cated by some other nondestructive technique, then acoustic emission monitors can be located near the defect to listen as, or if, it grows. Only when the crack reaches a dangerous size, would the part be replaced or repaired. The problem, as always, is discriminating and quantitatively characterizing acoustic signals from growing cracks as compared with other sounds.

According to Jerry Posakony of Battelle, one experiment in progress involves a jet trainer in Australia. A plane with a known defect, which is being monitored by acoustic emission, is flown about with the object of learning what flight conditions put a load on the craft and make the crack grow.

One reason aircraft are not taken apart and inspected more often is the cost. Consider the case of fasteners. All planes are put together with hundreds of thousands of fasteners, such as rivets and bolts. The areas around certain fastener holes are highly stressed and therefore natural places to look for cracks caused by fatigue. The most reliable method of inspection is to remove the fastener and use a special eddy current technique. But in some planes, estimates Don Forney of the Air Force Materials Laboratory (AFML), the cost per hole inspected can amount to over $150, a prohibitive expense where there are thousands of critical fastener holes per plane and hundreds of planes. Moreover, fastener removal always incurs the risk of damaging the hole.

Researchers at Systems Research Laboratories in Dayton, Ohio, recently developed an ultrasonic technique that can detect cracks as small as 0.7 millimeter in the area under fastener heads, but only in the upper layer. The problem is that the area around fastener holes consists of two layers separated by a sealant, which strongly attenuates ultrasonic waves.

To penetrate beneath the sealant, AFML scientists are working on a new eddy current technique. They hope to be able to detect cracks as small as 2 millimeters long in the second layer, says Forney, by using a much lower than normal frequency, a specially designed coil, and a microprocessor to analyze the eddy current signal.

For more sensitive crack detection, ultrasonics must eventually be used. To overcome the problem with the sealant, AFML researchers are also studying a computerized signal-enhancement technique that operates in a manner similar to some advanced radars. The ultrasonic pulse sent out by the transducer is in the form of a code. On reflection, the transducer recognizes only signals containing that code, so that even the highly attenuated reflection of ultrasonic pulses passing beyond the sealant layer can be extracted from the background noise.

These and other new techniques on the way will without doubt considerably improve the sensitivity and reliability of nondestructive evaluation. Everyone agrees, however, that there are limits imposed in part by the requirements that humans must know where to look before any of the methods can be used. There is, therefore, always the possibility of a disaster because people will never be able to think of everything. Furthermore, knowledge about when a structural material will fail has an inherently statistical character, and the probability of failure can be made small but never zero.

—ARTHUR L. ROBINSON

Einstein Pictures the X-ray Sky

New satellite telescope has capabilities on par with those of the best optical telescopes

This is the second of two articles on the early results of the Einstein Observatory.

Launched only last November, the second High Energy Astronomy Observatory (HEAO-2, "Einstein") is revolutionizing x-ray astronomy just as its namesake revolutionized physics. Earlier x-ray observatories, including HEAO-1, were designed to scan the sky for x-ray emitters. With Einstein, the challenge has shifted from discovering x-ray sources to understanding the processes producing the x-rays. But having 500 times the sensitivity of previous detectors, Einstein makes more than its share of discoveries, too. For example, it sees distant quasars and clusters of galaxies that can barely be detected by the largest optical telescopes.

Einstein has opened the field of x-ray astronomy of ordinary stars. Previously only a handful of ordinary stars were observed to emit x-rays, and only one, the sun, could be studied in detail. Einstein reveals that stars of virtually all types and ages, from hot to cold and from birth to death, are x-ray sources. A big surprise is that many stars that are quite hot may have coronas, like the sun. If they do, this observation conflicts with astrophysical theory.

With only half of Einstein's intended 1-year mission completed (x-ray astronomers hope the satellite will operate longer) and only some of the data analyzed, many of the results are preliminary. Nonetheless, a variety of astrophysical insights are emerging already.

Is the universe closed, or will it continue to expand forever? This question has been boggling cosmologists for many years. According to generally accepted theory, the universe is expanding. It will reverse its expansion only if the gravitational attraction between the objects in the universe is strong enough to overcome their motion away from each other. Cosmologists would be convinced that the universe is closed if they determine that it contains at least ten times the amount of mass thought to be included in all galaxies.

To see whether there is a lot of extragalactic mass, Einstein has been taking a close look at the seemingly diffuse x-ray background radiation of the universe—radiation that comes from all directions. Evidence gathered by HEAO-1 within the last $1^1/_2$ years suggested that the background was produced by vast amounts of intergalactic gas at a temperature of 500 million degrees Kelvin. It was thought that this hot gas might be five times as massive as all the galaxies—nearly enough mass to ensure a closed universe. But Einstein has not found the gas.

Einstein looks at the background by peering at patches of sky where there are

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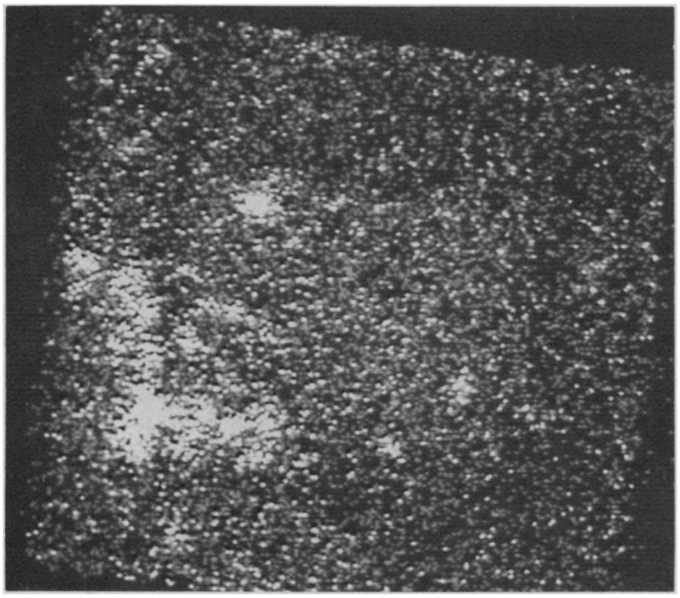
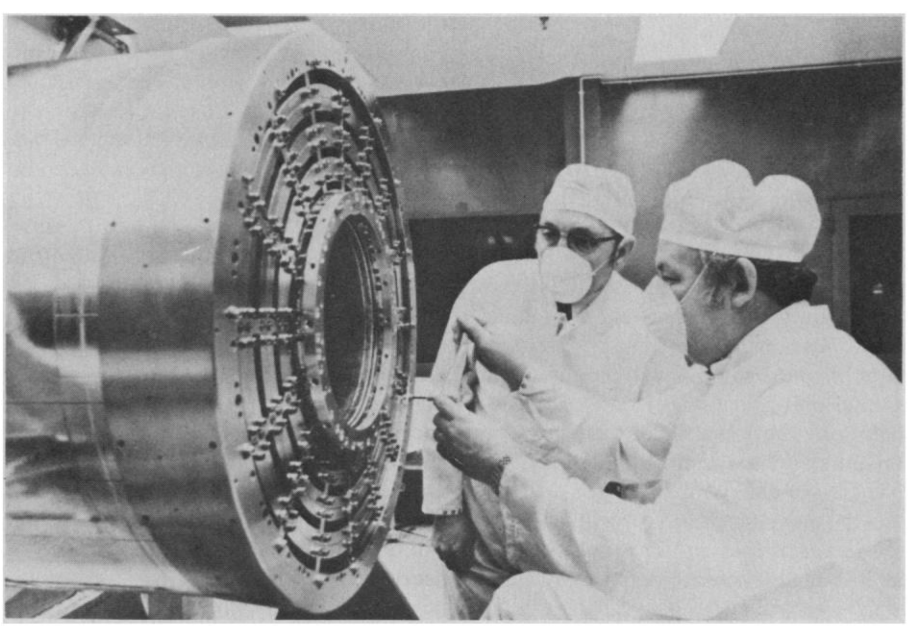


Einstein's picture of the Orion Nebula includes Trapezium, a very hot star, in the lower left, and at least a dozen other stars, mostly young stars in the process of formation [Source: Columbia University]

no known x-ray emitters, and it has found several faint but discrete sources. According to Riccardo Giacconi of the Harvard-Smithsonian Center for Astrophysics (CFA), these newly discovered sources include nearby stars in our own galaxy as well as extremely distant objects, such as quasars and some clusters of galaxies. The strength and number of discrete x-ray objects found in "blank" patches of sky convince Giacconi that it is these sources, not pervasive hot gas, that produce much of the x-ray background. Preliminary calculations extrapolated from the distribution and brightness of the newly discovered sources suggest that quasars alone could account for 10 to 100 percent of the background radiation, while nearby stars probably contribute 20 to 30 percent. Giacconi is skeptical that there is very much, if any, hot intergalactic gas to supply the mass needed to halt the expansion of the universe.

When Einstein locates a new x-ray emitter, the researchers turn to visible-light astronomy to find out what type of object it is. If the object is truly a new discovery, then astronomers at observatories with large optical telescopes, such as Mount Palomar, Kitt Peak, or the Anglo-Australian Observatory in Siding Spring, Australia, are asked to search for the visible-light counterpart of the x-ray emitter. Even though very little of the x-ray data has been analyzed, and very few of the visible-light identifications have been completed, several new quasars and an extremely distant cluster of galaxies—possibly the most distant one known—already have been confirmed.



The nesting mirrors for Einstein's telescope were designed by researchers at the Center for Astrophysics and American Science and Engineering, and built by the Perkin-Elmer Corporation. [Source: Harvard-Smithsonian Center for Astrophysics]

It is possible that many of the new x-ray sources located with Giacconi's surveys are quasars, but are all quasars x-ray sources? Before HEAO-2 was launched, only three quasars had been confirmed to emit x-rays. Already Einstein has detected x-rays from at least two dozen others. In fact, teams of astronomers at CFA and Columbia University have observed x-ray emissions from nearly every quasar Einstein's telescope was pointed at. The quasars were all strong sources. In soft (low energy) x-rays alone, these objects emit roughly 1 trillion times the total energy output of the sun.

According to Harvey Tananbaum, head of CFA's quasar team, the power source of one relatively weak quasar could be an extremely massive black hole. This quasar's x-ray output was observed to halve in less than 3 hours, indicating that the energy-generating volume must be smaller than 3 light hours across—less than half the diameter of the solar system. The largest black hole that can fit inside such a small volume is 200 million times as massive as the sun. A lower limit on the mass of the black hole is set by the energy output of the quasar, which requires a source at least 800,000 times the mass of the sun. Tananbaum's team plans to make similar calculations for other quasars as more observations on quasar variability are made and analyzed.

With strong x-ray emissions seeming to be a common property of quasars, the scientists suggest that x-ray surveys, such as those conducted by Giacconi, should be an efficient way to locate quasar candidates. According to Tananbaum, Einstein has sufficient sensitivity to detect quasars more distant than the farthest one known, if there are any, and thereby provide clues to the conditions in the early universe. If no quasars—thought to be among the first objects formed after the "big-bang" birth of the universe—were found beyond a certain distance, that would set the time at which quasars first formed.

Einstein's observations of distant clusters of galaxies are providing clues to the evolution of galaxies and clusters. According to Patrick Henry at CFA, the most distant clusters may be intrinsically fainter than nearer ones. Prior to HEAO-2, only clusters of galaxies nearer than about 2 billion light years had been seen in x-rays. Einstein already has observed clusters up to ten times farther away. From plots of the x-ray brightness of clusters as a function of the distance to them, Henry perceives that the distant clusters may be anomalously dim. If they are, they may be very young and in the process of formation.

In our own galaxy, one of Einstein's surprises is that an assortment of seemingly normal stars emit x-rays. X-ray emission had been observed previously from binary star systems in which one of the pair is a compact object, such as a neutron star or a black hole. Mass flowing from one of the stars emits x-rays as it is accreted onto the compact companion. However, the newly discovered x-ray stars do not appear to be such compact binaries, and their x-ray output is much smaller—one billionth to one ten-thousandth the output of a compact binary.

Giuseppe Vaiana, head of the stellar survey team at CFA, says that the stellar x-ray emissions appear to originate in some process that does not involve a very close companion star. In one mechanism, proposed previously, material in an extremely strong stellar wind, ejected continuously and rapidly from the star, emits x-rays when it encounters diffuse, stationary interstellar material. However, according to the CFA team, two other possibilities are more consistent with Einstein's data. One is that the x-rays are emitted when mass flows between two widely spaced stars in a so-called detached binary system. The other possibility, which conflicts with traditional theories of stellar physics, is that the x-rays are emitted from a corona—a gas with a temperature of several million degrees that comprises the upper atmosphere of some stars—just as x-rays are emitted by the sun.

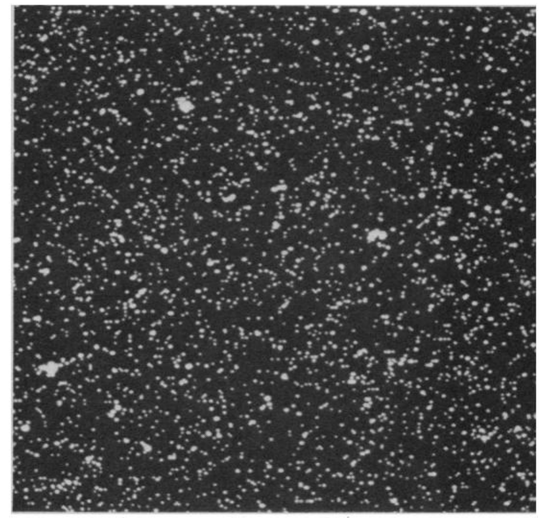
If the final suggestion is correct, then many more types of stars have coronas than was suspected previously. In that case astrophysicists would be forced to reexamine their theories of corona formation. According to the traditional view, coronas are associated with stars in which convection is an important mechanism for transporting heat from the interior of the star to the surface, where energy is radiated out to space. Convection, a vigorous mixing or overturning of the gas within the star, will be an important mechanism only when other means of heat transport are not effective. In extremely hot stars, the heat generated within the star is thought to be carried to the surface by radiation rather than convection. However, Einstein has shown that the hottest stars—those with surface temperatures near 35,000 degrees Kelvin—consistently emit x-rays. Other stars thought to be slightly too hot for convection to occur, emit x-rays as well. If the x-rays are emitted from coronas, then convection does not appear to be the sole factor influencing corona formation. Vaiana suggests that magnetic fields may be important as well.

Before Einstein, astrophysical theories of high energy processes that occur in stars could be checked only by observing the sun, the one star whose emissions in many spectral regions could be studied in detail. Judging from observations of the sun, x-rays are a sensitive monitor of a star's activity—fluctuations in its energy output. When the sun flares, its x-ray brightness increases by a factor of 1000, while its visible light intensity increases only a few thousandths of a percent.

With Einstein, many stars are accessible to detailed x-ray monitoring. David J. Helfand and co-workers at Columbia and CFA's stellar survey team are interested in classifying the stars according to their x-ray luminosity and spectrum, in a manner analogous to the classification based on their visible-light output. Data from a large sample of stars can thus help astronomers unravel the effects of magnetic fields, convection, and other processes on the structure and energy output of the stars.

Einstein's great achievements are possible because it is the first satellite to have capabilities in the x-ray region of the spectrum that rival the visible-light capabilities of the largest optical telescopes. The dramatic improvements in sensitivity and resolution result from focusing the x-rays onto a small detector. In this way the astronomical signal is enhanced, while the noise inherent to the detector—the stumbling block to increased sensitivity—is minimized. But focusing x-rays is tricky. Only when x-rays graze a mirror—strike it at an angle of less than 1 degree—do they reflect the way visible light does. Einstein's reflector is a sleevelike paraboloid-hyperboloid mirror. X-rays entering the sleeve, very near the mirror surface, are reflected from the paraboloid to the hyperboloid (which shortens the focal length so that the optical path fits inside the satellite) to a detector at the telescope's focus. To increase the light-gathering area of the telescope, four paraboloid-hyperboloid sleeves, sharing the same focus, are nested inside each other. The telescope efficiently collects x-rays with energies between 0.2 and 4.5 kiloelectron volts—soft x-rays. (HEAO-1 could collect much higher energy photons.)

Four different instruments can be placed in turn at the telescope's focus. A fifth instrument, sensitive to x-rays up to 20 kiloelectron volts, is external to the telescope but points in the same direction. This detector is similar to x-ray sensors carried on previous satellites.



A long exposure of a "blank" patch of sky in the constellation Eridanus reveals three weak x-ray sources, including two newly discovered quasars (top center and middle right) and one star similar to our sun (lower left). [Source: Harvard-Smithsonian Center for Astrophysics]

Two imaging detectors, which essentially take pictures of x-ray emitters, were developed at CFA. One has the finest spatial resolution (3 arc seconds) of any astronomical x-ray detector—nearly on par with the best optical telescopes. The other instrument, which is much more sensitive, can discriminate between x-rays of different energies—producing in effect a "color" x-ray image—but it has a spatial resolution of only 1 arc minute.

Einstein also carries two spectrometers. One, developed by researchers at Goddard Space Flight Center, is a solid state detector capable of observing the x-ray spectrum between 0.5 and 4.5 kiloelectron volts simultaneously and of resolving spectral lines due to ions of many elements. The other spectrometer, designed at the Massachusetts Institute of Technology, uses crystals to diffract the incoming x-rays. This detector can look at only one narrow spectral band at a time, but it has sufficient energy resolution (typically much better than 1 percent) to examine the fine structure of particular spectral features. However, the crystal spectrometer is not very sensitive; it requires an exposure of a day or more to collect several photons from a strong emission line of a bright source.

With the capability to image and do detailed x-ray spectroscopy, Einstein has set new standards for x-ray astronomy, so much so that the challenge in the field has switched from discovering sources to understanding the astrophysical phenomena.

—Beverly Karplus Hartline