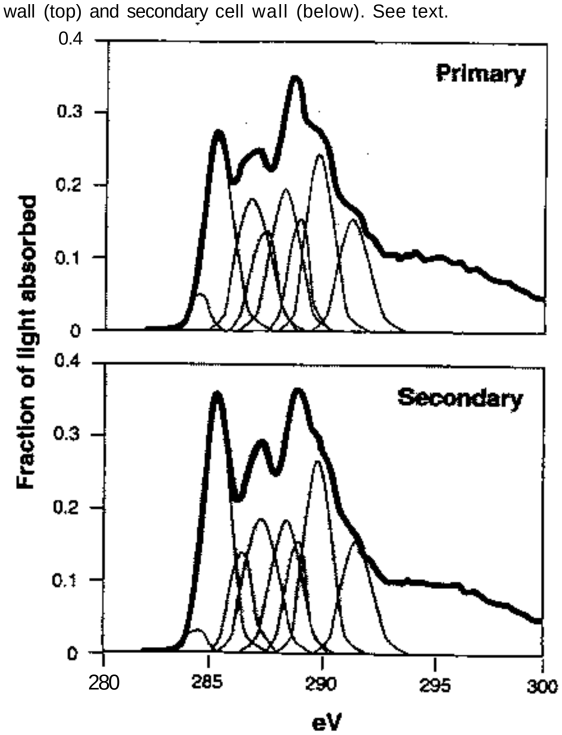
Figure 5. STXM image of the Cretaceous wood at 285 eV. The primary cell wall is still visible.

addition to the aromatic and hydroxylated aromatic carbon resonances at 285 and 287.2 eY there is now relatively strong absorption intensity at 286.3 eV. This is an indicator of the presence of aldehydes or ketones, which are additional oxidized forms of carbon. Indeed, an image obtained with the monochromator tuned to 286.3 eV (Fig. 7) yields a contrast reversal, revealing that the primary cell wall is enriched in the aldehyde or ketone functional group.

What the STXM clearly reveals (and ^{13}C NMR and pyrolysis gas chromatographic—mass spectrometry techniques are incapable of revealing) is that although the Cretaceous sample is considerably more chemically evolved than the Eocene sample, it still retains a degree of chemical differentiation. STXM also reveals that the diagenetic evolution oi these samples involves considerably more than losses of carbohydrate and selective preservation of lignin. The results suggest, in fact, that a diagenetic pathway other than what has been traditionally proposed may be operating in these samples. Instead of carbohydrate being lost during diagenesis, it is highly probable that it is being transformed into hydroxylated aromatic compounds and other oxygenated carbon compounds, like ketones.

Carbohydrates have been shown to undergo reactions which form hydroxylated aromatic carbon as well as other oxidized forms of carbon (such as ketones) under relatively mild conditions. It is not, therefore, unreasonable to assume that similar chemistry operates during diagenesis. If, as I suspect, carbohydrates evolve into hydroxylated aromatic products during the diagenesis of plant-derived organic matter, it would explain the increased

Figure 6. C-NEXAFS spectra of discrete regions within the Cretaceous wood's cell walls: primary cell wall (top) and secondary cell wall (below). See text.



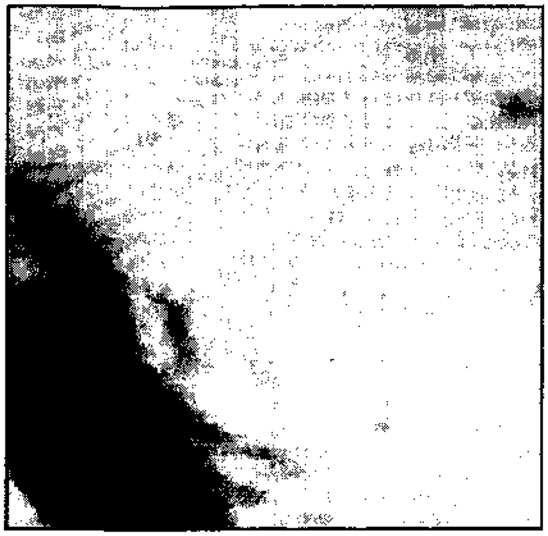


Figure 7. STXM image at 286.3 eV. The dark areas corresponding to the primary wail indicate ketone or aldehyde enrichment.

amount of hydroxylated carbon found in the primary cell-wall regions of the Eocene wood. It would also be consistent with the presence of aldehyde and ketone functional groups we saw in the Cretaceous wood's primary cell wall.

Currently, I am in the process of developing methods to look for specific molecular compounds traceable to such reactions. If the carbohydrate carbon is in fact retained in kerogen, albeit in a molecularly transformed incarnation, some major assumptions constraining the organic carbon budget within the geosphere will have to be reexamined. Furthermore, the presence *of* substantial quantities of carbohydrate-derived aromatic compounds will necessitate a serious revaluation *of* our understanding of the Jiagenetic evolution *of* lignin, which has been based on the assumption that all of the carbon in mature samples is derived from lignin.

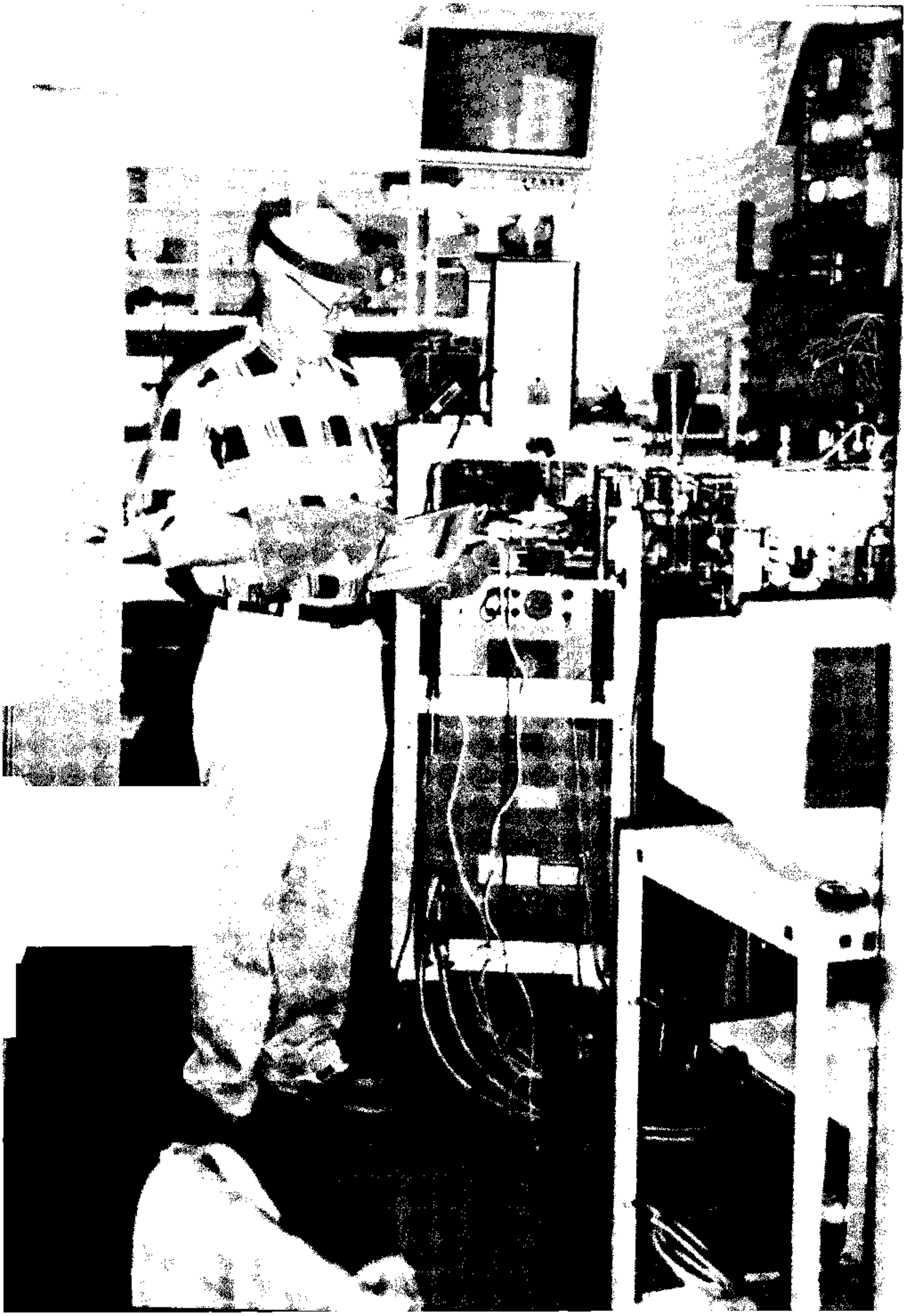
Other Problems and Future Work

The example described here, showing how STXM can be applied to a fundamental problem in organic geochemistry, is a very small part of a much larger effort. I am also using the technique to study the physical chemistry controlling the transformation of organic matter into graphite during metamorphism, as well as the chemistry controlling the transformation of organic molecules into diamonds through industrial processes. And, I am using the STXM to analyze the diagenetic co-evolution of kerogens derived from different biomacromolecular precursors. This latter effort will help me obtain time-temperature pathways during sedimentary basin evolution.

In this essay, I have emphasized spectroscopy and imaging of carbon chemistry. The STXM also enables me to explore the chemistry of chlorine, calcium, potassium, and oxygen at the submicroscopic level Changes in the microscope configuration will soon allow for the analysis of nitrogen. This has exciting implications, for it will enable me to follow the fate of proteins and nucleic acids during early diagenesis.

Clearly, there is no one analytical tool that can address all questions in a field as complex as organic geochemistry. Nevertheless, the scanning transmission x-ray microscope is providing unique and, in some cases, crucial information that is allowing us *to* unravel the convoluted reaction pathways that characterize diagenesis.

Next puge: Ok»u$ Rumble at the Geophy\kdl Laboratory's ultraviolet laser isotope miuoprohe.



UHP Metamorphism and the Qinglongshan Oxygen Isotope Anomaly

by Douglas Rumble, III

In June 1994, visiting investigator TzervFu Yui (Academia Sinica, Taiwan) and I made an astonishing discovery at the Geophysical Laboratory. We measured severely depleted oxygen isotope ratios in eclogites from Qinglongshan, China, indicating unambiguously the presence of rainwater This was surprising because the rocks had been metamorphosed at a depth of 80 kilometers, where the pressure was at least 25,000 times that at sea level. How, we wondered, could evidence of rainwater survive the rigors of subduction, heating, compression, and faulting, followed by uplift back to the surface—a vertical round trip down and back of 160 km?

> The *presence of rainwater in metamorphosed rocks from China presents intriguing clues about events that occurred millions of years ago.*

Subsequent research has demonstrated a remarkable sequence of events responsible for the Qinglongshan anomaly. Eruption of basaltic lavas at Earth's surface was followed by alteration of oxygen isotopes in the lavas by heated rainwater in a geothermal system. (This environment was probably replete with hot springs and geysers, similar to present-day Iceland.) The altered volcanics were buried and later subjected to subduction and ultra-high-pressure metamorphism during plate tectonic collisions between the ancient Sino-Korean and Yangtze continents. Finally, uplift and erosion returned the lavas to the surface in the form of the metamorphic rock eclogite. The entire process took more than 200 million years.

Most metamorphic rocks form in the mid-to-lower crust at depths of 10-30 km. Our eclogite samples, however, reached a depth of 80 km before exhumation

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Exploring rocks at Wumiao. Anhui Province. China, participants of the Third International Field Symposium receive some attention from villagers. (Photo by Doug Rumble.)

brought them back to the surface. It is remarkable that the lavas survived such adventures with evidence of their surface origin still more or less intact.

The phenomena of ultra-high-pressure metamorphism was recognized little more than a decade ago with the discovery of minerals stable at pressures far higher than those previously calibrated in crustal rocks. The high-pressure form of quartz, the mineral coesite, for example, was found in quartzite by Christian Chopin in 1984. Newly crystallized microdiamonds were identified in metamorphosed sediments by Nick Sobolev and Vladimir Shatsky in 1990.•

A surprising feature of ultra-high-pressure metamorphism is the huge size of its outcrop areas. Thousands *of* square kilometers in central and eastern China are underlain by coesite-bearing sediments and volcanics. This area corresponds to the faulted margins of the pre-Cambrian Sino-Korean and Yangtze continents. Other belts of ultra-high-pressure rocks are found along continental margins (such as in western Norway), in continental suture zones on the Siberian platform, and in the Alps, where ancient Africa and Europe collided. Only events as dramatic as the collision of continents and the stacking *of* continental plates one upon the other could lead to the deep burial required to produce coesite and diamond in rocks of surface origin.

Following our 1994 discovery, 1 secured funds from the U. S. National Science Foundation to join colleagues

'Mantle xenohths, winch may contain k»th a>esite and diamond, are excluded by definition from UHP metamorfhisin because of differences in origin. Mantle xcnohths are brought to Earth's surface by volcanic eruptions. Many were nppeJ explosively out uf the mantle *dt* much greater depths than the deepest limit of UHP metamorphism,

J. G. (Louie) Liou and Ruth Y. Zhang (Stanford University) and Bolin Cong and Qingchen Wang (Chinese Academy of Sciences, Beijing) to map the anomaly geologically and to obtain additional samples. Field work was successfully undertaken in China in August and September of 1995, concurrent with the Third International Field Symposium there.

Shortly after returning from China, I completed building a new analytical instrument, the ultraviolet (UV) laser isotope microprobe, at the Geophysical Laboratory. The new instrument makes prospects for the project very favorable. Using it, we can analyze small spots for oxygen isotopes on polished surfaces of eclogite samples. The measurement of oxygen isotope ratios in minerals gives a sensitive record of the origins of waters, be they from the surface, as in the rainwater eclogites, or from greater depth in the crust or mantle. The UV laser microprobe is being used not only to map the distribution of rainwater in ultra-high-pressure metamorphic rocks but also to detect possible contamination by waters from other sources.

Although the Qinglongshan oxygen isotope anomaly has ephemeral interest as a possible entry in the Guinness Book of World Records as the world's most ^{IH}O depleted eclogite, the data have potential for wider application.

Our preliminary results reveal that the Qinglongshan anomaly extends at least two kilometers from the discovery outcrop. The eclogites, quartzites, gneisses, and calcite veins in the area all have unusually low $^{IH}0/^{if}O$ values, though not all of the rocks within the zone are as low in ^{18}O as those of the discovery site. The areal extent of depleted ^{IH}O shows that the destructive processes of faulting, subduction, and uplift did not succeed in fragmenting the ancient geothermal system. The piece of crust hosting the geothermal system remains today coherent and recognizable.

The Qinglongshan data also have some bearing on a much debated question: How much free water can occur under ultra-high-pressure conditions, and in what physical state does it occur? The phrase 'free water" refers to minute amounts of water wetting grain boundaries, not to water bound inside hydrous ultra-high-pressure minerals, such as phengite or epidote. We observe that minerals in eclogite and quartzite separated by less than two meters have the same oxygen isotope ratios. Minerals from rocks separated by distances of ten meters or more, however, have dissimilar ratios. These results suggest that water was absent beyond a thin film trapped along grain boundaries and, further, that the water that was present was not free to infiltrate more than a few meters.

A final surprise from Qinglongshan is that rocks subducted to 80 kilometers depth could have significance as indicators of Earth's past climate. The negative ^{IH}O values could only have come from rain or snow at cold latitudes. The alteration of basaltic lavas must have taken place in a geothermal system located in the far north or south on a Paleozoic or pre-Cambrian Earth that, like today, had cold poles and a warm equator.

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Extradepartmental and Administrative

Director of administration and finance John Lively and administrative coordinator Vickie Tucker

• *Administrative Personnel* •

Carnegie Institution Adminis tratixm

1530 P Street, N.W.
Washington, D.C. 20005

Lloyd Allen, Building Maintenance Specialist
Sharon Bassin, Secretary to the President
Sherill Berger, Research Assistant, Institutional and External Affairs
Ray Bowers, Editor and Publications Officer[1]
Gloria Brienza, Budget and Management Specialist
Don A. Brooks, Building Maintenance Specialist
Cady Canapp, Human Resources and Insurance Manager
Margaret Charles, Secretary
Patricia Craig, Editor and Publications Officer[2]
Nicholas DeCarlo, Grants and Operations Manager
Susanne Garvey, Director, Institutional and External Affairs
Ann Keyes, Payroll Coordinator
Jennifer King, Assistant Editor*
Jeffrey Lightfield, Financial Accountant
John J. Lively, Director, Administration and Finance
Trong Nguyen, Financial Accountant
Danielle Palermo, Administrative Assistant, Grants and Operations[4]
Loretta Parker-Brown, Administrative Secretary
Catherine Piez, Systems and Fiscal Manager
Arnold Pryor, Facilities and Services Supervisor
Maxine F. Singer, President
John Strom, Administrative Support Assistant
Kris Sundback, Financial Manager
Vickie Tucker, Administrative Coordinator/Accounts Payable
Ernest Turner, Custodian (on call)
Susan Y. Vasquez, Assistant to the President
Yulonda White, Human Resources and Insurance Records Coordinator
Jacqueline J. Williams, Assistant to Human Resources and Insurance Manager

Carnegie Academy for Science Education (CASE)

Natalie Barnes, Mentor Teacher[5]
Michael J. Charles, CASE Intern
Inés L. Ctfuentes, CASE Program Coordinator
Linda Feinberg, CASE Administrator and Editor
Eduardo Gamarra, Mentor Teacher[6]
Theresa Gasaway, Mentor Teacher[6]
Patricia Goodnight, Mentor Teacher[5]
Margaret E. Jackson, Mentor Teacher[5]
Charles James, Director, Curriculum and Instruction, CASE, and Director, First Light
Alida James, CASE Mentor[6]
Jacqueline Lee, Mentor Teacher[s]
Avis McKinney-Thornas, Mentor Teacher[5]
Charles Mercer, Mentor Teacher[s]
Sandra B. Norried, Mentor
Rose Marie Patrick, CASE Mentor[6]
Ollie Smith, Mentor Teacher[5]
Gregory Taylor, Mentor Teacher and First Light Assistant[6]
Jerome Thornton, Mentor Teacher and First Light Assistant[5]
DeRon Turner, CASE Intern[6]
Darryll Vann, CASE Mentor*
Sue P. White, Mathematics Coordinator
Laurie Young, CASE Mentor[6]

'Retired May M, 1996
-From June I, W6
'From June 4, 1996
•To October 27, 199S
'To August 15, 1995
'From June 24, 1996

Photo, facing page: Schcx>I teachers participating in the Carnegie Academy for Science Education fCASE) gather in the rotunda of the administration building, **July 19%.** Since 1994, CASE has conducted summer training sessions for Washington, D.C. elementary school teachers, offering them Interactive science-teaching skills they can bring back to their classrooms.

• *Publications and Special Events* •

Publications of the Institution

Carnegie Institution of Washington Year Book 94,
vi + 194 pages, 71 illustrations*
December 1995.

Spectra: The Newsletter of the Carnegie Institution,
issued in November 1995, March 1996,
and June 1996.

Carnegie Evening 1996,
16 pages, 12 illustrations, May 1996.

Publications of the President

Singer, M. E, and P. Berg, The recombinant DNA controversy: twenty years later, *Proc. Natl Acad.* Sri. USA 92, 9011-9013, 1995.

Singer, M. E, Minireview: unusual reverse transcriptases, J. *Biol. Chem. 270,* 24623-24626, 1995.

Hohjoh, H., and M. E Singer, Cytoplasmic ribonucleoprotein complexes containing human LINE-1 protein and RNA, EMBO J. *15,* 630-639, 1996.

Singer, M. E, Assault on science, *The Washington Post,* Op ed page, June 26, 1996.

Carnegie Evening Lecture

Christopher B. Field,
Global Change and Terrestrial Ecosystems,
May 2, 1996

Capital Science Lectures

Michael J. Novacek, Evolutionary Trees: From Gobi Dinosaurs to Gene Sequences, October 24, 1995

Donald D. Brown, How Hormones Control Development, November 28, 1995

Marcia McNutt, The Building of Tibet, December 19, 1995

Irwin Shapiro, Peering at the Universe Through Gravitational Lenses, January 30, 1996

Arthur E Hebard, Buckminsterfullerene (C^): From Soot to Superconductivity and Beyond, February 20, 1996

Anneila I. Sargent, Other Solar Systems: Searches for Planetary Systems in Formation, March 19, 1996

Carla J. Shatz, Brain Waves and Brain Wiring, April 9,1996

Albert James Hudspeth, How the Ear's Works Work: The Basis, Loss, and Restoration of Hearing, May 14, 1996

• *Abstract of lMinutes* •

of the One Hundred and Fourth Meeting of the Board of Trustees

The Trustees met in the Board Room of the Administration Building on Friday, May 3, 1996. The meeting was called to order by the Chairman, Thomas N. Urban.

The following Trustees were present: Philip H. Abelson, William T. Coleman, Jr., John E Crawford, John Diebold, James D. Ebert, Wallace Gary Ernst, Sandra M. Faber, Bruce W. Ferguson, Michael E. Gellert, William T. Golden, David Greenewalt, Gerald D. Laubach, John D. Macomber, Richard A. Meserve, Frank Press, David E Swensen, Charles H. Townes, Thomas N. Urban, and Sidney J. Weinberg, Jr. Also present were Caryl P. Haskins, Trustee Emeritus; Maxine E Singer, President; John J. Lively, Director of Administration and Finance; Susanne Garvey, Director of Institutional and External Affairs; Allan C. Spradling, Director of the Department of Embryology; Charles T. Prewitt, Director of the Geophysical Laboratory; Sean C. Solomon, Director of the Department of Terrestrial Magnetism; Augustus Oemler, Jr., Director of the Carnegie Observatories; Susan Y. Vasquez, Assistant Secretary; and Marshall Hornblower and William J. Wilkins, Counsel.

The minutes of the One Hundred and Third Meeting, held at the Administration Building on December 14-15, 1995, were approved.

The Chairman notified the Trustees of the death of Garrison Norton. He read a memorial statement in tribute to Mr. Norton and the following resolution was unanimously adopted:

> Be It Therefore Resolved, That the Board of Trustees of the Carnegie Institution of Washington hereby records its deep sense of loss at the death of Garrison Norton.
>
> And Be It Further Resolved, That this resolution be entered on the minutes of the Board of Trustees and that a copy be sent to the family of Mr. Norton.

The reports of the Executive Committee, the Finance Committee, the Employee Benefits Committee, and the Auditing Committee were accepted. On the recommendation of the latter, it was resolved that KMPG Peat Marwick be appointed as public accountants for the fiscal year ending June 30, 1996.

The Bylaws of the Institution were amended. The amended language is given in the Bylaws printed on pages 153- 159 of this Year Book.

On recommendation of the Nominating Committee, the following were re-elected for terms ending in 1999: John Diebold, James D. Ebert, Wallace Gary Ernst, Sandra M. Faber, Bruce W. Ferguson, Kazuo Inamori, Frank Press, and William I. M. Turner, Jr.

The following were elected for one-year terms: Richard A. Meserve, as chairman of the Research Committee; John D. Macomber, as Chairman of the Development Committee; William T Coleman, Jr., as Chairman of the Employee Affairs Committee; and Philip H. Abelson, as Chairman of the Audit Committee. William L M. Turner, Jr. was appointed Chairman of the Nominating Committee for a one-year term.

Vacancies in the Standing Committees, with terms expiring in the years indicated in parentheses, were filled as follows: Philip H. Abelson (1998), John Diebold (1999), Richard E. Heckert (1999), John D. Macomber (1998), William J. Rutter (1997), and Sidney J. Weinberg, Jr. (1999) were elected members of the Budget and Operations Committee. David E Swensen (1998), Robert G. Goelet (1999), William T. Golden (1997), Richard E. Heckert (1999), William I. M. Turner, Jr. (1999), and Sidney J. Weinberg (1998) were elected members of the Finance Committee. William T. Coleman, Jr. (1998), John F. Crawford (1999), Sandra M. Faber (1998), David Greenewalt (1999), and Richard E Heckert (1997) were elected members of the Employee Affairs Committee. Richard A. Meserve (1999), Philip H. Abelson (1997), James D. Ebert (1998), Sandra M. Faber (1997), Bruce W. Ferguson (1998), Michael Gellert (1999), William T. Golden (1998), David Greenewalt (1999), William R. Hearst III (1998), Richard E. Heckert (1999), Kazuo Inamori (1997), Frank Press (1997), and William J. Rutter (1999) were elected members of the Research Committee. John D. Macomber (1999) was elected a member of the Development Committee- Philip H. Abelson (1997), John Diebold (1999), and Bruce W. Ferguson (1998) were elected members of the Audit Committee. William I. M. Turner, Jr. (1999), John Diebold (1999), Richard A. Meserve (1997), Frank Press (1998), and Sidney J. Weinberg, Jr. (1998) were elected members of the Nominating Committee.

The annual report *of* the President was received.

To provide for the operation of the Institution for the fiscal year ending June 30, 1997, and upon recommendation of the Executive Committee, the sum of $35,2 38, W2 was appropriated.

• *Bylaws of the Institution* •

As *amended May* 3, 1996

ARTICLE I

The Trustees

Section 1.1. The Board of Trustees shall consist of up to twenty-seven members as determined from time to time by the Board.

Section 1.2. The Board of Trustees shall be divided into three classes approximately equal in number. The terms *of* the Trustees shall be such that those of the members of one class expire at the conclusion of each May meeting of the Board. At each May meeting of the Board vacancies resulting from the expiration of Trustees' terms shall be filled by their reelection or election of their successors. Trustees so reelected or elected shall serve for terms of three years expiring at the conclusion of the May meeting of the Board in the third year after their election. A vacancy resulting from the resignation, death, or incapacity of a Trustee before the expiration of his or her term may be filled by election of a successor at or between May meetings. A person elected to succeed a Trustee before the expiration of his or her term shall serve for the remainder of that term unless the Board determines that assignment to a class other than the predecessor's is appropriate. There shall be no limit on the number of terms for which a Trustee may serve, and a Trustee shall be eligible for immediate reelection upon expiration of his or her term.

Section 1.3. No Trustee shall receive any compensation for his or her services as such.

Section 1.4. Trustees shall be elected by vote of two-thirds of the Trustees present at a meeting of the Board of Trustees at which a quorum is present, subject to compliance with Section 5.9(c) and (d), or without a meeting by written action of all of the Trustees pursuant to Section 4.6.

Section 1.5. If, at any time during an emergency period, there be no surviving Trustee capable of acting, the President, the Director of each existing Department, or such of them as shall then be surviving and capable of acting, shall constitute a Board of Trustees pro *tern,* with full powers under the provisions of the Articles of Incorporation and these Bylaws. Should neither the President nor any such Director be capable of acting, the senior surviving Staff Member of each existing Department shall be a Trustee *pro* tem, with full powers of a Trustee under the Articles of Incorporation and these Bylaws. It shall be incumbent on the Trustees *pro tern* to reconstitute the Board with permanent members within a reasonable time after the emergency has passed, at which time the Trustees *pro tern* shall cease to hold office. A list of Staff Member seniority, as designated by the President, shall be kept in the Institution's records.

Section 1.6. A Trustee who resigns or elects not to stand for reelection after having served at least six years and having reached age seventy shall be eligible for designation by the Board of Trustees as a Trustee Emeritus. A Trustee Emeritus shall he entitled to attend meetings of the Board but shall have no vote and shall not be counted for purposes of ascertaining the presence of a quorum. A Trustee Emeritus may be invited to attend any meeting of a committee of the Board and to serve as an advisor to any such committee.

ARTICLE II

Officers of the Board

Section 2.1. The officers of the Board of Trustees shall he a Chairman, a Vice-Chairman, and a Secretary, who shall he elected by the Trustees, from the members of the Board, to serve for terms of three years and shall be **eligible** for reelection. A vacancy resulting from the resignation, death, or incapacity of an officer before the expiration of his or her term shall be filled by the Board for the unexpired term; provided, however, that the Executive Committee shall bave power to fill a vacancy in the office of Secretary to serve until it is filled by the Board.

Section 2.2. The Chairman shall preside at all meetings of the Board of Trustees and shall have the usual powers of a presiding officer.

Section 2.3. The Vice-Chairman, in the absence or disability of the Chairman, shall perform the duties of the Chairman.

Section 2.4. The Secretary shall issue notices of meetings of the Board of Trustees, record the actions and minutes of the meetings of the Board and the Executive Committee, and conduct that part of the correspondence relating to the Board and the Committee and to his or her duties.

ARTICLE III

Executive Administration

Section 3.1. There shall be a President who shall be elected by, and hold office during the pleasure of, the Board of Trustees. The President shall be the chief executive officer of the Institution and, subject to the directions and policies of the Board and the Standing Committees of the Board, shall have general charge of all matters of administration and supervision of all arrangements for research and other work undertaken by the Institution or with its funds. He or she shall prepare and submit to the Board and to the Standing Committees plans and suggestions for and reports of the work of the Institution. He or she shall have power to remove, appoint, and, within the scope of funds made available by the Board, provide for compensation of subordinate employees, and to fix the compensation of such employees within the limits of a maximum rate of compensation to be established from time to time by the Board. The President shall be a member of each Standing Committee except the Audit Committee,

Section 3.2. The President shall be the legal custodian of the corporate seal and of all property of the Institution whose custody is not otherwise provided for. He or she shall sign and execute on behalf of the Institution contracts and instruments necessary in authorized administrative and research matters and affix the corporate seal thereto when necessary. He or she may sign and execute other contracts, deeds, and instruments on behalf of the institution (and affix the corporate seal thereto when necessary) pursuant to general or special authority from the Board of Trustees, the Executive Committee, or the Budget and Operations Committee. He or she may, within the limits of his or her own authorization, delegate to other corporate officers or to the Directors of the Departments authority to sign and execute contracts, deeds, and instruments, to act as custodian of and affix the corporate seal, and to perform other administrative duties. He or she shall be responsible for the expenditure and disbursement of all funds of the Institution in accordance with the directions of the Board and of the Executive and the Budget and Operations Committees and for the keeping of accurate accounts *oi* all receipts and disbursements. He or she shall, with the assistance of the Directors of the Departments, submit to the Budget and Operations Committee annual operating and capital budgets to enable the Committee to present its budget recommendations to the Board in accordance with Section 6.4. He or she shall prepare for timely presentation to the Trustees and for publication an annual report on the activities of the Institution.

Section 3.3. The President shall attend all meetings of the Board of Trustees.

Section 3.4. The Institution shall have such other corporate officers as may be appointed by the Board of Trustees or the Executive Committee, having such duties and powers as may be specified by the Board or the Committee or by the President under authority from the Board or the Committee.

Section 3.5. The President shall retire from office at the end of the fiscal year in which he or she becomes sixty-five years of age, except as retirement may be deferred by the Board of Trustees for one or more periods of up to three years each. The other corporate officers shall retire as officers, and the Directors of the Departments shall retire as Directors, at the end of the fiscal year in which they become sixty-five years of age, except as otherwise required by law or as retirement may be deferred by the Board or the Executive Committee.

ARTICLE IV

Meetings and Voting

Section 4.1. Regular meetings of the Board of Trustees shall be held in the City of Washington, in the District of Columbia, in May and December of each year on dates fixed by the Board, or in such other month or at such other place as may be designated by the Board, or if not so fixed or designated before the first day of the month, by the Chairman of the Board, or if he or she is absent or is unable or refuses to act, by any Trustee with the written consent of the majority of the Trustees then holding office.

Section 4.2. Special meetings of the Board of Trustees may be called, and the date, time, and place of meeting designated, by the Chairman of the Board, or by the Executive Committee, or by any Trustee with the written consent of the majority of the Trustees then holding office. Upon the written request of seven members of the Board, the Chairman shall call a special meeting.

Section 4-3. Notices of meetings of the Board of Trustees shall be given at least ten days before the date thereof. Notice may be given to any Trustee personally, or by mail, telegram, or other means of record communication sent to the usual address of such Trustee. Notices of adjourned meetings need not be given except when the adjournment is for ten days or more.

Section 4.4. The presence of a majority of the Trustees holding office shall constitute a quorum for the transaction of business at any meeting of the Board of Trustees. An act of the majority of the Trustees present at a meeting at which a quorum is present shall be the act of the Board except as otherwise provided in these Bylaws. If, at a duly called and noticed meeting, less than a quorum is present, a majority of those present may adjourn the meeting from time to time until a quorum is present. Trustees present at a duly called and noticed meeting at which a quorum is present may continue to do business until adjournment notwithstanding the withdrawal of enough Trustees to leave less than a quorum.

Section 4.5. The transactions of any meeting of the Board of Trustees, however called and noticed, shall be as valid as though carried out at a meeting duly held if a quorum is present and if, either before or after the meeting, each of the Trustees not present in person signs a written waiver of notice, or consent to the holding of such meeting, or approval of the minutes thereof. Ail such waivers, consents, and approvals shall be filed with the corporate records, and an officer's certificate as to their receipt shall be made a part of the minutes of the meeting.

Section 4.6. Any action which, under law or these Bylaws, is authorized to be taken at a meeting of the Board of Trustees or any of the Standing Committees may be taken without a meeting if authorized in a document or documents in writing signed by all the Trustees, or all the members of the Committee, as the case may be, then holding office and filed with the Secretary together with an officer's certificate as to their receipt.

Section 4.7. During any emergency peritxi the term "Trustees holding office" shall, for purposes of this Article, mean the surviving members of the Board of Trustees who have not been rendered incapable of acting for any reason including difficulty of transportation to a place of meeting or of communication with other surviving members of the Board.

ARTICLE V

Committees

Section 5.1. (a) There shall he eight Standing Committees of the Board of Trustees, denominated Executive, Budget and Operations, Finance, Employee Affairs, Research, Development, Audit, and Nominating.

(b) Members of the Standing Committees (other than those identified in this Article by the office they hold) shall be appointed by the Board of Trustees to serve for terms of three years, staggered so that at least one expires at each May meeting of the Board. They shall be eligible for reappointment. Except as otherwise provided in Sections 5.2(a), 5.3(a), and 5.9(a) with respect to the Executive, Budget and Operations, and Nominating Committees, the chair of each Standing Committee shall be appointed by the Board to serve until the next May meeting of the Board.

(c) A vacancy created before the expiration of a committee member's term by his or her resignation, death, incapacity, or ineligibility because of termination of service as Trustee shall be filled by the Board of Trustees at its next May meeting and may be filled at an earlier meeting of the Board to serve for the remainder of the predecessor's term. A vacancy in the Executive Committee and, upon request of the remaining members of any other Standing Committee, a vacancy in such other Committee may be filled by the Executive Committee by temporary appointment to serve until the next meeting of the Board.

(d) Committee members may participate in a meeting by means of conference telephone or similar communications equipment whereby all persons participating in the meeting can hear and speak to one another, and such participation shall constitute presence in person at the meeting. Prompt notice of action taken at such a meeting shall be given to any members not present. Committee action may be taken by unanimous consent in writing as provided in Section 4.6.

(e) Unless otherwise specified in this Article, the presence of a majority of the members of a Standing Committee shall be necessary to constitute a quorum for the transaction of business.

(f) No Standing Committee shall have any of the powers of the Board of Trustees relating to proposing amendment of the Articles of Incorporation, amending the Bylaws, or electing or removing a Trustee or the President.

(g) At each May and December meeting of the Board, each Standing Committee shall present to the Board a report, suitable for publication if the Board so desires, describing meetings and actions of the Committee.

Section 5.2. (a) The *Executive Committee* shall consist of the Chairman, Vice-chairman, and Secretary of the Board of Trustees, the Chairman of the Finance Committee, and the President. The Chairman of the Board shall be the chair of the Committee.

(b) Subject to Section 5.1 (f), the Executive Committee may, when the Board of Trustees is not in session and has not given specific directions, exercise the powers of the Board including the power to authorize the purchase, sale, exchange, or transfer of real estate.

Section 5.3. (a) The *Budget and Operations Committee* shall consist of the Chairman, Vice-chairman, and Secretary of the Board, not less than five and not more than seven other Trustees, and the President. The Chairman of the Board shall be the chair of the Committee. The presence of four members of the Committee shall be sufficient to constitute a quorum for the transaction of business at any meeting.

(b) The Budget and Operations Committee shall have general control of the administration and affairs of the Institution and general supervision of all arrangements for administration; research, and other matters undertaken or promoted by the Institution. Amendments of employee benefit plans other than those required by law or government regulation shall be approved by the Committee. The Committee's responsibilities relating to financial matters shall include those described in Section 3.2 and Article VI.

(c) Regular meetings of the Budget and Operations Committee shall be held in March and September of each year.

Section 5.4. (a) The *Finance Committee* shall consist of the Chairman of the Board, not less than three and not more than six other Trustees, and the President. The presence of three members of the Committee shall be sufficient to constitute a quorum for the transaction of business at any meeting.

(b) The Finance Committee shall have general charge of the Institution's investments and invested funds and shall care for and dispose of them subject to the directions of the Board of Trustees. It shall have power to authorize the purchase, sale, exchange, or transfer of securities and to delegate this power. It shall consider and recommend to the Board from time to time such measures as in its opinion will promote the financial interests of the Institution and improve the management of investments under any retirement or other benefit plan.

(c) The Finance Committee shall be advisory to the Budget and Operations Committee on spending policies.

(d) Regular meetings of the Finance Committee shall be held in March and September of each year and immediately before the May and December meetings of the Board of Trustees.

Section 5.5. (a) The *Employee Affairs Committee* shall consist of the Chairman of the Board, the Chairman of the Finance Committee, not less than three and not more than five other Trustees, and the President.

(b) The Employee Affairs Committee shall periodically review the compensation of the officers and other employees of the Institution and, if desired, make recommendations to the Budget and Operations Committee with respect thereto; review summaries of staff evaluations including pertinent aspects of the reports of the departmental Visiting Committees; supervise the activities of the administrator or administrators of retirement and other benefit plans for the Institution's employees; receive reports from the administrator or administrators of the employee benefit plans with respect to administration, benefit structure, operation, and funding; and consider and recommend to the Budget and Operations Committee from time to time such measures as in its opinion will improve the plans and their administration.

(c) Regular meetings of the Employee Affairs Committee shall be held immediately before the May meetings of the Board of Trustees. The Committee shall hold additional meetings as necessary or advisable for the performance of its duties.

Section 5.6. (a) The *Research Committee* shall consist of the Chairman of the Board, the President, the chairs of the departmental Visiting Committees, and not less than eight other members.

(b) The Research Committee shall review the research output of the Departments of the Institution, major needs for staff, facilities, and equipment, and the overall direction and future planning of the Institution's research and joint projects with other institutions. It shall receive reports of the departmental Visiting Committees and periodic reports from the Directors of the Departments.

(c) The Research Committee shall meet once a year, immediately before or after the December meeting of the Board of Trustees.

Section 5.7. (a) The *Development Committee* shall consist of not less than five and not more than ten Trustees, and the President.

(b) The Development Committee shall have general responsibility for strategic planning of fund-raising for the Annual Fund, the Endowment, and capital projects.

(c) Regular meetings of the Development Committee shall be held in conjunction with the semiannual meetings of the Board of Trustees in December and May. The Committee shall hold additional meetings as necessary or advisable for the performance of its duties.

Section 5.8. (a) The *Audit Committee* shall consist of three trustees.

(h) The Audit Committee shall cause the accounts of the Institution for each fiscal year to he audited by public accountants and a report by the accountants to be submitted to the Committee. The Committee shall present the report for the preceding fiscal year at the May meeting of the Board with such recommendations as the Committee may deem appropriate.

(c) Regular meetings of the Audit Committee shall he held in March of each year. The Committee shall hold additional meetings as necessary or advisable for the performance of its duties.

Section 5.9, (a) The *Nominating Ommittee* shall consist of the Chairman of the Board, not less than three or more than five other Trustees, and the President. The chairman of the Board shall appoint another member of the Committee as chair for a term expiring no Liter than the expiration of his or her term as a member.

(M The duties of the Nominating Committee shall he to discover, recruit, and propose[4] candidates for election to the Board of Trustees and as officers of the Board and for appointment as members and chairs of the Standing Committees. The Committee shall meet at least twice a year and make reports to the Board at each *of* its regular meetings.

(c) At least sixty days before each May meeting of the Board of Trustees, the Nominating Committee shall notify the Trustees by mail of the vacancies expected to be filled in the membership of the Board, the offices of the Board, and the Standing Committees. Each Trustee may submit nominations for such vacancies in the Board. At least ten days before the May meeting, the Committee shall submit to the members of the Board by mail a list of the persons so nominated, with its recommendations for election of Trustees and officers of the Board and appointment of Committee members and chairs thereof. No other nominations shall be received by the Board at the May meeting except with the unanimous consent of the Trustees present.

(d) A Trustee may be elected at a meeting of the Board of Trustees other than the May meeting if the recommendation of the Nominating Committee with respect to his or her candidacy was submitted to the members of the Board by mail at least ten days before the date of the meeting or the Trustees present at the meeting unanimously agree to waive this requirement. The solicitation of consents to election of a Trustee without a meeting of the Board pursuant to Section 4.6 shall include or be accompanied by the recommendation of the Nominating Committee.

ARTICLE VI

Financial Administration

Section 6.1. No expenditure shall be authorized or made except in pursuance of a previous appropriation by the Board of Trustees, or as provided in Section 5.4 (b).

Section 6.2. The fiscal year of the Institution shall commence on the first day of July in each year. Financial statements for and as of the end of each fiscal year, together with the report thereon of the firm of public accountants appointed by the Audit Committee, shall be sent to the Trustees promptly after receipt of such report and shall be presented to the Board of Trustees as provided in Section 5.8 (b).

Section 6.3. The President shall submit to the Board of Trustees at its December meeting a full statement of the finances and work of the Institution for the preceding fiscal year.

Section 6.4. The Budget and Operations Committee shall present to the Board at its May meeting a statement of estimated revenues and expenses for the current fiscal year and operating and capital budgets for the succeeding fiscal year, including detailed estimates of revenues and expenses.

Section 6.5. The Board of Trustees at its May meeting shall adopt operating and capital budgets and make general appropriations for the succeeding fiscal year; but nothing contained herein shall prevent the Board from making special appropriations at any meeting.

Section 6.6. The Budget and Operations Committee shall have general charge and control of all appropriations made by the Board of Trustees. When the Board is not in session, the Committee shall have full authority to allocate appropriations made by the Board, to reallocate available funds, as needed, and to transfer balances.

Section 6.7. In accordance with Section 5.4 (b), subject *to* directions of the Board of Trustees, securities of the Institution and funds invested and to be invested shall be placed in the custody of such financial institution or institutions and under such safeguards as the Finance Committee may from time to time direct. Authority for investment of such securities and funds may *be* delegated to such managers or advisors as the Finance Committee may from time to time designate. Income of the Institution available for expenditure shall be deposited in such financial institution or institutions as may from time to time be designated by the Board. The Board may authorize the President to designate financial institutions to hold funds of the Institution.

Section 6.8. The property of the Institution is irrevocably dedicated to scientific, educational, and charitable purposes, and in the event of dissolution its property shall be used for and distributed one or more of such purposes as specified by the Congress of the United States in the

Articles of Incorporation, Public Law No. 260, approved April 28, 1904, as the same may be amended from time to time.

ARTICLE VII

Indemnification; Transactions with interested persons

Section 7.1. The Institution shall, to the fullest extent required or permitted by applicable law, indemnify any person who is or was, or is the personal representative of a deceased person who was, a Trustee, officer, employee, or agent of the Institution against—

(a) any liability asserted against him or her and incurred by him or her—

(1) by reason of the fact that he or she (or his or her testator or intestate) is serving or served in such capacity or at the request of the Institution as a director, trustee, partner, officer, employee, or agent of another corporation, partnership, joint venture, trust, or other enterprise, or as fiduciary of an employee benefit plan; or

(2) arising out of his or her (or his or her testator's or intestate's) service or status as such; and

(b) costs reasonably incurred by him or her in defending against such liability.

Unless applicable law otherwise requires, indemnification shall be contingent upon a determination, by majority vote of a quorum of the Board of Trustees consisting of disinterested Trustees or, if such a quorum is not obtainable or a quorum of disinterested Trustees so directs, by independent legal counsel in a written opinion, that indemnification is proper in the circumstances because such Trustee, officer, employee, or agent has met the applicable standard of conduct prescribed by District of Columbia law.

Section 7.2. No contract or transaction between the Institution and any of its Trustees or officers, or between the Institution and any other corporation, partnership, association, or other organization in which any of its Trustees or officers is a director or officer or has a financial interest, shall be void or voidable solely for that reason, or solely because the Trustee or officer is present at or participates in the meeting of the Board of Trustees or a committee thereof at which the contract or transaction is authorized, approved, or ratified or solely because his or her vote is counted for such purpose, if—

(a) the material facts as to his or her relationship or interest and as to the contract or transaction are disclosed or are known to the Board or the committee, and the Board or the committee in good faith authorizes the contract or transaction by the affirmative vote of a majority of the disinterested Trustees or committee members, even though they are less than a quorum; and

(b) the contract or transaction is fair to the Institution as of the time it is authorized, approved, or ratified by the Board or the committee.

ARTICLE VIII

Amendment of Bylaws

Section 8.1. These Bylaws may be amended (a) at any meeting of the Board of Trustees, by a two-thirds vote of the incumbent members of the Board, or (b) by a two-thirds vote of the members present at a meeting at which a quorum is present if notice of the proposed amendment has been given in accordance with Section 43 to each member of the Board at least twenty days before the meeting and the amendment as adopted is substantially the same as proposed in the notice, or (c) by unanimous written action pursuant to Section 4.6.

Section 8.2. Promptly after any amendment, notice thereof or the complete Bylaws as amended shall be delivered or mailed to each Trustee.

Photo, next page: The rotunda In the administration building, 1530 P Street, N.W.

Financial Statements

for the year ended June 30, 1996

• *Financial Profile* •

Reader's note: all references to spending amounts and Endowment values are on a cash or cash~equivalent basis. The figures used in this profile do not include capitalization, depreciation, or other non-cash amounts.

Carnegie Institution of Washington relies upon its Endowment as the principal source of support for its activities. This reliance affirms the fundamental independence of the Institution's research and programs. The Endowment, which was valued at $338 million as of June 30, 1996, is allocated across a range of assets that include fixed-income instruments (bonds), equities (stocks), arbitrage positions and distressed securities, hedge funds, private equity, and real estate partnerships. The Institution does not manage these assets itself. Rather, it utilizes external managers to do so, with the custody of these assets, where applicable, being placed with a central custodian bank.

For the fiscal year ended at June 30, 1996, the percentage of total return (net of management fees) on Carnegie's total Endowment was 15.8%. The five-year running, total average return on the Institution's Endowment was 13.6%. The following chart shows the allocation of the Institution's Endowment among the asset classes it employs as of June 30, 1996:

Asset Allocation

	Target Asset Allocation	Actual Asset Allocation
Common Stock	40%	44.5%
Alternative Assets	35%	29.5%
Fixed Income	25%	23.4%
Cash	0%	2.6%

Actual Asset Allocation

Common Stock: small to large capitalization, marketable U.S. and International equity securities.

Alternative Assets: real estate, absolute return strategies, and non-marketable investments, such as private equity and special situations.

Fixed income: bond instruments, primarily U.S. domestic.

Cash: funds reserved for specific operating projects and funds awaiting reinvestment.

Spending from the Endowment is budgeted with the goal of preserving the Endowment's long-term spending power. To do so, the Institution utilizes a budget methodology that:

- averages the total Endowment market values at the close of the three most recent fiscal years, and
- provides for spending a percentage of this three-year market value average each fiscal year.

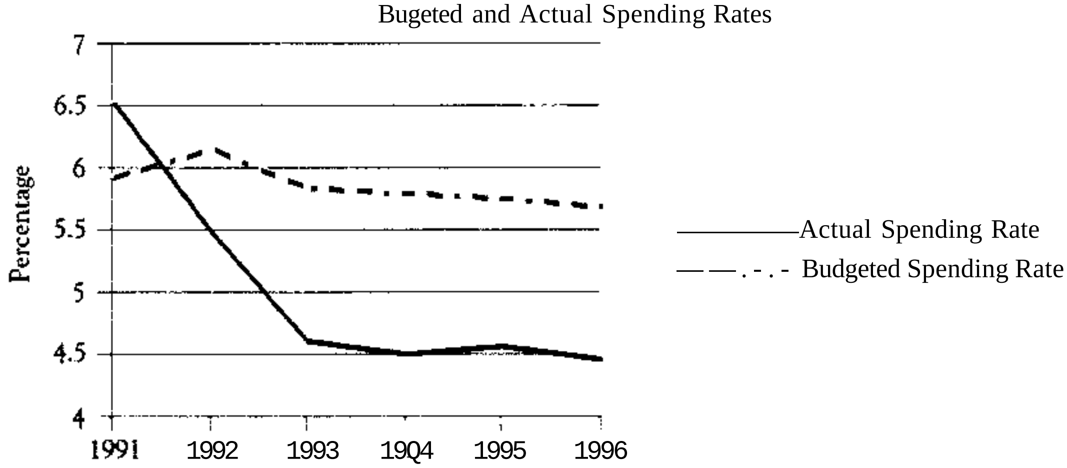
Since the beginning of this decade, the percentage or "spending rate" used for budgeting has been undergoing a planned reduction towards an average of 4.5% as an informal, non-mandatory goal For the 1996—1997 fiscal year, this percentage is 5.66%. Concomitant with this reduction in the planned rate of spending has been significant growth in the size of the Endowment. This has resulted in progressively higher spending levels. The following table shows the planned versus actual spending rates and the market value of the Endowment for the six-fiscal-year period, beginning with 1990-199L

Endowment Market Values and Spending Rates

	Fiscal Years ending June 30,					
	1991	1992	1993	1994	1995	1996
Market Value in millions	$225.9	$246.6	$270.4	$275.5	$304.5	$338.0
Actual Spending Rate	6.53%	5.49%	4.63%	4.51%	4.57%	4.48%
Budgeted Spending Rate*	5.94%	6.16%	5.86%	5.81%	5.76%	5.71%

* applied to three-year average of total market value

Bugeted and Actual Spending Rates



Within the Endowment, there are a number of "Funds" that provide general support or particular, targeted support for defined purposes. The largest of these funds, the Andrew Carnegie Fund, was established with a gift of $10 million from Andrew Carnegie at the time the Institution was founded. This $10 million, along with an additional $12 million he gave during his lifetime, have now grown to a fund valued at nearly $278 million. The following table shows the market value of the principal Funds within Carnegie's Endowment as of June 30, 1996.

Market value of the principal Funds within Carnegie's Endowment

Andrew Carnegie	$277,959,578
Capital Campaign	18,200,059
Anonymous	7,756,513
Astronomy Funds	6,012,189
Mellon Matching	5,285,834
Anonymous Matching	4,954,874
Carnegie Futures	3,963,494
Wood	3,537,945
Golden	2,022,459
Bowen	1,687,557
Colburn	1,422,070
McClintock Fund	1,001,771
Special Instrumentation	763,325
Bush Bequest	636,682
Moseley Astronomy	562,898
Special Opportunities	503,745
Roberts	289,541
Lundmark	225,726
Starr Fellowship	200,000
Morgenroth	168,830
Hollaender	157,734
Bush	112,394
Moseley	97,084
Forbush	94,030
Green	65,631
Hale	60,321
Harkavy	60,268
Hearst Education fund	**50,000**
Other	194,773
Total	$338,047,325

Independent Auditors' Report

To the Auditing Committee of the
Carnegie Institution of Washington:

We have audited the accompanying statement of financial position of the Carnegie Institution of Washington (the Institution) as of June 30, 1996, and the related statements of activities and cash flows for the year then ended. These financial statements are the responsibility of the Institution's management. Our responsibility is to express an opinion on these financial statements based on our audit.

We conducted our audit in accordance with generally accepted auditing standards. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audit provides a reasonable basis for our opinion.

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of the Carnegie Institution of Washington as of June 30, 1996, and its changes in net assets and its cash flows for the year then ended, in conformity with generally accepted accounting principles.

Our audit was made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supplementary information included in Schedule 1 is presented for purposes of additional analysis and is not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the audit of the basic financial statements and, in our opinion, is fairly presented in all material respects in relation *to* the basic financial statements taken as a whole.

As described in notes 1 and 7 to the financial statements, the Institution adopted the provisions of Statements of Financial Accounting Standards No. 116, *Accounting for Contributions Received and Contributions Made;* No. 117, *Financial Statements of Not-far-Profit Organizations;* No. 124* *Accounting for Investments Held by Not^for^Profit Organizations;* and No. 106, *Employers' Accounting for PostretirementB<mefitsQ^tkerThanPensions.*

KPMG Peat Marwick LLP

Washington, D.C.
September 27, 1996

• *Statement of Financial Position* •

June 30, 1996

Assets

Current assets:	
Cash and cash equivalents	$ 97,012
Accrued investment income	867,735
Pledges receivable (note 4)	2,622,740
Accounts receivable and other assets	2,219,112
Bond proceeds held by trustee (note 5)	15,032,558
Total current assets	20,839,157
Noncurrent assets:	
Investments (note 6)	362,041,971
Construction in progress (note 2)	23,413,297
Property and equipment, net (note 2)	38,282,583
Total noncurrent assets	423,737,851
Total assets	$444,577,008

Liabilities and Net *Assets*

Current liabilities:	
Accounts payable and accrued expenses	$ 2,519,359
Deferred revenues	1,247,330
Broker payable (note 6)	23,752,995
Total current liabilities	27,519,684
Noncurrent liabilities:	
Bonds payable (note 5)	34,732,731
Accrued postretirement benefits (note 7)	8,660,871
Total noncurrent liabilities	43,393,602
Total liabilities	70,913,286
Nee assets (note 3):	
Unrestricted:	
Board designated:	
Invested in fixed assets, net	26,963,149
Designated for managed investments	298,055,655
Undesignatcd	5,788,857
	330,807,661
Temporarily restricted	10,511,799
Permanently restricted	32,344,262
Total net assets	373,663,722
Commitments and contingencies (notes 8, 9, and 10)	
Total liabilities and net assets	$444,577,008

See auvmjMnvinj; nrte* *tt)* financial statements.

• *Statement of* Activities •

Year ended June 30, 1996

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Program and supporting services expenses:				
Terrestrial Magnetism	$ 4,948,551	–	–	4,948,551
Observatories	5,601,435	–	–	5,601,435
Geophysical Laboratory	5,963,455	–	–	5,963,455
Embryology	4,366,256	–	–	4,366,256
Plant Biology	4,278,272	–	–	4,278,272
Other Programs	972,927	–	–	972,927
Administrative and general expenses	2,962,056	–	–	2,962,056
Total expenses	29,092,952	–	-	29,092,952
Revenues and support:				
Grants and contracts	10,143,786	–	-	10,143,786
Contributions and gifts	212,159	3,354,873	1,244,592	4,811,624
Net gain on disposals of property	3,480,506	–	–	3,480,506
Other income	650,021	–	–	650,021
Net external revenue	14,486,472	3,354,873	1,244,592	19,085,937
Investment income (note 6)	44,521,860	2,208,597	89,818	46,820,275
Net assets released from restrictions	2,056,057	(2,056,057)	-	-
Total revenues, gains, and other support	61,064,389	3,507,413	1,334,410	65,906,212
Increase in net assets before cumulative effect of the change in accounting for postretirement benefits	31,971,437	3,507,413	1,334,410	36,813,260
Cumulative effect of the change in accounting for postretirement benefits (note 7)	(8,129,000)	–	-	(8,129,000)
Increase in net assets	23342,437	3,507,413	1,334,410	28,684,260
Net assets at the beginning of the year, as restated (note 1)	306,965,224	7,004,386	31,009,852	344,979,462
Net assets at the end of the year	$330,807,661	10,511,799	32344,262	373,663,722

See accompanying notes to the financial statements

• *Statement of Cash Flows* •

Year ended June 30, 1996

Cash flows from operating activities:	
Increase in net assets	$ 28,684,260
Adjustments to reconcile increase in net assets to net cash provided by operating activities:	
Depreciation	2,425,292
Net gains on investments	(37,297,991)
Gain on sale of land and buildings	(3,442,177)
Amortization of bond issuance costs and discount	36,864
(Increase) decrease in assets:	
Receivables	358,122
Accrued investment income	(103,764)
Bond proceeds held by trustee	4,614,925
Increase (decrease) in liabilities:	
Accounts payable and accrued expenses	(1,318,884)
Deferred revenues	995,281
Brokerpayable	13,021,309
Accrued postretirement benefits	8,660,871
Contributions and investment income restricted for long term investment	(2,085,846)
Net cash provided by operating activities	14,548,262
Cash flows from investing activities:	
Acquisition of property and equipment	(1,608,289)
Proceeds from sale of land and buildings	3,780,673
Construction of telescope, facilities, and equipment	(8,408,479)
Investments purchased	(403,634,956)
Investments sold or matured	393,114,394
Net cash used for investing activities	(16,756,657)
Cash flows from financing activities:	
Proceeds from contributions and investment income restricted for:	
Investment in endowment	921,635
Investment in property and equipment	1,164,211
Net cash flows from financing activities	2,085,846
Net decrease in cash and cash equivalents	(122,549)
Cash and cash equivalents at the beginning of the year	219,561
Cash and cash equivalents at the end of the year	$ 97,012
Supplementary cash flow information:	
Cash paid for interest	$ 1,638,829

See accompanying notes to financial information.

• Notes *to Financial Statements* •

June 30, 1996

(I) *Organization and Summary of Significant Accounting Policies*

Organization

The Carnegie Institution of Washington (the Institution) conducts advanced research and training in the sciences. It carries out its scientific work in five research centers. They are the Departments of Embryology, Plant Biology, and Terrestrial Magnetism, the Geophysical Laboratory, and the Observatories (astronomy). The Institution's external income is mainly from gifts and grants. It also relies heavily on income from invested gifts.

Basis of Accounting and Presentation

The financial statements are prepared on the accrual basis of accounting.

The financial statements have been prepared in accordance with Statement of Financial Accounting Standards (SFAS) No. 117, *Financial Statements of Not-for-Profit Organizations,* which was adopted effective July 1, 1995 by the Institution. In accordance with SFAS No. 117, expenses are separately reported for major programs and administration. Revenues are classified according to the existence or absence of donor-imposed restrictions. Also, satisfaction of donor-imposed restrictions are reported as releases of restrictions in the statement of activities.

Investments

Effective July 1, 1995, the Institution adopted the provisions of SFAS No. 124, *Accounting for Investments Held by Not-far* Profit Organizations.* In accordance with this standard, the Institution's debt and equity investments must be reported at their fair values. The Institution also reports investments in partnerships at fair value as determined and reported by the general partners. All changes in fair value are recognized in the statement of activities. Adoption of this new standard had no impact un net assets since the Institution's previous policy was also to record investments at fair value. The Institution considers all highly liquid debt instruments purchased with remaining maturities of 90 days or less to be cash equivalents.

Income Taxes

The Institution is exempt from federal income tax under Section 501 (c)(3) of the Internal Revenue Code (the Code). Accordingly, no provision for income taxes is reflected in the accompanying financial statements. The Institution is also an educational institution within the meaning of Section 170(b)(l)(A)(ii) of the Code. The Internal Revenue Service has classified the Institution as other than a private foundation, as defined in Section 5O9(a) of the Code.

Fair Value of Financial Instruments

Financial instruments of the Institution include cash equivalents, receivables, investments, bond proceeds held by trustee, accounts and broker payable, and bonds payable. The fair value of investments in debt and equity securities is based on quoted market prices. The fair value of investments in limited partnerships is based on information provided by the general partners.

The fair value of Series A bonds payable is based on quoted market prices. The fair value of Series B bonds payable is estimated to be the carrying value since these bonds bear adjustable market rates.

The fair values of cash equivalents, receivables, and accounts and broker payable approximate their carrying values based on their short maturities.

Use of Estimates

The preparation of financial statements in conformity with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and disclosure of contingent assets and liabilities at the date of the financial statements. They also affect the reported amounts of revenues and expenses during the reporting period. Actual results could differ from those estimates.

Property and Equipment

The Institution capitalizes expenditures for land, buildings and leasehold improvements, telescopes, scientific and administrative equipment, and projects in progress. Routine replacement, maintenance, and repairs are charged to expense.

Depreciation is computed on a straight-line basis over the following estimated useful lives:

Buildings and telescopes	50 years
Leasehold improvements	lesser of 25 years or the remaining term of the lease
Scientific and administrative equipment	5 years

Contributions

Effective July 1, 1995, the Institution adopted the provisions of SFAS No, 116, *Accounting for Contributions Received and Contributions Made,* which generally requires that unconditional contributions to the Institution be recognized in the period pledged by the donor. Prior to this new standard, the Institution recognized unrestricted contributions in the period they were received. Restricted contributions were deferred until the period in which expenses were incurred for the intended purposes of these gifts. The impact of this new standard was an increase and restatement of net assets as described below.

In accordance with this standard, contributions are classified based on the existence of donor-imposed restrictions. Contributions and net assets are classified as follows:

Unrestricted—includes all contributions received without donor-imposed restrictions on use or time.

Temporarily restricted—includes contributions with donor-imposed restrictions as to purpose of gift or time period expended.

Permanently restricted—generally includes endowment gifts in which donors stipulated that the corpus be invested in perpetuity. Only the investment income generated from endowments may be spent.

Gifts of long-lived assets, such as buildings or equipment, are considered unrestricted when placed in service. The Institution adopted the provisions of SFAS No. 116 fur expiration of restrictions on temporarily restricted net assets on a retroactive basis.

The following table summarizes the effects of those accounting changes on net assets (previously referred to as fund balance) as of the beginning of the year.

	Total
Balance, June 30, 1995, as previously reported	$341,165,173
Effect of accounting changes:	
Pledges not previously recorded	1,896,681
Gifts previously deferred	1,917,608
Balance, July 1, 1995, as restated	$344,979,462

These beginning net assets are classified as follows:

Unrestricted	$306,965,224
Temporarily restricted	7,004,386
Permanently restricted	31,009,852
	$344,979,462

Contributed Services

The Institution recognizes the fair value of contributed services meeting certain criteria in the financial statements as contributions. Generally, only needed professional services provided by specialists are recognized.

Grants

The Institution records revenues on grants from federal agencies only to the extent that reimbursable expenses are incurred. Accordingly, funds received in excess of reimbursable expenses are recorded as deferred revenue, and expenses in excess of reimbursements are recorded as accounts receivable. Reimbursement of indirect costs is based upon provi' sional rates which are subject to subsequent audit by the Institution's federal cognizant agency.

(2) Property and Equipment

At June 30, 1996, property and equipment placed in service consisted of the following:

Buildings and improvements	$34,037,604
Scientific equipment	13,593,569
Telescopes	7,910,825
Administrative equipment	2,163,650
Land	787,896
Art	34,067
	$58,527,611
Less accumulated depreciation	(20,245,028)
	$38,282,583

At June 30, 1996, construction in progress consisted of the following:

Telescope	$21,741,034
Buildings	1,355,800
Scientific equipment	316,463
	$23,413,297

At June 30, 1996, approximately $31 million of construction in progress and other property, net of accumulated depreciation, was located in Las Campanas, Chile. During 1996, the Institution capitalized interest costs of $745,295 as construction in progress.

(3) *Net Assets*

At June 30, 1996, temporarily restricted net assets were available to support the following donor-restricted purposes:

Specific research programs	$ 5,020,928
Equipment acquisition and construction	5,490,871
	$10,511,799

At June 30, 1996, permanently restricted net assets consisted of endowments, the income from which is available to support the following donor-restricted purposes:

Specific research programs	$ 9,139,543
Equipment acquisition and construction	1,204,719
General support (Carnegie ertcfowment)	22.000,000
	$32,344,262

During 19%, the Institution met donor-imposed requirements on certain gifts and therefore released temporarily restricted net assets as follows:

Specific research programs	$1,008,966
Equipment acquisition and construction	1,047,091
	$2,056,057

(4) *Pledges Receivable*

Pledges receivable consisted of the following at June 30, 1996 :

Due in year ending June 30,	
1997	$1,600,585
1998	743,817
1999	175,800
2000	27,600
2001	15,000
2002 and later	59,938
	$2,622,740

(5) Bonds *Payable*

On November 1, 1993, the Institution issued $17.5 million each of Series A and Series B California Educational Facilities Authority Revenue tax-exempt bonds. Bond proceeds are used to finance the Magellan telescope project and the renovation of the facilities of the Observatories at Pasadena. The balances outstanding at June 30, 1996 on these issues totaled $34,732,731, which is net of unamortized bond issue costs and bond discount. Bond proceeds held by the trustee and unexpended at September 30, 1996 totaled $15,032,558.

Series A bonds bear interest at 5.6 percent payable in arrears semiannually on each April 1 and October 1 and upon maturity on October 1, 2023. Series B bonds bear interest at variable money market rates in effect from time to time, up to a maximum of 12 percent over the applicable money market rate period of between one and 270 days and have a stated maturity of October 1, 2023. At the end of each money market rate period, Series B bondholders are required to offer the bonds for repurchase at the applicable money market rate. If repurchased, the Series B Kinds would be resold at the current applicable money market rate and for a new rate period.

The Institution is not required to repay the Series A and B bonds until the October 1, 2023 maturity date, and the Institution has the intent and the ability to effect the purchase and resale of the Series B bonds through a tender agent; therefore all bonds payable are classified as long term. Sinking fund redemptions begin in 2019 in installments for both series. The fair value of Series A bonds payable at June 30, 1996 based on quoted market prices is estimated at $17,610,607. The fair value of Series B bonds payable at June 30, 1996 is estimated to approximate carrying value as the mandatory tender dates on which the bonds are repriced are generally within three months of year end.

(6) *Investments*

At June 30, 1996, investments at fair value consisted of the following:

Time deposits	$ 1,207,346
Debt mutual funds	8,399,448
Debt securities	109,478,430
Equity securities	143,155,883
Real estate partnerships	25,385,382
Limited partnerships	74,415,482
	$362,041,971

Investment income for the year ended June 30, 1996 consisted of the following:

Interest and dividends	$ 10,398,641
Net realized gains	23,076,251
Net unrealized gains	14,217,243
Less investment management expenses	(871,860)
	$46,820,275

The Institution purchased and sold certain investment securities on dates prior to June 30, 1996. These trades will be settled subsequent to June 30, 1996 and are reflected in the investment balances reported at year end. The net obligation for these unsettled trades is reported as broker payable in the accompanying statement of financial position.

The Institution enters into futures contracts to manage portfolio positions and hedge transactions. Risks relating to futures contracts arise from the movements in securities values and interest rates.

Realized gains and losses based on changes in market values of open futures contracts have been fully recognized. The contracts are settled daily for changes in their fair value. Accordingly, the fair value of the contracts at June 30, 1996, is zero. At June 30, 1996, investments with a fair value of approximately $112,000 were being held by an intermediary as ongoing collateral against the Institution's obligations under futures contracts. The total notional value of these contracts at year end was approximately $4,500,000.

(7) *Employee Benefit Plans*

Retirement Plan

The Institution has a noncontributory, defined contribution, money-purchase retirement plan in which all United States personnel are eligible to participate. After one year's participation, an individual's benefits are fully vested. The Plan has been funded through individually owned annuities issued by Teachers' Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF). There are no unfunded past service costs. Total contributions made by the Institution totaled approximately $1,737,000 in 1996.

Postretirement Benefits Plan

The Institution provides postretirement medical benefits to all employees who retire after age 55 and have at least ten years of service. Prior to 1996, the cost of postretirement benefits was charged to expense only on a cash basis (pay-as-you-go). Cash payments made by the Institution for these benefits totaled approximately $398,000 in 1996.

Effective July 1, 1995, the Institution adopted SFAS No. 106, *Employers' Accounting for Postretirement Benefits Other Than Pensions,* and changed its method of accounting for postretirement benefits from a cash basis to an accrual basis. This accounting change resulted in a one-time, noncash expense in 1996 of approximately $8,129,000 for the transition obligation. The transition obligation represents the fully recognized actuarially determined estimate of the Institution's obligation for postretirement benefits as of July 1, 1995. The expense for postretirement benefits in 1996 under the provisions of SFAS 106 was approximately $930,000, which is an increase of $532,000 over what the cash expense would have been, and was allocated among program and supporting services expenses.

The following items are the components of the net postretirement benefit cost for 1996:

Service cost—benefits earned during the year	$335,000
Interest cost on projected benefit obligation	595,000
	$930,000

The following table sets forth the funded status of the postretirement medical benefits plan as of its June 30, 1996 actuarial valuation date for 1996:

Actuarial present value of the accumulated postretirement benefit obligation for:	
Inactive participants	$4,541,000
Fully eligible active participants	1,828,000
Other active participants	2,025,000
Accumulated postretirement benefit obligation for services rendered to date	8,394,000
Unrecognized net gain	266,871
Accrued postretirement benefit cost	$8,660,871

The present value of the transition obligation as of July 1, 1995 was determined using an assumed health care cost trend rate of 10 percent and an assumed discount rate of 7.5 percent. The present value of the benefit obligation as of June 30, 1996 was determined using an assumed heath care cost trend rate of 10 percent and an assumed discount rate of 7.5 percent. The Institution's policy is to fund postretirement benefits as claims and administrative fees are paid.

For measurement purposes, a 10 percent annual rate of increase in the per capita cost of covered health care benefits was assumed for 1996; the rate was assumed to decrease gradually to 5.5 percent in 15 years and remain at that level thereafter. The health care cost trend rate assumption has a significant effect on the amounts reported. An increase of 1.0 percent in the health care cost trend rate used would have resulted in a $1,192,000 increase in the present value of the accumulated benefit obligation and a $191,000 increase in the aggregate of service and interest cost components of net periodic postretirement benefit cost.

(8) Federal Grants and Contracts

Cost charged to the federal government under cost-reimbursement grants and contracts are subject to government audit. Therefore, all such costs are subject to adjustment. Management believes that adjustments, if any, would not have a significant effect on the financial statements.

(9) Commitments

In 1992, the Institution entered into a collaborative agreement with the University of Arizona for the construction and operation of a large-aperture telescope (Magellan project) and its installation and operation in Chile. The agreement requires the University of Arizona to deliver a primary mirror to be used in the Magellan project for $635 million, subject to adjustment. The telescope is currently under construction. The Institution has agreed to share use of the Magellan telescope for a period lasting until expiration of the agreement in 2022. Viewing time on the telescope and annual operating costs will be shared by each of the parties in amounts to be determined based on amounts ultimately contributed by each party for construction.

During 1996, the Institution also entered into memoranda of understanding with three other universities to jointly construct and operate another telescope in Chile. These agreements will provide for the creation of a consortium to construct and manage the telescope. Advance payments received from these universities totaling approximately $518,000 have been classified as deferred revenue (liability) in the accompanying statement of financial position.

(10) Lease Arrangements

As landlord, the Institution leases land and a laboratory, under noncancelable agreements to certain tenants. Future rents to be received for the leased land is $120,000 annually expiring in fiscal year 2001.

The lease for the laboratory is for an indefinite term. Rents to be received under that agreement are approximately $179,000 annually, adjusted for CPI increases.

• *Schedule of Expenses* •

Year ended June 30, 1996

	Carnegie Funds	Federal and Private Grants	Total Expenses
Personnel costs:			
Salaries	$ 9,415,732	3,114,712	12,530,444
Fringe benefits and payroll taxes	3,532,528	820,783	4,353,311
Total personnel costs	12,948,260	3,935,495	16,883,755
Fellowship grants and awards	758,565	1,045,956	1,804,521
Equipment	884,230	1,820,383	2,704,613
General expenses:			
Educational and research supplies	615,634	1,153,041	1,768,675
Building maintenance and operation	1,387,370	896,318	2,283,688
Travel and meetings	518,233	558,106	1,076,339
Publications	24,570	67,408	91,978
Shop	65,521	16,984	82,505
Telephone	174,765	217	174,982
Books and subscriptions	211,156	6,592	217,748
Administrative and general	1,563,973	404,981	1,968,954
Fundraising expense	112,522	—	112,522
Total general expenses	4,673,744	3,103,647	7,777,391
Indirect costs-grants	(2,693,547)	2,693,547	—
Indirect costs capitalized on scientific construction projects	(77,328)	—	(77,328)
Total expenses	$16,493,924	12,599,028	29,092,952

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