Smithsonian Institution

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Research Reports

ASTROPHYSICS

Chandra X-ray Observatory: On a mission to explore the hot universe

By Wallace Tucker and Karen Tucker
Smithsonian Astrophysical Observatory

Liftoff. We have liftoff of Columbia. Reaching new heights for women and X-ray astronomy!

Those words from Kennedy Space Center commentator Lisa Malone on the evening of July 23, 1999, were music to the ears of hundreds of Smithsonian scientists and staff. Many of them had been waiting for a week—make that 23 years in the case of Harvey Tananbaum—for the space shuttle to deliver the National Aeronautics and Space Administration's Chandra X-ray Observatory into space.

Eight hours later, under the direction of Col. Eileen Collins, the first female commander of a space shuttle mission, Chandra was gently pushed away from the shuttle. Over the next two weeks, two separate rocket systems would fire a total of seven times and boost Chandra to its operating Earth orbit, an ellipse that ranges from approximately 6,000 miles at its low point to about 86,500 miles at its high point.

The Chandra X-ray Observatory, named in honor of one of the foremost astrophysicists of the 20th century, the late Nobel Laureate Subrahmanyan Chandrasekhar, joins the Hubble Space Telescope and the Compton Gamma-Ray Observatory as the third in NASA's fleet of four great observatories. They are designed to observe the cosmos from infrared through gamma-ray wavelengths. The fourth observatory, the Space Infrared Telescope Facility, or SIRTF, is slated for launch in 2001.

In its first months of operation, Chandra gave astronomers an unprecedented look at the extreme universe of black holes, exploding stars and galaxy clusters. "Chandra is everything we ever hoped for and more," says Tananbaum, who, along with Riccardo Giacconi, wrote the first proposal in 1976 to fund the Chandra project.

"It is one of the most significant astronomy missions of our time and a great source of pride to SAO," says Irwin Shapiro, director of SAO and the Harvard-Smithsonian Center for Astrophysics. "Many talented and dedicated people here have played key roles in the transformation of a grand vision into a working telescope that promises to revolutionize our understanding of the high-energy universe."

Tananbaum now serves as the director of the Chandra X-ray Center, which controls operations of the observatory under contract to NASA. The center is located at the Smithsonian Astrophysical Observatory in Cambridge, Mass.

The Chandra project is managed by NASA's Marshall Space Flight Center in Huntsville, Ala., and TRW, an automotive, space defense and information technology company headquartered in Cleveland, Ohio. (See the article on Page 2 for details on the Chandra X-ray Center.)

Studying X-rays

The high energies of X-rays, which are invisible forms of light, have two important consequences for astronomers. First, they are absorbed by the atmosphere, so telescopes must be placed on spacecraft that travel above the atmosphere in order to detect them. Second, X-ray telescopes must be constructed differently than optical telescopes.

X-rays will reflect off mirrors, but only if they strike at grazing angles, like a stone skipping across a pond. For this reason, X-ray mirrors have to be specially shaped, then aligned nearly parallel to incoming X-rays. These barrel-shaped mirrors are nested one inside the other to increase the collection area and thereby the sensitivity of the telescope.

The crew of the space shuttle Columbia pause in front of the launch pad before their historic flight into space. From left, Mission Specialist Michel Tognini, Pilot Jeffrey Ashby, Flight Commander Eileen Collins and mission specialists Steven Hawley and Catherine Coleman. (Photo courtesy of the National Aeronautics and Space Administration)

Chandra's telescope consists of four pairs of such mirrors. These mirrors are the smoothest mirrors ever constructed. The largest of the mirrors is almost four feet in diameter and three feet long. These unique mirrors enable Chandra to make images 25 times sharper than any previous or planned X-ray telescope.

Two sensitive, electronic X-ray cameras are used to collect the X-rays focused by the mirrors. Scientists specify which camera will be at the focus for their observation. The High Resolution Camera—conceived, designed and constructed at SAO—uses an array of 69 million tiny glass tubes and a grid of electrically charged wires to determine the position and arrival time of each individual X-ray. In addition, the camera reconstructs a high-resolution image of the celestial source of the X-rays.

The other camera, a product of the Massachusetts Institute of Technology and Pennsylvania State University, is the Advanced Charge-Coupled Device Imaging Spectrometer, or ACIS, which works much like a camcorder or digital camera. It contains 10 X-ray-sensitive charged coupled devices, or CCD chips, each with more than a million pixels, or "detection elements," to record the position and energy, or color, of the X-rays.

Even more details about the energy of the incoming X-rays can be obtained by inserting two screenlike instruments, called transmission gratings, into the path of the X-rays. The gratings, built by MIT and the Space Research Organization of the Netherlands, disperse the X-rays into a high-energy rainbow, containing thousands of distinct X-ray colors.

As the following sample of recent observations shows, Chandra has already begun to transform astronomy.

Star birth

One of Chandra's early targets was the brilliant Orion star cluster, a cosmic birthing ground for stars. Stars in the Orion cluster were formed during the last few million years, so they are infants compared with our 4.5-billion-year-old sun.

'Chandra,' continued on Page 6

Research Vistas

A tradition of research ■ Some readers of this special issue devoted to the Chandra X-ray Observatory may be surprised to discover the central role of the Smithsonian Astrophysical Observatory in Cambridge, Mass., in the development of this spacecraft and in the history of X-ray astronomy.

Other readers may be just as surprised to discover that the Institution even has an "observatory," especially one making observations across the entire electromagnetic spectrum, using a variety of Earth- and space-based instruments. In addition to X-ray astronomy, researchers at SAO conduct experiments in laboratory astrophysics, studies in geophysics and earth sciences, and research in science education.

In fact, the Smithsonian has had an observatory since 1890, when the Institution's third secretary, Samuel Pierpont Langley, founded SAO to study what he called "the new astronomy." He was referring to what we now know as astrophysics, a then-revolutionary notion that one might study the physical nature of astronomical bodies, as well as their positions and motions.

The first half of SAO's scientific life was devoted primarily to solar research, until the dawn of the Space Age, when the observatory moved to Cambridge, Mass. From there, SAO embarked on a multifaceted research program, eventually encompassing almost every major field in modern astronomy and astrophysics—from the study of large-scale structures in the universe to the composition of comets in our solar system. Today, SAO is part of the Harvard-Smithsonian Center for Astrophysics. It boasts more than 800 staff, major field observatories atop mountains in Arizona and Hawaii, and experiments aboard a host of orbiting spacecraft. Together, SAO and its partner, the Harvard College Observatory, form the world's largest center for basic research in astrophysics.

But SAO is not alone among Smithsonian research centers in its pursuit of knowledge or in its prominence in the international scientific community. The Smithsonian Tropical Research Institute in Panama is a world leader in tropical biology, geology and anthropology. Field biologists come each year to STRI's natural "laboratory" on Barro Colorado Island to study the complex and delicate ecosystems of the rain forest, while marine scientists pursue research at stations on Panama's Atlantic and Pacific coasts.

Similarly, the Smithsonian Environmental Research Center is in its 35th year of studying the relationships between land and estuarine environments, the interactions of fresh and salt water, and the impact of human activity on coastal ecosystems. From its main laboratories and field stations on the shore of the Chesapeake Bay, SERC research radiates to sites around the world.

In addition to SAO, STRI and SERC, there are more than a half-dozen other centers of research at the Smithsonian—ranging from the Archives of American Art to the Center for Latino Initiatives, where scholars come to use the Institution's matchless collections of artifacts, specimens, books and papers. Moreover, every Smithsonian museum has its own research staff and facilities. For example, the Center for Earth and Planetary Studies is part of the National Air and Space Museum, and the Smithsonian Marine Station at Fort Pierce, Fla., is part of the National Museum of Natural History.

Much of the research at these extraordinary centers is never seen or appreciated by the general public. For most Americans, the Smithsonian is identified with the great museums on the National Mall in Washington, D.C. Nonetheless, the Institution has conducted visionary basic research since its beginnings. Occasionally, the Smithsonian's long-term, behind-the-scenes basic research bursts into public consciousness with discoveries of both scientific significance and stunning beauty. Such is the case with the Chandra images of the cosmos. We hope you enjoy the fruits of this special synergy between "increase and diffusion" of knowledge at the Smithsonian.

—Dennis O'Connor, Under Secretary for Science, Smithsonian Institution

Dan Shropshire, left, and Eric Martin, both of TRW, monitor the progress of the Chandra X-ray Observatory in the Operations Control Center managed for the National Aeronautics and Space Administration by the Smithsonian Astrophysical Observatory. (Jon Chase photo)

ASTROPHYSICS

Chandra X-ray Observatory opens up a 'whole new world' of astronomy

By Wallace Tucker and Karen Tucker
Smithsonian Astrophysical Observatory

As a precedent-setting example of the National Aeronautics and Space Administration's initiative to streamline the operations of its space science missions, the Chandra X-ray Observatory is operated by the Smithsonian Astrophysical Observatory in Cambridge, Mass. Chandra, the largest space observatory ever operated outside of a NASA facility, is now receiving data at an all-purpose facility in Cambridge called the Chandra X-ray Center.

The center, which is operated under a contract with NASA's Marshall Space Flight Center, is a collaboration of personnel from SAO and the Massachusetts Institute of Technology. TRW, an automotive, space defense and information technology company, is the prime contractor for Chandra. The center is directed by Harvey Tananbaum and managed by Roger Brissenden, both of SAO.

Chandra was activated during a three-week period after launch last July. The Chandra X-ray Center's routine is to serve as the space science equivalent of a one-stop shopping superstore. From the time that a scientist types out a proposal and sends it to the center until the happy days when data are received and findings published, the center is involved.

Behind-the-scenes support

The User Support group organizes peer review of proposals from aspiring observers. For the first year of observation, about 800 proposals were submitted from around the world, and about 200 were accepted. Successful proposals are passed along to the Mission Planning group, which uses input from the Calibration group and the Science Operations team to schedule the observation. The Science Operations team and the Flight Operations team then work together to "run the load" by sending a series of commands up from the Operations Control Center to Chandra via NASA's Deep Space Network, which has stations in California, Spain and Australia.

When the observation—which may take anywhere from an hour to three days

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In pursuit of a target of opportunity, Chandra rises to the occasion

By Wallace Tucker and Karen Tucker
Smithsonian Astrophysical Observatory

The first Chandra rapid-response observation of an exploding star began one Friday afternoon in October 1999. Alex Fillipenko, an astronomer at the University of California at Berkeley, notified Robert Kirshner, associate director of optical and infrared astronomy at the Harvard-Smithsonian Center for Astrophysics, that his supernova search project had a good candidate in a relatively nearby spiral galaxy, NGC 1637. In this case, "nearby" meant about 25 million light-years from Earth!

Wei Dong Li, a visiting astronomer from the Beijing Astronomical Observatory who was working with Fillipenko's group, called his colleagues in Beijing, who made confirming observations of the supernova, which was given the official name SN1999em.

Kirshner's group at the Smithsonian's Whipple Observatory in Arizona took a spectrum of the object on Saturday. The spectrum showed that the object was a Type II supernova, an explosion produced by the collapse of the core of a star 10 or more times as massive as the sun. Such supernovae are of great interest to cosmologists such as Kirshner, for these supernovae can serve as heavenly milestones helping to mark cosmic distances.

Interrupting a late dinner, Kirshner sent an e-mail message to Harvey Tananbaum, director of the Chandra X-ray Center, around 11 p.m. "There's a bright supernova in NGC 1637," he wrote. After giving some of the details, Kirshner signed off, "Explosively yours, Bob."

A brewing dilemma

The discovery presented a dilemma for the Chandra team. On the one hand, a supernova this close to Earth goes off only once every five or 10 years, and it would be the first time ever that an X-ray telescope with Chandra's sensitivity had looked at a new supernova. It definitely qualified as a Target of Opportunity, or TOO, which is an exceptional and fleeting astronomical event for which Chandra's normal—and prescheduled—observing program could be interrupted.

On the other hand, implementation of an accepted, coordinated, "quick-response" TOO Program was not planned to begin until the Chandra X-ray Center had more experience running the space observatory, learning about its quirks and testing the software used to command it.

Making a decision

Tananbaum decided to go for it, pending a review by various experts on the risks and rewards of such an undertaking. Shortly after 9 a.m. on Sunday, Tananbaum sent an e-mail message to key team members, asking for their advice and counsel.

Pat Slane, a principal investigator on the Smithsonian Astrophysical Observatory's Chandra Science Mission Planning team, was the first to respond, and he passed the word along to William Forman, an SAO astronomer and head of the group. Soon, e-mail messages and phone calls were zipping back and forth across Cambridge—and the country—as the pros and cons of the observation were discussed.

In the meantime, the scientists needed to juggle their professional and personal responsibilities, including their children's Halloween parties. (Slane managed to attend his child's party and stay in touch with the center. He went as a vampire with a cell phone.)

The countdown

At 9:59 a.m. on Sunday, SAO's Roger Brissenden, manager of the Chandra X-ray Center, weighed in with practical considerations, such as pointing problems and how to interrupt the "load"—the semi-automated program already in place to direct Chandra's operations for a week. Ken Gage or Kevin Marsh, TRW mission planners on the Flight Operations team, would have to be brought in to write the necessary software to do the interruption.

At 10:29 a.m., Walter Lewin, a scientist at the Massachusetts Institute of Technology, urged Tananbaum to "go for this one! A unique chance that we have been hoping for!"

At 10:59 a.m., Paul Plucinsky, an SAO astrophysicist and member of the Chandra Center's Advanced Charge-Coupled Device Imaging Spectrometer, or ACIS, team, passed along information on the instrument, which would be useful for the actual observation.

At 11:30 a.m., Li supplied an updated position of the supernova. At 11:42 a.m., Forman emphasized the need to carefully review the procedures to maintain spacecraft safety.

Anil Dosaj, an SAO mission planner in the Science Mission Planning group, volunteered to come in and prepare the official Observation Request file to observe the supernova. At 3:42 p.m., Dosaj notified Tananbaum that the "load" could be replaced by 2 a.m. Monday morning.

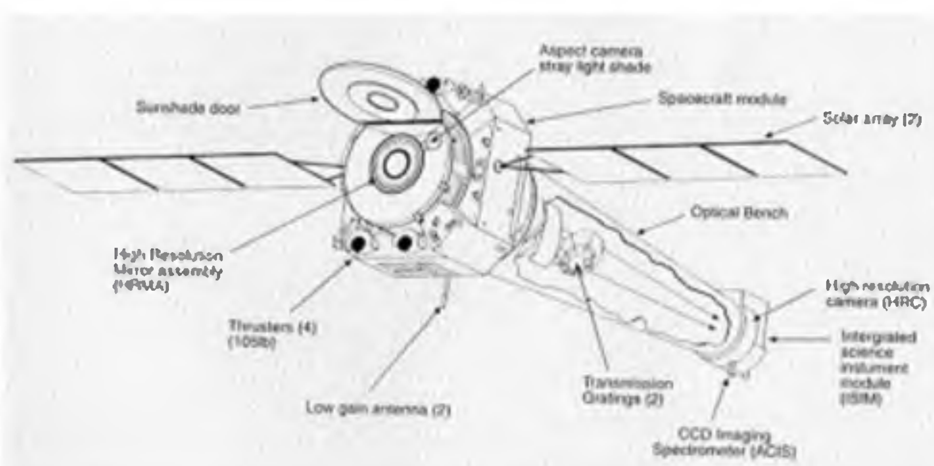
For the next five hours, the team worked furiously, with Lewin and Derek Fox, an MIT graduate student, consulting with Plucinsky and Royce Buehler of MIT's ACIS team to plan the details of the observation. When they were finished, Brissenden called the team together for a final review at 9 p.m.

Team members present were Jeff Shirer of TRW's Flight Operations team, Buehler, Dosaj, Slane, Forman and Marsh. Additional SAO members with responsibilities for other aspects of the mission included Rob Cameron, Jon Chapell and Gerry Austin.

The results

"The review is complete and there are no issues," Brissenden reported to Tananbaum. "Overall, a good effort from the team...."

All that remained was the wait for the time slot (late Monday afternoon) to uplink to Chandra and for the spacecraft to slew over to and point on the source, which would take about half an hour. The observation began at 6:37 p.m. Monday and continued for several hours. It would then take a week or so to analyze the data.



A schematic illustration of the Chandra X-ray telescope shows its complex mirror assembly.

"I was impressed by how rapid the Chandra response was," Kirshner says. "It typically takes a week for the Hubble Space Telescope to be reprogrammed for such an opportunity."

In its first special TOO operation, Chandra observed an X-ray glow from SN1999em with the total power of 50,000 suns. Ten days later, it observed the supernova for another nine hours and found that the X-rays had faded to half their previous intensity. The optical luminosity, which had the brightness of 200 million suns, had somewhat faded. No radio emission was detected at any time.

With this information, the MIT group and their colleagues began piecing together a picture of the catastrophic explosion. The intense heat generated in the collapse of the original star produced a cataclysmic rebound that sent high-speed debris flying outward at speeds in excess of 20 million miles per hour. The debris crashed into matter shed by the former star before the explosion. This awesome collision generated shock waves that heated the expanding debris to millions of degrees.

The X-ray glow from this hot gas detected by Chandra provides astrophysicists with a better understanding of the dynamics of the explosion, as well as the behavior of the doomed star in the years before its explosion.

"The combination of X-ray detection and radio nondetection is unusual, but may have less to do with the supernova and more to do with the great sensitivity of Chandra," says Roger Chevalier, a professor at the University of Virginia, Charlottesville, and a supernova expert.

Chevalier explained that the combined observations indicate that SN1999em shed a relatively small amount of matter before it exploded, compared with other supernovae observed in X-rays. The Chandra observation is important because it may represent a more common type of supernova.

A little more than two months after outburst, radio emission was detected, probably signaling the arrival of the shock wave at the outer shell.

Another Chandra observation of SN1999em is scheduled for the near future and is eagerly awaited by supernova specialists around the world.

Outreach and Education

The Education and Outreach program at the Chandra X-ray Center covers a full range of activities, which include producing and distributing electronic and print materials to lay and professional audiences and developing educational materials to acquaint students and teachers with astrophysical research and discovery.

The Chandra X-ray Center's Web site at chandra.harvard.edu has received more than 27 million hits and 28 awards for design and content. It contains a wealth of information about the satellite. Visitors can get information on the construction of the satellite, technology involved in making the mirror and general background information on the types of astronomical objects and questions that Chandra is designed to investigate. In addition, there are educational games and puzzles for children and a "photo album" of images taken from Chandra.

An array of other materials, including classroom modules, slide sets for the public, activities for young children and new science materials are in development. A documentary film is in production and expected to be released this year.

Getting Chandra into orbit was the work of a team back on Earth

By Wallace Tucker and Karen Tucker
Smithsonian Astrophysical Observatory

Like all major space science projects, the success of the Chandra X-ray Observatory is due to the contributions of literally hundreds of individuals—at the Smithsonian Astrophysical Observatory; the National Aeronautics and Space Administration; the Massachusetts Institute of Technology; Pennsylvania State University; TRW, an automotive, space defense and information technology company; and dozens of other academic, industrial and commercial partners.

At the Smithsonian Astrophysical Observatory alone, scores of people—administrators, secretaries, contract specialists, computer programmers, purchasing agents and even public affairs writers—provided behind-the-scenes support of the scientific endeavor that would lead to Chandra's new visions of the universe.

Irwin Shapiro

Irwin Shapiro has been the director of the Harvard-Smithsonian Center for Astrophysics and SAO, both in Cambridge, Mass., since 1983. As director of the centers, he oversees the research of hundreds of scientists. Under his leadership, the centers have embarked on several major research initiatives in addition to Chandra.

Those initiatives include the development of a unique array of telescopes to be used for submillimeter astronomy; the conversion of the Multiple Mirror Telescope in Amado, Ariz., to a single-mirror instrument 6.5 meters in diameter; participation in a consortium to build two 6.5-meter-diameter optical telescopes; and the establishment of a Science Education Department.

Harvey Tananbaum

Harvey Tananbaum, director of the SAO-operated Chandra X-ray Center, is responsible for overseeing operation of the space observatory and providing support to its scientific users. The launch and operation of Chandra was the culmination of a lifelong commitment for Tananbaum, who had been working in X-ray astronomy since his graduate days at MIT. Motivated by the space program, Tananbaum's thesis was on a mysterious type of cosmic X-ray source. Later, he was involved with the Uhuru X-ray satellite and, after joining SAO, with the Einstein Observatory.

Harvey Tananbaum

In 1976, Tananbaum and Riccardo Giacconi, along with SAO astrophysicists Paul Gorenstein, Rick Harnden, Pat Henry, Ed Kellogg, Stephen Murray, Herb Schnopper and Leon Van Speybroeck, submitted a proposal to NASA for the "Study of the 1.2-Meter X-ray Telescope National Space Observatory."

The next year, preliminary work began at NASA's Marshall Space Flight Center in Huntsville, Ala., and at SAO on the Advanced X-ray Astrophysics Facility (later renamed Chandra).

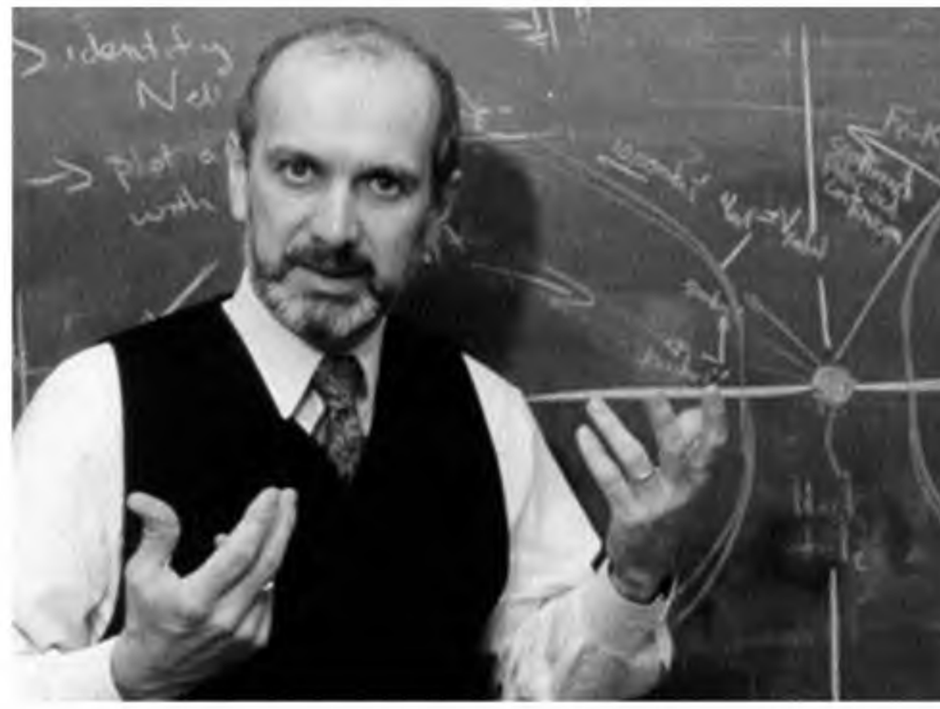
In 1981, Tananbaum became the SAO team leader, overseeing SAO's mission study and mirror development efforts. During this period, he also served as associate director for high-energy astrophysics at the Harvard-Smithsonian Center for Astrophysics. In 1991, he was appointed director of the Chandra X-ray Center.

Roger Brissenden

A graduate of the University of Adelaide in Australia, Roger Brissenden received his doctorate in astronomy from the Australian National University in 1990—the same year he joined SAO as a software scientist for the Chandra mission. Within three years, he was named manager of the Chandra X-ray Center. And in 1997, he assumed the additional role of flight director for the Chandra mission.

Roger Brissenden

On Oct. 26, 1999, during a post-launch visit to the Operations Control Center in Cambridge, the shuttle flight crew presented Brissenden with the coveted "Silver Snoopy Award," the astronauts' own special tribute recognizing his extraordinary "contributions to the success and safety" of the Chandra mission.



Martin Elvis

Dan Schwartz

Involved in the Chandra project at SAO since 1984, Dan Schwartz served as the project scientist for the Mission Support team. The team consisted of a group of some 40 scientists, engineers and other technical professionals who developed the technical requirements, evaluated the prime contractors and provided independent technical analysis of the X-ray optics, coatings and alignments of the mirrors.

Since 1991, he also has been the leader of the Development and Operations Science Support group in the Chandra X-ray Center. The group is responsible for monitoring the focal plane instruments and the aspect camera, especially in the pre-launch, launch, activation and checkout operation phases of Chandra's life.

For the last four years, Schwartz has served as the Science Operations team coordinator, working with the Flight Operations team to carry out the overall mission.

When Schwartz is not working on the Chandra project, he enjoys playing soccer and visiting historical and natural sites throughout the country.

Martin Elvis

Martin Elvis has been with the Chandra X-ray Center since its beginning in the 1980s. But even before Chandra, he worked on SAO's Einstein Observatory project in a succession of roles.

In addition, he worked with Einstein data to produce the first X-ray spectra of quasars, which, when combined with data from other spacecraft, mapped out the powerful quasar light sources across the whole spectrum.

For Chandra, Elvis is leading the team that has defined new software tools that enable astronomers to analyze and interpret the observatory's detailed three- and four-dimensional images and spectra.

With his wife, Giuseppina Fabbiano, Elvis is a partner in one of the two husband-and-wife astronomer teams working on Chandra. The other couple is Christine Jones and William Forman.

Giuseppina Fabbiano

An SAO astrophysicist who has been involved in X-ray astronomy since 1973, Giuseppina "Pepi" Fabbiano has made groundbreaking contributions to the study of the X-ray properties of galaxies. She also is working to develop large-area, high-resolution X-ray telescopes that can further these studies in the future.

She has a long-standing interest and involvement in issues of scientific data processing and archiving. Thus, as head of the Chandra X-ray Center's Data Systems Division, she leads those scientists and computer specialists responsible for the development of Chandra data-processing and analysis software. She also oversees the processing and archiving of Chandra data and the distribution of data and software to the scientific community.

Giuseppina Fabbiano

Claude Canizares

Claude Canizares is the Bruno Rossi Professor of Experimental Physics at MIT and director of its Center for Space Research. He is a principal investigator for the Chandra X-ray Center, leading the development

'Chandra team,' continued on Page 5

'Chandra team,' continued from Page 4

of the High-Resolution Transmission Grating Spectrometer.

In addition, he is associate director of the Chandra X-ray Center. Canizares, the author and co-author of some 135 scientific papers, received undergraduate and graduate degrees in physics from Harvard University. He came to MIT as a postdoctoral fellow in 1971 and joined the faculty in 1974.

Canizares' main research interests are high-resolution spectroscopy and X-ray studies of supernova remnants, galaxies

Claude Canizares

and clusters, dark matter, quasars and active galactic nuclei, as well as gravitational lenses.

His nonastronomical interests include tennis, hiking, skiing and dancing to a Latin beat.

Robert Kirshner

Robert Kirshner is associate director for optical and infrared astronomy at the Harvard-Smithsonian Center for Astrophysics. After graduating from Harvard College, he went on to receive a doctorate in astronomy from the California Institute of Technology.

Kirshner has authored 200 research papers on supernovae, the large-scale distribution of galaxies, and the size and shape of the universe. His work on the suspected "acceleration" of the universe was dubbed the "Science Breakthrough of the Year for 1998" by Science magazine. A member of the National Academy of Sciences, Kirshner is a popular lecturer among Harvard undergraduates and a frequent public speaker on astronomy.

Stephen Murray

Stephen Murray is principal investigator for the High-Resolution Camera, the imaging instrument conceived and constructed by SAO. A member of the original group of young X-ray astronomers who joined SAO in the mid-1970s, Murray has been actively involved in what was called the Advanced X-ray Astrophysics Facility program (later renamed Chandra) since the initial proposals for an orbiting telescope were sent to NASA more than two decades ago.

Stephen Murray

In 1990, as a member of the team that proposed SAO as a site for the Chandra X-ray Center, he coordinated production of the proposal's technical book that outlined the data system and the implementation plan. Today, with Chandra in orbit, Murray is carrying out a broad program of science, using all of the Chandra instruments.

"My major projects include monitoring the Andromeda galaxy (M31) and overseeing studies of star-forming regions and clusters of galaxies, as well as research on distant quasars and violent galaxies," he says.

Lester Cohen

As chief engineer for the Structural Analysis and Design group, Lester Cohen represents the scores of technical experts in SAO's Central Engineering Department who contributed to Chandra's success. His specific tasks included overseeing the optics fabrication, working with SAO project scientists, NASA technicians and other team members to verify that manufacturing and assemblage of the Chandra optics met the program requirements.

This meant he would spend about three years at Hughes Danbury Optical Systems in Connecticut reviewing technical plans and schedules to ensure compliance with program requirements, as well as providing real-time, interactive and technical input on all aspects of mirror fabrication, mounting and metrology. For his efforts, he received NASA's Public Service Medal for Outstanding Technical Leadership during the development of the mirror fabrication program.

Lester Cohen

Martin Weisskopf

Martin Weisskopf is project scientist for the Chandra X-ray Center and chief of X-ray astronomy at NASA's Marshall Space Flight Center. He received his doctorate from Brandeis University.

His career began at Columbia University in 1969 before becoming senior astronomer at the Marshall Space Flight Center. Throughout his career, he has held numerous special appointments on many spaceborne X-ray missions, including the Chandra project.

Weisskopf spends some of his leisure time playing Scrabble. In fact, he is a

Martin Weisskopf

tournament-level Scrabble player and ranked, as he puts it, "about 100th in the country, or at the bottom of the experts."

Christine Jones and William Forman

Christine Jones is head of the Chandra Calibration team. The team's job is to compare the performance of Chandra's telescope and instruments in space with what had been expected from pre-launch ground testing and what previous observations of cosmic sources have shown.

After receiving undergraduate and graduate degrees from Harvard University, Jones joined SAO and worked on the

Christine Jones and William Forman

Uhuru X-ray satellite and Einstein projects prior to Chandra. She still finds time to supervise the SAO Summer Science Intern Program for undergraduates and to participate in many public outreach activities.

Her husband, William Forman, is head of Chandra's Mission Planning team. Like his wife, he has worked at SAO on the Uhuru, Einstein and Chandra projects since receiving his doctorate from Harvard. Together, they have made major contributions to our understanding of X-ray emission from galaxy clusters—research for which they were jointly awarded the American Astronomical Society's prestigious Bruno Rossi Prize.

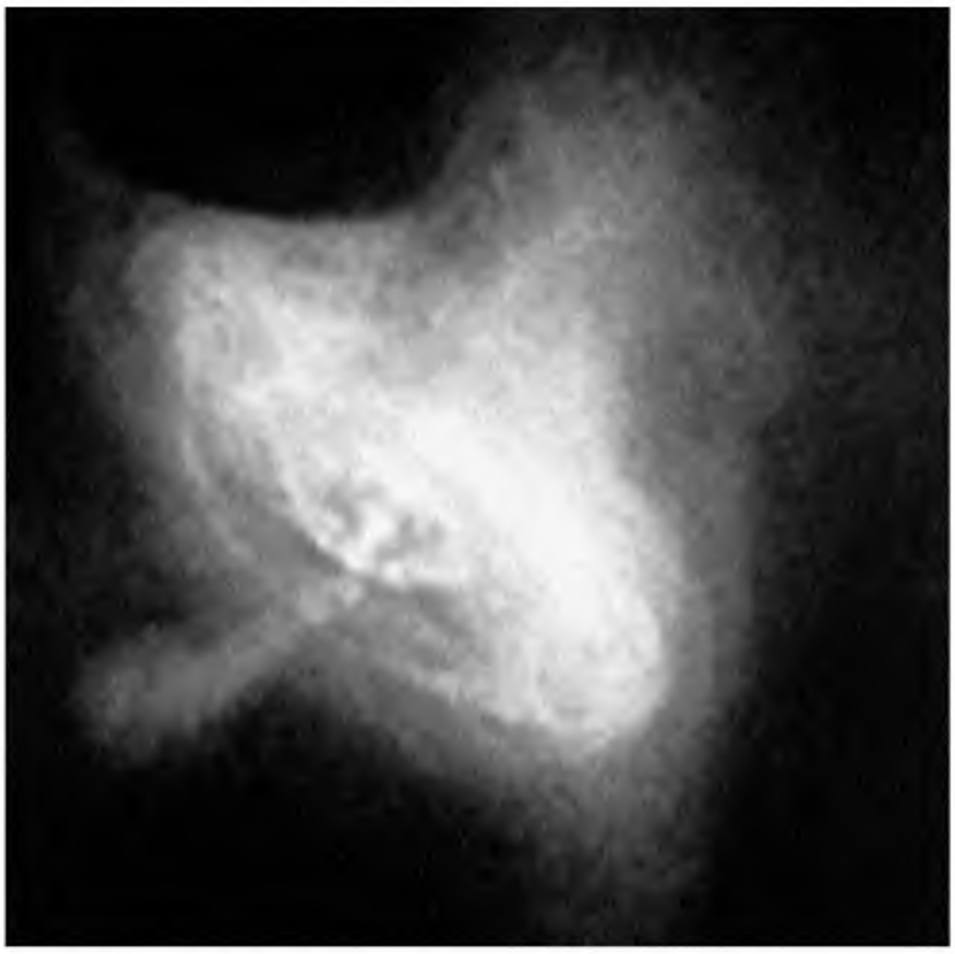
Pat Slane

Pat Slane has been a member of SAO's Chandra team since 1988, when he con-

Pat Slane

centrated on laboratory measurements of X-ray reflectivity, work that resulted in the selection of iridium as the coating material for the Chandra optics. He also participated in testing the Chandra mirrors before flight and now serves on Chandra's Mission Planning team.

Slane's own research includes the study of supernova remnants. As principal investigator on three approved research programs, he will use Chandra to observe supernova remnants and neutron stars.



The Crab Nebula, a supernova remnant in the Constellation Taurus, was seen and recorded by many cultures when it exploded in 1054 A.D. and was briefly visible to the naked eye, even in daylight. For modern astronomy, the Crab Nebula has become one of the most important—and most extensively studied—objects in the sky. This Chandra image shows the central pulsar (discovered by previous X-ray observations) surrounded by tilted rings that were produced by high-energy particles and flung outward more than a light-year from the pulsar. This unusual bell shape could be due to the interaction of particles, magnetic fields and nearby clouds of gas and dust. (Chandra X-ray Center, NASA and SAO image)

'Chandra,' continued from Page 1

In one observation of the Trapezium region of the cluster, Chandra detected a thousand X-ray stars. Some are well known, massive, optically bright stars. Some are still embedded in the cloud of dust and gas from which they formed and can be seen with an infrared, but not an optical, telescope. A few are thought to be failed stars called brown dwarfs, because of their small mass.

Many young stars produce intense flares that make them a thousand times brighter in X-rays than the sun. The cause of these flares is poorly understood, but Chandra's ability to detect and track the X-ray radiation from so many stars simultaneously should advance our knowledge of such phenomena.

"X-ray astronomy now penetrates as deeply into the clouds as the best infrared and optical telescopes, allowing us to study high-energy processes during the earliest phases of star formation," says Pennsylvania State University's Eric Feigelson, one of Chandra's principal scientific users.

Supernovae

If the early stages of a star's development are turbulent, the end game can be full of sound and fury, and full of significance for our own existence. Carbon, nitrogen, oxygen and other heavy elements necessary for life are created in the interior of massive stars. When a massive star runs out of fuel, it undergoes a catastrophic explosion called a supernova. The explosion, which is one of the most violent events in the universe, blows the star apart and disperses its elements into space, where they may eventually make up a planet like Earth.

The matter thrown off by the supernova creates a bubble of multimillion-degree gas known as a "supernova remnant." This hot gas will expand and produce X-radiation for thousands of years. Chandra is ideal for studying these remnants.

Claude Canizares and his team at MIT used Chandra to observe E0102-72, the remains of a star that exploded in a nearby galaxy. They found a ringlike structure that was 30 light-years across and expanding at 5 million miles an hour. Using the Advanced Charge-Coupled Device Imaging Spectrometer and the grating spectrometer, they determined that the ring was exceptionally rich in oxygen, confirming the theory that massive stars provide most of the oxygen in the universe.

A supernova explosion also can leave behind a dense, rapidly rotating core that consists of a magnetized ball of neutrons called a neutron star. Roughly 10 miles across, the rotating neutron star revolves at 30 times a second, sending beams of radiation and particles into space. The remarkable Chandra image of the Crab Nebula shows this cosmic powerhouse at work.

Black holes

Some of the most intense X-ray sources in the universe are caused by gas that swirls toward a black hole. As the tremendous gravity of a black hole pulls gas and dust particles toward it, the particles speed up. Collisions between the in-falling particles heat them to temperatures of many millions of degrees. Matter at such temperatures radiates primarily in X-rays, so Chandra is an efficient black hole probe.

Among Chandra's most surprising early observations are the giant black hole in the center of our Milky Way galaxy, which is surprisingly weak in X-rays, and the giant black hole in the center of the Andromeda galaxy, which is surrounded by gas at an unexpectedly cool 1 million degrees Celsius. Current theories predict that the gas falling into the central black hole in Andromeda should be at least 10 times hotter than is observed.

"The Chandra observation is telling us that an entirely different flow pattern is operating around the Andromeda black hole," says Eliot Quataert, an expert on black holes at the Institute for Advanced Study in Princeton, N.J.

X-ray jets

One of the most intriguing features of giant black holes is that they do not suck up all the matter that falls within their sphere of influence. Some of the matter falls inexorably toward the black hole, and some explodes away from the black hole in high-energy jets that move at nearly the speed of light.

Chandra has imaged a spectacular example of such a jet in Centaurus A, a nearby galaxy noted for its explosive activity. The image shows X-ray jets erupting from the center of the galaxy over a distance of 20,000 light-years. Using Chandra, astronomers also have detected a group of X-ray sources clustered around the nucleus, which is believed to harbor a giant black hole.

The X-ray jets and the cluster of sources may be a byproduct of a titanic collision between Centaurus A and a companion galaxy several hundred million years ago that triggered a burst of star formation and supplied the gas to fuel the giant black hole's activity. The presence of bright X-ray jets means that electric fields are continually accelerating electrons to extremely high energies over enormous distances. Exactly how this happens is a puzzle that Chandra may help to solve.

X-ray background

At the relatively nearby distance of 11 million light-years from Earth, Centaurus A has long been a favorite target of astronomers because it is the nearest example of a class of galaxies called active galaxies. Active galaxies are noted for their intense, bright cores and explosive activity, which are presumed to be due to a giant black hole in their center. They may be the solution to one of the oldest mysteries of X-ray astronomy.

On the rocket flight that discovered the first X-ray source in 1962, a pervasive background X-ray glow was observed. Many astronomers suspected that it was due to extremely distant active galaxies. They were unable to prove this, however, for no X-ray telescope until Chandra has had both the sharp vision and sensitivity to detect the individual sources.

Now, two teams of astronomers, one led by Richard Mushotzky of NASA's Goddard Space Flight Center and another led by Gordon Garmire of Pennsylvania State University, appear to have cracked the problem. Using Chandra, they have resolved more than 70 percent of the background glow into individual sources, most of which are galaxies with a bright central core. The nature of the remaining sources, though, is still a mystery.

"There are new mysteries coming to the forefront in the form of objects that we can't identify with any known object," Garmire says. What are these objects? Helping to solve these mysteries is what Chandra is designed to do.

'Operations' continued from Page 2

with an average time of about eight hours—is completed, the data is transmitted back to the Operations Control Center during the next pass over one of the Deep Space Network stations. The data is then processed by the Science Data Systems group and sent to the scientists who analyze it.

Finally, when the scientific results are published, the center's Education and Public Information group may assist in informing the public about the observation via press releases, the Chandra Web site at chandra.harvard.edu and educational activities. When one year has passed after the receipt of the data from the observation, it is placed in a public archive that is maintained by the center. The data then becomes available to all astronomers, amateur and professional, worldwide.

In addition to the science data from observations flowing into the Chandra X-ray Center, the Cambridge-based team also is receiving vital information about the state of the observatory, such as power consumption and temperature. This "monitoring" information is sent from the spacecraft to the center, via the Deep Space Network, about every eight hours.

In this X-ray image taken by Chandra, the supernova remnant E0102-72 reveals an expanding multimillion-degree ring of oxygen created deep inside a massive star and then hurled into space by the explosion of that star. Some 30 light-years across, the ring contains more than a billion times the oxygen found in the Earth's ocean and atmosphere combined. (Image courtesy of the Chandra X-ray Center, NASA and SAO)

Research Highlights

New lecture series. Smithsonian Secretary Lawrence M. Small's Distinguished Research Lecture Series has recently been established to promote excellence and to highlight the breadth and quality of Smithsonian research. The lecture will take place each year in the spring and will feature an individual who has made exceptional contributions to a field of knowledge and whose career exemplifies sustained excellence. Margaret Geller, an astrophysicist at the Smithsonian Astrophysical Observatory in Cambridge, Mass., and professor of astronomy at Harvard University, presented the first Distinguished Research Lecture on April 18.

Grant makes tracking easier. A grant from the Tamkin Foundation of Los Angeles has permitted the creation of a high-speed computer network for the Minor Planet Center, the international clearinghouse for astronomical information, based at the Smithsonian Astrophysical Observatory in Cambridge, Mass. The network will allow more rapid determination of the paths of newly discovered asteroids and comets, including those on possible crash courses with Earth. The center, operated by SAO for the International Astronomical Union, serves the scientific community by collecting, checking and disseminating positional observations and orbital data for asteroids and comets. The Minor Planet Center currently keeps tabs on the orbits of some 57,000 asteroids and 1,050 comets. In 1999 alone, 25,000 asteroids and 60 comets were discovered. This new technology will revolutionize the way astronomers make their observations, according to an SAO official.

Museum endowment. The Smithsonian's National Postal Museum received a $10 million endowment from former postmaster general and Alabama businessman Winton Blount to create and support a Center for Postal Studies at the museum. The new center will serve as an educational resource and will sponsor research exploring the role of the U.S. postal system in the new millennium. The contribution was the largest single gift received by the museum since its creation in 1990.

Moving online. The Smithsonian Center for Education and Museum Studies recently initiated a new program designed to prepare staff working in community-based museums and arts and cultural centers to translate their research and history skills into new-media skills and to use the Internet to supplement their education and public service missions. The program, Moving On-Line, combines theoretical approaches to interpretation on the World Wide Web with practical instruction in Web site development. To find out more about the program, check out the Web site at mignon2.si.edu/moveon. Moving On-Line is made possible by a generous grant from the Nathan Cummings Foundation.

Puerto Rican culture. The construction and representation of Puerto Rican cultural identities in Puerto Rico and the United States is the focus of a research project by Smithsonian fellow Jorge Duany of the University of Puerto Rico. The goal of the project is to produce a richly illustrated, well-rounded and finely hued portrait of cultural identities in Puerto Rico and in its large migrant communities throughout the United States. Additional visiting scholars are working on other aspects of the vast collection of Puerto Rican artifacts donated in 1997 by Teodoro Vidal. The collection, with objects dating from the 17th to the 20th century, is being used as a foundation for their research.

This 19th-century Puerto Rican santo, titled "La Mano Poderosa" (the all-powerful hand of God), was made by the Caban group.

Forest dynamics. The Smithsonian Tropical Research Institute's Center for Tropical Forest Science started its fifth census of the 125-acre Forest Dynamics Plot on Barro Colorado Island in the Republic of Panama, which has become STRI's primary site for the study of lowland moist tropical forest. During the re-census, all trees greater than four-tenths of an inch in diameter will be measured. Saplings that are new to the plot since the last census will be tagged, mapped and identified according to species, and trees that have died since the last census will be recorded. This census of about 250,000 trees should take about 10 months to complete.

Series Publications

The following publications on research in various fields were issued during the period Nov. 1, 1999, through Jan. 31, 2000, by Smithsonian Institution Press in the regular Smithsonian series. Diane Tyler is managing editor. Requests for series publications should be addressed to Smithsonian Institution Press, Series Division, 470 L'Enfant Plaza, Suite 7100, Washington, D.C. 20560-0950.

Smithsonian Contributions to Paleobiology

• 89 *Avian Paleontology at the Close of the 20th Century: Proceedings of the 4th International Meeting of the Society of Avian Paleontology and Evolution, Washington, D.C., 4-7 June 1996*, by Storrs L. Olson, editor; Peter Wellnhofer, Cécile Mourer-Chauviré, David W. Steadman and Larry D. Martin, associate editors; 344 pages, frontispiece, 168 figures, 49 tables.

Smithsonian Contributions to Zoology

• 606 *Myodocopid Ostracoda from Exuma Sound, Bahamas, and from Marine Caves and Blue Holes in the Bahamas, Bermuda and Mexico*, by Louis S. Kornicker and Thomas M. Iliffe, 98 pages, 56 figures, 6 maps, 5 tables.

Books & Recordings

Vikings: The North Atlantic Saga, edited by William W. Fitzhugh and Elisabeth I. Ward (Smithsonian Institution Press, 2000, $60 cloth; $34.95 paper). Replete with color photographs, drawings and maps of Viking sites, artifacts and landscapes, the book explores and celebrates the Vikings' expansion from their Scandinavian homelands across the Atlantic to North America 1,000 years ago.

Home on the Road: The Motor Home in America, by Roger B. White (Smithsonian Institution Press, 2000, $24.95). Chronicling more than 50 years of individual and industrial tinkering, the author describes how the technological innovations and cultural ideals of each era influenced motor home design and popular use.

Fair America: World's Fairs in the United States, by Robert W. Rydell, John E. Findling and Kimberly D. Pelle (Smithsonian Institution Press, 2000, $29.95 cloth; $15.95 paper). The authors show how world's fairs reflected and influenced not only the ideals but also the cultural tensions of the times.

Prides: The Lions of Moremi, by Chris Harvey and Pieter Kat (Smithsonian Institution Press, 2000, $34.95). This striking volume of 200 color photographs reveals the worlds of four neighboring prides that roam the diverse habitats of Botswana's Okavango Delta.

Inventing Jerry Lewis, Frank Krutnik (Smithsonian Institution Press, 2000, $44.95). Drawing on films, rare TV shows, recordings, trade reviews, magazine articles, biographies and documentaries, the author looks at Lewis' physical comedy and multifaceted star persona as mediated responses to wider cultural anxieties.

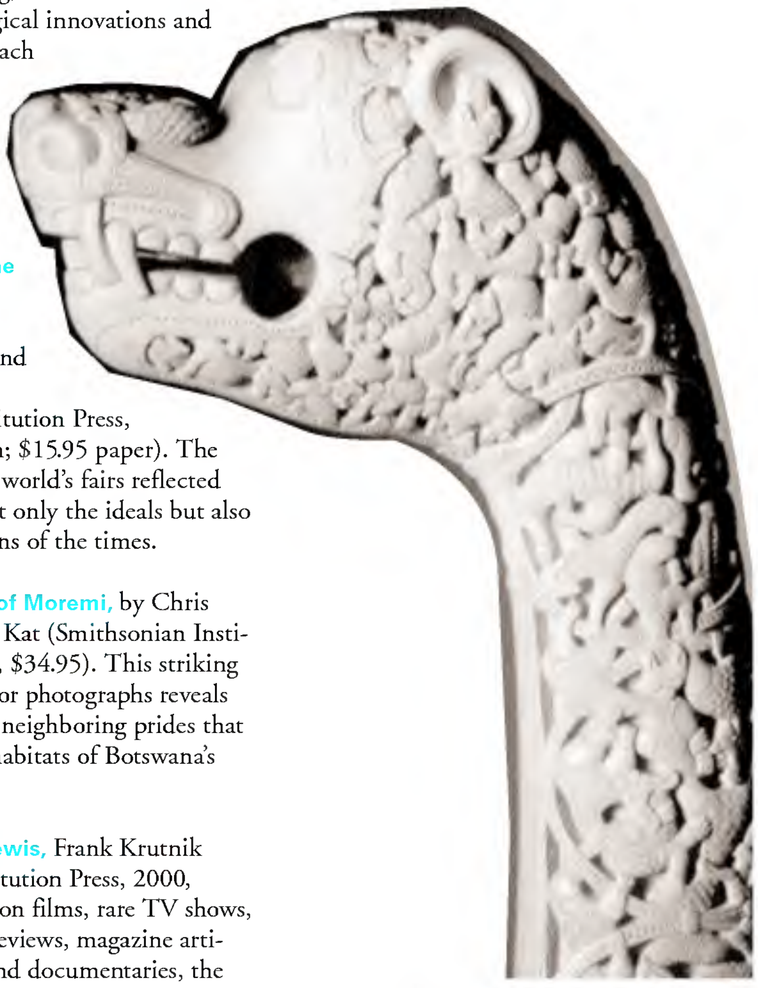
The Power of the Written Tradition, by Jack Goody (Smithsonian Institution Press, 2000, $45 cloth; $18.95 paper). Drawing upon several decades of fieldwork in Africa, as well as research on a range of societies worldwide, Goody, a noted anthropologist, demonstrates that writing not only has empowered formerly subordinate groups but also has allowed ancient empires and modern nations to dominate their nonliterate counterparts.

Museums and History in West Africa, edited by Claude Daniel Ardouin and Emmanuel Arinze (Smithsonian Institution Press, 2000, $29.95). Representing museums throughout western Africa, including those in Benin, Ghana, Nigeria and Senegal, 24 contributors argue that their institutions must become active, research-related centers capable of developing historical knowledge and communicating it locally.

Alerta Sings and Songs for the Playground/Canciones Para el Recreo (Smithsonian Folkways Recordings, 2000, $14 CD). This compact disc of children's songs from Latin America and the Caribbean joins two of Suni Paz's acclaimed Smithsonian Folkways recordings.

Richard Dyer-Bennet: #6, With Young People in Mind (Smithsonian Folkways Recordings, 2000, $14 CD). From fairy tales to ancient adventures, this compact disc, originally released in 1958, offers soothing bedtime stories, exciting epics and real-life experiences.

'Recordings,' continued on Page 8



Four ornate beastlike animal head carvings, such as this one, were found on posts in the elaborate eighth-century ship burial of a pagan high-status female. The "gripping beast" carving is typical of early pagan Viking art. (Photo courtesy of Universitets Oldsaksamlings, Oslo)

Off the Shelf

Forces of Change: A New View of Nature

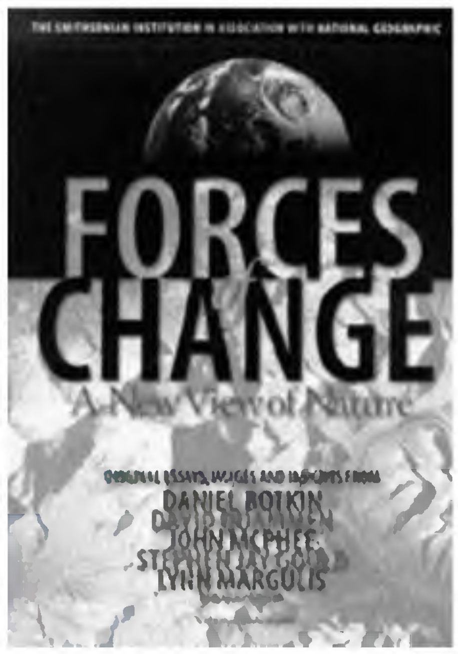
(Published by the National Museum of Natural History in association with National Geographic, 2000, $40)

Forces of Change offers a sweeping vision of our Earth and illuminates the forces that define and continue to profoundly transform our planet and all of its inhabitants. It provides a forum for exploring a broad range of scientific and social questions relating to change, both natural and human-induced.

"The growing public awareness of potential climate shifts, diminishing biodiversity, and other environmental and social issues is enough to make change a timely and provocative theme," Alan Cutler writes in the book's introduction. He adds, "But the complexity of the issues that confront us and of the underlying forces of change leads inevitably to more basic questions—questions regarding our relationship with nature and our complicated, often ambivalent attitudes toward change."

In the book, almost two dozen of the world's most innovative and visionary scientists, scholars and writers, including George Horse Capture, deputy assistant director for cultural resources at the Smithsonian's National Museum of the American Indian, approach the Earth as a dynamic system, where interrelated forces affect people and environments on a global scale. They explore different facets of Earth's interdependent systems and what the unpredictable future may hold.

Beautifully illustrated with some 200 color photographs, the book is divided into four parts—"Forces of Nature," "Time and Complexity," "Adapting to Change" and "Changing Views."



Forces of Change **is a new 200-page, full-color book produced by the Smithsonian's National Museum of Natural History in association with National Geographic.**

In Part 3, "Adapting to Change," Horse Capture presents a chapter titled "Leave it to the School Children." In his moving personal account of how a mining company forever changed the Fort Belknap Reservation in Montana where he grew up, Horse Capture focuses on the economic factors, mainly gold, that brought the miners to the reservation. In addition, he writes about the impact of these "intruders" on the land and its native people.

"No laws existed to protect our sacred ground from desecration," Horse Capture says. "Economics eventually sent the miners away again, but not before they reduced once proud mountains to rubble."

Mining in the mountains had been going on since the late 1800s, Horse Capture says, but it was taking place primarily in tunnels and shafts with little irreparable damage to the surface. "In other words," he explains, "the damage was out of view of the people."

But when open-pit mining began, he continues, the mountains were destroyed. "Massive destruction in our American Indian world is inconceivable. These mountains, which were sacred to us, were destroyed for gold, and we never directly benefited from any of it." In addition, Horse Capture says, mining left the rivers, from which water was used for drinking and swimming, full of pollutants.

"We were helpless," he adds. When the price of gold dropped, the mining company shut down. Even though they have long been gone, he continues, it is only a matter of time before they return again. When the price of gold escalates, the spirits of the sacred grounds will once again be "awakened" to the sounds of bulldozers and dynamite.

"Should we cut down the forest tonight so that we can build a big fire and cook supper?" Horse Capture asks. "What about tomorrow? What about the children?

"As we enter the new millineum," he adds, "it would be an ideal time to reconsider some of the values and standards of the past, because what was good for one time may not be good for another. We must think of tomorrow."

Other segments of the book focus on forces of change such as climate, biodiversity, mass extinctions, migration, technology and the Information Age.

—Jo Ann Webb

Editor's Note: This spring, Contributing Members will receive Forces of Change *as a benefit of membership.*

'Recordings,' continued from Page 7

Ella Jenkins: Seasons for Singing (Smithsonian Folkways Recordings, 2000, $14 CD). This compact disc of children's songs, recorded live at a music workshop, features original and traditional songs from around the world.

Memphis Slim: The Folkways Years, 1959-1973 (Smithsonian Folkways Recordings, 2000, $14 CD). This compact disc features a compilation of Memphis Slim's historic Folkways recordings, including three previously unreleased tracks.

Big Bill Broozy: Trouble in Mind (Smithsonian Folkways Recordings, 2000, $14 CD). The releases on this compact disc feature intricate guitar playing, soaring vocals and commentary and demonstrate Broozy's amazing skill as a solo performer.

Pete Seeger: American Folk, Game and Activity Songs for Children (Smithsonian Folkways Recordings, 2000, $14 CD). This collection presents many classic songs for children of all ages.

Books published by Smithsonian Institution Press can be ordered from P.O. Box 960, Herndon, Va. 20172-0960. To order by phone or for more information, call 1 (800) 782-4612. There is a $3.50 postage and handling fee for the first book ordered and $1 for each additional book.

Smithsonian Folkways Recordings can be ordered by writing to Smithsonian Folkways Mail Order, 955 L'Enfant Plaza, Suite 7300, Washington, D.C. 20560-0953. To order by phone or for more information, call (202) 287-7297 or 1 (800) 410-9815. There is a $4 fee for shipping and handling of the first three recordings ordered; call for other shipping prices.

Special Issue

This issue of Research Reports, devoted to the Chandra X-ray Observatory, was written by Wallace Tucker and Karen Tucker. It was edited by James Cornell, with the production assistance of Mary Juliano and Megan Watzke and special photography by Jon Chase, in cooperation with the Smithsonian's Office of Public Affairs, which publishes Research Reports quarterly.

Staff at the Smithsonian Astrophysical Observatory, the Chandra X-ray Center, the National Aeronautics and Space Administration, the Massachusetts Institute of Technology and Pennsylvania State University made significant contributions to the gathering of text and images.

We want to hear your comments about this single-theme issue. Contributing Members may call 1 (800) 931-3226, and information will be forwarded to us. Other readers, see Page 2 for ways to contact us.

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