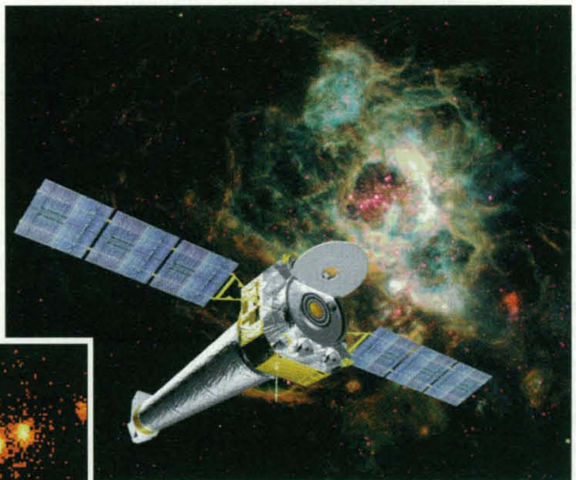
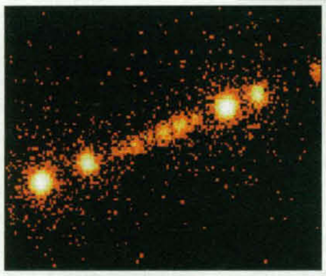
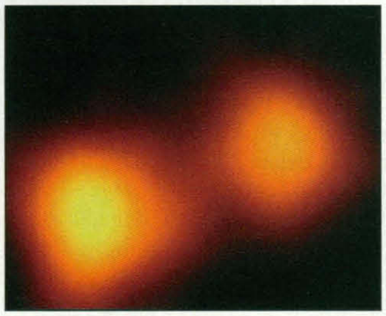
Starting next month, a spacecraft called Chandra will image the hottest and most violent parts of the universe and inaugurate x-ray astronomy's golden age

X-ray Observatory Takes To the Sky

After a couple of decades, a couple billion dollars, and some deflected careers, U.S. x-ray astronomers finally have a telescope of their own. Last week, anticipation finally gave way to reality when the Chandra X-ray Observatory rode the Space Shuttle into space. Planning for Chandra began when the last American x-ray telescope, called Einstein, was launched in 1978; and by the time Chandra's 5- to 10-year lifetime is over, it will have cost $2.8 billion. The payoff will start to come in 2 weeks, when the telescope's doors will open and its instruments start recording x-rays from objects all the way back to the beginning of the universe. For x-ray astronomers, says Claude Canizares of the Massachusetts Institute of Technology, principal investigator for one of Chandra's instruments, "Einstein just cracked the door open. Chandra's a thousand times better."







Attention to details. A simulated image from Chandra reveals a jet of hot gas at the center of the galaxy M87 *(left)*. The jet, known from other observations, is a smudge in an image from an earlier x-ray satellite, ROSAT *(below)*.

As a result, Chandra, named for the late astrophysicist Subrahmanyan Chandrasekhar, is likely to be the revelation to x-ray astronomy that its sister space telescope, the Hubble, has been to optical. Like Hubble, it's been subject to delays that have taken a toll on the U.S. astronomical community, while European and Japanese x-ray astronomers pushed ahead with their own telescopes. But for now no one is inclined to carp. Once Chandra starts observing, says Riccardo Giacconi, who is generally acknowledged to be the father of x-ray astronomy, "I'll be so happy. I'll play the old man and bless everybody in sight."

X-ray astronomy began with the space age; because (happily for us) Earth's atmosphere blocks x-rays, they can be detected only in space. A small rocket experiment came first; then, in 1970, a team led by Giacconi, now director of Associated Universities Inc., launched a pointable instrument similar to a Geiger counter and detected x-rays coming from outside our galaxy. Einstein, a true telescope, followed in 1978—"it was a dynamic field where we worked fast," says Giacconi—with the first images of the violence that emits x-rays, including supernova explosions, material disappearing into black holes, and clouds of fiery intergalactic gas.

That was the warm-up; the 14-meter, 4.6-ton Chandra is the long-delayed ball game. Thanks to its exquisite mirrors and instruments, an x-ray telescope will for the first time be able to see detail as fine as most optical telescopes. X-rays don't reflect off ordinary glass mirrors but go straight through, so Chandra, like all x-ray telescopes, has mirrors consisting of sets of nested reflective cans arranged so that x-rays graze them rather than strike them head-on. Chandra's four sets of iridium-coated quartz mirrors, however, are smoother and lighter than any previous. "Chandra's got the best x-ray mirrors that have ever been made," says Stephen Murray of the Harvard-Smithsonian Center for Astrophysics (CfA), principal investigator for Chandra's high-resolution camera. That camera is 20 times more sensitive than anything before; the imaging spectrograph has a resolution eight times finer.

Such finesse had a messy birth—a record of "de-scoping" (in NASA's jargon), missed deadlines, software bugs, and doors that stuck in tests. The Challenger disaster slowed the start of construction, and the program suffered a major cut in 1992, when designers stripped out mirrors and instruments to save money. Last April the explosion of an Air Force Titan 4 rocket, which has an upper stage like the one that boosted Chandra toward its final orbit after it was released from the shuttle, set back the schedule by a couple of weeks. And just last week a faulty sensor and bad weather delayed the launch two more times.

All along, the pace has been slowed by the need to make Chandra near-perfect because its orbit is unreachably high, a third of the way to the moon. "Sending it high," says Giacconi, "you don't have Earth in the way of observing," nearly doubling the effective observing time. But the high orbit rules out repair missions by the Space Shuttle, and given the several rounds of fixes that Hubble has needed, that's a worry. "Of course I'm concerned," says Giacconi, who directed the Space Telescope Science Institute (STScI) in Baltimore during Hubble's repairs. "But everything we've learned about redundancy and reliability" has gone into Chandra, he says.

Whether Chandra's prolonged incubation has hurt x-ray astronomy is a matter of debate—"it's hard to estimate the effects of something that didn't happen," says Wallace Tucker of CfA. In the 20 years between Einstein and Chandra, Europe and Japan have taken the lead. A 1990 German satellite called ROSAT used a telescope that im-

CREDIT: CHANDRA X-RAY CENTER, SMITHSONIAN ASTROPHYSICAL OBSERVATORY

Other Eyes on the X-ray Sky

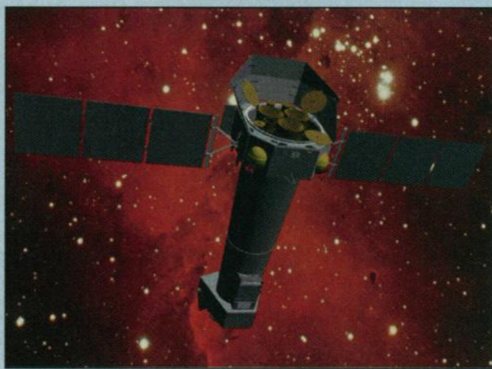
For the next few months, NASA's giant new x-ray telescope Chandra will reign alone (see main text). But by next January, after launches by the Europeans and the Japanese, it will be one of a triumvirate of x-ray observatories, each with unique strengths.

Whereas Chandra's forte is very high resolution imaging, capturing x-ray sources such as the hot gas between galaxies in detail never seen before, the European X-ray Multi-Mirror (XMM) mission will outdo it in sheer x-ray gathering power. And the Japanese Astro-E will be able to analyze very short wavelength, "hard" x-rays from the universe's most violent corners. "The three [spacecraft] complement each other very nicely," says Steve Holt of the Goddard Space Flight Center in Greenbelt, Maryland, NASA's project scientist for Astro-E.

XMM, a "cornerstone" mission in the European Space Agency's (ESA's) Horizons 2000 program, is scheduled for launch on 15 December atop an Ariane 5, Europe's new heavy-duty rocket. The craft's size—a length of 10 meters and a weight of 3.9 tons—approaches that of Chandra, and it will follow a similar orbit, a high, eccentric path taking it as far as 114,000 kilometers from Earth, letting it view a single target continuously for a day or more. Sometime in March the $640 million craft (the cost figure includes launch and operations for 2 years) will make its first observations. Like Chandra, it will collect x-rays with conical mirrors shaped so that photons will graze the surfaces and be funneled to a camera and a spectrograph. But XMM's designers opted for sensitivity over ultimate resolution.

The craft carries a bundle of three x-ray telescopes with 58 concentric gold-plated nickel alloy mirrors each, giving it a total mirror area of 4500 square centimeters—four times that of Chandra. Its ability to capture x-rays should enable XMM to find 100 new x-ray sources in each patch of sky it examines, estimates Robert Lainé, ESA's project manager for XMM. Because it will bring in such a large haul of photons, XMM should also excel at spectroscopy—in which the x-rays are analyzed by wavelength—and at detecting the subtle x-ray flickers that might, for example, be the signature of a black hole. And while XMM's x-ray telescopes capture images and spectra, a fourth, 30-centimeter optical telescope will observe the same object in visible light. "So if we observe a fluctuating source, like a pulsar, we can see if it pulsates simultaneously in the visible, in x-rays, and what the spectral contents of the source are," says Lainé.

In late January 2000, the third member of the x-ray triumvirate, Astro-E, will be launched from the Kagoshima Space Center in Japan aboard an M-5 rocket. The $200 million craft, a joint project of NASA and Japan's Institute of Space and Astronautical Science, will orbit just 550 kilometers up. The low orbit means that the spacecraft will not be able to observe most objects for more than about an hour before Earth blocks its view or its instruments have to be shut down as it passes through the radiation belts near Earth.



Four telescopes in one. Europe's X-ray Multi-Mirror mission, due to be launched in December.

Like XMM, Astro-E carries multiple telescopes—four of them, each containing 130 nested, foil-like mirrors, making a total collecting area twice that of Chandra's mirrors. Astro-E won't have anything like Chandra's eye for detail, or even XMM's; its strength will be analyzing the hard x-rays given off by the turbulent centers of "active" galaxies and by the debris clouds left by exploding stars. The key instrument, developed at Goddard, is a microcalorimeter—an array of 32 heat detectors, essentially—placed at the focus of one of the telescopes. Operating at liquid-helium temperatures, the calorimeter can precisely determine the energy (equivalent to wavelength) of each hard x-ray photon by measuring the tiny amount of heat deposited when it strikes a cooled crystal.

Although some astrophysical events will play to the strengths of just one instrument, the three spacecraft will spend a lot of time looking at the same things. But x-ray astronomers welcome the overlap. Says Jeffrey McClintock of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, "They will milk different things out of these objects." –ALEXANDER HELLEMANS

Alexander Hellemans is a science writer in Naples, Italy.

proved on Einstein's to survey x-ray sources, and an instrument aboard the 1993 Japanese satellite ASCA is a prototype of one of Chandra's instruments. Both the Europeans and Japanese are now set to launch their own giant x-ray telescopes, which will not match the quality of Chandra's images but will surpass Chandra in some other ways (see sidebar). And although the instruments and mirrors aboard Chandra are state of the art, says Giacconi, the art is old. Murray concurs: "If we'd flown in '86 or '87 when we thought, we'd be working on new kinds of optics by now."

The fairest mirrors. Chandra's concentric quartz mirrors, which focus x-rays that graze their surfaces.

CREDITS: (TOP TO BOTTOM) ESA; EASTMAN KODAK

Gordon Garmire of Pennsylvania State University in University Park, principal investigator for the imaging spectrograph, points out a more human cost: "If I'd known it would be this long, I might not have stuck with it." Ethan Schreier, an x-ray astronomer who didn't stick with it and moved on to STScI, notes that the delay is reflected in an aging community: "[It] doesn't get a lot of new blood. People dominating the field now are the ones who dominated it 20 years ago." But CfA's John Huchra says that "once a telescope in space goes up, astronomers are back in fast. The field is pretty robust." Indeed, 800 proposals came in for Chandra's first cycle of 200 observations. X-ray astronomers won't be the only ones using the data and images from Chandra, says Huchra: "Chandra will probably touch half of all astronomers in the country." In anticipation, NASA is now inviting astronomers to write joint proposals for observations on both Hubble and Chandra.

In one crosscutting effort, Chandra will map the million-degree gas bound within galaxies and clusters of galaxies, allowing astronomers to chart the distribution of much of the universe's matter and to understand the formation of galaxy clusters.

Chandra's resolution is so good, says CfA's Tucker, "you'll see shock waves from galaxies falling into the cluster." Chandra will also observe active galaxies, whose brilliance at radio and other wavelengths is fueled by gas falling into a mammoth black hole; Meg Urry at STScI hopes to find out whether active galaxies can thrive in isolation or whether they have to live in clusters of other galaxies to keep the black hole well fed.

Garmire will use Chandra to reobserve a tiny patch of sky called the Deep Field, which Hubble observed in exquisite detail at optical wavelengths, seeing galaxies in the farthest reaches of the cosmos. "Lots of [optical Deep Field] objects are ho-hum things," Garmire says, but the same field in x-rays should show galaxies filled with hot young stars, helping astronomers understand the universe's history of star formation. Chandra may also pick out black holes at that great distance, allowing astronomers to test the possibility that black holes are born small and have grown larger over cosmic history. And like every new instrument, Chandra is certain to find something completely unexpected, says Harvey Tananbaum, director of the Chandra X-ray Observatory Center: "My favorite observation is going to be the one I couldn't have told you about today."

Such far-reaching, serendipitous, interdisciplinary astronomy was the reasoning behind NASA's Great Observatories program, in which Chandra is the third of four. (The Compton Gamma Ray Observatory and Hubble preceded it, and a planned infrared telescope called SIRTF will follow.) These ambitious missions suffer from lengthy time scales and high costs, but Schreier says nothing else offers as good a chance for fundamental discoveries. Agrees NASA's Alan Bunner: "You can do breakthrough science with small missions if you're clever and lucky, but usually it takes breakthrough observatories."

For now, says Murray, "seeing the light at the end of the tunnel and knowing it's not a train, I'm so excited you can't imagine."

–ANN FINKBEINER

Ann Finkbeiner is a writer in Baltimore.

EVOLUTIONARY BIOLOGY

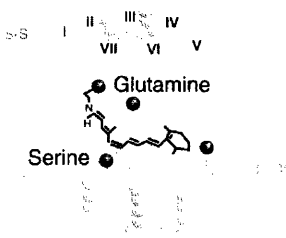
Gaining New Insight Into the Molecular Basis of Evolution

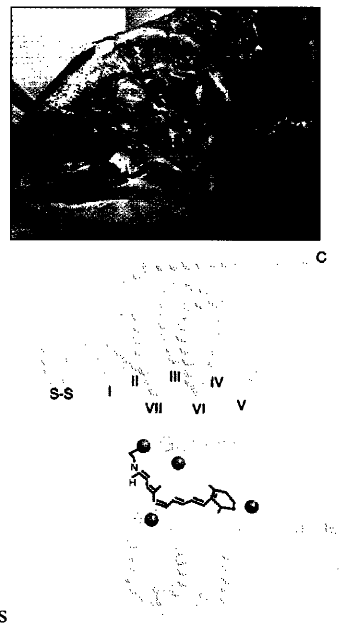
By tying mutations in the sequences of visual proteins to altered function, researchers get a handle on how those changes may influence fitness

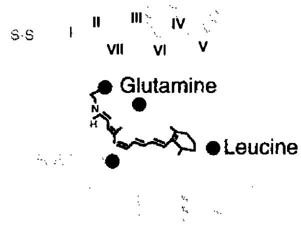
Every step in evolution, from a darkening of a moth's pigment to the development of the opposable thumb, is caused by a change in molecules. But biologists have rarely traced adaptive changes to their molecular roots in genes and proteins. Now Shozo Yokoyama, an evolutionary geneticist at Syracuse University in New York, has studied how natural selection works at the molecular level in a fish that is already celebrated in textbooks of evolution: the "living fossil" called the coelacanth.

At a meeting* last month, Yokoyama and his colleagues described how they pinpointed the changes in visual pigment genes that enabled the coelacanth to see in the dim light of the deep ocean, 200 meters below sea level. And in an upcoming report in *Genetics*, the group describes changes in similar genes from a wide range of other animals, which may have enabled them to adapt to their particular habitats. "There's just a few changes being driven by selection, and it's hard to ferret those out," says Charles Aquadro, an evolutionary geneticist at Cornell University in Ithaca, New York. "What Yokoyama has done is really clever."

The work may have applications beyond evolutionary biology, in the practical realm of biotechnology and protein engineering. "If you want to be able to engineer enzymes to carry out novel reactions, what better way [to design them] than by looking at how nature did it," explains Anthony Dean, a biochemist and evolutionary biologist at the University of Minnesota, St. Paul.







Custom eyes. Amino acid changes yielded two pigments (circles) that are better adapted than the ancestral opsin *(center)* for deep-sea vision in the coelacanth *(top)*.

CREDITS: (TOP) LAURENT POUYAUD; (BOTTOM THREE) ADAPTED FROM S. YOKOYAMA

Yokoyama decided to focus on how the light-sensing pigments had changed through evolutionary time nearly 15 years ago after the first genes for human eye pigment proteins, which are called opsins, were cloned, an achievement that prompted the cloning of these genes from many more species. He wanted to see not just which changes took place during the evolution of a particular species but how each one affected the protein's function and the organism's ability to see. "It was very important to me to be able to manipulate these molecules," he recalls.

Other researchers had already devised one opsin assay. It involves putting an opsin gene, with or without specific mutations, into monkey kidney cells growing in laboratory dishes, giving the cells time to produce the opsin, and then adding the second component of the visual pigment, the light-absorbing chromophore, to the cells. Then the complete pigment can be purified and its light-absorbing properties tested.

As Yokoyama described at the meeting, he decided to use this assay to look at opsins from the coelacanth as part of his study of the molecular evolution of vision. The coelacanth was one creature for which the opsin genes had not yet been identified, so Yokoyama's team used mammalian opsin sequences as probes to pull out similar genes from the coelacanth genome. This search picked up two genes belonging to the rhodopsin family, plus a third gene that appeared to be incapable of producing a complete protein.

Rhodopsins are generally most sensitive to green light of 500 nanometers—a longer wavelength than that of the light penetrating down to where coelacanths live. To identify which amino acid changes in the coelacanth

* The American Genetic Association met from 11 to 13 June in State College, Pennsylvania.