Progress in x-ray astronomy

Recent satellite studies of celestial x-ray sources have enabled some binary-system components to be identified as white dwarfs, neutron stars, and in one case a black hole.

Riccardo Giacconi

The most significant progress in x-ray astronomy in the past few years has been brought about by the advent of satellite observatories and by the great number of new radio and optical identifications of cosmic x-ray sources. Since the discovery, with rocket-borne instruments, of extrasolar sources of x radiation ten years ago, it has been clear to most experimenters that a very considerable advance in our knowledge could be obtained with satellite instrumentation. The launch on 12 December 1970 of the first small astronomy satellite, UHURU, entirely devoted to x-ray observations, was expected to lead to the detection of fainter sources with finer angular resolution and positional accuracy, thereby expanding our catalog of celestial x-ray emitters. What was unexpected was the qualitative change in our understanding of the nature of cosmic x-ray emitting objects that several new discoveries by UHURU have brought about.

The discovery of pulsating x-ray sources in binary systems has offered us the first clear evidence of the role of *accretion* as the energy source for the generation of the very large x-ray fluxes observed from stellar objects. The presence in these systems of white dwarfs, neutron stars or black holes gives us a most fortunate astrophysical laboratory in which to study their properties. Evidence is becoming more convincing, almost on a weekly basis, in favor of the interpretation of the Cygnus X-1 in terms of a black hole orbiting a massive companion.

In extragalactic x-ray research the increase in the number of observed sources has been so great that for the first time an attempt at classification of different types of extragalactic emitters is possible, as is an evaluation of their contribution to the isotropic x-ray background. The detection of stellar sources in external galaxies of the local group has established an unequivocal value for the intrinsic x-ray luminosities of stellar objects. Detection of diffused emission from clusters of galaxies furnishes important clues on the dynamics of the clusters and on the existence of intracluster gas, and it may provide a very powerful tool with which to investigate cosmological questions.

As the scope of x-ray astronomy expands and the observations yield a greater and greater wealth of experimental data, it becomes impossible in a short review to give a comprehensive description of the experiments and of the results. I will base most of this article on results obtained from UHURU, with a sprinkling of data from the two satellite experiments by MIT and La Jolla on the OSO-7 satellite and some from rocket flights.

I will not attempt to describe results obtained on x-rays of lower energies than observable from UHURU, about 1–20 keV, except as they pertain to the discussion of particular objects. This is not due to any lack of progress in the field, but rather to the fact that the sky appears quite different below and above 1 keV. At lower energies the diffused background appears to be dominated by galactic contributions, in net contrast to what we believe to be the case at higher energies. Also the individual sources observed, such as extended supernova remnants, appear in general to be characterized by lower temperatures than are observed for compact stellar sources and are, therefore, unobservable at higher energies. The production mechanisms giving rise to the observed radiation also appear to be different in the two regions of the spectrum. Finally, with the exception of old supernova remnants, there is no evidence for the existence of sources below 1 keV, not observed at higher x-ray energies.

The night sky in x rays

Before discussing individual properties of x-ray sources, let us consider some of their general properties—such as number-count, ranges of intrinsic luminosity and spatial distribution in *b* and *l* (galactic longitude and latitude). UHURU has given us the most complete catalog of x-ray sources in the 2–20 keV range. The 2U Catalog lists 125 sources detected during the first 70 days of operation of the satellite, with the coverage of approximately half of the sky. The intensity of the observed sources ranges from 2×10^4 counts per second for Sco X-1 to 2 cts/sec for M-31, as observed by the UHURU in-

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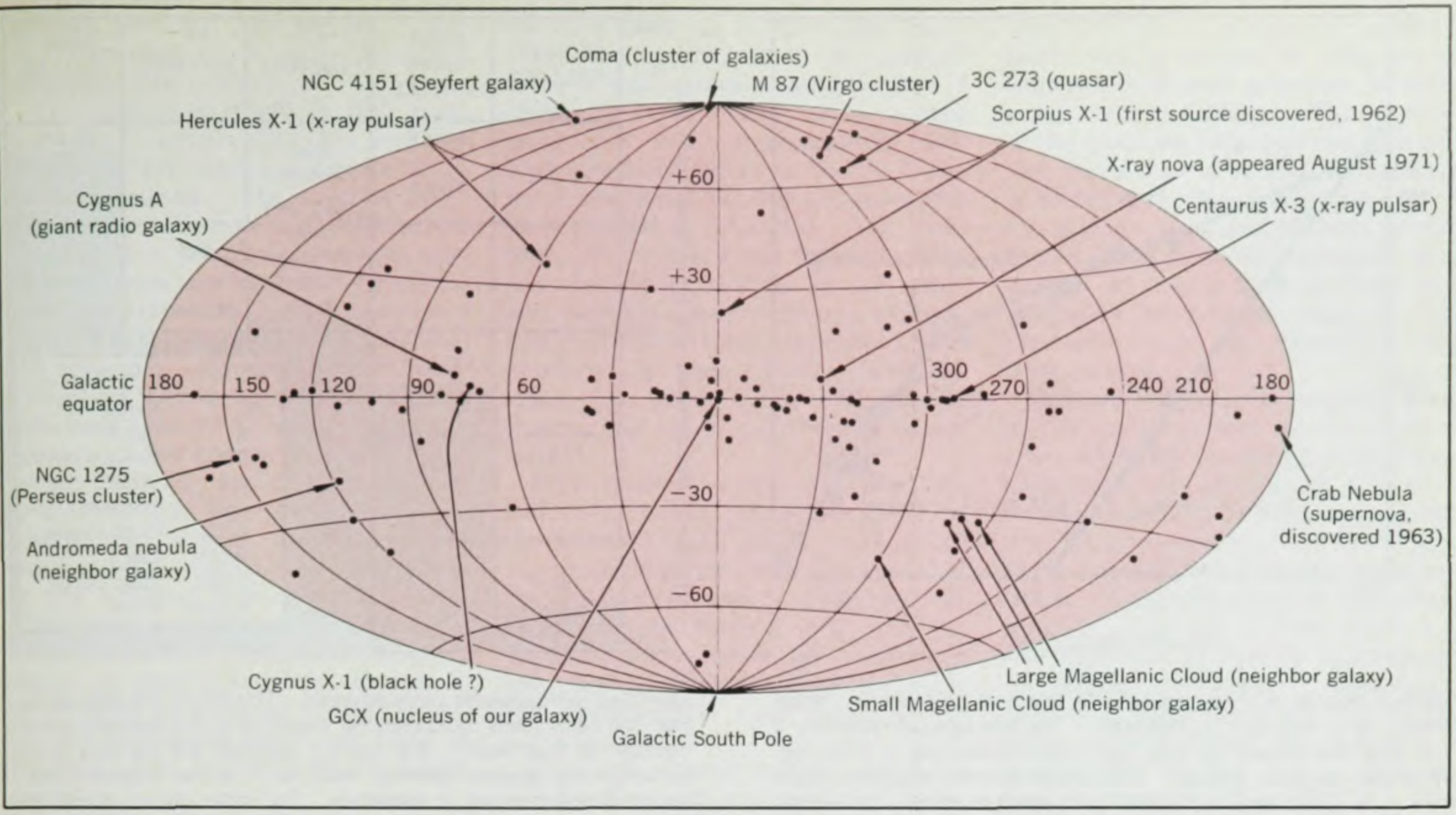


The x-ray sky as seen by the UHURU satellite. The dots indicate x-ray sources in the 2U catalog. This is an equal-area projection in galactic coordinates. Figure 1

struments in the 2 to 6 keV range. A map of the sky in galactic coordinates containing all the 2U sources is shown in figure 1.

The sources divide naturally into two groups: those that are clustered along the galactic plane ($|b| < 20$ deg) and those at high latitude ($|b| > 20$ deg). Sources along the galactic plane are on the average much more intense than those at high latitude. This is just the opposite to what one would expect for a single galactic population. If the latitude of a source was taken as indicative of distance, high-latitude sources should be nearby and brighter than those in the plane, as is the case for common stars. In fact, we shall see that almost all the low-latitude sources are galactic, whereas almost all the high-latitude sources are extragalactic. (Of 44 sources with $|b| > 20$ deg, 14 have been identified with extragalactic objects and two with strong nearby galactic objects: Sco X-1 and Her X-1.)

Using the 2U Catalog and taking into account in detail the fraction of the sky surveyed at each sensitivity, we can construct a log N–log S distribution for the two classes of sources, as shown in figure 2. The qualitative difference we observe between the distribution of intensity in sources at low and high latitude is striking. We have investigated the possibility that it might be due to experimental biases, and we find that the possible corrections one could estimate would not be sufficient to alter this effect significantly.

Examining in detail the distribution in galactic coordinates (as well as the number count) of the sources clustered along the galactic equator, we find that we observe two kinds of galactic sources. These are a small number of sources in the central region of our galaxy with very large intrinsic luminosity (10^{38} erg sec^{-1}) and a large number of less intense sources (10^{36} erg sec^{-1}) disposed along the spiral arms of our galaxy. The bulk of the emission from our galaxy comes from the integrated emission of only a dozen very powerful sources. One hundred or so more sources contribute about 10% of the total. About two thirds of all existing sources in the galaxy with intrinsic luminosity above 10^{36} erg sec^{-1} have already been observed.

The 2U Catalog lists 44 sources at high latitude $b > 20$ deg. Of these, two have high intensity (2×10^4 cts/sec for Sco X-1, and 10^2 cts/sec for Her X-1) and are identified with galactic objects. Five are identified with individual stars in the Large and Small Magellanic Clouds at about 20 cts/sec. Ten with intensity ranging from 20 cts/sec (Virgo Cluster M-87) to 2 cts/sec (M-31) are identified with individual galaxies or clusters, and the remainder is unidentified.

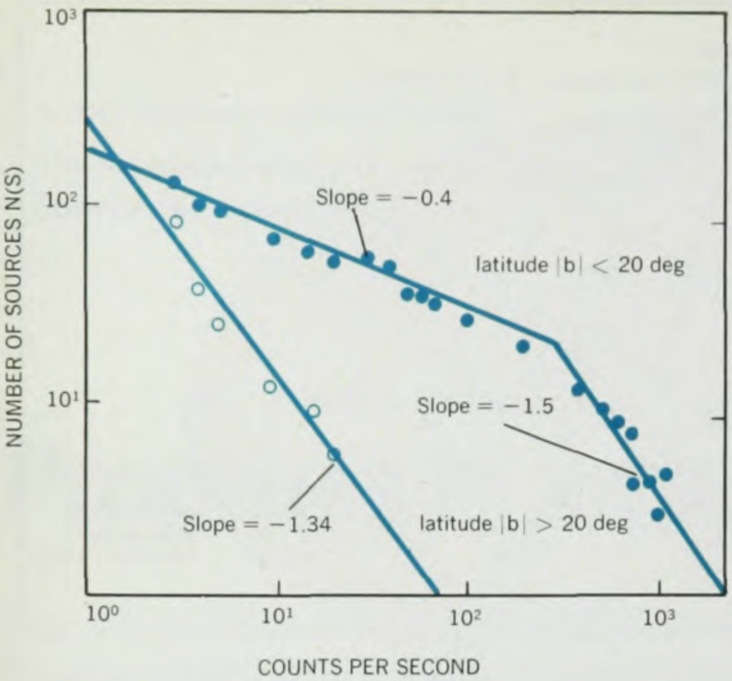
Because all of the weak sources that have been identified have been found to be extragalactic, we are led to question whether the unidentified sources with $b > 20$ deg might also be extragalactic. Examining their l and b distributions, we note that they are consistent with isotropy. This result could be reconciled with galactic origin only if the sources were members of a halo population, or were very nearby objects. The first possibility is excluded by the fact that we observe no excess in the direction of the galactic center; the second, by the fact that we do not observe an intense galactic ridge. Unless we invent an *ad hoc* galactic population with appropriate intrinsic luminosity and distribution, we are led to conclude that all high-latitude sources are extragalactic.

This view is confirmed by the number-count distribution for these sources, which is consistent with what we expect for isotropically distributed extragalactic sources in a static Euclidian Universe.

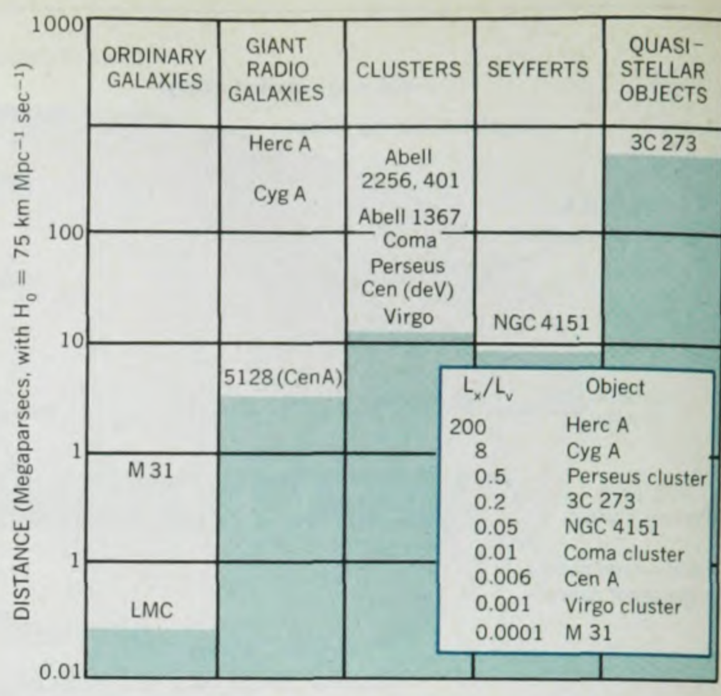
Galaxies of the local group

In normal galaxies, including our own, the x-ray emission appears to be dominated by the integrated output of individual stellar sources. The x-ray luminosity (10^{39} erg/sec) appears to be a small fraction of the total light emitted at all wavelengths $L_x/L_{rad} = 10^{-5}$. In all other identified extragalactic sources the total energy emitted in x rays is much larger in absolute value, ranging from 10^{42} to 10^{46} erg/sec in the 1 to 10 keV range, and is also larger relative to the total emission at all wavelengths.

In figure 3 a summary of the observed classes of x-ray emitting objects is given. On the left are distances in megaparsecs. Plotted in each class are



Number counts of x-ray sources in the 2–6 keV energy range plotted as a function on intensity. The low-latitude sources, b <20 deg. are shown as dots; high-latitude sources, b >20 deg, are shown as open circles. Also shown are the best-fit straight lines. All data are corrected for non-uniform sky coverage. The scale on the right-hand ordinate, $N(S)$ per steradian, applies only to the high-latitude sources. Figure 2



Identified extragalactic x-ray sources. The top of the colored region for each class indicates the distance of the nearest known member of that class. The Seyfert galaxies are the only group for which the nearest member, NGC 4051, is not detected, but a more distant member is detected. The table (inset) shows the ratio of x-ray luminosity to optical luminosity, L_X/L_V, for nine representative identified sources. Figure 3

the observed objects at their distance; the color tint is extended to the distance of the nearest known object in each class. We note that we observe close to the nearest or brightest member in each class. The identified extragalactic sources include Seyfert galaxies, QSO's, giant radio galaxies and clusters.

The x-ray data available on each source are the location, the energy spectrum and the angular size. We find an important distinction in the emission characteristics of individual extragalactic objects and clusters of galaxies. For sources identified with individual galaxies we measure a definite low-energy cutoff, whereas only upper limits (consistent with no cutoff) are observed in cluster sources. In Table 1 we summarize these results, and also we list the measured angular sizes for the different sources. We note that for all sources identified with individual galaxies we observe spectra that are cut off at low energy, and these sources have small angular size. For cluster sources we observe no cutoff and extended size.

In the case of 4151 the stated limit of 15 arc minutes corresponds to about 50-kiloparsecs diameter at the distance of 4151. In fact, the emitting region may be much more compact. The very large cutoff, which corresponds to a column density of absorbing matter in excess of 10^{23} atoms cm^{-2}, could be taken to indicate that the x rays are coming from a small region at the nucleus of NGC 4151. In fact, if we assume that the source is as large as the computed upper limit, then the total mass one can derive for the absorbing gas is prohibitively large ($3.5 \times 10^{11} M_\odot$). Similar considerations apply in the case of NGC 5128 and 3C 273. Figure 4 shows the observed location of the source in NGC 5128. It is clear that the emission is concentrated in a region not much larger than the optical galaxy.

We conclude that the x rays we observe from these individual galaxies are emitted in small regions near the nucleus of the galaxy. Presumably they are not due to the collective emission of a number of individual stars because the x-ray output is 10^3 times larger than in normal galaxies and the L_x/L_v ratio is also much larger. At present we do not have sufficient data to distinguish between thermal bremsstrahlung emission and synchrotron or inverse Compton emission processes for the emission occurring in individual galaxies.

The detection of x-ray emission from extended regions in clusters of galaxies is potentially one of the most important new results from UHURU. We have identified about ten sources associated with clusters. In figure 5 the positional information of the x-ray source region for the clusters in Virgo, Centaurus, Perseus and Coma is shown. We find that the center of emission is centered on active galaxies when present, as in Virgo and Perseus. They have great physical size (≈1 Mpc). The x-ray emission appears to be strongly dependent upon cluster richness, and for richness class 2 we observe a narrow range of luminosities

Table 1. Sizes and X-Ray Luminosities of Extragalactic X-Ray Sources

Source	Size: Angular	Size: Kiloparsec	Luminosity (erg/sec)	Low-energy cut-off (keV)
Abell 2256	35′ ± 15′	2800	5×10^{44}	≤1.7
Perseus—NGC 1275	35′ ± 3′	740	3×10^{44}	≤1.1
Coma	36′ ± 4′	1050	2×10^{44}	≤1.0
Cen—NGC 4696	37′ ± 8′	500	2×10^{43}	≤1.9
Virgo—M 87	50′ ± 5′	200	7×10^{42}	≤1.0
NGC 4151	≤15′	≤60	1×10^{42}	5.7 ± 1.1
NGC 5128	≤10′	≤20	6×10^{41}	3.0 ± 0.4
GCX*	≈2°	≈0.3	≈10^{37}	2.8 ± 0.2
3C 273	?	?	2.7×10^{45}	2.6 ± 0.7

** Extended source at the center of our own galaxy, included for comparison* between 10^{44} and 10^{45} erg/sec. They are, therefore, much more luminous than individual galaxies.

The absence of cutoffs in their spectra seems to require that they are truly diffused rather than a collection of individual sources. The spectral information available from UHURU alone is insufficient to distinguish between possible emission mechanisms. In particular, one cannot distinguish between a power-law spectrum and an exponential spectrum. However, rocket observations of Coma and Virgo at long wavelength (10–20 Å) appear to favor a turnover at low energy, as would be expected for an exponential thermal bremsstrahlung spectrum.[1,2] These results also appear to indicate the presence of a more complex structure in the emission region of Coma and Virgo than is indicated by our simple fit to a uniformly illuminated extended source. In particular, there appears to be evidence for a region of small angular size containing about one third of the total flux centered on the active galaxy.

If the mechanism for emission is thermal bremsstrahlung from a hot intercluster gas, we find that the gas would have a total mass comparable to the mass contained in the observed galaxies and a temperature of some 70×10^6 K. This gas could be heated by energy output from active galaxies. It might be that the x-ray emission is not simply related to cluster richness, but to specific parameters describing the dynamics of the clusters. A. Solinger and W. Tucker[3] have suggested, for example, that the x-ray emission be related to the fourth-power velocity dispersion of the galaxies of the cluster and although not proven, this suggestion appears consistent with all available data.

It is to be expected that further study of the powerful extended sources in clusters will tell us much about the evolution of clusters and perhaps about cosmological phenomena. The rich clusters, being very luminous and of great angular size, will be identifiable out to distances where redshift effects dominate. We might be able, with the advent of large orbiting x-ray observatories, to detect clusters to $Z = 3$ and learn about their evolution in the early stages of the formation of the Universe.

Galactic sources

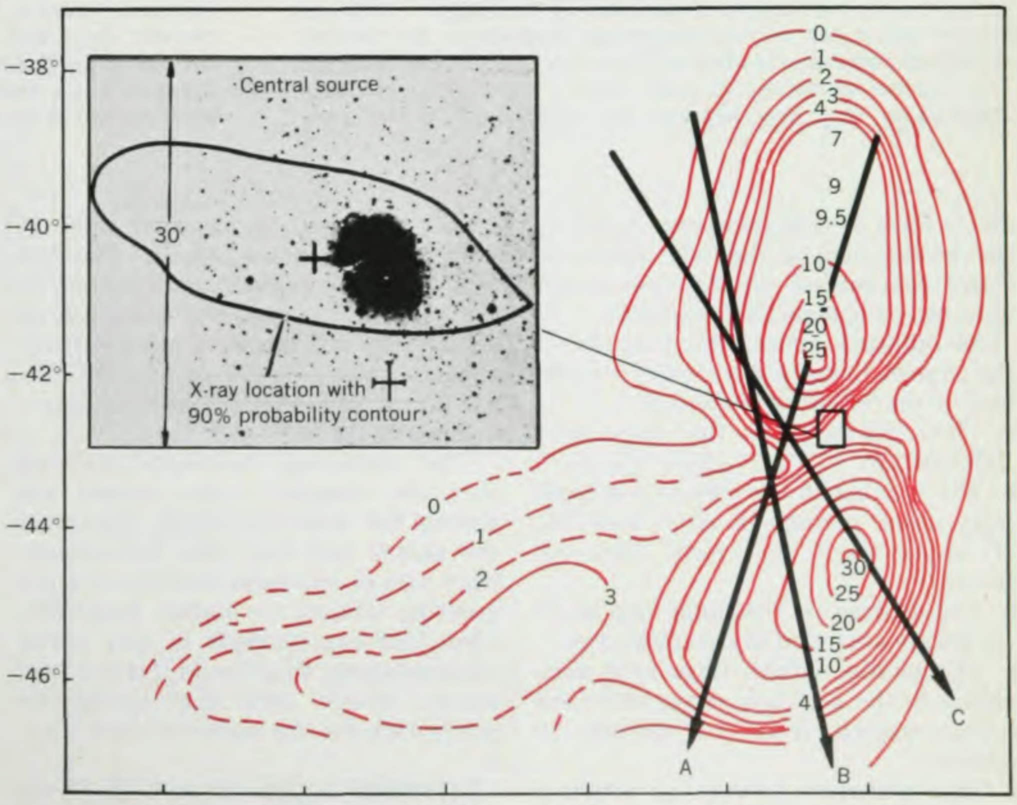
The major new results in the study of galactic x-ray sources have been produced by the refinement in our ability to measure positions in the sky, which has led to several new identifications with radio and optical objects, and by the opportunity afforded by satellite observatories to monitor with high time resolution (0.1 sec) the x-ray flux of specific sources for periods of time spanning intervals of up to two years.

Of the approximately 65 galactic sources with intensity greater than 8 cts/sec (4×10^{-4} Sco) in the energy range 2–8 keV, approximately 60% have positional errors in the 2U Catalog of less than 0.02 deg^2 and some 20% have positional errors less than 0.003 deg^2. While this is not better than the best that could be done for the strongest individual sources from a modulation collimator rocket experiment,[4] the extension of these precise measurements to many more and weaker sources has led to significant new results.

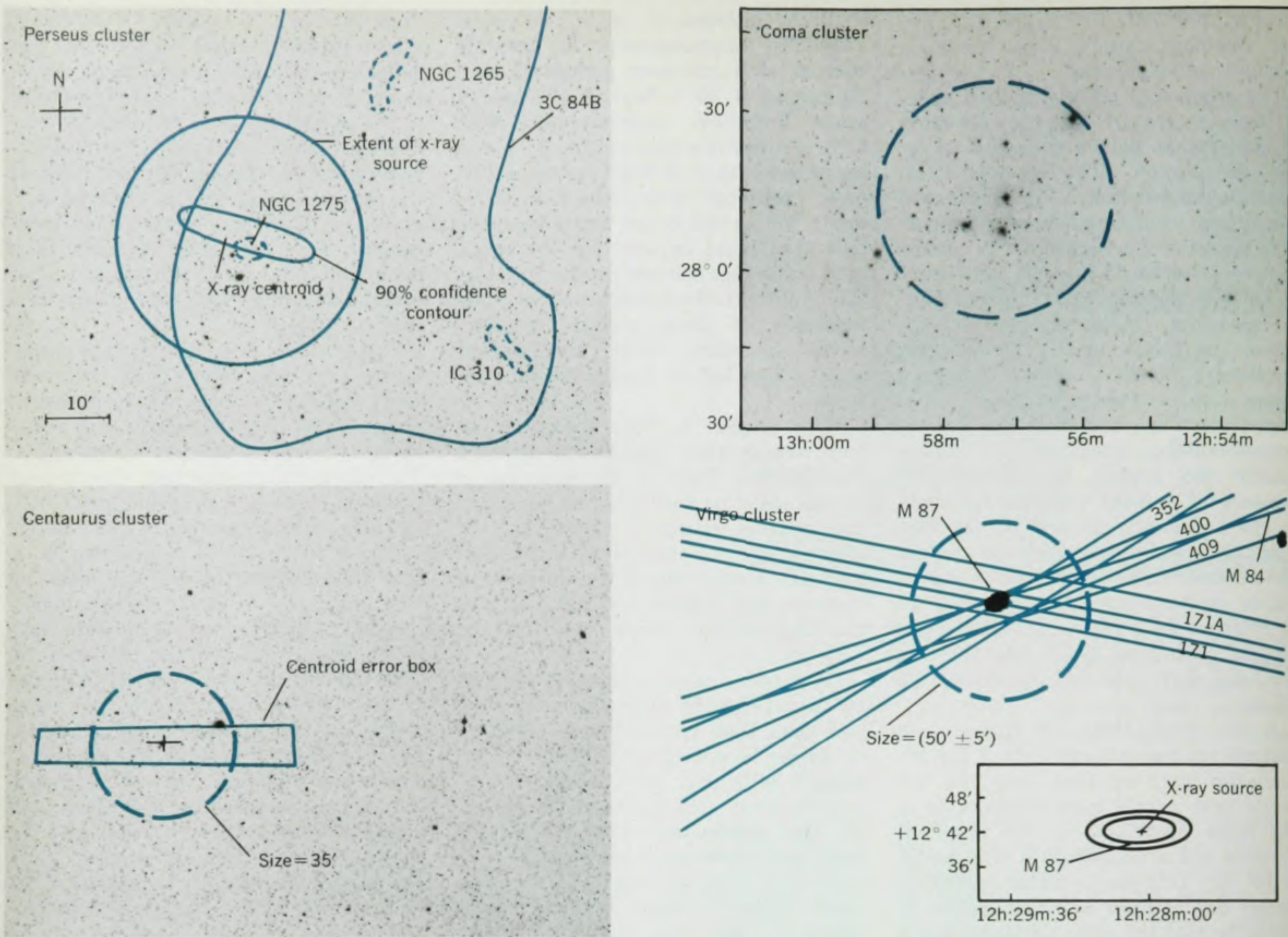
With respect to time variation, we had considerable indications prior to the UHURU flight for the existence of significant time variability in several of the galactic sources.[5] However, the short glimpses obtained with different payloads always raised the question of instrumental effects and did not give the characteristic time scale for the variation.

Of the 65 galactic sources, seven can be identified with supernova remnants, and their flux averaged over a second or longer is not observed to vary, although, of course, NP0532 is known to exhibit x-ray pulsations at 33 m/sec. Of the remainder, more than 60% have been observed to vary on the time scales of 0.1 sec or longer. In only five cases, of the 21 where no variation was observed, was the intensity greater than 10^{-3} Sco X-1; thus, for several it might simply be that we have not yet achieved sufficient precision to determine their variability. The precision of the available locations and this general prevalence of short-time variability excludes the possibility that most of the galactic x-ray sources may be connected with extended supernova remnants. At most, 20% of them may ultimately fall into this category. The remainder must be associated with compact objects.

Considerable progress has been made in the past few years in the study of x-ray emission connected with supernova remnants, particularly with rocket measurements at long wavelengths. The energy source has been determined in the case of Crab to reside, probably, in the rotational energy of the pulsar, which is observed to slow down at a rate sufficient to provide the required 10^{38} erg/sec of energy. A particularly important experiment by Robert Novick[6] has established the existence of polarization of the x-ray radiation, thereby strongly supporting the view that x rays are emitted *via* synchrotron radiation from energetic electrons. The x-ray emission from the diffused nebulae surrounding the older supernovas can apparently be explained as thermal bremsstrahlung emission from gas heated by the transformation of kinetic energy of the shell ejected by the supernova explosion. Satellite experi-



Centaurus A. The optical galaxy NGC 5128 is located within the x-ray source error box. The size of the source is less than 10 arc min. This still allows the x-ray emission to be coming from the inner radio lobes shown in the inset, or from the optical galaxy. The nucleus of the optical galaxy is the most likely location of the source, because it is so strongly cut off at low x-ray energies. Figure 4



The four strongest x-ray sources in clusters of galaxies. In each case, the extent of the source is indicated by the simplest figure, a circle, since we have no information on the shape. The Virgo picture also shows the one-directional locations for the centroid of the extended source obtained from five scans, labelled by the orbit number pertaining to each scan. The inset is the two-dimensional error box obtained by combining the five one-directional locations. The inner contour corresponds to 68% confidence, and the outer contour is for 90% confidence. The Centaurus source, 2U 1247-41, contains NGC 4696 within its centroid error box. The Perseus source contains NGC 1275, the exploding Seyfert galaxy, within the centroid error box. In Coma, both the giant elliptical NGC 4874 and the kinematic center of the cluster lie within the error box. Figure 5

ments have contributed very slightly to the development in the field; therefore, I will concentrate on the new results obtained on compact x-ray sources.

As outlined above, the majority of the sources in our galaxy are characterized by the following properties:

▶ Their luminosity is the range 10^{36}–10^{38} ergs/sec.

▶ The number in the galaxy is exceedingly small; perhaps no more than 100, of which about half have been observed.

▶ The sources in the outer regions of the galaxy are found in the spiral arms.

▶ The sources exhibit large (>2) variability in the 2–20 keV range with time scales ranging from 0.1 seconds to months.

▶ The excitation process by which x rays are emitted favors the production of 2–10 keV photons, or most of the sources are embedded in an absorbing envelope with column density of order of 10^{22} atoms/cm^2 of hydrogen. These last statements stem from the fact that no x-ray source is observed only at energies greater than 20 keV. The flux at $E > 20$ keV is much smaller than in the 1–20 keV region. At most one or two sources are observed only at energies less than 1 keV, a result that cannot be explained on the basis of interstellar absorption.

The preceding comments indicate that the compact x-ray sources are among the most luminous objects in our galaxy and that they are exceedingly rare or represent short-lived x-ray emitting phases in stellar evolution. Thus, one can conceive of very exotic circumstances that could furnish the energy source and the production mechanism for the observed x-ray fluxes.

In several of the sources, however, we are as yet unable to determine the nature of the energy input and of the acceleration or heating mechanism. This includes not only weak unidentified sources for which data may be insufficient, but also some of the strongest and best identified such as Sco X-1, Cyg X-2, GX 17 + 2, and so on.

A notable exception exists, however, in this puzzling situation. One of the most important recent results from UHURU is the discovery of x-ray sources in the binary system. Although we may not yet be able to understand completely all the details of these systems, we have an energy source, accretion, and well defined ideas as to the dimensions and nature of the systems themselves.

Sco X-1-like sources

Sco X-1 was the first x-ray source observed. It was correctly identified in 1966 from positional data only. The optical Sco X-1 has been subject to intensive study since its discovery, as has been reviewed by W. H. Hiltner.[7] As part of the UHURU observing program, more than one week was devoted to correlated x-ray optical studies of this source.

An important characteristic has been

revealed in the infrared region[8]; namely, that the flux density falls off as expected from free-free absorption in the emitting region, from which the size of the emitting region can be inferred as between 10^4–10^5 km, depending on the distance to the object. The observed absence of x-ray line emission is consistent with an object of the size; the lines become broadened and weakened by electron scattering.[9]

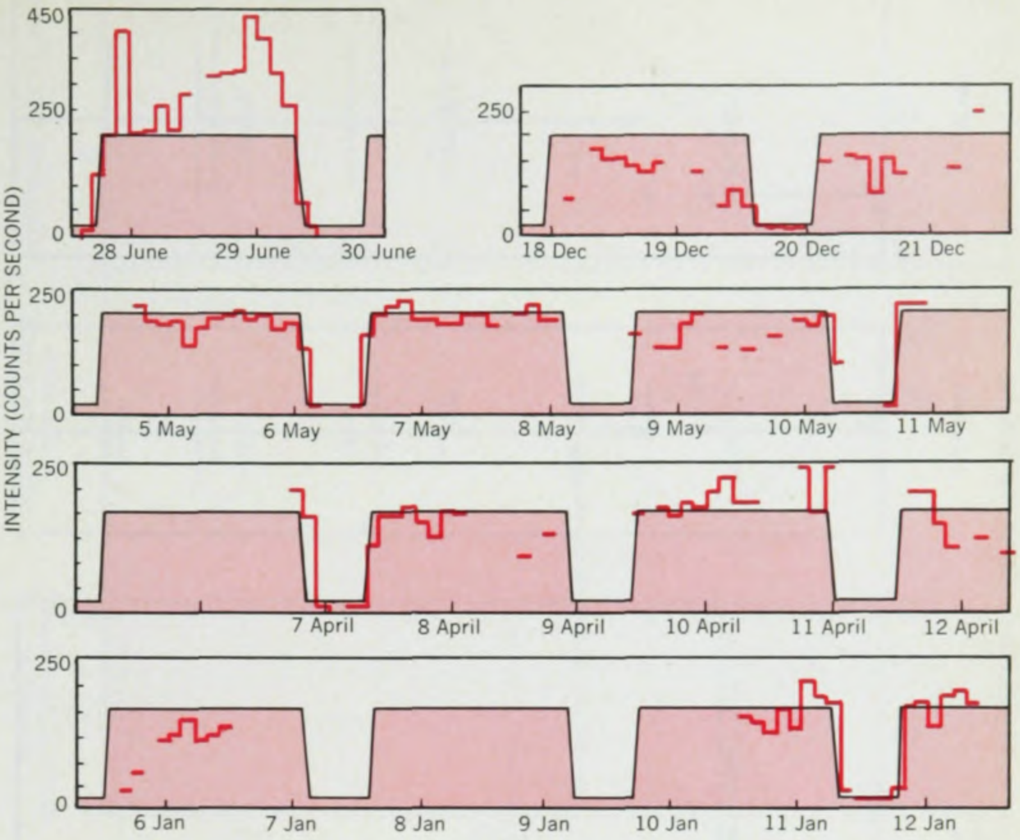
Optically, Sco X-1 varies between 12–13 magnitude. The intensity varies by a few percent on a time scale of minutes (flickering) and flares by a factor of two on a time scale of hours. The spectrum shows a strong continuum plus a number of high excitation emission lines. There is no evidence for a periodic component in the optical intensity or in the Doppler shift of the spectral lines, although the spectral lines do vary in both intensity and position.

In radio, Sco X-1 is the seat of a faint, highly variable radio source radiating from about 0.2 flux units to below present limits of detectability of 0.005 flux units. There are present two weak steady radio sources, several arc minutes on either side of Sco X-1. To a precision of arc seconds the line joining these two sources passes through Sco X-1.[10]

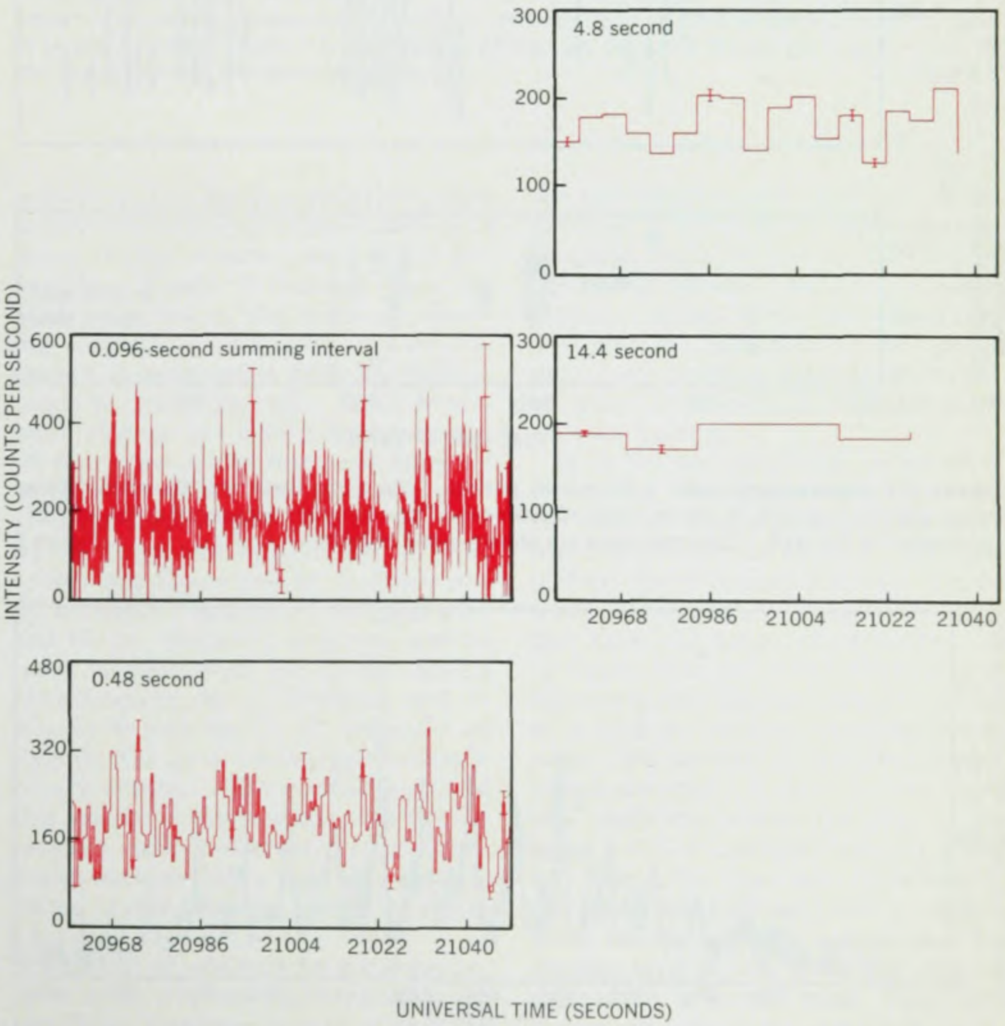
In spite of an enormous amount of observational material, the only information available is on the size of the x-ray emitting region; there is no information on the mass or dimensions of the system.

Cyg X-2 is believed to be similar to Sco X-1, but there is not nearly so much information available concerning it. Its intensity is only about 1/40 of Sco X-1. The optical identification was proposed in 1967,[11] based on the discovery of a star with characteristics similar to that of Sco X-1 within the area of uncertainty of the x-ray source. The distance is estimated to be 500 to 700 pc. Assuming this distance, we estimate the x-ray luminosity to be of order 10^{36} erg/sec; the optical luminosity is lower by a factor of 100 and is dominated by the G-type star. The optical emission from the x-ray region could be, as in Sco X-1, about 10^{-3} of x-ray emission.

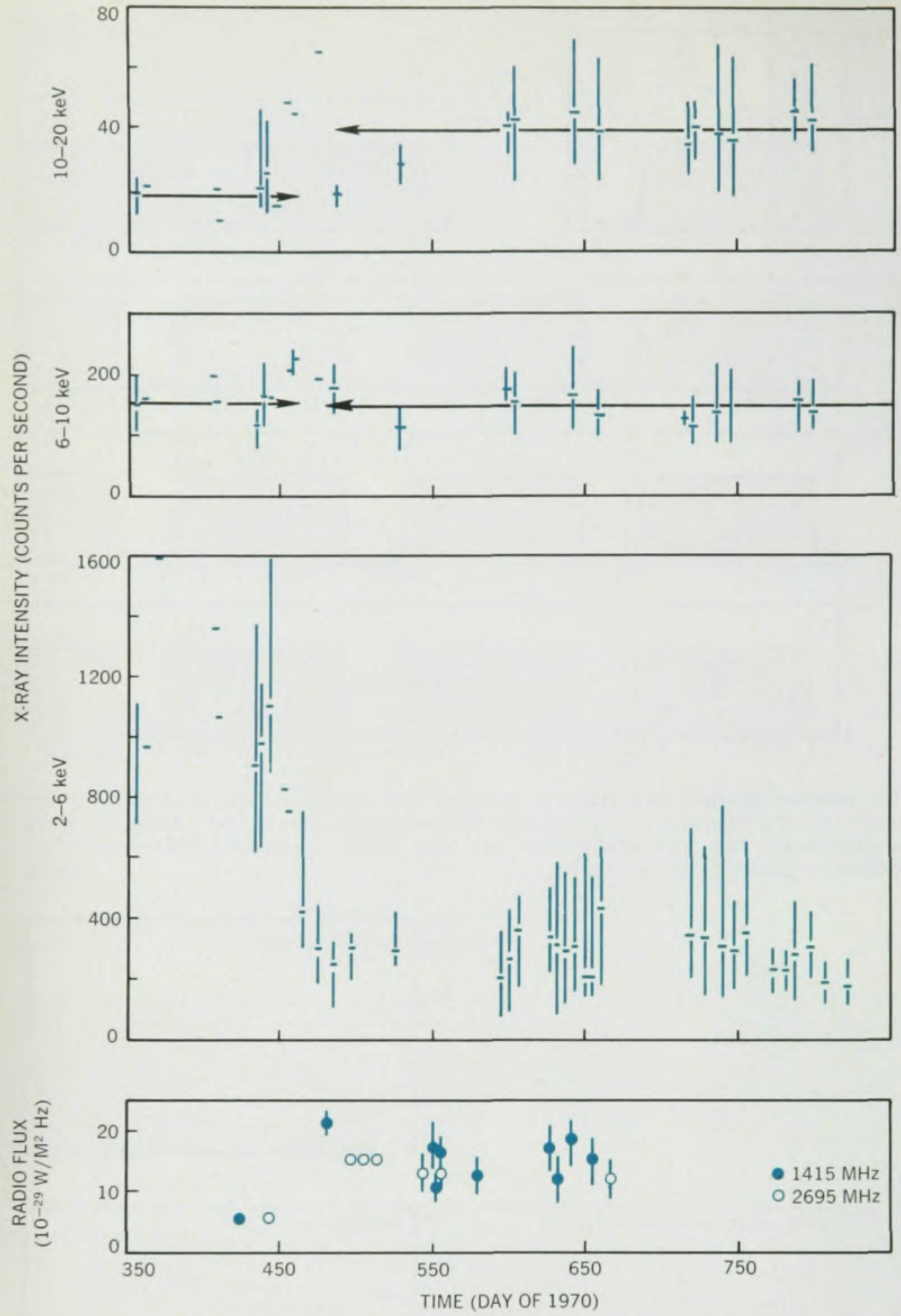
Several other x-ray sources have properties, in terms of the spectrum and variabilities of the x-ray intensity, similar to Sco X-1 and Cyg X-2 (for instance, GX17 + 2); however, there has been no other identification of a similar optical object. If, however, the ratio $L_x/L_{opt} = 10^3$ then this is not so surprising. Sco X-1 and Cyg X-2 are not only bright in x rays, but they are located at high galactic latitude out of regions of high optical obscuration. The visible emission from a source 10^{-2} of Sco X-1 located in the galactic



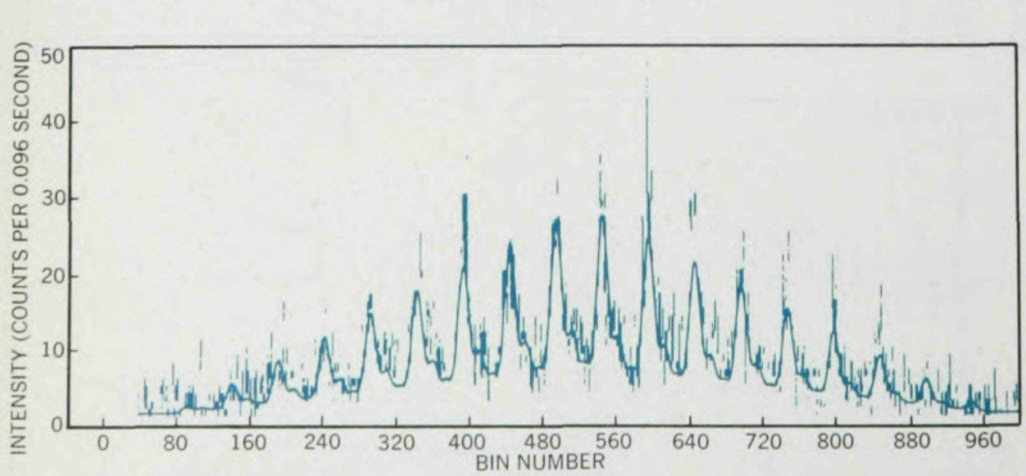
The observed intensity from Cen X-3 averaged over intervals of one tenth of a day and corrected for elevation in the field of view, plotted as a function of time. Statistical errors are not shown; they are typically about 1%. Also shown, by the color tint, is the average intensity predicted by the light curve. Figure 6



Observations of Cygnus X-1 on 10 July 1971, corrected for triangular collimator response. The four versions show data summed over 0.096 sec, 0.48 sec, 4.8 sec and 14.4 sec intervals. Typical one-standard-deviation error bars have been added. Figure 7



Cygnus X-1 observations over a 16-month period. The x-ray data are shown for three energy bands, 2–6 keV, 6–10 keV and 10–20 keV. The transition discussed in the text occurred around day 450. The radio data are shown at the bottom. Figure 8



X-ray variability of Cen X-3. This curve shows the 4.8-sec pulsations as they appear in the raw data (each bin is 0.096 sec). The fitted curve is the result of a Fourier analysis and contains a sine wave and harmonic components. Figure 9

plane would appear to be of 17 m if its optical emission were 10^{-3} of its x-ray emission. With several magnitudes of obscuration, such a star would be hopelessly difficult to find.

X-ray binaries

Some of the observed properties of the known or suspected x-ray binaries are listed below to indicate the degree of certainty or uncertainty surrounding their assignment to this category. We have a total of seven sources for which we have evidence of binary nature.

Cyg X-1—a randomly pulsating x-ray object with extremely rapid intensity variation on the time scale of 50 milliseconds or less. It has been identified with a variable radio source, which in turn leads to an optical identification with a spectroscopic binary of 5.6 days period (HDE226868).

Cen X-3—an eclipsing (2.1 days) periodically pulsating (4.8 seconds) x-ray source. Doppler shifts in the period of pulsation in phase with the 2.1-day occultation period give us, from the x-rays alone, conclusive evidence for binary nature. No radio source or optical counterpart is yet known.

Her X-1—an eclipsing (1.7 days), periodically pulsating x-ray source (1.24 sec). Doppler shifts in the period of pulsation, in phase with occultation period, demonstrated the binary nature. There is recent identification with a 1.7-day-period eclipsing optical binary (NZ Her), but there is no radio identification yet. Her X-1 is the best-known object after the Crab pulsar.

2U(1700-37)—a 3.4-day x-ray eclipsing binary. The suggested candidate star is HD153919 07f^{6m}, on the basis of positional coincidence (similar to Cyg X-1).

2U(0115-73)—a 3.9-day eclipsing x-ray binary. The source is in the Small Magellanic Cloud. Its importance is that we have some idea of its distance, and we can derive a value for the intrinsic luminosity: $L_x \approx 10^{38}$ erg sec^{-1} cm^{-2}.

2U(0900-40)—a variable x-ray source, identified on the basis of positional coincidence with a B-type supergiant that has a companion with period of 9 days (SAO 220767). UHURU data and OSO-7 data confirm periodic behavior with a 9-day period.[12]

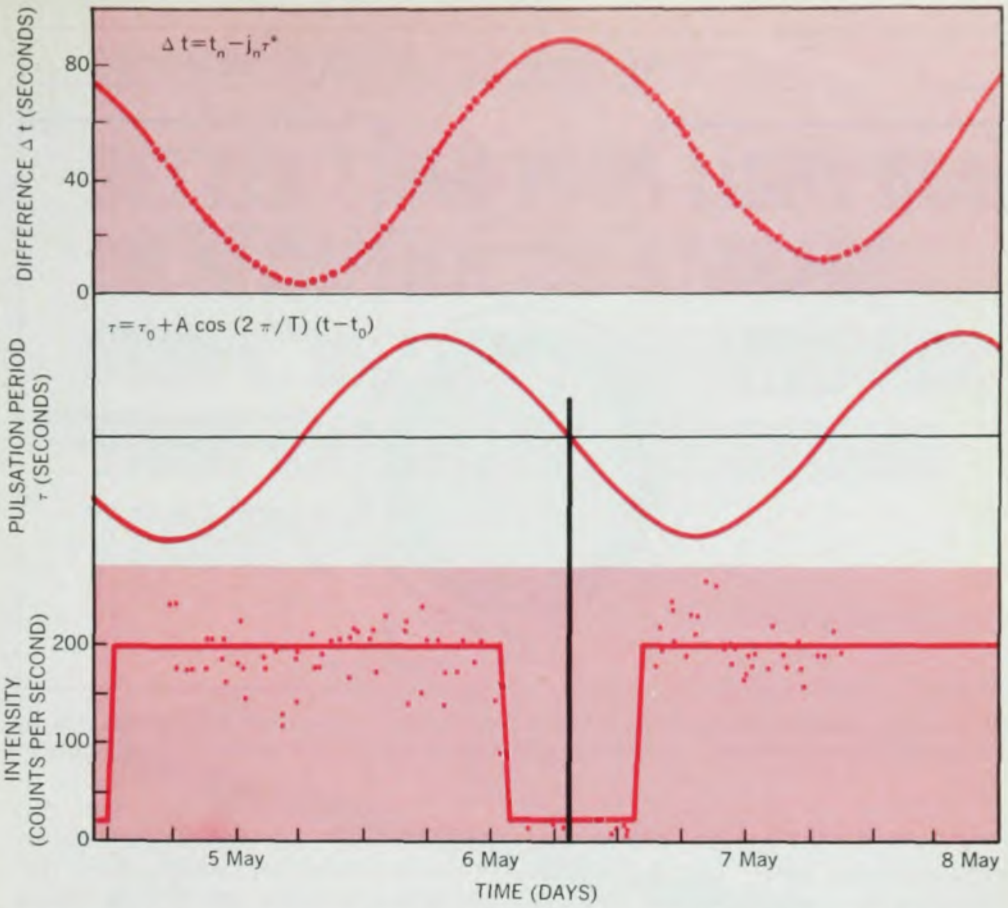
Cyg X-3—a 4.8-hour eclipsing x-ray source or periodically pulsating x-ray source. It has been identified with the source of a giant radio burst on 2 September 1972 on the basis of positional coincidence only.

All of the above sources, with the exception of Cygnus X-1, share a common feature in that they show definite intensity variations periodically recurring over times of the order of 0.2 to 9 days; Cen X-3 was the first source observed to show eclipses in the x-rays. The light curve, derived from observations that have now extended over two years, is shown in figure 6. All sources we have considered as binaries show deep and broad eclipses except for Cygnus X-1. Most of these sources show extreme variability in their x-ray fluxes. Another common feature is their spectral shape and the existence of large and variable low-energy cut-off, except again for Cygnus X-1.

If we consider the seven sources we believe to be binaries, the only one whose spectrum is not cut off is Cyg X-1. This is also the only one that does not occult. If we consider this to be more than a chance occurrence, we may offer a plausible explanation. To view occultation, the observer must be close to the plane of the binary orbit. Furthermore, most of any matter being transferred between the members of the system (as with an accretion disk), as well as any matter leaving the system, will be concentrated in the orbital plane. Thus, low-energy absorption at the source would be most pronounced in the orbital plane and would thus be greatest for the occulting sources. I might also add that C. T. Bolton[13] has recently stated that the Cyg X-1 optical binary candidate does have a rather low inclination, in agreement with the lack of x-ray occultations and thus of low-energy absorption.

To summarize the foregoing: There are a number of x-ray sources that we believe to be binaries either because of their x-ray behavior or because the candidate object has been shown to be a member of a binary system. All of the sources that exhibit eclipses in the x-rays also show very flat spectra and large and variable low-energy cut offs. All sources appear to exhibit large fluctuations in intensity. Periodic pulsations of seconds occur in Cen X-3 and Her X-1, aperiodic fluctuations in times of milliseconds in Cyg X-3, intensity changes in times of seconds or less on 2U1700-37 and in 2U0900-40. This is a very strong indication that x rays originate from compact regions of the order of less than 10^{10} or 10^{9} cm.

When we attempt a more detailed examination of the characteristic of the x-ray emitting binaries, we find that they appear to fall into two different types: irregular pulsating objects, like Cyg X-1, and X-ray pulsars, like Cen X-3 and Her X-1.



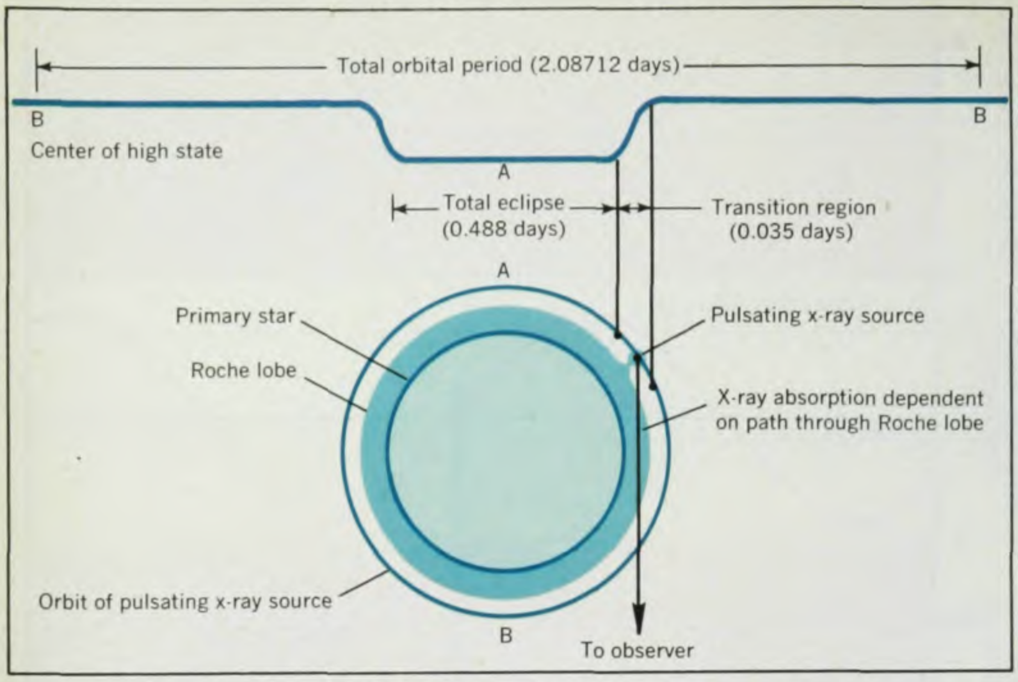
Comparison of the period function and the intensity variation for Cen X-3. The bottom curve shows observed intensity and the light-curve predictions for 5–7 May. At the top, the difference Δt between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. The sinusoid is the best-fit analytic function. In the center is shown the dependence of the pulsation period t on time as derived from the best-fit phase function. Note the coincidence of the null points of the period function with the centers of the high and low intensity states. Figure 10

Cygnus X-1

Perhaps the most significant of the UHURU results for the galactic x-ray sources has been the discovery of pulsations from Cygnus X-1, which led to further study of this object and to the present belief that we are dealing with a black hole. The discovery of the pulsations also led to a search for other rapidly varying x-ray sources leading to many of the results I have been discussing. Figure 7 contains data already reported in the literature showing substantial variations in x-ray intensity on time scales from 100 milliseconds to tens of seconds. Some 80 seconds of data are shown here summed on four time scales from 100 msec up to 14 sec. With the relatively good x-ray location determined by an MIT rocket flight and by UHURU, a radio source was discovered by L. Braes and G. K. Miley[14] and by R. M. Hjellming and C. M. Wade.[15] It is this precise radio location that led to the optical identification, by L. Webster and P. Murdin[16] and by C. T. Bolton,[17] of Cygnus X-1 as a 5.6-day spectroscopic binary system. The central object of this system is a 9th-magnitude BO supergiant, and conservative mass estimates such as $12M_{\odot}$ lead to a mass in excess of $3M_{\odot}$ for the unseen companion.

There is no evidence for a 5.6-day eclipse in the 2–6-keV region, and we believe that previous reports of such an effect at higher energies was caused by the large-scale time variability and not by a 5.6-day effect. This does not rule out the identification, and can be understood in terms of an appropriate inclination angle for the orbital plane of the binary system. Bolton in a recent preprint agrees with this conclusion and presents a refined 5.6-day period that is not in phase with the high-energy x-ray observations, in accordance with our findings.

With the use of UHURU as an observatory, we have now accumulated over 16 months of data on Cygnus X-1, which are shown in figure 8. We have plotted the 2–6 keV intensity against time. The vertical lines for a given day show the range of variability observed on that day. For some days we have only the average intensity shown by a dash available in our analyzed results. We see that a remarkable transition occurred in March and April 1971, with the source changing its average 2–6 keV intensity level by a factor four. We have also indicated in the figure the 6–10 keV and 10–20 keV x-ray intensities, and we see that the average level of the 10–20 keV flux increased by a factor two. The figure also shows that at the same time as the x-ray intensity changed, a weak radio source appeared at the Cyg X-1 location and was detected by the Wester-



An occulting binary x-ray system, shown schematically. It consists of a compact x-ray object orbiting a central star. Numerical data apply to the Cen X-3 system. Figure 11

bork and NRAO groups. Reviewing the arguments then: Cyg X-1 undergoes large intensity changes in times as short as 100 millisecs, so requiring the x-ray emitting region to be compact. The very good x-ray position, plus the correlated x-ray–radio variation, demonstrate the x-ray–radio identification. The optical–radio identification is based on position agreement better than 1 arc second. Then the optical data taken conservatively require at least three solar masses in the unseen companion, which is the compact x-ray source. Thus we have the strong possibility that Cygnus X-1 is a black hole—it is compact and its mass exceeds $3M_\odot$.

Cen X-3 and Her X-1

We come now to two x-ray sources, Cen X-3 and Her X-1, that can be identified as binaries solely from their x-ray properties. The first source is Cen X-3, shown in figure 9. Here we see a regular pulsing source with a period of 4.8 seconds. The histogram shows the actual counts observed and the heavier curve is a sine-wave-plus-harmonics fit to the data. The x-ray emission is at least 90% pulsed with the 4.8-sec period. Figure 10 shows some of the data that demonstrate that Cen X-3 is an occulting binary system. The bottom portion shows three days of intensity data accumulated in May 1971 with a clear-cut downward transition followed by an upward transition about a half-day later. Many such transitions have been observed, and all are fit to a 2.08712 ± 0.00004 day period. By measuring the arrival time of individual 4.8-second pulses we have also determined that the pulsation frequency is Doppler shifted in phase with the 2.097-day occultation cycle, as is shown in the top portion of the figure where the pulse arrival time delays are fit by a sine wave. Under the model of an occulting binary system, we have made very precise determinations of the projected orbital velocity, 415.1 ± 0.4 km/sec, the projected orbital radius $(1.191 \pm 0.001) \times 10^{12}$ cm, and the mass function of the system $(3.074 \pm 0.008) \times 10^{34}$ gm.

Figure 11 is a schematic representation of this system with a compact x-ray object orbiting a central star. We find from the Doppler velocity that the mass of the central star must be at least 15 solar masses, and calculations, such as those of R. E. Wilson[18] for close binaries, lead to masses of the order of a few tenths of a solar mass for the x-ray emitting object. These calculations assume that the sharpness of the occultation means that the radius of the Roche lobe is greater than, or equal to, the size of the occulting region. At present there has not been an optical identification of Cen X-3. Similar, but more precise, information is available on Her X-1, where we also have a positive identification.

Following the suggestion of W. Liller that HZ Her could be a strong candidate object for Her X-1 due to the strong ultraviolet excess and variability, many observations[19,20,21] have definitively established that HZ Her exhibits eclipses in the visible with period and phase in exact agreement with the x-ray observations.

There appears therefore to be absolutely no doubt, on the basis of the 1.7-day eclipse and of a very recent and finer position determination by the MIT group, that the identification is correct. Recently, D. Crampton and J. B. Hutchings succeeded in obtaining measurements of the radial velocities of several lines in the optical spectrum from 3500 to 5000 Å for the visible companion. The radial velocity of the x-ray star is measured from the Doppler effect on the 1.24-second pulsations. Under this condition we can compute the mass of each of the stars in the system. Crampton and Hutchings deduce masses of approximately 2.5 $M_\odot$ for the occulting object and about 1.3 $M_\odot$ for the x-ray emitting object.

W. Forman, C. Jones and W. Liller estimate distances of 2.5 to 4.5 kpc for the source, depending on the spectral type. This corresponds to an x-ray luminosity of about 10^{36} ergs/second, although this could decrease to 10^{35} ergs/sec by accounting for the limited solid angle that the pulsed source fills. We have analyzed the x-ray period for December 1971, January 1972, March 1972 and April 1972, and can set an upper limit of 2 microsec change (slowdown) in period in four months. For a one-solar-mass neutron star of 10-km radius, the rotational kinetic energy is 2.5×10^{44} ergs, and with our upper limit on the period slowing down we find that only 2.5×10^{32} ergs/sec could be converted into x-rays by a 100% efficient mechanism if the source were slowing down at the determined upper limit rate. This, then, demonstrates that rotation cannot be the energy source, and one turns to accretion as the most likely alternative energy source, with rotation still presumably providing the clock mechanism.

Some conclusions

Several significant results have come about from the UHURU mission that have greatly expanded the scope of galactic and extragalactic x-ray astronomy.

In extragalactic research we may have the beginning of an explanation for the diffused x-ray background. We may have detected the presence of high-temperature, intercluster gases. The relationship of the mass and temperature of this gas to other cluster parameters, as determined by visible-light observations of the galaxies in the cluster, may furnish us a tool with which to study cluster dynamics and to investigate evolutionary effects of cluster matter at redshifts of cosmological significance.

In galactic x-ray astronomy, the discovery of x-ray sources in binary systems gives us some understanding of the mechanisms (accretion) leading to the production of copious x-ray fluxes in stellar objects. Because the systems contain massive luminous stars, optical identifications are relatively straightforward and, thus, we can determine distances and absolute luminosities.

When such identifications occur, we have available a radial velocity for the x-ray star, directly from the x-ray data, and for the massive companion from the Doppler shift of the visible-light emission or absorption lines. We also have additional information from the length of the occultation. We can, therefore, determine the masses of both objects and thus we can distinguish between different possible compact objects, such as white dwarfs, neutron stars and black holes. We are indeed very fortunate that exotic objects of such great astrophysical significance may be located in binary systems where we can conveniently study them.

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This article is adapted from a talk given at the Sixth Texas Symposium on Relativistic Astrophysics, New York, last December.

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