X-ray Astronomy: Observations of New Phenomena

The discovery of pulsars by radio astronomers in 1968 was enthusiastically hailed as a chance to learn about the properties of a star near the end of its lifetime. Pulsars are now generally thought to be rotating neutron stars. Recently x-ray astronomers have found other new phenomena that are apparently different from pulsars but may also be associated with very old stars. Many interpretations of x-ray data suggest that a new class of objects, or possibly more than one class, has been found. Astronomers have speculated that the new objects may be peculiar white dwarfs or new variations of neutron stars. At least one object, some astronomers think, may be the most exotic of all possible ends of stellar evolution—a black hole.

The current flurry of activity in x-ray astronomy has been motivated by early data taken with the first Small Astronomy Satellite, launched off the coast of Kenya in December 1970 jointly by the space agencies of the United States and Italy. The operating satellite, which has been named UHURU (the Swahili word for "freedom"), has detected several new objects that produce complex bursts of x-ray pulses. The scientists who designed the x-ray experiment, Riccardo Giacconi and his associates at the American Science and Engineering Company (AS&E) in Cambridge, Massachusetts, have found x-ray patterns that have changing frequencies and drastically changing intensities. There is little doubt that the new objects are different from pulsars because no pulsed radio emissions are observed. At least one new source appears to have an intrinsic pulsation that may be as clocklike as a pulsar, however. It is likely that the new objects are very small and very dense, so that many astronomers are closely scrutinizing the possibility that they may be black holes.

In addition to finding unexpected phenomena, the UHURU experiments have been very successful in completing the basic goal for which the satellite was designed: to survey the sky for new x-ray sources. The AS&E scientists have identified 116 x-ray sources, almost three times the number known before. In the pattern of previously known x-ray objects, most of the sources are observed in directions within the galactic plane and are almost certainly part of the galaxy. Of the new sources, 30 do not appear to be part of the galaxy, nor do they appear to be associated with prominent extragalactic objects. The new sources are interesting to astronomers, among other reasons, because to be seen from extragalactic distances, they would have to radiate very large amounts of energy.

Many of the measurements of UHURU could have been made several years ago with experiments carried in rockets, the standard vehicles for transporting x-ray detectors above the earth's highly absorptive atmosphere. But rockets have an especially short observing time, only about 5 minutes, so that it is difficult to obtain enough data on one object to study rapid time variations.

X-ray Satellite

The satellite has the great advantage that its observations are continuous. On any given day the x-ray detectors on UHURU repeatedly scan a single circle through the sky, measuring any x-rays with energies in the range of 2 to 20 kev (½ to 5 Å). After a day the spinning satellite is magnetically torqued into a new orientation so that another great circle can be scanned. Sources varying in intensity from the brightest x-ray source in the sky (Scorpius X-1) to one ten-thousandth of that intensity can be detected. The only difficulty with the satellite, the failure of a tape recorder, has been circumvented by collecting data continuously from several tracking stations around the equator, rather than from a single station. The UHURU experiment has already exceeded the useful lifetime originally projected, and there is no reason, according to Henry Riblet of the Applied Physics Laboratory of Johns Hopkins University, that the spacecraft cannot take data indefinitely.

The scientists controlling UHURU completed the preliminary x-ray map of new sources from data taken only in the first 70 days; this data corresponded to approximately 50 percent coverage of the sky away from the galactic plane. Thus more sources can be expected. About half of the new sources show evidence of some variability but only a few have been examined in detail.

Collapsed stars can often be distinguished from normal-sized stars by their pulsations; a short pulse length indicates a small object. Several new x-ray sources appear to undergo large changes of intensity in times as short as 50 milliseconds. Normal stars, such as the sun, are so large that, if the entire star suddenly flared up and immediately died down, the pulse would appear to last at least 5 seconds—the time for light to travel across the sun. Fluctuations in a time interval as short as observed can only come from a region that is very small, such as a collapsed object.

Two new objects that emit sharp pulses characteristic of a very small star appear to be in binary systems. In many ways the two seem to be complementary. One of the new objects, Centaurus X-3, has a repeating x-ray emission pattern that can be easily explained by a binary system. The optical properties of Centaurus X-3 are not yet known. Another object, Cygnus X-1, appears from optical data to be part of a binary system; however the x-ray emissions of Cygnus X-1, which are extremely sporadic, are not well understood. It is likely, though not certain, that in each of these binary systems one member is a collapsed object significantly different from the only collapsed object previously known to produce x-rays, the pulsar in the Crab Nebula.

The x-ray intensity of Centaurus X-3 displays pulsations every 5 seconds and these are blacked out for a while every 2 days. In addition, small changes of frequency of the 5-second pulsations are observed. The blackouts of the 5-second pulsations suggest that some object is orbiting about a pulsating object, eclipsing it. The hypothesis that Centaurus X-3 is an eclipsing two-star system is further confirmed by the details of the fast pulsations. The small variations of the frequency of the 5-second pulsations are exactly those expected from Doppler shifts—the apparent increases and decreases of frequency from a moving source as it approaches and recedes from the observer.

Because the mass of the eclipsing object is not known, the mass of the pulsating object cannot be calculated separately. However, the combined mass of both objects calculated from the 2-day period is large, 12 to 15 solar masses. The radius of the eclipsing object, estimated from the duration of the low intensity (½ day) compared to the duration of high intensity, appears to be typical of a giant star. Indeed, astronomers expect that the eclipsing object may be a giant star and have proposed that the pulsating object may be a new type of neutron star or white dwarf.

Complex Variations

The x-ray variations of Cygnus X-1 are complex and confusing by comparison with the predictability of even subtle variations of Centaurus X-3. The intensity of Cygnus X-1 often doubles in as short a time as 50 msec, but with apparently no predictability from one minute to the next. Early evidence from UHURU for regular pulsations—several tenths of a second and several seconds were suggested—was based on short intervals of data from UHURU. Now that more data are available, it appears that although Cygnus X-1 radiates regular pulse trains lasting as long as 20 or 30 seconds, it has no true period. The only similar x-ray phenomenon, according to Herbert Friedman of the Naval Research Laboratory, is the x-ray pattern observed in auroral displays, produced by particles accelerated in the earth's magnetosphere. However, the analogy is far from exact, Friedman points out. The emissions could possibly be varying in predictable patterns that do not repeat very often, but Norman Terrell, of Los Alamos Scientific Laboratory, has shown that many significant characteristics of several short sequences of UHURU data for Cygnus X-1 can be explained by random pulses.

Optical observations indicate that Cygnus X-1 is probably part of a binary system, the details of which correspond surprisingly well with the predicted characteristics of a black hole orbiting a normal star. To make a good correlation between some star and a typical x-ray source seen by UHURU is difficult because the typical error in the position of sources (about 0.1 degree) is large enough to encompass many stars seen in the same plane.

Radio observations by Robert Hjellming of the National Radio Astronomy Observatory at Charlottesville, Virginia, assisted optical astronomers to locate near the x-ray source a star that was previously thought to be a perfectly normal, class B supergiant. The certainty that this star coincided with Cygnus X-1 was significantly increased as a result of a rocket-borne experiment with very high resolution by Saul Rappaport of the Massachusetts Institute of Technology. (The chance of finding any star as bright as the supergiant or brighter within the improved x-ray error is 1 in 10^5.) Measurements of the spectroscopic properties of the supergiant by optical astronomers C. T. Bolton, of the David Dunlap Observatory of the University of Toronto, and Paul Murdin and Louise Webster, of the Royal Greenwich Observatory in Sussex, England, show radial velocity variations that are the signature of a binary system. Every 5.6 days the star orbits an unseen companion, presumed to be associated with the unusual x-ray emissions. There is fragmentary evidence observed from balloons for an eclipse of the "hard" x-rays (those emissions with energies greater than 20 kev) which appears to be consistent with a 5.6-day period.

According to Joseph Dolan of the Warner and Swasey Observatory of Case Western Reserve University the "hard" x-ray phenomena may possibly be associated with a very hot (10^8 degrees K) collapsed object, and the lower energy UHURU x-ray phenomena associated with gas streaming from the supergiant to the collapsed object. Although Dolan's suggestion is speculative, there is good evidence from the spectroscopic measurements of Bolton and his colleagues that gas streaming from the B star to its companion is occurring. Such flow from one star to another is common for close binary systems, but no x-radiation usually emerges.

If black holes exist, then Cygnus X-1 appears to be one of the most likely candidates. A black hole in orbit about the supergiant could possibly explain the x-ray emissions and the period of the orbit, if the x-ray astronomers and optical astronomers are really observing the same system. Based on the observed period of the supergiant and a reasonable estimate of its mass, calculations made by Jeremiah Ostriker, of Princeton University, give a result greater than 5 solar masses for the unseen object. Present theories of collapsed objects predict that any star collapsed to the apparent size of Cygnus X-1 with mass five times the sun or greater will be a black hole. White dwarfs and neutron stars are not expected to be so massive. Few scientists agree about the properties of an isolated black hole that might be directly observable, if any; but black holes in binary systems could possibly produce x-rays as a result of gas streaming.

The data from UHURU give indications that neither of these two stars is unique. Preliminary analyses of data show that an object in the constellation Hercules has similar fluctuations to Centaurus X-3, but with a significantly shorter period (1.2 seconds). Another x-ray object exhibits similar variations to those of Cygnus X-1.

Another phenomenon observed at x-ray wavelengths is flaring. Scorpius X-1 brightens steadily to a peak intensity, then dies back in the course of 2 or 3 days. These flares have been observed in both x-ray measurements and radio measurements. They seem to come at unexpected times, and there appear to be no pulsations of a shorter period.

Phenomena similar to flaring but more spectacular have also been observed, although extremely infrequently. Twice in the last decade rocket experiments have suddenly detected a source as bright as Scorpius X-1 that died down in a few weeks or months until it completely disappeared. Another such source has recently been found by UHURU. Very similar behavior is observed for a well-known class of optical stars called novae; there is no evidence, however, that stars from this class are producing the x-ray phenomena.

Proposed Models

Many models have been proposed to explain the x-ray sources. A gaseous stream falling onto any collapsed object might explain the Cygnus X-1 observations. A particular neutron star model may best explain Centaurus X-3, the object that seems to have the most potential for discrimination between models. Some astronomers think that white dwarf models may be less likely for Centaurus X-3, but that they cannot be ruled out by the data now available.

A stream of matter falling toward a collapsed object could be a source of x-ray emissions because the gravitational field of a massive object would accelerate the stream to very high velocity. Falling particles might produce hot spots on the surfaces of white dwarfs or neutron stars. The hot spots, if at a temperature greater than 10^6 degrees could radiate x-rays. Y. Zel'dovich and associates at the Lebedev Institute in Moscow predicted in 1964 that even a black hole—which has no surface in the classical sense—could produce x-rays through a sort of funneling effect. The gravitational field of a black hole, Zel'dovich calculated, would compress a stream of falling particles until it reached an extremely high temperature (10^{11} or 10^{12} degrees); radiation would be emitted mainly in the visible or x-ray region, depending on the mass of the black hole. In a binary system, a black hole very near to a normal star could draw in matter from its companion to produce a stream. Astronomers are not sure whether radiation produced by falling matter could be unsteady, possibly periodic, but Thomas Gold, of Cornell University, has suggested that nearly periodic pulses might be produced if radiation pressure outward from the hot region temporarily slowed the falling stream of particles, later to speed up again. Although the properties of Cygnus X-1 appear to be similar to those Zel'dovich predicted for a black hole, Edwin Salpeter, of Cornell, has warned that if matter streaming toward a collapsed object is producing x-rays the nature of the object—whether it be a white dwarf star, neutron star, or black hole—probably won't make much difference in the type of emissions observed.

A model with pulsations produced by a rotating object is appealing for Centaurus X-3 because of the regularity of the underlying period. Kris Davidson, Franco Pacini, and Edwin Salpeter of Cornell have proposed that a rapidly rotating neutron star could produce x-ray pulses by transferring energy to a more slowly rotating gas cloud surrounding it. Although the model was constructed to explain the flaring behavior of Scorpius X-1, it predicts pulsations with approximately the observed period of Centaurus X-3. A rapidly rotating white dwarf of the sort proposed by Ostriker during early investigations of pulsars could also produce pulsations with the 5-second period of Centaurus X-3.

Another white dwarf model that may explain Centaurus X-3 has been proposed by Wallace Tucker, of AS&E, and others. Rather than rotating, a white dwarf could produce x-ray pulses by surface oscillations driven by hydrogen burning in the outer shell of the white dwarf. Variations in the parameters of this model could explain the phenomena in Cygnus X-1 and the nova-like sources. Criticizing white dwarf models in general, Ostriker has pointed out that it is difficult by these mechanisms to produce periods as short as 1.2 seconds (the period of the object seen in Hercules).

Whether a neutron star could exist in a binary system has been questioned by Herbert Gursky, of AS&E, among others, because a violent supernova by which neutron stars are thought to be formed may be likely to blow away the companion star. Although nearly half of the stars of all types exist in binary systems, none of the nearly 40 known pulsars do. Other scientists think that the supernova process is not well enough understood to rule out the preservation of a binary system through the supernova.

Astronomers are extremely eager to locate optically the star that they think is eclipsing the pulsed x-ray source in Centaurus X-3. It should have the specific properties of a single line spectroscopic binary with exactly the same period observed for the x-ray eclipses. From the combined optical and x-ray data, the mases of both objects could be determined exactly without estimates of the sort necessary for calculating the mass of the unseen object in Cygnus X-1. In addition the distances, luminosities, and possibly even radii of the objects could be determined. Astronomers are particularly intrigued because no one yet knows the mass of a neutron star. More detailed optical data on Centaurus X-3 may provide rather stringent constraints on the types of models that apply to this object.

Extragalactic Objects

Most x-ray sources seem to be objects within our galaxy. Of the 116 sources known, about 75 either are seen in the same direction as the Milky Way or are otherwise known to be part of our galaxy, including all the well-known variable sources. But about 40 of the new sources in the UHURU catalog are seen in directions that might indicate that they were extragalactic. Some of these have been correlated with known extragalactic objects, such as the quasar 3C273, the peculiar Seyfert galaxies (sometimes considered to be small-scale quasars), and the most densely populated clusters of galaxies. The rest have not been identified with any visible objects, but appear to be uniformly distributed in space. Giacconi has pointed out that if the unidentified sources are part of our galaxy, they must have much smaller luminosities than Scorpius X-1, Cygnus X-1, or any other galactic x-ray sources known. The population would have an extremely concentrated distribution, and white dwarfs might fit the characteristics. If the unidentified objects are extragalactic, the x-ray emissions from these sources must be comparable to or greater than their optical emissions, in contrast to the output of most common galaxies, including our own. The objects, if extragalactic as some astronomers think, may be a new class of sources of greatly increased luminosity. The x-ray data may lead to a different map of the distribution of matter in the universe than determined by previous galaxy and cluster surveys with optical telescopes.

The Coma cluster is an example of an extragalactic object that appears to be a new phenomenon. Herbert Friedman and others at the Naval Research Laboratory have determined that a source of x-rays which appears to be associated with the Coma cluster (a group of several thousand galaxies) is unusually intense. Summing the amounts of x-radiation expected from all the galaxies of the cluster, assuming those galaxies produce approximately the same amount of energy as our own, gives a number that is only one-twentieth the power observed. One possible explanation for the apparent excess is the possibility that a hot gas is distributed through the cluster. The size of the x-ray source, as measured with UHURU, is larger than the size of a source from a single galaxy and is comparable to the cluster size. If the radiation is coming from a hot gas, a temperature of 10^7 degrees is consistent with the distribution of x-ray energies observed with UHURU. The gas could also constitute part of the unobserved mass that many astronomers have reason to believe may be there.

Many properties of the new x-ray sources are already known, and new data is being rapidly accumulated. Because some, if not all, of the new objects are observed in binary systems, their properties are likely to be much more rapidly determined than those of pulsars.—William D. Metz