X-ray Astronomy Coming of Age

The HEAO satellites are helping X-ray astronomy build up its catalogs and sharpen its astrophysics

BY DIETRICK E. THOMSEN

A glance at the sky on a dark, clear night quickly reveals the multiplicity of objects that astronomers have to consider. The business of classifying them according to their appearance, making astrophysical models based on the features of that appearance and checking the models against more and more examples of the class continues decade after decade with seemingly endless ramifications and elaborations. And there are always new objects to be looked at, new classifications to be made.

This overwhelming richness of opportunity that characterizes optical astronomy does not extend into stretches of the electromagnetic spectrum where detection is difficult. X-ray detectors do not have the sensitivity, the pointing accuracy or the field of view of optical equipment. X-ray detectors have to be lifted above most of the atmosphere, which means lifting them on rockets or satellites. For years X-ray astronomy has been painstakingly locating and cataloging sources. At the same time it has been trying to decide what their physics is, often on the basis of a very few examples.

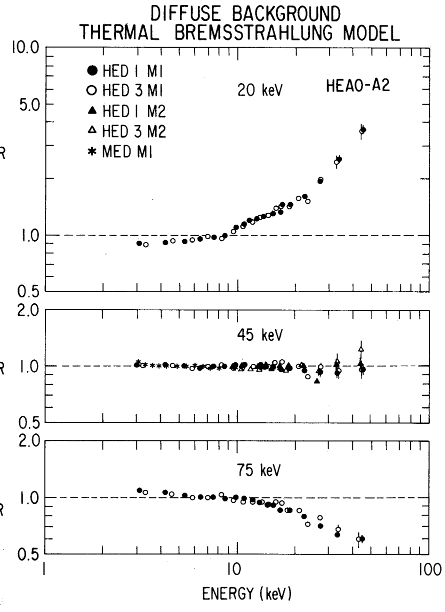
The High Energy Astronomy Observatories are a series of three satellites intended to make a systematic investigation of the sky in the high-energy range of the electromagnetic spectrum, an undertaking that means mostly X-ray and gamma-ray work. The first of them has just ended its active career; the second is in orbit; the third is awaited. As astronomers discussed the achievements of HEAO-1 at a session of a recent meeting of the American Physical Society, an observer got the feeling that X-ray astrophysics was really beginning to get down to it.

The physics of X-ray output mechanisms of galaxies, say, or quasars was being discussed with more detail and precision. The behavior of neutron stars was being discussed in the light of observation as well as theory. Theoretical models that had been based on one or two examples or simply derived from theoretical principles without any guarantee of existence in actuality now have catalog lists of sources to be compared with. There is even a catalog of suspected black holes. It has four members so far.

Over and above all these things, in fact literally enveloping them, is HEAO-1's most surprising discovery of all, a diffuse background glow that is the dominant feature of the sky in the X-ray range of the spectrum. This is something that our consciousness is simply not prepared for. It is as if the stars and galaxies did not stand out against almost total blackness but had to compete to be seen against a very light gray background. We are used to a diffuse background glow in the daytime but not at night.

In fact 150 years ago, Heinrich Olbers asked why the night sky did not have a background glow that washed out everything in bright whiteness. His reasoning was that if the universe was infinite in extent, it should possess an infinite number of stars (nobody had heard of galaxies in those days). This infinitude of stars would fill the sky and produce an undifferentiated whiteness.

Olbers's paradox, as it is usually called in the textbooks, is solved by pointing out that the universe is not in fact infinite. Nevertheless, Olbers's basic idea still works. A finite group of compact objects at great distance can still produce the effect of a diffuse background though it will not generally be as bright as Olbers had in mind. Richard Mushotzky of the Goddard Space Flight Center relates that before HEAO-1 went up he and his co-workers calculated the sort of diffuse background that might be produced by the sorts of distant X-ray sources they knew about: clusters of galaxies, Seyfert galaxies, BL Lacertae objects, quasars. When the actual X-ray background was discovered, it proved to have the wrong spectrum.



Mushotzky

Fitting the diffuse background spectrum to gases of various temperatures. 45 keV fits; 20 keV is too cool, 75 keV too hot.

The diffuse background glow can be attributed, rather, to a hot gas spread out across the universe. This gas can be distinguished from another kind of X-ray-emitting gas, the gas found in the space within clusters of galaxies, by composition (it has no iron) and by temperature (it is much hotter). The temperature of the universal X-ray gas is a whopping 500 million degrees K (the hottest stars are mostly under 100,000° K). By measuring the total X-ray flux and knowing the temperature and the emissivity of a hot gas, the astrophysicists can calculate how much material is there. "If the gas is isotropic, homogeneous and fills the universe," says Mushotzky, "there is more material in this hot gas than in the sum of every other type of object we know about."

A temperature of half a billion degrees cannot be attributed to ordinary processes of stellar physics, and so the production of this universal gas is assigned to a primeval epoch in the history of the universe. But not too primeval. Just because it is very hot, the gas could not come from the big bang at the beginning of the universe, from the earliest moments when matter was made. If so, it could not be so hot now. Adiabatic cooling with the expansion of the universe would have made it cooler. (The background *radio* flux, which is considered radiation made directly in the big bang, has cooled to 3° K.) The X-ray-emitting gas must have become hot about 10 billion years ago. That is the time usually assigned to the formation of the galaxies, and it suggests a possible relation between that process and the cosmic gas.

The other important X-ray-emitting gas, which must be kept separate from the cosmic background gas — at least in thought — is the gas found in the space within clusters of galaxies. To take one example, the Virgo cluster is pervaded by a mass of gas equal to that of 1,000 galaxies like our own, which is 10 to 50 times the mass in the galaxies visible in the cluster. Its temperature averages 70 million degrees.

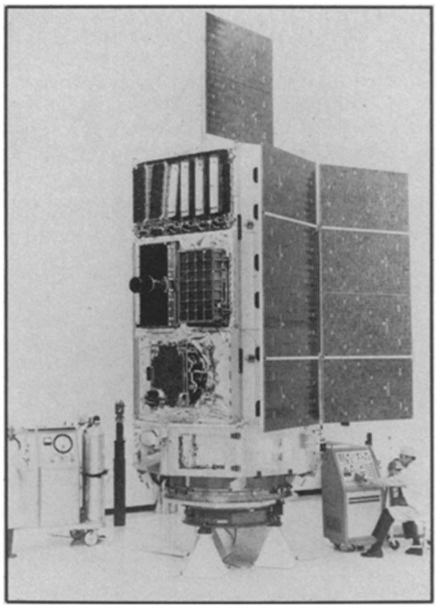
One of the significant spectroscopic factors is a line that testifies to the presence of iron in the gas. "Iron is not made in the gas according to current theory," Mushotzky says, "but the iron must come from somewhere." And so must sulfur, calcium and silicon found in similar gas in the Perseus cluster. These elements are characteristically made in stars and stellar explosions. The theory now is that early in the history of the galactic clusters there was a large population of stars that exploded and injected these elements into the gas of the cluster.

The gas also adds something to the so-called missing mass problem, but does not solve it. The galaxies in different clusters are seen to be moving as if they were bound together by a gravitational field, according to the virial theorem, as it is usually described. But the visible galaxies do not have the mass to generate a field strong enough to hold together galaxies with the velocities observed and force their motion into a "virial character."

The simplest suggestion is that there is unseen mass in the cluster, and many have supposed it to be gas or dust. In spite of its huge mass, this X-ray-emitting cluster gas does not go far enough to solve the problem of where the gravitational field comes from. Still, it seems to follow that field. The gas appears to be distributed in the way that would be expected from the virial theorem. That adds to the evidence for a real binding of galactic clusters and goes against those astronomers who have suggested that the association of galaxies in clusters may be a matter of chance rather than gravity.

Galactic clusters as collective X-ray sources are part of HEAO-1's locate-and-identify mission. A diffuse cosmic background glow can be listed as a single global entry, but it is compact objects, "point sources," that can be located and pinned on a map of the sky. The best X-ray source catalog to date, the fourth one prepared from observations by the Uhuru satellite, contains 339 entries. Analysis of the first 70 days of HEAO-1's mission indicates that it is finding many more sources at higher galactic latitudes — that is, at high angles to the plane of our galaxy — than Uhuru did, says Kent Wood of the Naval Research Laboratory. Many of these high-latitude objects are outside our galaxy. "It seems there will be a large number of [galactic] cluster identifications in the final catalog," Wood says. Within our galaxy there are so far 47 new sources. At least one new black hole candidate, GX 339-4, will be added to the standing three (Cygnus X-1, Circinus X-1 and V861 Scorpii).

Within our galaxy "a wide variety of situations can lead to X-ray production," says Frederick K. Lamb of the University of Illinois. Keeping to point sources, there are seven classes on Lamb's list. There are three situations in which matter falls or, as they say, accretes, onto a central body, accretion onto a neutron star, a black hole or a degenerate dwarf star. The others are flare emission from a magnetically active region on the surface of a star, hot stellar coronas, cooling of hot condensed stars and stellar winds from one star impinging on the surface of another as might happen in a binary system. HEAO-1's capacity to detect faint sources is credited with greatly increasing knowledge of the last four varieties.


NASA

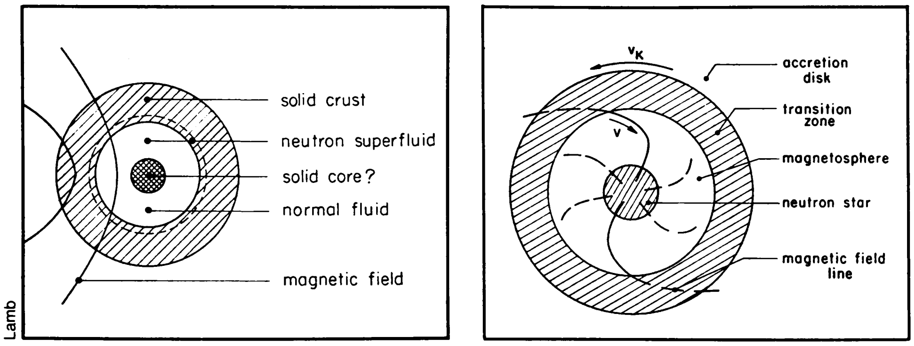
HEAO-1, which carries four experiments, has finished its assigned activities.

Lamb discussed three cases in which the HEAO-1 results give major new information: RS Canorum Venaticorum stars, accreting white dwarfs and accreting black holes. RS Can Ven stars are low mass stars very similar to our sun located in binary systems with stars of very similar character. They have a lot of star spots as the sun has sunspots. Magnetic fields connecting the spots confine a hot plasma that emits X-rays. Occasionally these plasma loops tear loose as they do on the sun. On the sun this results in a solar flare that is a strong X-ray emitter. One would expect to see a star flare and analogous X-ray production from the RS Can Ven star. "This has now been confirmed," says Lamb. Furthermore, the X-ray emission should show a phase drift as the star spot region drifts across the surface of the star, and the X-ray emission should come and go as the spot regions come and go.

In the accretion situations the observed X-rays are usually produced by the accreting matter, and it is the spectrum of the X-rays that is likely to give some detail about what is going on. In the case of accreting white dwarfs the question was whether the accreting matter is falling directly on the surface of the star or passing through an accretion disk that rotates around the star. Predictions for both cases have been drawn up, and in general the direct fall yields a spectrum dominated by hard (high-energy) X-rays; the accretion disk gives a soft X-ray spectrum. It is the hard spectrum that was found, and the details indicate that the matter is falling on "a tiny fraction of the surface."

Neutron stars are generally believed to have accretion disks. The question here is whether study of the disk can give information about the interior of the neutron star. Neutron stars are very interesting to physicists because they are the one known place where gravity binds neutrons and similar particles together more strongly than does the strong interaction that holds ordinary atomic nuclei together. A neutron star probably has a solid crust (a kind of nuclear crystal), a liquid mantle (often thought of as a neutron superfluid) and a core that could be another solid or a "hadron soup" — a region where neutrons and other particles lose their identity and are mashed together in a kind of elemental pea soup.

The theoretical models of a neutron star's interior differ greatly in detail. A way to find out what actually is there was proposed in 1974. It is by studying fluctuations in the rotation of the accretion disk that should come out in the characteristics of the X-ray emission, and is based on the proposition that fluctuations in the disk rotation are connected to fluctuations in the star's rotation. According to the model, the fluctuations should follow a statistical or "white noise" pattern. This has now been found in studies of Hercules X-1. It is, says Lamb, "a dramatic confirmation of the statistical model." The source of the fluctuations may be torques inside the star, vortices in the neutron superfluid or other things. More important, says Lamb, is that the spin fluctuations on the surface connect to the core, and the core acts back. "We can use it to explore the interior of the neutron star," he says. ☐



Lamb

The picture of a neutron star's interior is not yet very detailed. Neither is that of the same star set within its magnetosphere and its accretion disk.