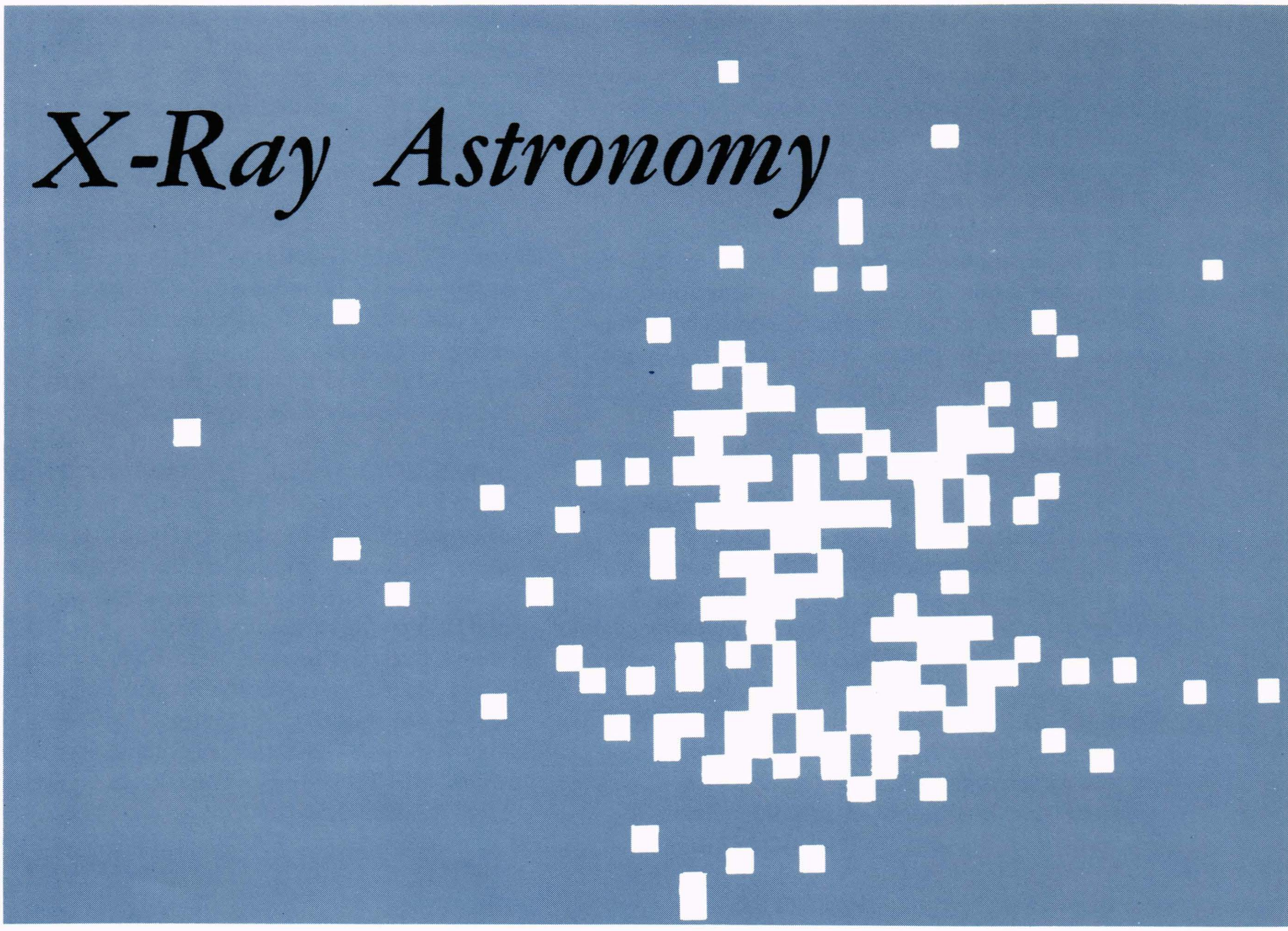
X-Ray Astronomy



Introduction

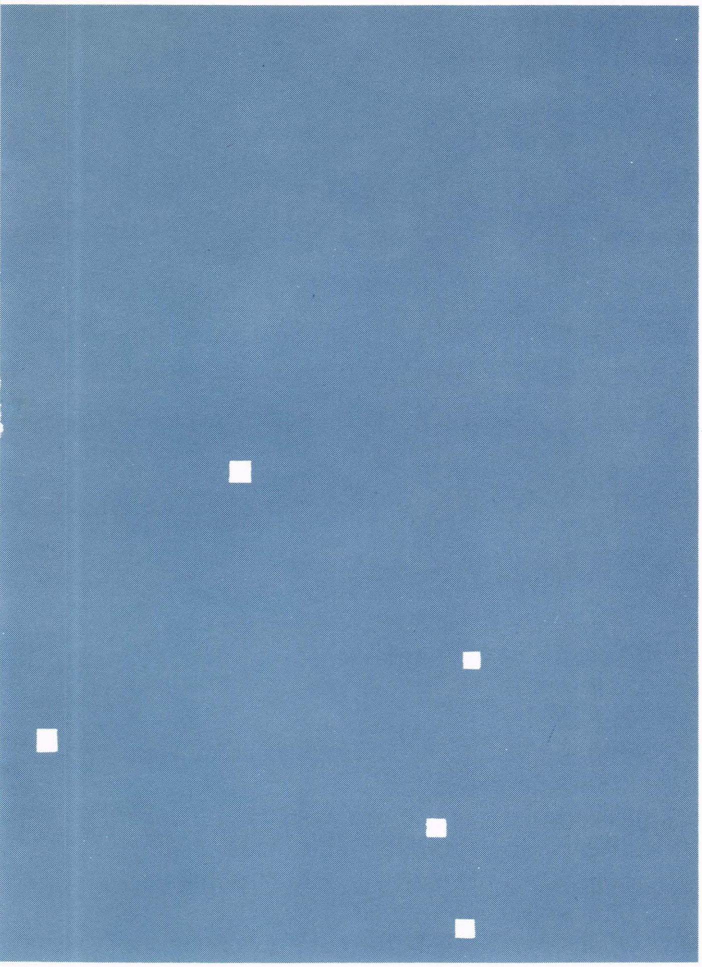
The discovery in the last two decades of the large amounts of energy released in supernovae, of radio galaxies and quasars, of the microwave background radiation and more recently of X-ray sources and pulsars, has demonstrated that high energy processes play a major, possibly decisive, role in our universe.

In these processes, the energy released per gram is much greater than for normal stellar matter. For instance, gravitational forces, weak in our normal experience, become all-important in the late phases of stellar evolution. Matter is crushed to inconceivably high densities and the stars can release enormous amounts of energy, of the order of 10 to 40% of their total mass energy as compared to less than 1% liberated by nuclear burning during their entire previous lives.

The study of these high energy processes defines a new field, high energy astrophysics, the central problem of which is to understand the source of the energy released in X-ray sources, supernovae, radio galaxies, quasars, etc., and the processes by which the high energy particles, responsible for the radiation from these objects, are produced. The resolution of these problems constitutes one of the most important and fascinating tasks in all of physics.

Since production of high energy photons is expected wherever high energy particles exist, it was anticipated that observations in the X-ray and gamma-ray range of the electromagnetic spectrum would become important as soon as the means to carry them out became available.

During the last two decades, space observatories have allowed us for the first time in man's history to observe the sky unimpeded by the atmospheric blanket that surrounds the earth. High energy photons, from a few hundred electron volts to several million electron volts, that do not penetrate the



atmosphere could now be observed. The promise of unsuspected discoveries, intrinsic in this statement, has been realized by X-ray astronomy.

Early History

The detection and study of cosmic sources of X-ray radiation has progressed very rapidly since the discovery in 1962 of the X-ray star, Sco X-1. However, while considerable progress was made in the 60's by using short duration rocket flights, several important questions remained unanswered. For instance, while it was understood that in Sco X-1 the X-ray emission corresponded to 10^3 times the luminosity of the sun at all wavelengths and exceeded the visible light emission from the system by a factor of 10^3, the basic source of this very large energy loss could not be determined. More significantly, due to the lack of positional accuracy and consequent inability to identify optical or radio counterparts of a sufficiently large sample of the X-ray sources, the connection between X-ray observations and the main body of astrophysical knowledge relating to stellar and galactic evolution could not be established.

This situation was considerably changed with the advent of UHURU (SAS-1), the first orbiting X-ray observatory, launched on December 12, 1970 from the San Marco platform in Kenya and operated continuously for four years (Fig. 1). The long time available for observations (years, instead of the few minutes available in rocket flights) and the much finer temporal and spatial resolution have resulted in a qualitative change in our understanding of the X-ray sky. The increased positional accuracy ($\sim$ 1 arc minute) was particularly important because it made possible the identification and study of the optical and radio counterparts of X-ray sources. Several later satellite missions, such as OAO, OSO-7, ANS, and UK 5, have confirmed and refined the UHURU results. With these missions, we have reached a new level in understanding X-ray emission mechanisms and the connection between X-ray sources and many of the astrophysical objects of greatest present interest such as collapsed objects (neutron stars and black holes), quasars and Seyfert galaxies, and clusters of galaxies. I will attempt to give a glimpse of the rich phenomenology that is being uncovered and some indication of the directions of the interpretative efforts.

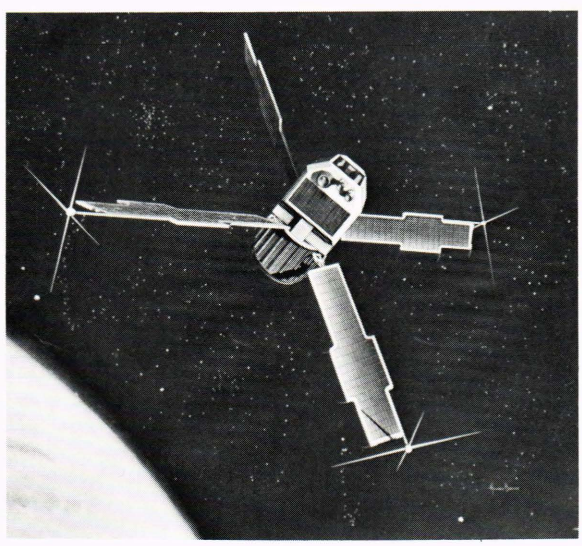


Fig. 1—UHURU Satellite (SAS-1).

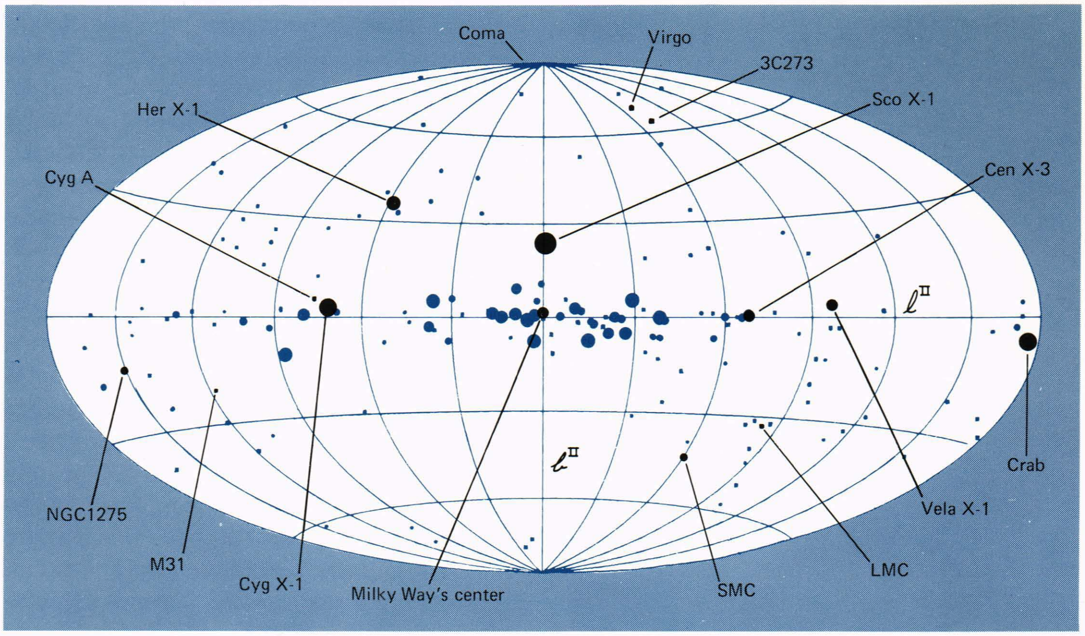


Fig. 2—Sky map showing X-ray sources detected by the UHURU satellite.

The X-Ray Sky

The UHURU Catalog of X-ray Sources contains 161 sources that have been detected in the 2 to 6 keV energy range. The weakest source in the survey corresponds to a flux of about 3×10^{-11} erg cm^{-2} s^{-1} at earth and the strongest to about 3×10^{-7} erg cm^{-2} s^{-1}. A map of the sky is shown in Fig. 2 superimposed on a representation of our galaxy. The sources divide naturally into two groups: those that are clustered at low latitude along the galactic plane (the Milky Way) and those that spread more uniformly about the sky. We believe that most of the sources we observe along the Milky Way are stellar systems in our own galaxy. Most of those we observe at high galactic latitude (toward the galactic pole) are connected with extragalactic objects.

Studying in detail the distribution of sources in the sky, the relationship between the number of sources and apparent luminosity, and the rough spectral information available, and making use of identifications with visible light objects, we reach the following general conclusions:

1. The luminosity of galactic X-ray sources in the 2 to 10 keV range is in the range of 10^{35} to 10^{38} erg/s. X-ray sources are among the most luminous objects in our galaxy; the mechanism for production of X rays by these objects must therefore be connected with their basic energetics.
2. There are about 100 sources in our galaxy in this range of luminosity. Thus, highly luminous X-ray stars are only 10^{-9} times as abundant as normal stars.
3. Of the identified galactic sources, 7 are supernova remnants, 9 are definitely associated with binary stars, and 5 with globular clusters.
4. All galactic sources except for supernova remnants show an extraordinary degree of variability. Some show pulsations as short as milliseconds (Cyg X-1); others wax and wane in intensity by factors of as much as 10^3 over time spans of days, months, and years.
5. All galaxies are X-ray emitters at some level. Normal galaxies such as M 31 and the Large and Small Magellanic Clouds (LMC and SMC) emit about 10^{39} erg/s due to the integrated emission from X-ray stars. In these galaxies $L_x/L_{rad} = 10^{-5}$, where L_x is the X-ray luminosity and L_{rad} the visible light luminosity.
6. In active galaxies, such as Seyferts (NGC 4151), radio galaxies (NGC 5128), or quasars (3C273), the X-ray luminosity (10^{42} to 10^{46} erg/s) and L_x/L_{rad} are much greater.

It is likely that the X rays we observe originate in small regions near the nucleus of the galaxies, regions where the occurrence of explosive events has been inferred from optical and radio studies.

7. In clusters of galaxies, X-ray emission appears to originate from extended low density regions between galaxies, as well as from individual galaxies. At present, we attribute the extended X-ray emission to the existence of a hot intergalactic gas, unobservable at other frequencies, and containing approximately the same mass as is present in the condensed galaxies of the cluster.
8. A diffused X-ray background in the 2 to 6 keV range is also observed that is isotropic to within small observational limits ($< 5\%$). This implies an extragalactic origin at great distances. Its study might then have a bearing on a number of outstanding astronomical problems, such as the mass density of the universe, early galaxy formation, and galactic activity.

If one adds to the previous brief summary the fact that the coronae of normal stars, such as the sun and the recently discovered Algol and Capella, are also the source of abundant X-ray emission, we find that X-ray astronomy encompasses virtually the entire span of stellar and galactic objects. Since it is impossible in a short review to cover adequately all facets of X-ray astronomy, I will limit myself to discussing binary X-ray sources and X-ray sources in galactic clusters, which are representative topics. I will conclude with a brief description of X-ray observations of extragalactic X-ray sources and directions of future research.

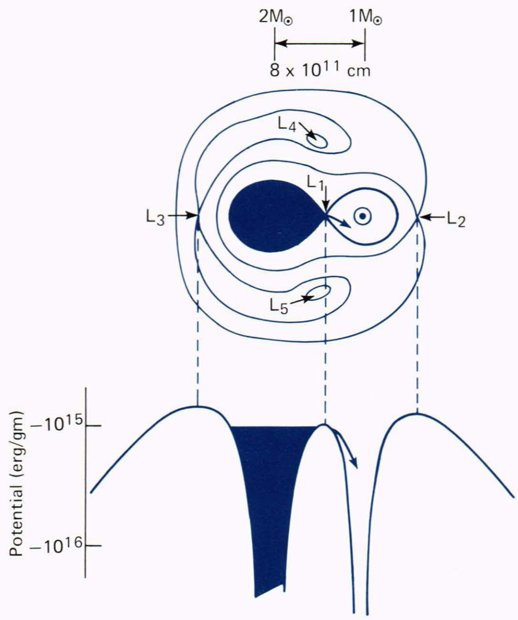
Binary Sources

The discovery of the association of X-ray sources with short-period binary systems in which mass transfer is occurring from a normal star to a condensed companion has been one of the most exciting and fruitful contributions of the UHURU mission and of the cooperative efforts of optical, radio, and X-ray astronomers.

As early as 1964, Zel'dovich and Guseynow, and Hayakawa and Matsuoko had suggested that the infall of gas onto compact stars could give rise to very large releases of energy. The kinetic energy acquired by a particle during the fall is proportional to the mass of the compact star and inversely proportional to its radius. For stars of sufficiently small radii, the energy acquired and subsequently released per particle becomes quite large. In white dwarfs of 1 $M_\odot$ (solar mass) with a radius of 10^9 cm, each nucleon falling on the star can provide $\sim$ 0.1 MeV of energy. Nuclear burning of hydrogen provides about 7 MeV per nucleon. In a neutron star of 1 $M_\odot$ with a radius of 10^6 cm, each nucleon can provide 100 MeV. Similarly, for a 1-$M_\odot$ black hole, each nucleon can provide between 60 to 400 MeV depending on the nature of the black hole. It is clear, therefore, that if sufficient matter is allowed to accrete onto a compact star, a large amount of energy can be released in the form of radiation.

It was shown that the infalling material would achieve temperatures of about 10^8 °K and, therefore, would radiate in the X-ray region of the spectrum. Since the energy acquired by each particle increases with decreasing radius of the accreting object, the more compact the star, the less matter is required to achieve a given luminosity L_x. The accretion rate necessary to yield luminosities of 10^{37} erg/s for white dwarfs is about 10^{-6} $M_\odot$/year, while for neutron stars and black holes only 10^{-9} $M_\odot$/year are required. These values of mass accretion are much greater than can be achieved by isolated stars gathering matter from the very tenuous interstellar gas (density of about 1 particle/cm^3). However, compact stars in close binary systems can gather material blown off their companion. Since the rate of matter loss during particular stages of stellar evolution can be as large as 10^{-3} $M_\odot$/year, conditions exist for X-ray emission.

Although this argument appears clear now, with the advantage of hindsight, it did not receive general acceptance when it was first proposed. This was largely due to the fact that no compelling evidence had been found for the existence of neutron stars or black holes, or for the binary nature of either of the best known sources, Sco X-1 and Cyg X-2. On the other hand, when the pulsar in the Crab Nebula was discovered, it became clear that the X-ray emission was associated with the pulsar emission mechanism. In that case, the energy released in radiation comes from the slowing down of the rotation period of the magnetized neutron star and does not involve accretion. Thus, models invoking pulsar mechanisms for all X-ray sources became widely accepted. It was not until clear evidence was found from UHURU X-ray



(Accretion rate for yielding luminosity of 10^{36} erg/s for a neutron star is $10^{-12} M_{\odot}$ /yr).

Fig. 3—Energetics of a binary system consisting of a normal size star and a neutron star of one solar mass.

observations that two pulsating X-ray sources, Cen X-3 and Her X-1, were in fact members of short-period (2.0 and 1.7 days) and, therefore, close binary systems that serious consideration was given to models based on accretion onto compact objects in mass-transfer binaries.

Since then a large body of evidence has been obtained from X-ray, visible, and radio observations to support this picture. Before proceeding with the description of some of the evidence, it will be useful to describe more fully how the accretion process would actually take place. Let us consider two stars in a binary system: one of normal size (such as the sun, with a radius of about 10^{11} cm), and one condensed. For a neutron star of 1 $M_{\odot}$ the accepted radius is about 10 km (10^{6} cm). If we draw the equipotentials about each star, as in Fig. 3, we find that if the stars move in circular orbits and corotate with the system, the equipotentials are approximately circles of increasing radius about each star. We can continue drawing equipotentials, which will be deformed with increasing distance from the stars, until the two sets meet. At that point, we have reached a well-known figure-8 configuration that is often referred to as the Roche lobes, after the French astronomer who first realized their significance. If matter is released at rest inside one lobe, it will fall on the star within it. Let us suppose that the atmosphere of one star expands until it overflows its lobe. This matter can then fall onto the other star and, in the case of a compact companion, acquire large amounts of kinetic energy while falling into its deep gravitational well. In the case of at least one system (Her X-1), the overflow of the Roche lobe actually appears to be taking place; in other X-ray binaries we believe that the material is blown off one of the stars by means of a stellar wind driven by radiation pressure. This distinction is important in terms of what is actually observed in X-ray sources and in terms of the evolution of the binary systems associated with them; however, the specific origin of the gas flow has little effect on its behavior in the neighborhood of the accreting object.

If we consider this behavior in more detail, we find (as was pointed out by Prendergast) that because of the angular momentum possessed by the material, it cannot simply infall radially. It must therefore spiral about the compact star, losing angular momentum by viscous interactions with the surrounding gas. It can be shown that the matter will dispose itself in a differentially rotating thin disk in which a particle spirals slowly toward the inner edge, losing angular momentum, until it finally falls onto the compact star. If the compact star is a magnetized neutron star, there will be a radius at which the magnetic energy density will

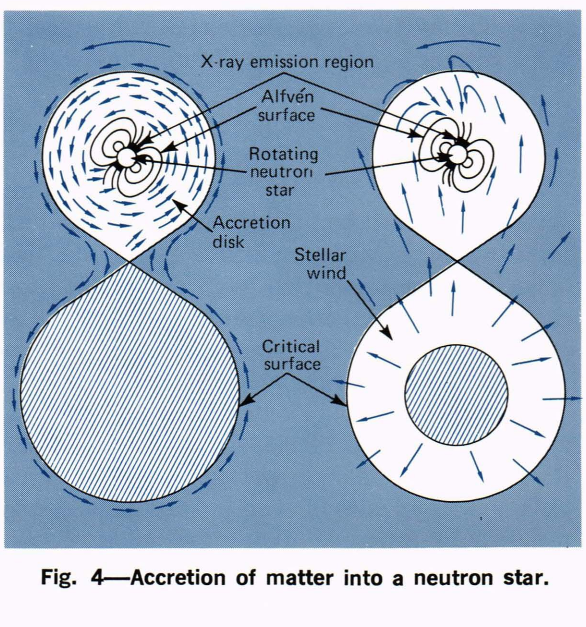


Fig. 4—Accretion of matter into a neutron star.

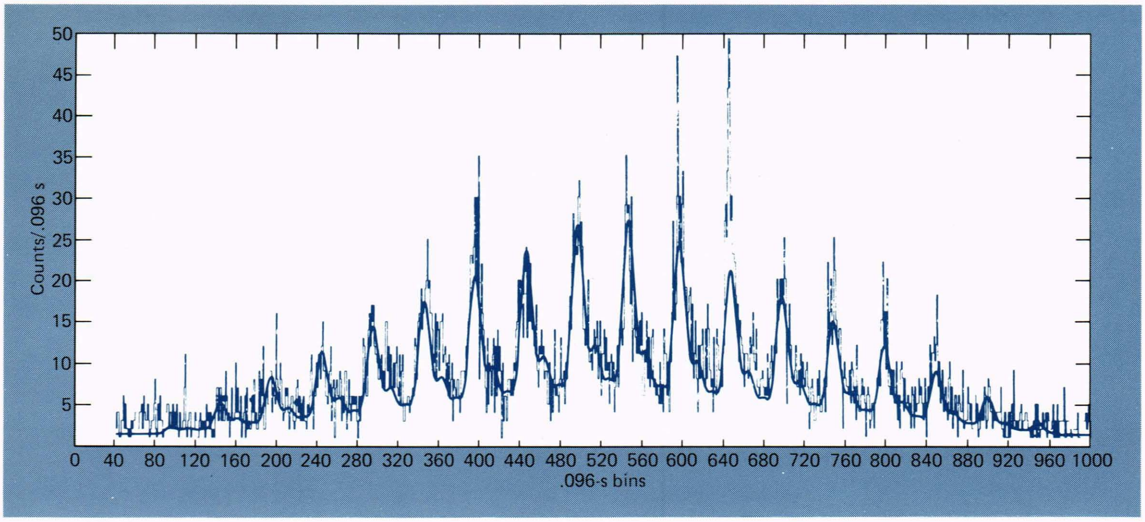


Fig. 5—Regular short-period pulsations of an X-ray source.

equal the kinetic energy density of the accreting gas. Since the gas is exposed to high energy radiation, it will be ionized and highly conductive. It will therefore be constrained to follow magnetic field lines and will be guided to the poles of the neutron star (Fig. 4).

If the star is rotating about an axis different from the magnetic axis, the emitted radiation will appear to us to be pulsed with a period equal to the star's period of rotation. If, on the other hand, the compact star is a black hole, the gas will disappear from sight as it crosses the Schwarzschild radius of the object (the radius beyond which no radiation can reach us because it will be captured by the star's gravitational field). Thus, the only radiation we will be able to observe would come from the heated gas at the inner edges of the accretion disk. No periodic pulsations will be observed, although flickering of very high frequency could occur if instabilities develop in the disk.

Observations

The observational evidence that forms the basis for our present understanding of binary X-ray sources has been obtained in the X-ray, visible light, and radio regions of the spectrum. In most cases, the optical observations are essential to measure some of the important parameters of the system, such as distance and mass. I would like to review briefly some of the key observations that have formed the basis of our present belief that X-ray sources are associated with binary systems in which material that is transferred either by Roche lobe overflow or by stellar wind accretes onto a neutron star or black hole.

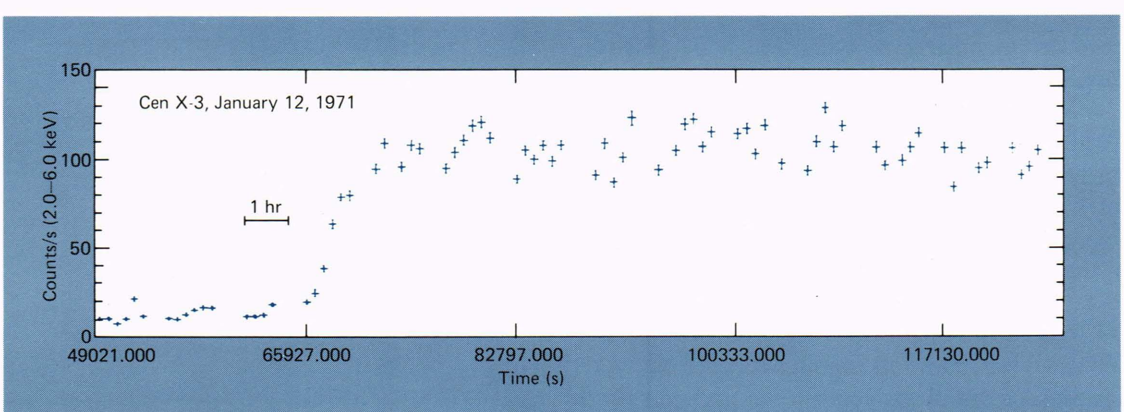


Fig. 6—Abrupt changes in X-ray intensity observed for source Cen X-3.

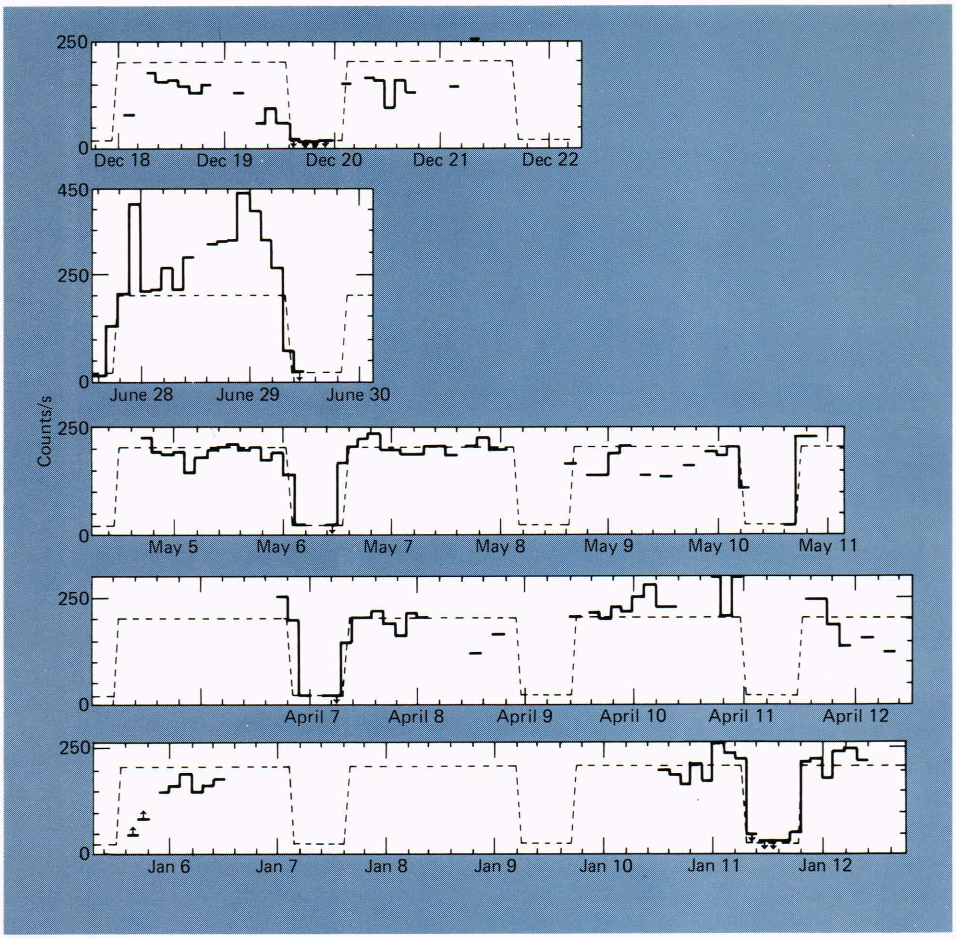


Fig. 7—Intensity variation of X rays from source Cen X-3 showing a 2-day periodicity.

The behavior of the X-ray sources Her X-1 and Cen X-3 that first caught our attention was the regular nature of the 1.24- and 4.8-s pulsations in the 2 to 6 keV region of the spectrum (Fig. 5). Soon after, we noticed that the average intensity seemed to undergo abrupt changes of as much as one order of magnitude within an hour (Fig. 6). Observing several such transitions, we were struck by their apparent regularity (Fig. 7); we interpreted them as being due to the periodic orbital motions of the X-ray source about a companion star. The intensity variation would then result from eclipse of the X-ray source once every orbit by the companion (Fig. 8). The orbital periods were of 1.7 and 2.09 days for Her X-1 and Cen X-3, respectively. This interpretation was strongly confirmed when, by examining the period of the pulsations more accurately, the period was found to vary in a sinusoidal manner as would be expected from the Doppler shift of the frequency due to circular orbital motion (Fig. 9). Note in particular that the phase of the variations agrees exactly with what would be expected under these conditions. The source pulsations appear to have a minimum change in period when the X-ray

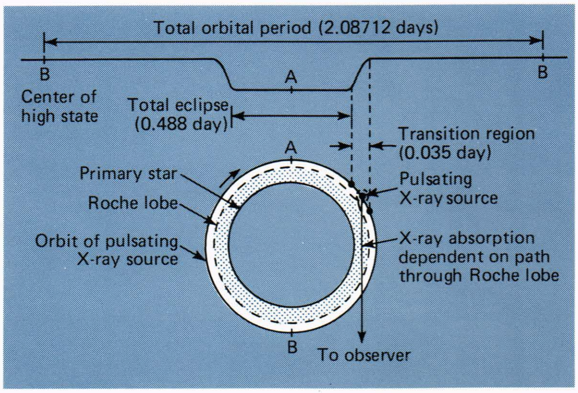


Fig. 8—Eclipse of a pulsating X-ray source caused by orbit around a companion star.

source is at the closest and furthest points in its orbit to and from us, corresponding to the centers of maximum and minimum intensity. From these data, we also could infer that the orbit was circular within a few parts in a thousand; we could directly measure the orbital diameter from the travel time of light across the diameter and deduce the orbital velocity and reduced mass of the system with unprecedented accuracy. Also, extending the measurement over a week, we could determine the average pulsation period with an accuracy of 1 part in 10^7.

It was due to these observations that it became established that at least Her X-1 and Cen X-3 were in binary systems. The subsequent discovery of their optical counterparts showing the same periodic behavior in intensity further confirmed this view and allowed us unambiguously to identify Her X-1 and Cen X-3 with their optical counterparts HZ Her and Kreminsky's star.

Since Her X-1 and Cen X-3 are the only regularly pulsating X-ray sources, the same techniques could not be used in other cases to establish their binary nature. Therefore, we have relied mainly on the variation in average intensity for all those sources exhibiting eclipses (such as 3U1700–37, 3U0900–40 and SMC X-1) and on the coincidence between the periods of optical intensity variations and X-ray eclipses.

In one case, Cyg X-1, the identification with binary system HDE 226868 was based on positional coincidence between an unusual variable radio source and the optical star, and on a correlated transition occurring in the X-ray and radio

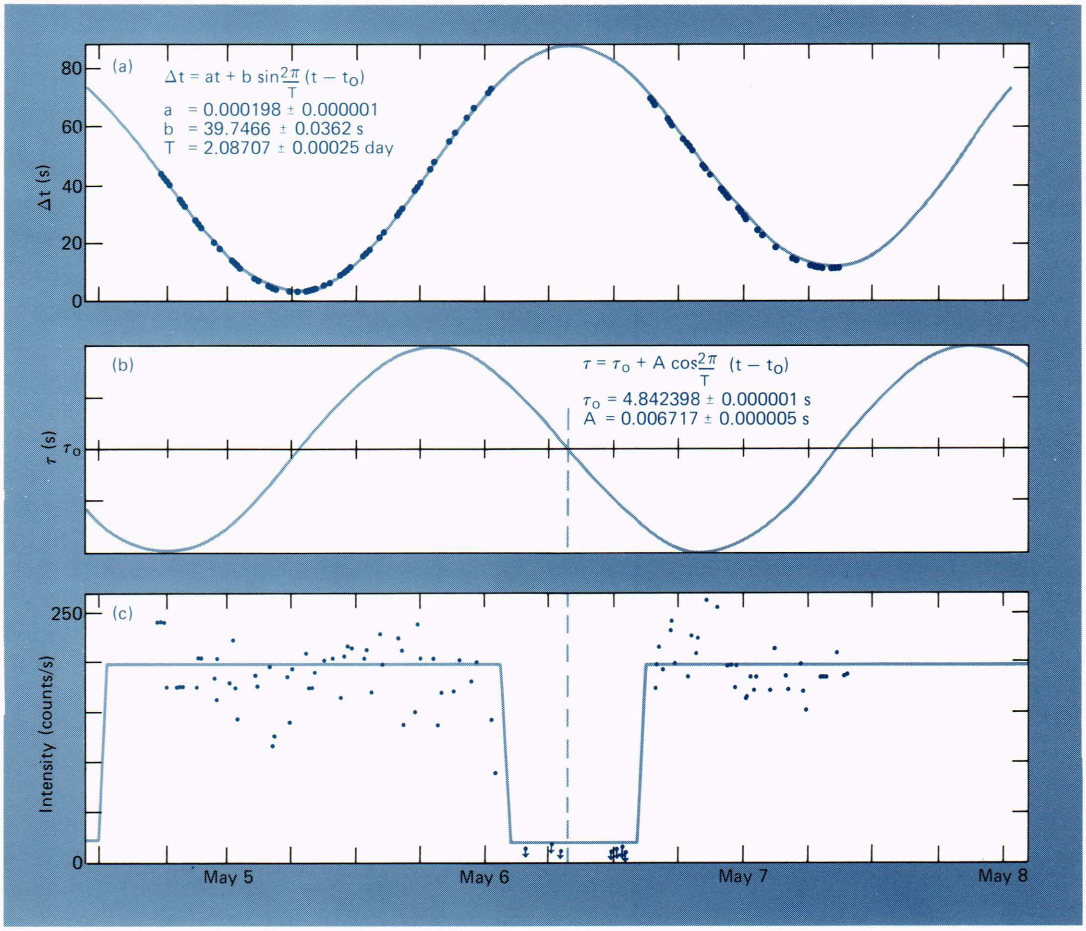


Fig. 9—Doppler shift in the frequency of pulsations due to orbital motion of X-ray star, Cen X-3, about its companion. Curve a shows the variation in the time of arrival, Δt, of the signal resulting from the orbital motion. The phase of the time variation agrees with that predicted from the X-ray intensity variation shown in curve c. Curve b shows the effect of the orbital motion on the observed period, τ, of the X-ray pulsations.

TABLE 1
PARAMETERS OF X-RAY BINARIES

System	*Primary Spectrum*	*Light Amplitude* (M_v)	*X-Ray Eclipse Duration* (deg)	*Estimated Inclination Angle* (deg)	R/R_{crit}	M_p	M_x	q
Cyg X-1 226868	09.7 Iab	0.05	—	27	0.98	25.0	14.0	1.8
SMC X-1 SK160	BO	0.09	±26	70	≥1.0	25.0	2.0	12.0
3U0900-40 77581	BOIb	0.07	±35	90	1.0	30.0	2.5	12.0
3U1700-37 153919	06f	0.04	±58	90	≥1.0	27.0	1.3	20.0
Cen X-3 KRZ Star	06f	0.08	±45	90	≥1.0	17.0	0.7	25.0
Her X-1 HZ Her	A7-BO	1.5 on 0.3 off	±28	90	1.0 0.94	2.0	1.0	2.0
Sco X-1 —	Irreg.	0.25	—	Low	~1.0?	0.5?	1.0?	0.5?
3U0352+30 X-Per	BOe	—	—	90	0.2	20.0?	40.0?	0.5

Note: M_p is the mass ($M_\odot$) of the primary star; M_x is the mass ($M_\odot$) of the companion star; q is the ratio M_p/M_x.

regions of the spectrum which established the identification of the radio source with the X-ray source.

As soon as the binary nature of the X-ray source is established and a visible light companion is identified, we can use the information on periods and orbital velocities from either or both wavelength regions to determine the parameters of the system. It is important to note that the study of orbital motions in binary systems is the only certain method available to us to determine stellar masses. Also of crucial importance is the possibility of determining the distance of the source, which is normally done by observing the reddening of the optical companion spectrum due to interstellar matter. This then allows us to determine the intrinsic luminosity of the X-ray source.

The parameters of some of the identified binary X-ray sources are summarized in Table 1. It is clear from inspecting Table 1 that most binary sources contain a massive blue supergiant star (15 to 30 $M_\odot$) and a smaller object having a mass between 0.7 and 14 $M_\odot$. The companion of Her X-1 is a low mass star (~ 2 $M_\odot$); this might also be the case for Cyg X-3 and for the companions of Sco X-1 and Cyg X-2, if they also turn out to be binaries. The orbital periods are in the range of from 0.2 to 9 days. The distances are of the order of several kpc (1 parsec = 3.26 light years) and, therefore, the luminosities are of the order of 10^{36} to 10^{38} erg/s.

The compact nature of the star on which the X rays are generated can be inferred by the rapidity of the intensity variations we observe. In Her X-1 and Cen X-3 we have seen that regular pulsations occur with periods of 1.2 and 4.8 s, and in Cyg X-1 it was discovered that irregular pulsations occur on a time scale as short as milliseconds (Fig. 10). Most other binaries were observed to exhibit large changes in intensity in times of 0.1 to 1 s. This implies that the region of X-ray emission is smaller than the distance travelled by light in the same time interval and must be less than 10^9 cm in radius or no more than several times larger than the earth. We know in astronomy of only three possible states in the evolution of stars in which matter may reach such high density that a solar mass could be compressed into less than 10^9 cm in radius: white dwarfs, neutron stars, and black holes.

How can we distinguish between these three types of compact object? There are two considerations: the first discriminates against white dwarfs on the basis of the pulsation period and stability; the second relies on mass determination and X-ray morphology to distinguish between black holes and neutron stars.

It was soon recognized that the high degree of

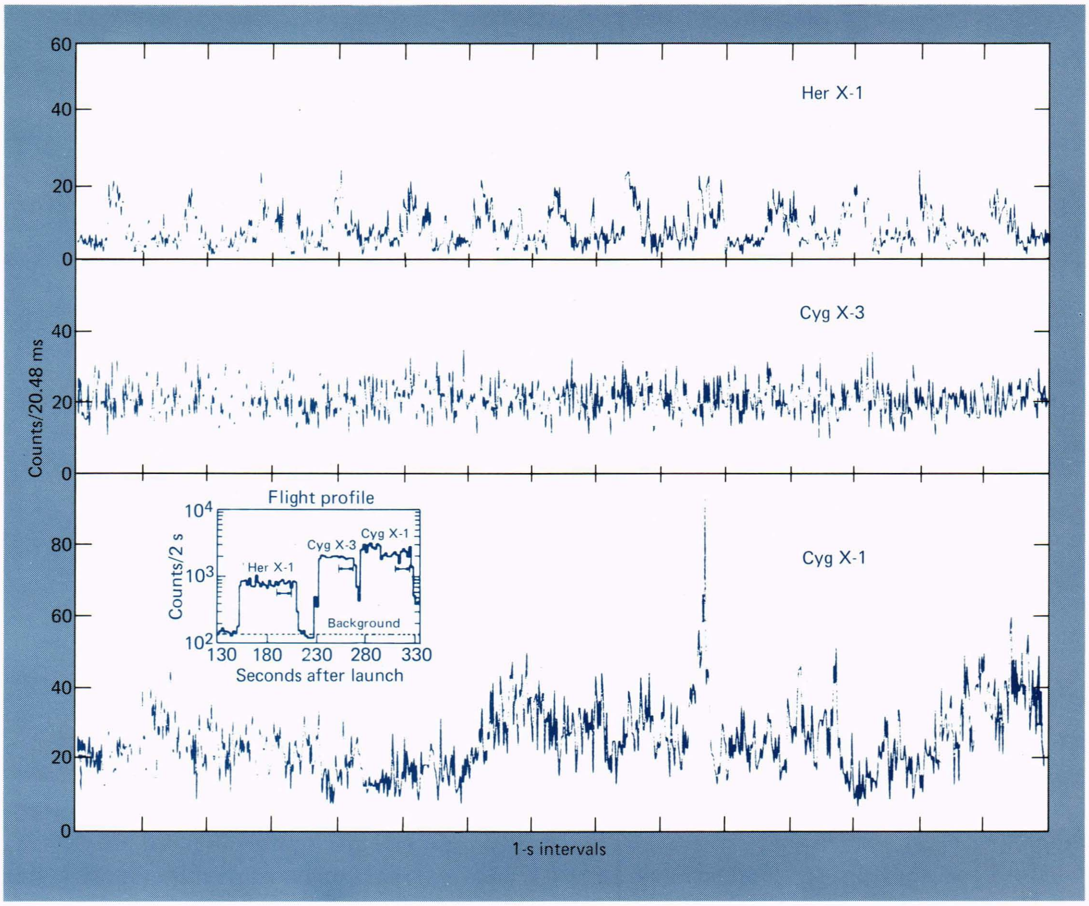


Fig. 10—Irregular pulsations from X-ray stars (courtesy Dr. S. S. Holt, NASA/GSFC, Greenbelt, Maryland).

regularity in the periods of Her X-1 and Cen X-3 implies a stable underlying clock that could be provided by either stellar rotations or pulsations. However, the periods appeared too short to be reconciled with the vibration or rotation of a white dwarf. Thus, we are left with the choice of either neutron stars or black holes as the X-ray source. The existence of regular pulsations in Her X-1 and Cen X-3 seems decisively to rule out black holes; this agrees also with the low estimate of mass. The existence of rapid intensity variations in X rays within periods of 0.1 to 0.001 s in all other binaries seems also to rule out white dwarfs as candidates for these sources. In these cases the choice between neutron stars and black holes is dictated by the mass estimate and by the morphology of the X-ray emission. On very general grounds, Ruffini has proven that no stable neutron star configuration could be obtained for stellar masses greater than 3 $M_\odot$. Therefore, compact X-ray sources with masses greater than 3 $M_\odot$ can be presumed to be black holes. In addition, the observational appearance of the X-ray emission should be quite different. No regularly pulsed emission should be expected from black holes, but rapid flickering could occur with characteristic times of 10^{-3} to 10^{-5} s. For Cyg X-1 the mass estimate of 8 $M_\odot$ and the existence of rapid flickering have led us to conclude that we are dealing with a black hole.

The question still arises as to whether the basic energy source for the X-ray emission could be the loss of rotational energy stored in the compact object, as is the case in radio pulsars. Even prior to any measurement, it seemed unlikely that 10^{37} erg/s could be produced by pulsar radiation from such a slowly rotating pulsar. If that were the case, the lifetime for the system would be quite short, and noticeable increases in the period should have been observable in a few months. The accurate measurement of the average pulsation periods of

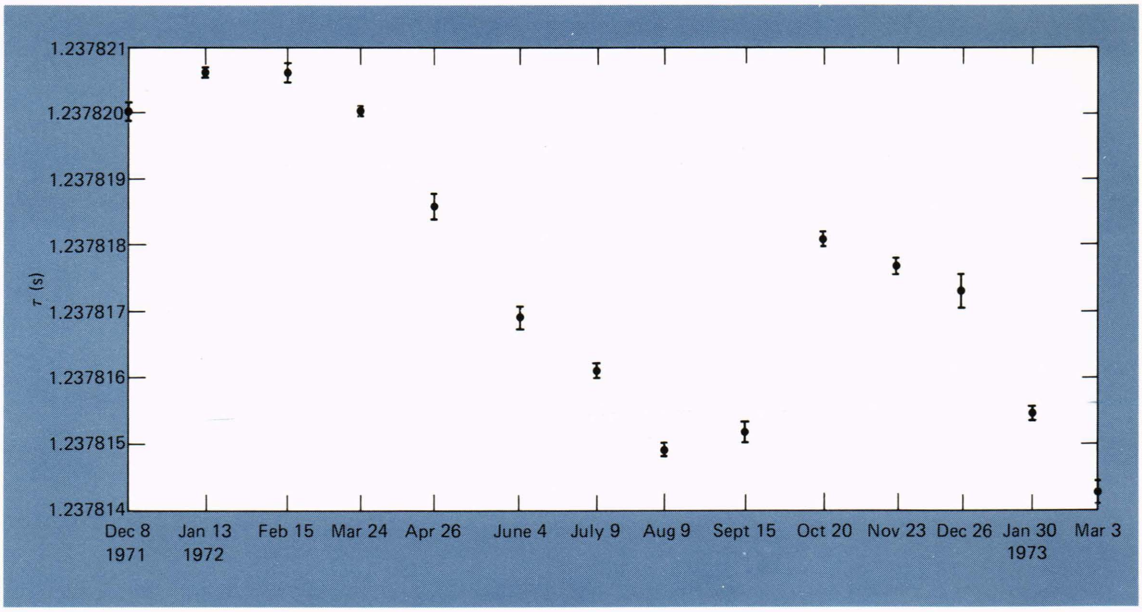


Fig. 11—Source Her X-1 pulsation period τ as a function of time.

Her X-1 and Cen X-3 completely rules out this possibility since it shows (Fig. 11) that the period is decreasing, not increasing, with time; thus rotational energy is being acquired, not lost.

On the other hand, many of the stars associated with binary X-ray sources are blue massive supergiants (O and BO) that are known to lose mass by stellar wind. Thus, *a priori*, accretion could be expected to lead to X-ray emission from such binary systems if the companion is a compact star.

There is independent evidence for gas streams and mass transfer in these systems. First, the changes in orbital periods and in pulsation period can be understood in terms of accretion and mass loss from the system. Also, visible light spectroscopic observations give evidence for emission occurring from gas streams midway between the two stars. Finally, examination of the dependence of X-ray emission on orbital phase gives us a direct measurement of density distribution in the system.

Reviewing the arguments:

1. X-ray sources are in binary systems.
2. The rapid fluctuations in X-ray emission require a compact emission region with a radius in the range of 10^6 to 10^9 cm.
3. Only three types of stars have a radius smaller than 10^9 cm: white dwarfs, neutron stars, or black holes.
4. Rotational or vibrational periods in white dwarfs are too long to explain the observed X-ray pulsations, leaving only neutron stars or black holes as candidates for most of the sources.
5. Pulsar-like emission from neutron stars cannot give rise to the observed phenomena.
6. Mass streams occur in the binary systems in which the X-ray sources are imbedded.
7. The most plausible mechanism is accretion onto neutron stars, or black holes, in a mass-transfer binary system.

Detection of a Black Hole

The conclusion that a black hole may have been detected for the first time is perhaps among the most startling of the results of X-ray astronomy. While the existence of black holes had been theoretically predicted by Oppenheimer and his collaborators as early as 1938, all previous efforts to detect them by visible light observations had proven fruitless.

On the other hand, following the discovery of X-ray stars, many theoretical astrophysicists, primarily in the Soviet Union (among them Zel'dovich, Schwartzman, Shakura, and Sunyaev), but also in the West (among them Prendergast, Burbidge, Rees, and Ruffini), had studied intensively the problem of the energy release from accretion onto a black hole. This culminated in 1971 with a paper by Shakura entitled "The Disk Model of Gas Accretion on a Relativistic Star (Black Hole) in a Close Binary System" that contained all the essential features of our present understanding of Cyg X-1.

Still the discovery that black holes may actually exist would be so significant that a great deal of caution must be exercised before the evidence can be accepted. The arguments in favor of this interpretation are essentially as follows:

Cyg X-1 is the invisible companion of HDE 226868. The two stars are in a binary system of a 5.6-day period. The system is at a distance from us of more than 2 kpc. The mass of the invisible companion is greater than 4 $M_\odot$ and more probably 10 $M_\odot$. The variability of the X-ray emission shown previously implies a very compact ($\simeq 10^6$ cm) source. A compact star of greater than 4 $M_\odot$ is a black hole. Each of the points above has been subjected to the most careful and extensive criticism. While some ad hoc and rather artificial hypotheses might still claim validity, the simplest and most convincing interpretation of the data seems to be that Cyg X-1 is the first black hole ever discovered.

Physics of Compact Objects

There is insufficient time to discuss here the evolutionary questions related to X-ray binaries. It is enough to say that thanks to the work of Kippenhahn and his associates in Germany, Paczynski in Poland, and van den Heuvel in the Netherlands we are now in the position to begin to understand the role of the X-ray emitting phase in the evolution of a massive binary system.

Instead, I would like to stress the significance of the information obtained in studying X-ray binary systems, for here nature has provided us with a unique astrophysical laboratory in which to study high-density collapsed objects. While neutron stars were first discovered as pulsars by radio astronomy, X-ray and visible light observations of X-ray binaries have already succeeded in giving us the first independent measure of mass of the neutron star in the Her X-1 system which, according to the latest studies of optical pulsations by Nelson and Middleditch, turns out to be 1.3 ± 0.1 $M_\odot$. This immediately permits us to differentiate between different equations of state in density regimes of 10^{15} g/cm^3. Also, Pines pointed out in 1972 that the possible existence of free precession in Her X-1 with a period of 35 days (which appears required to explain certain features of the X-ray emission) gives us conditions for the moments of inertia that imply a solid, rather than a liquid, core for the neutron star. Ruffini has pointed out that while accretion is proceeding, the moment of inertia of the neutron star is changed in a manner that is drastically dependent on the details of the equation of state of the neutron star material. Thus, careful study of the pulsational and orbital periods will give us further tools with which to explore the physical processes occurring at extreme densities.

The existence of a black hole in the X-ray binary Cyg X-1 has profound implications for all of astronomy. Once one such object is shown to exist, the possibility is immediately raised that many more may be present in all kinds of different astrophysical settings.

1. Small black holes of much less than a solar mass may have been created at the instant of the primeval explosion (big bang), as discussed by Hawking, and be slowly disappearing, perhaps giving rise to gamma-ray bursts.
2. Massive (10^3 $M_\odot$) black holes might lurk in the center of globular clusters, as suggested by Peebles in 1972 and by the recent discovery of X-ray sources and X-ray bursts from these objects.
3. Super-massive black holes may exist at the center of active galaxies, as discussed by Lynden-Bell, and explain the very large energy emission from such objects as quasars.

That these speculations may not be totally without foundation may best be illustrated by discussing the X-ray observations of two larger systems: the globular clusters in our own galaxy, and the compact extragalactic sources in the nucleus of active galaxies.

X-Ray Sources of Globular Clusters

Globular clusters and their associated X-ray emissions have become one of the most exciting current topics in astronomy. Figure 12 shows NGC 5139, a typical globular cluster containing some 10^5 stars. There are at least 150 such clusters in the galaxy scattered at random throughout the spherical volume of the halo.

Globular clusters are known to be almost as ancient as the Galaxy itself (10 billion years) and, in the most generally accepted theory, they are believed to have condensed at about the same time

Fig. 12—Globular cluster NGC 5139 (taken by Drs. Martha and William Liller, courtesy Kitt Peak National Observatory).

that the Galaxy itself was condensing from a gas cloud. This view is supported by the fact that examination of the Hertzsprung-Russell diagram for stars in the globular clusters demonstrates that most of the stars are very old and are in intermediate or advanced evolution. Only very low mass stars where time for evolution is very long (up to 10^{12} years) are still found in the main sequence. All others with greater masses have evolved long ago off the main sequence track.

In the study of the binary X-ray sources we have found that most such systems contain, in addition to a compact object, a young massive supergiant having evolution times of the order of 10^8 years at most. The discovery that several X-ray sources are associated with globular clusters, where such young stars are not believed to exist, presents us therefore with a considerable puzzle.

The UHURU survey identified 4 globular clusters as possible optical counterparts of X-ray sources. Three of these identifications (NGC 6624, NGC 6441, and HGC 7078, or M 15) were confirmed by the OSO-7 survey which discovered two additional cluster X-ray sources. The sources were found to have intrinsic luminosity from 4×10^{36} to 7×10^{37} erg/s and to exhibit intensity variations. Therefore, they are similar in many characteristics to the galactic binary sources. However, we are immediately faced with a problem: we have 5 X-ray sources associated with the 120 known clusters. This is an abundance of X-ray sources 100 times greater with respect to stars in the clusters than in the galaxy as a whole. This argument, which was first pointed out by Gursky and Schreier in 1974, therefore suggests that globular cluster X-ray sources are qualitatively different from the binary X-ray sources found elsewhere in the Galaxy. If we attempt to explain the X-ray sources in globular clusters as the product of the evolution of stars that were born as binaries, we are confronted with the basic problem that any massive binary system that could have evolved so as to form a neutron star or a black hole could not still contain a massive nuclear burning companion providing the mass for the accretion process. Such a companion would have burned out long ago leaving the compact object without a source of accreting material.

No doubt, therefore, we must find a different explanation for either the evolution or the nature of these sources. Several possible explanations are currently being tested observationally. The first invokes the recent formation of binary systems by capture. The collapsed remnant of early massive stars that evolved long ago must still be present in clusters. Clark (1975) suggested that these remnants can capture field stars which then supply them with accreting material. Several other authors have advanced specific suggestions as to how such capture could take place; the main difficulty is to assess accurately the frequency of such processes. No actual observational evidence can yet be invoked to support this explanation. None of the globular clusters sources has been shown to exhibit eclipsing behavior or regular pulsations with doppler shifts in frequency that could be considered actual proof of the binary nature of the sources.

Bahcall and Ostriker, and Silk and Arons suggested as an alternative hypothesis that X-ray sources in binary clusters are caused by accretion onto black holes of 10^3 solar masses. Peebles, in 1972, had pointed out that superdense cores could be formed in the evolution of clusters and proposed that such massive black holes would be the expected result of the collapse of the central core.

In the view of the proponents of this theory, X-ray emission could occur in those clusters with deep enough potential wells (or high enough escape velocities) to retain in the cluster the gas emitted from stars during successive traversals of the galactic plane. In most clusters the escape velocity is such that the gas would be lost as it is generated; therefore they could not be X-ray sources.

There are difficulties connected with this model as well, since it is not obvious (a) what are the measurable cluster conditions leading to X-ray source formation in some, but not others, and (b) why such sources, with black holes of 10^3 $M_\odot$, should be limited in emission to 10^{38} erg/s, the Eddington limit for stars of one solar mass.

One might well ask why such a model should be advanced when the very existence of black holes in nature rests up to now entirely on the experimental evidence furnished by only one object: Cyg X-1. As we have seen, this generally accepted evidence proves only the existence of black holes of about 10 $M_\odot$.

The fact is that some more recent evidence on the very peculiar behavior of these cluster sources is quite suggestive of the expected behavior of such massive black holes. I am referring, of course, to the discovery by Grindlay, Gursky, and their collaborators of giant pulses from the cluster NGC 6624 associated with 3U 1820–30 and to the subsequent beautiful work by Clark and his colleagues at M.I.T. and also by Forman and Jones at the Center for Astrophysics in discovering new bursting sources and in studying the detailed characteristics of the bursts. Figure 13 shows the appearance of the first X-ray burst discovered by Grindlay et al. from the ANS satellite. The source NGC 6624 appears quiescent at a luminosity equivalent to 10^{37} erg/s and then in half a second rises to about 30 times the quiescent level, only to decay exponentially in 10 s to the previous level. Grindlay and collaborators found two such bursts from the same source with identical appearances. (The characteristic appearance was confirmed by the observation of 9 additional bursts by SAS-3.) They reasoned that the same shape could not occur at random but either reflected some characteristic of the underlying source or could be due to some feature of the medium about the source that would modify the appearance and spectrum of these bursts and give them their characteristic features. They were struck in particular by the similarity of the appearance of these bursts to the light curves observed in supernovae: a fast rise, a peak, and then an exponential decay. Also, they noted that an essential feature of the bursts was the hardening of the spectra as the burst progressed.

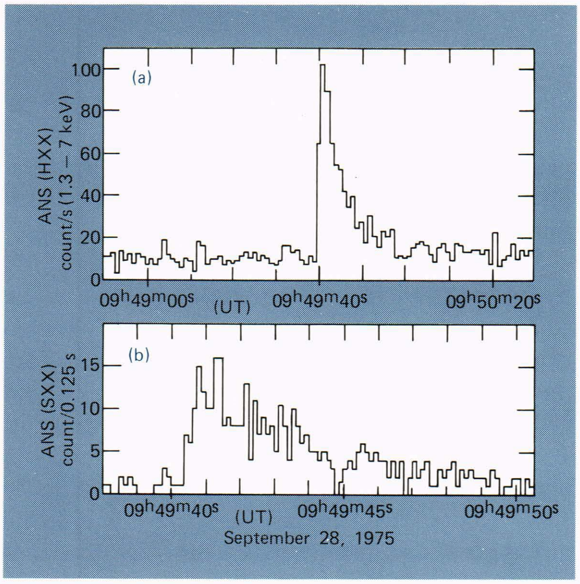


Fig. 13—ANS satellite observations of an X-ray burst from source NGC 6624 (3U1820-30).

By analogy between the Morrison and Sartori models and supernova events, Grindlay et al. suggested that the most "natural" explanation for the events is as follows: An initial prompt pulse is generated at the source. Some of the radiation reaches the observer unmodified by the surrounding medium. Some could be scattered by the surrounding medium and reach the observer with different delays from different regions. This would result in an exponential decay of the pulse. In order to explain the hardening of the spectrum, they assume that the cloud is composed of a hot gas. The scattering of the X rays from the energetic electrons in the cloud would then modify the spectrum as observed. The characteristic exponential decay time gives a measure of the cloud dimensions; the cloud temperature is known from the spectral measurement; and the value of the mass of the central object necessary to keep the hot cloud bound to it at its distance can be derived. The result is that the mass of the central object should be of the order of 1000 $M_\odot$. The bursts of NGC 1820–30 would then be the scaled-up version of Cyg X-1. The slower rise time, precisely as expected, is due to the difference in mass. More recently, Clark and his colleagues at M.I.T. found evidence that the pulses from this cluster come in quasi-periodic fashion at intervals of approximately 0.18 day and persist for at least 10 pulsations. They also found additional bursts from other sources with different characteristics and behavior but apparently denoted by the fact that the peculiar features of the bursts from each source remain constant and are, in effect, a characteristic thumbprint of that source.

Very recently, re-examination of UHURU data by Forman and Jones has revealed a similar event from yet another cluster source but with characteristic duration of decay time of about 25 s. Thus this complex phenomenology reveals a rich new field of exploration in X-ray burst phenomena. The relation of these bursts to the gamma-ray bursts found by Strong and his collaborators in 1973 is not clear. They appear somewhat different in temporal and spectral characteristics. The lack of precise location measurement for the gamma-ray bursts also makes it difficult to associate them with individual known sources, although it is suggestive that the only tentative identification proposed by Strong et al. is with Cyg X-1.

What all this means is rather obscure at the moment. However, the general excitement is quite understandable: such precise and distinct behavior as is observed in the bursting X-ray sources had not previously been observed in any of the well-studied binary X-ray sources. The energy involved, 10^{39} erg/s, is so large that the behavior must be tied at some fundamental level to the intrinsic energetics of the source. We hope that these studies might shed light on the existence of massive black holes and permit determinations of their parameters.

Extragalactic X-Ray Astronomy

No matter how fascinating and rewarding the study in X rays of galactic objects has proven, it is clear that the major new thrust in the years to come in X-ray astronomy will be the study of extragalactic sources. Some 60 high latitude sources have been observed to date; about 30 have been identified with known extragalactic objects, and the remainder are believed to be of extragalactic origin although their nature is not yet determined. These numbers are continuously increasing with the addition of more and more observations resulting from rapidly increasing sensitivity. For instance, a newly developed attitude-determination method using magnetometer data and X-ray stars has permitted us to begin to analyze UHURU data that could not previously be used because of an early failure of the visible light star sensor. We are in the process of compiling a 4U Catalog that might contain one or two hundred new sources. Many new high latitude sources have recently been discovered.

Most of the identified extragalactic sources are connected with clusters of galaxies that are among the most powerful known X-ray emitters (10^{44} erg/s). The X-ray emission appears to extend over the enormous distances spanning the entire cluster. The most generally accepted explanation is that the emission is due to the tenuous hot gas that had been postulated to pervade the space between galaxies. The temperature of the gas is so high (10^{8}°K) that emission from it could only be detected in X rays. The gas density is such that the total gas mass is comparable to the total mass in the galaxies. This mass is still insufficient to provide for the total closure mass in the clusters, as inferred by kinematics arguments; it is quite sufficient, however, to provide the necessary conditions to explain the radio tails of galaxies. The gas provides just the pressure required to contain the hot electrons whose radio emission is observed in the radio tails. Figure 14 shows a radio map of the Perseus clusters of galaxies. One can observe the radio tails of NGC 1265 and IC 310. One can also observe concentrated emission from NGC 1275 and diffused emission from the entire cluster. The X-ray data shown are the discovery data from UHURU that established the existence of diffused emission from a region centered on NGC 1275. More recently Gorenstein obtained

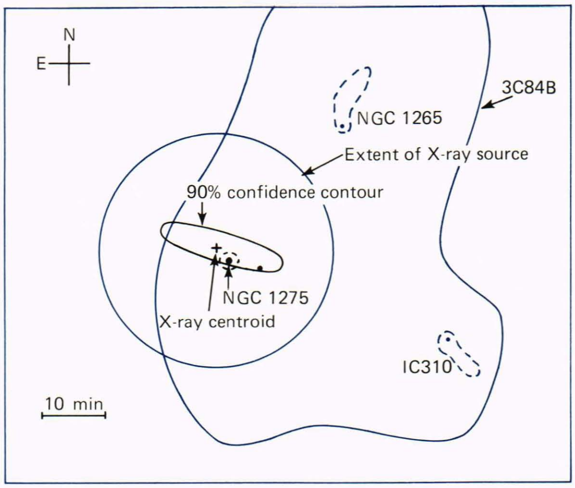


Fig. 14—Radio map of the Perseus cluster of galaxies.

the exciting X-ray map shown on the cover by using a large-area, moderate-resolution, X-ray telescope in a rocket flight.

We can observe an elongated region of diffused emission and the contribution from the central active galaxy NGC 1275. The analysis of these data is not yet complete. However, the raw data are exciting because they were obtained with focusing optics and a prototype of the imaging proportional counter detector to be used in the HEAO-B mission to be flown in 1978. The extremely low background and the sensitivity of the technique make us certain that, with observational times of days rather than the 300 s of a rocket flight, we will be able to study clusters at very great distances ($Z \gtrless 1$), equivalent to a much earlier time in the evolution of the universe. The study of the evolution of clusters that may then become possible will likely open a new and fascinating chapter in the study of cosmology.

Active X-ray-emitting galaxies, of which we have discussed the example of NGC 1275, but that also include Seyferts, radio galaxies, and quasars, are, of course, one of the most exciting subjects of study in astronomy today. Visible light and radio observations have revealed the occurrence of explosions in the extremely compact cores of such galaxies. The mechanisms that produce this activity are not currently understood. Variations in intensity occurring within days at several wavelengths have been confirmed by X-ray observations. For example, the source that has been identified with the nucleus of the galaxy NGC 5128 has been observed to double its emission within a week. Thus, we know that the region of activity is very small compared to the size of the galaxy.

The other important clue we have to the mechanism that may give rise to this tremendous energy output involves the fact that radio lobes in several sources appear to be aligned. The radio lobes are thought to result from clouds of energetic electrons produced in explosions millions of years apart. If clouds are emitted in the same direction, even though at very different times, some mechanism must be invoked that preserves direction. Of course, the most natural astronomical gyroscope is the rotation of giant stars or black holes of masses equal to 10^7 $M_\odot$. Therefore, several models of active galactic nuclei invoke such massive rotators as the *deus ex machina* of the explosive behavior.

It is clear that the X-ray emission we observe is originating in regions very close to the core and contains a large amount of the power emitted. Thus, as in the case of galactic sources, we can hope that the X-ray observations will give us some insight into the energetics and the physical processes occurring in these stupendous machines.

The substantial increase in sensitivity of 10^4 brought about by the flight of the UHURU observatory not only has given us the opportunity to discover new and unsuspected phenomena, but has permitted us to insert at least some of these new findings into the main body of astrophysical knowledge of galactic objects.

We look forward in the next several years to another four-order-of-magnitude increase in sensitivity with the advent of the HEAO class of X-ray observatories (Fig. 15). The observatories, to be launched in the late 1970's, will allow us to study sources 10^{-7} as strong as Sco X-1. We believe that this next step will create as profound a revolution in our understanding of extragalactic X-ray sources as UHURU brought about for the sources in our own galaxy.

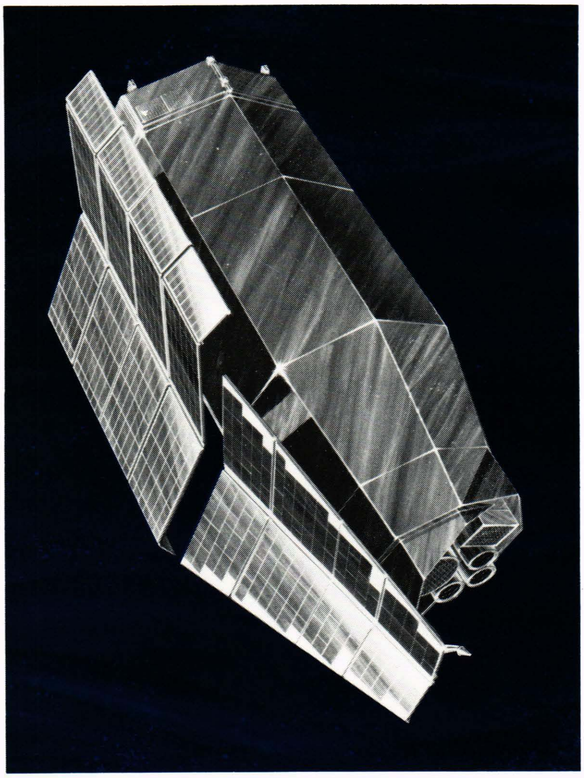


Fig. 15—HEAO X-ray observatory scheduled for launch in the late 1970's. (Courtesy TRW, Inc., Redondo Beach, California.)

Four factors give us confidence in this belief:

1. The solid experimental foundation given by detection at X-ray wavelength of several classes of extragalactic objects, such as radio galaxies, Seyferts, quasars, clusters of galaxies, and X-ray galaxies;
2. The existence of an isotropic, diffused X-ray background of extragalactic origin that is believed to originate at cosmological distances;
3. The advent of X-ray telescopes capable of imaging extended fields with angular resolution of 1 arc second; and
4. The improved sensitivity that will permit us, for example, to detect not only the brightest known quasar (3C 273), but possibly all known quasars, and not only the closest clusters, but all clusters of galaxies up to very large distances.

The HEAO-B Observatory to be launched in 1978 will be equipped with accurate spectrometers, as well as imaging devices, and will be capable of much higher times resolution than is now available. Figures 16 and 17 illustrate the power of the techniques that are being implemented in these observatories. Figure 16 shows how the improvement in angular resolution proved important in studying familiar objects in visible light. Figure 17, a recent picture from Skylab of the sun in X rays, was obtained with a smaller version of the X-ray telescope to be flown on HEAO-B.

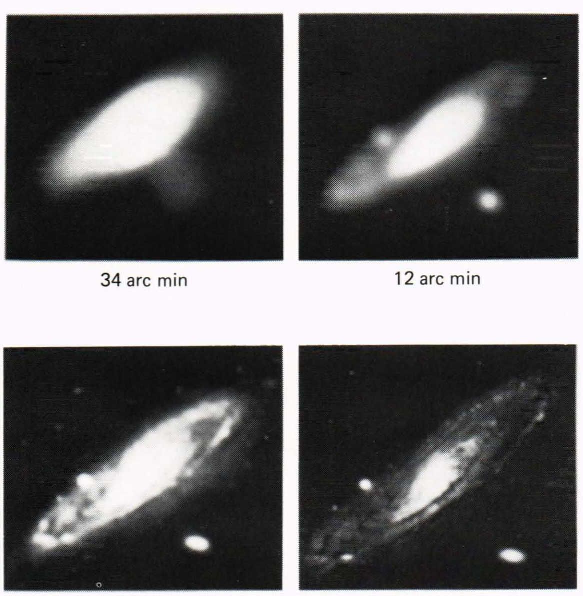


Fig. 16—Effect of angular resolution on observations with visible light.

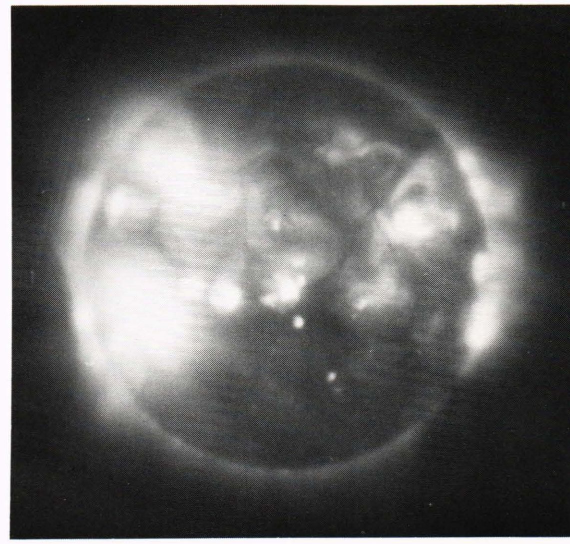


Fig. 17—Picture of the sun obtained with an X-ray telescope on Skylab.

The 10^8 improvement in sensitivity we have been discussing will have occurred within 20 years after the first discovery of cosmic X-ray sources; it is comparable to the improvement that has occurred in visible light astronomy during all of man's history. If the past can be taken as a guide, this very large improvement in capabilities should lead not only to a deepening and extension of present knowledge, but to many unsuspected discoveries that might once again revolutionize our understanding of high energy astrophysics. It is from this perspective that one should view the present and potential contributions of X-ray observations to the solution of such fascinating problems in astrophysics as the end states of stellar evolution, the evolution of individual galaxies and clusters, and the evolution of the universe as a whole.

X-ray astronomy is a new and powerful tool with which to study high energy processes occurring in the universe. It is a gift of space exploration and, intellectually, one of its most exciting accomplishments.