2. UHURU RESULTS ON GALACTIC X-RAY SOURCES

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Abstract. Galactic X-ray sources studied by UHURU can be classified into several categories, including supernova remnants, transient or nova-like sources, Sco X-1 like sources, and pulsating sources. The latter are discussed in some detail with particular emphasis upon the characteristics of the periodic binary X-ray sources, Cen X-3 and Her X-1. It is suggested that all galactic X-ray sources (except S/N remnants) may be binary systems.

1. Introduction

The UHURU satellite has now been scanning the sky for seventeen months. The satellite was built by American Science and Engineering and the Applied Physics Laboratory of Johns Hopkins University for NASA's Goddard Space Flight Center. The original objectives of the satellite were an all sky survey down to a sensitivity of 10^{-4} Sco X-1 designed to locate stronger sources to 1′, the study of source spectra from 2–20 keV using proportional counters and 8 channels of pulse height analysis, and a search for time variability. Recently the UHURU group at American Science & Engineering generated a catalog of some 125 X-ray sources (Giacconi *et al.*, 1972). The first figure shows the distribution of these sources on the sky plotted in galactic coordinates. Approximately 35 of the sources were known before UHURU and about 90 new sources have now been found. The sources range from an intensity of $\sim$20/000 cts s^{-1} for Sco X-1 down to about 2 cts s^{-1} for the source identified with M31 (Andromeda). Note that coverage off the galactic plane is incomplete at present – we have analyzed only some 70 days out of 200 spent scanning the sky.

This paper is concerned with the nature of the galactic X-ray sources while the paper by Dr. Kellogg will discuss extragalactic sources. For the galactic sources the most exciting impact of the UHURU satellite has been the discovery of widespread time variability. In several cases, we have found intensity changes of factors of 2 or more in times of seconds or less, requiring the X-ray sources to be compact. With the satellite we have for the first time been able to conduct detailed precise measurements on a number of the galactic sources.

After a brief description of the X-ray emission of our galaxy as a whole, I would like to discuss the evidence for a working hypothesis that the galactic X-ray sources (except for the supernova remnants) are in fact binary systems. The first to consider the possibility of binary systems being X-ray sources were Hayakawa and Matsuoka in 1964 and the others since are too numerous to list here. Along these lines, I will discuss the general properties of sources similar to Sco X-1 (called Sco X-1-like sources) and then in some detail the properties of 3 pulsating sources showing evidence of a binary nature. Then I would like to discuss some new results on 2 objects – GX263+3 (2U0900−40) and the X-ray source in the Small Magellanic Cloud (2U0115−73)

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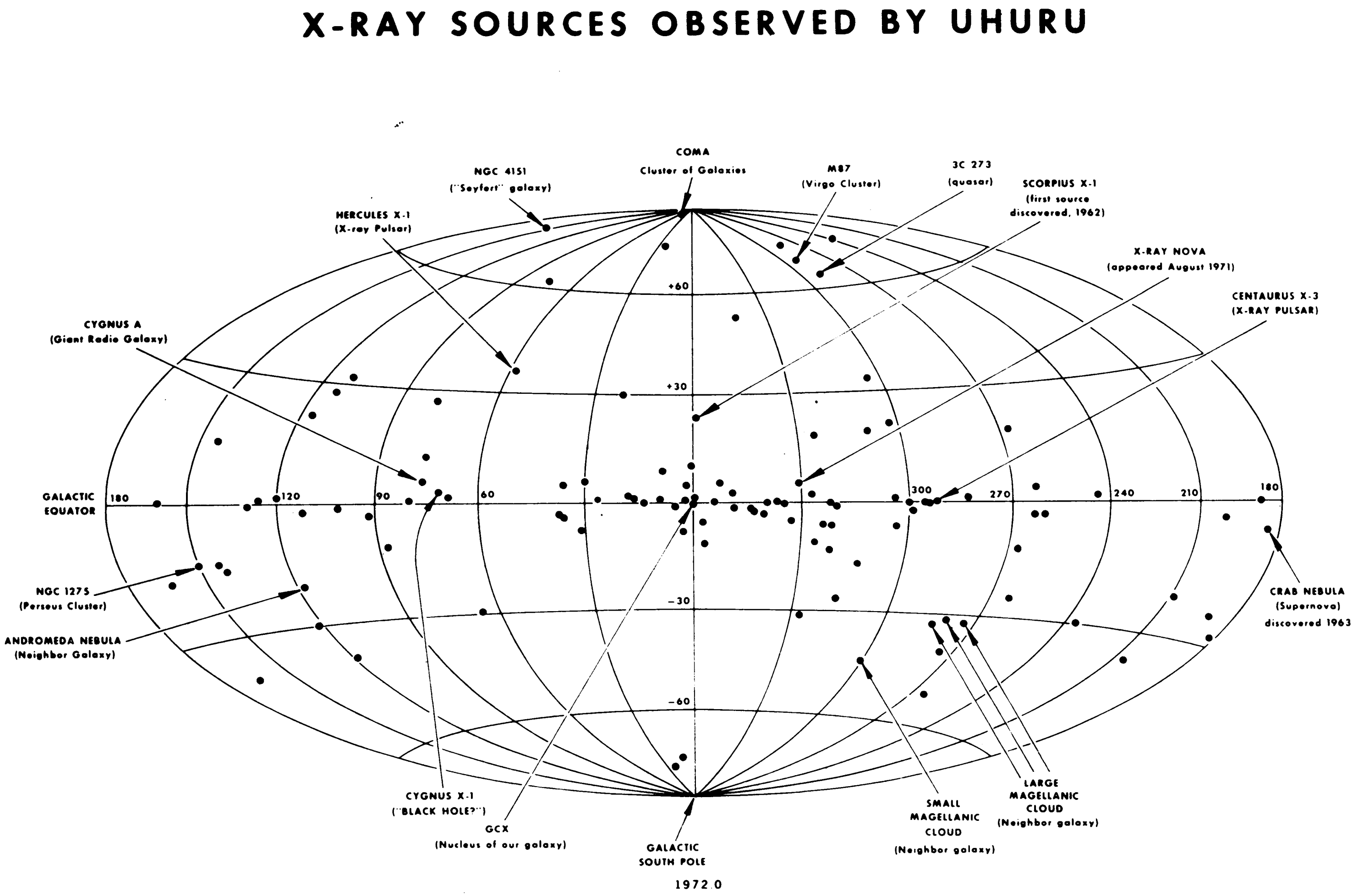

Fig. 1. The X-ray sky as seen by UHURU. Circles indicate X-ray source locations; many of the X-ray sources are labelled. The map is an equal area projection in galactic coordinates.

which both show evidence of a binary nature, yet have some of the properties of the Sco X-1-like objects. These links between the Sco X-1-like objects and the pulsating, binary sources are what lead to the suggestion that all of the galactic X-ray sources (except S/N remnants) may in fact be binaries.

2. The Galaxy as a Whole

When we turn to the X-ray emission from our galaxy we consider first the number versus intensity curve which is shown in Figure 2. We have plotted here for sources within 20° of the galactic plane the number of sources brighter than a given intensity versus intensity with the data corrected for sky coverage. The actual number of sources observed to date within 20° of the plane is 81. The most striking feature of the curve is the difference between the observed slope of the distribution – approximately 0.4 – and a slope of 1 expected for a uniform disk distribution of equal luminosity sources. The much flatter observed slope indicates that we are seeing essentially all of the bright sources in our galaxy and that there is a spread in intrinsic luminosities. Recent work by the Livermore group (Seward *et al.*, 1972) and to a lesser extent by the UHURU group has attempted to determine intrinsic luminosities by measuring low energy cutoffs of sources and assigning distances. This leads to the result that several sources in the direction of the galactic center have a luminosity of order 10^{38} ergs s^{-1}, comparable to the intensities found for 3 sources in the Large Magellanic Cloud (to which

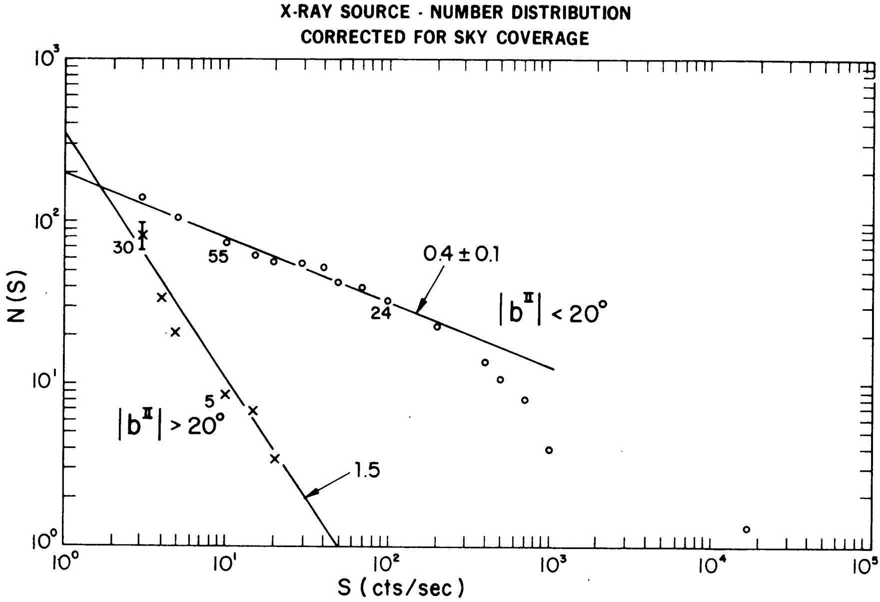

Fig. 2. X-ray source number distribution as a function of intensity. The number of sources brighter than a given intensity are plotted versus intensity. The sources are divided into 2 groups, those within 20° of the galactic plane and those more than 20° away from the galactic plane.

we know the distance). Many of the other sources can be assigned distances placing them in the various spiral arms of the galaxy. Taken altogether we get a luminosity of order 2×10^{39} ergs s^{-1} for our galaxy, which is comparable to the luminosity which we observe for M31.

3. Classification of X-Ray Sources

Passing on to the nature of individual galactic X ray sources, I will not discuss sources which can be identified with supernova remnants. These will be discussed in a paper by Dr Pounds. Also I will not dwell upon the transient or nova-like sources which have been reported in the literature – Cen X-2, Cen X-4, and more recently from UHURU, 2U1543−47. I would like to point out that the UHURU data on 2U1543−47 show outbursts following the initial appearance of the source and sudden changes in the spectrum. This appears to rule out simple models involving a blast wave or the expansion of a hot gas. Also the absence to date of an optical counterpart, in spite of the small location uncertainty, means that either the object is underluminous for an optical nova or that its distance is of order 10 kpc, producing optical obscuration, and implying an energy of 10^{39} ergs s^{-1} for the X-ray emission.

For the bulk of the galactic sources, based on the observation of large scale time variations, we have previously divided the sources into Sco X-1-like and pulsating. The Sco X-1-like sources show intensity changes of order 50% on time scales of minutes to hours. Their spectra are exponential suggesting thermal bremsstrahlung, and their temperatures vary on the same time scale as the intensity, ranging from 50 to 150 million degrees. Two of the objects, Sco X-1 and Cyg X-2, have similar optical counterparts – blue stars with UV excess, variable intensity – flicker and flare, complex line emission and absorption, and overall electromagnetic emission dominated by the X-rays. Despite several years of study, the behavior of these stars is sufficiently complex that at present we are unable to answer, either way, whether they are binary systems. Sco X-1, GX17+2 and GX9+1 also have similar radio counterparts – highly variable, weak sources. These objects will be discussed in much greater detail in the papers on optical and radio counterparts and coordinated observations.

Turning to the pulsating X-ray sources we find they are dominated by intensity changes of factors of 2 or more on time scales of seconds or less. The spectra tend to be flat and are often cut off at low energies. There is considerable evidence linking a number of these sources to binary systems. In the following sections I present some of the results for these sources.

4. 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. I would like to present the data we have on this object and consider the status of the black hole identification. Figure 3 contains data already reported in the literature (Schreier *et al.*,

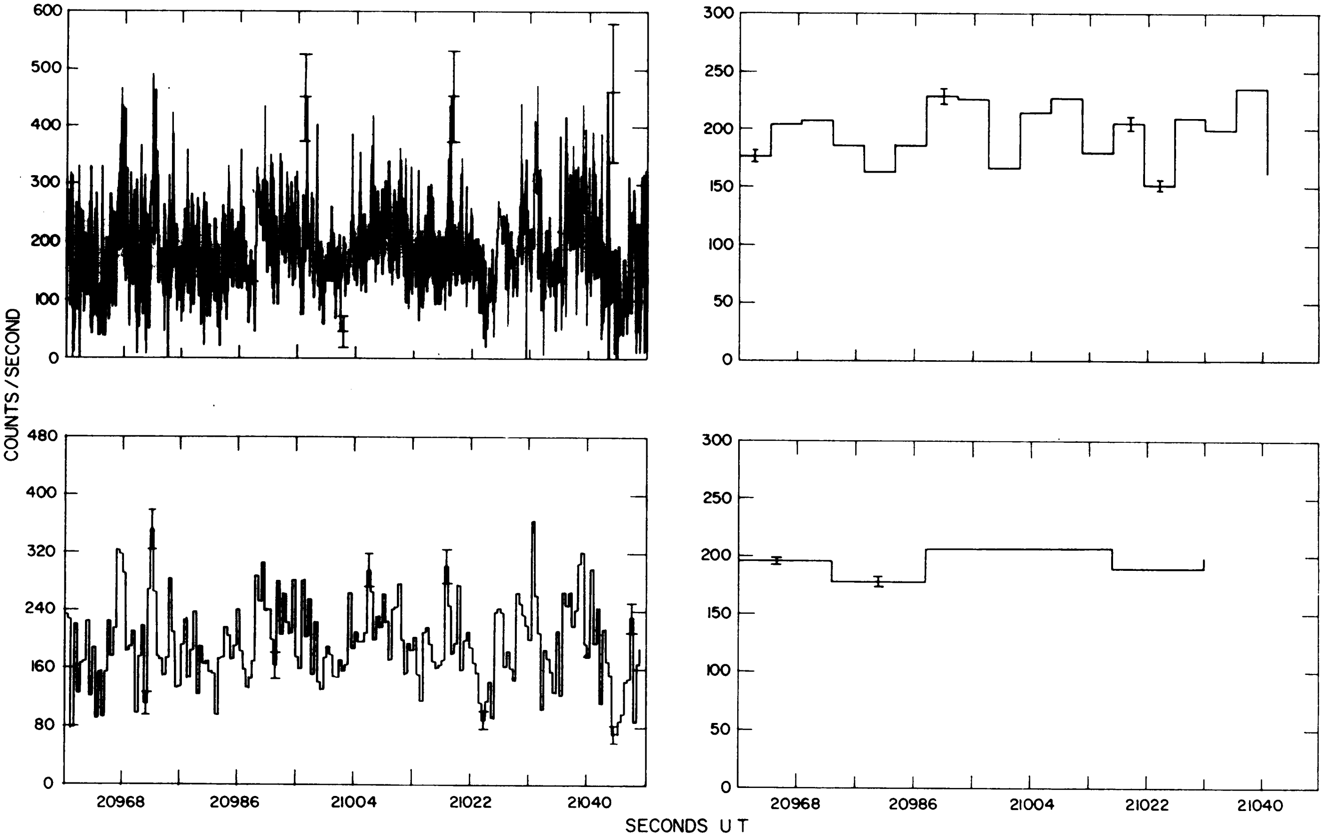

Fig. 3. Observation of Cygnus X-1 on 1971 June 10. Data have been corrected for triangular collimator response. Data are summed over 0.096 s, 0.48 s, 4.8 s, and 14.4 s intervals. Typical 1σ error bars are shown (Schreier *et al.*, 1971).

1971) showing substantial variations in X-ray intensity on time scales from 100 ms to 10's of seconds. Some 80 s of data are shown here summed on 4 time scales from 100 ms up to 14 s. I should point out that similar X-ray variability also reported by scientists at MIT, (Rappaport *et al.*, 1971a), Goddard Space Flight Center (Holt *et al.*, 1971) and Naval Research Laboratory (Shulman *et al.*, 1971) requires us to consider compact objects smaller than 10^9 cm for the X-ray source. With the relatively good X-ray location determined by an MIT rocket flight (Rappaport *et al.*, 1971b) and by UHURU, a radio source was discovered by Braes and Miley (1971) and by Hjellming and Wade (1971). It is this precise radio location that led to the optical identification by Webster and Murdin (1972) and by Bolton (1972) 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 12 $M_\odot$ lead to a mass in excess of 3 $M_\odot$ for the unseen companion. If the companion is the compact X-ray source then it could be a neutron star more massive than previously considered or it could be a black hole.

We attempted to confirm the identification by looking for a 5.6 day effect on the X-ray light curve. In December 1971 and January 1972 we observed Cygnus X-1 continuously for 35 days. We folded the X-ray data with many different periods including 5.6 days and the results are shown in Figure 4. Data are shown folded modulo 3.0, 5.6, and 6.2 days, the average is indicated by the dotted lines, and 2.0 σ error bars are indicated by the solid lines. We conclude that there is no evidence for a 5.6 day eclipse here, and believe that previous reports of such an effect at higher energies were caused by the large scale time variablility 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.

With the use of UHURU as an observatory we have now accumulated 16 months of data on Cygnus X-1 which are shown in Figure 5. We have plotted the 2–6 keV intensity vs. day of 1970. 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 of 4. We have also indicated in the figure the 6–10 keV and 10–20 keV X-ray intensities and see that the average level of the 10–20 keV flux increased by a factor of 2. The figure also shows that at the same time the X-ray intensity changed, a weak radio source appeared at the Cyg X-1 location and was detected by the Westerbork and NRAO groups. It is this correlated X-ray – radio behavior that I believe is a most important experimental link in the identification of Cyg X-1 as a black hole.

Reviewing the arguments then, Cygnus X-1 undergoes large intensity changes in times as short as 100 ms requiring the X-ray emitting region to be compact. The very good X-ray position plus the correlated X-ray – radio variation shown in Figure 5 demonstrate the X-ray – radio identification. The optical-radio identification is based on position agreement better than 1″. Then the optical data taken conservatively require at least 3 solar masses in the unseen companion which is the compact X-ray

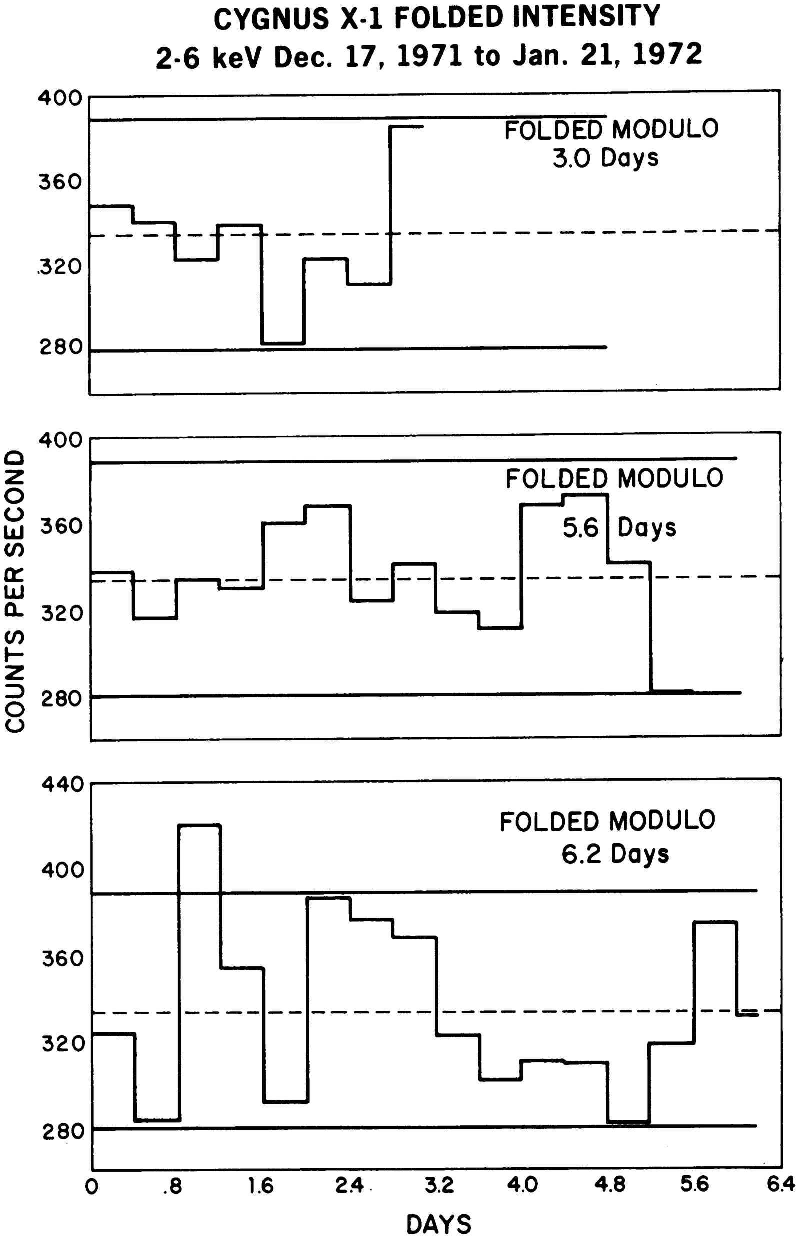

Fig. 4. Cygnus X-1 folded intensity, 17 Dec. 1971 to 21 Jan. 1972. 35 days of 2–6 keV data are shown folded modulo 3.0, 5.6, and 6.2 days. The dotted lines give the average intensity and the solid lines are 2σ error bars.

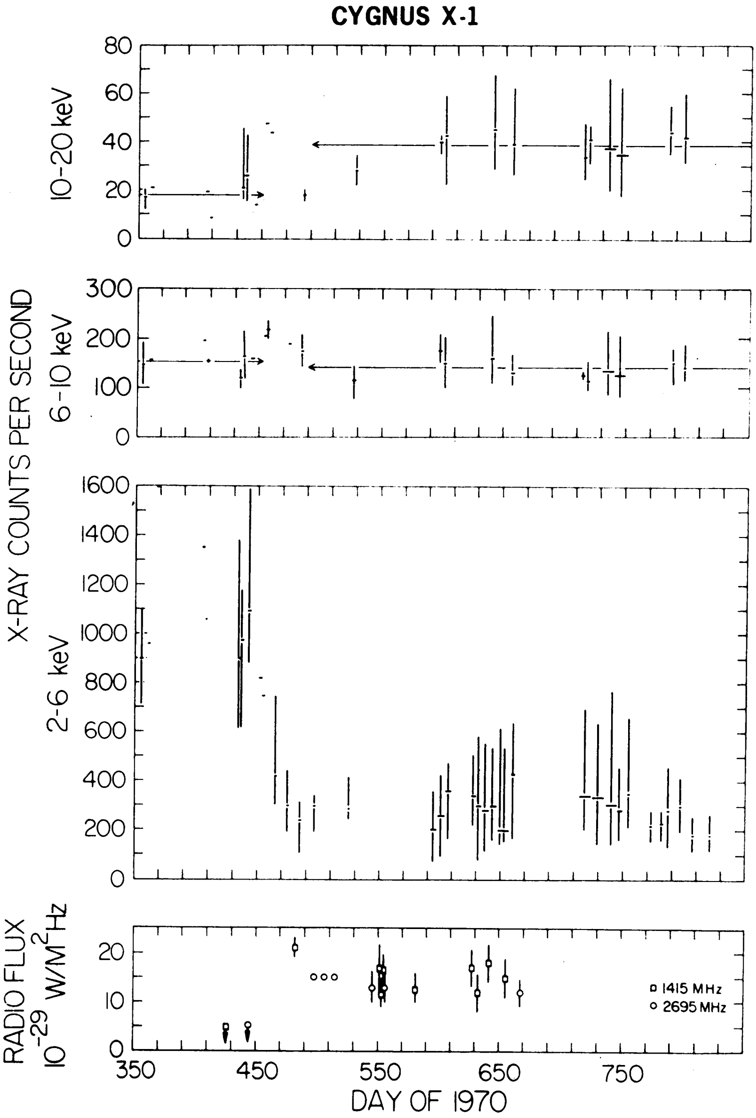

Fig. 5. 16 months of observations of Cygnus X-1. X-ray data are shown for 3 energy bands, 2–6 keV, 6–10 keV, and 10–20 keV plotted vs. day of 1970. The transition discussed in the text occurred in the period near day 450. The radio data are shown at the bottom of the figure.

source. Whether this object could be a massive neutron star or must be a black hole, is a subject more appropriately discussed by the theoreticians.

5. Centaurus X-3 and Hercules X-1

We now come to 2 X-ray sources, Cen X-3 and Hercules X-1, which are identified as

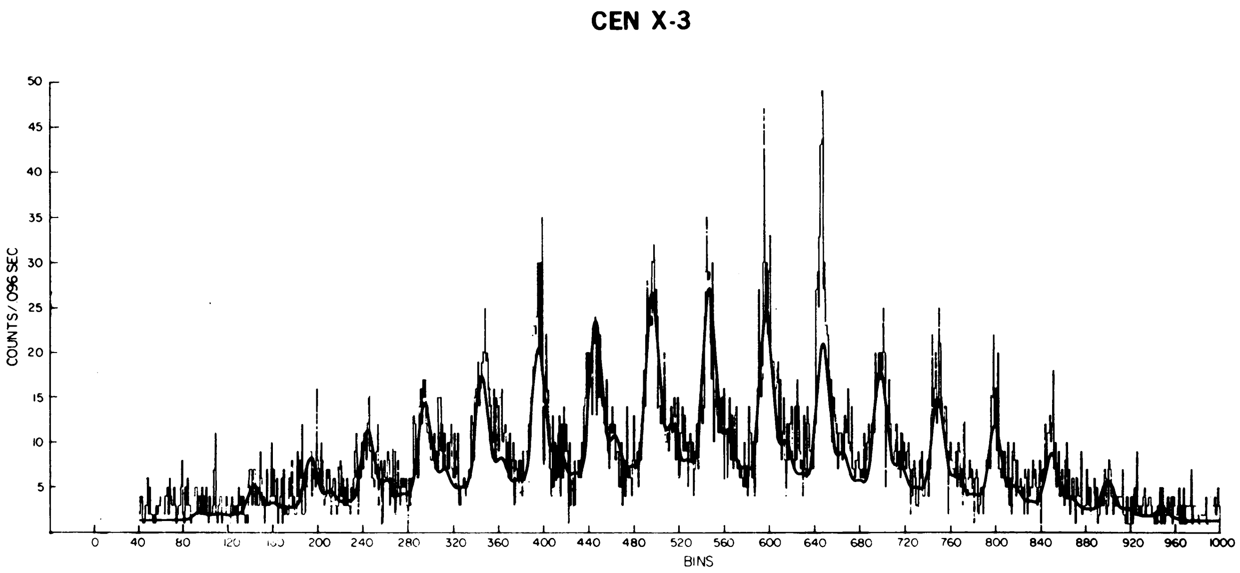

Fig. 6. Counts accumulated in 0.096 s bins from Cen X-3 during a 100-s pass on 7 May 1971. The functional fit obtained by minimizing x^2 is shown as the heavier curve (Schreier *et al.*, 1972, *Astrophys. J. Letters* **172**, L79.)

binaries solely from their X-ray properties. The first source is Cen X-3 which is shown in Figure 6. Here we see a regular pulsing source with a period of 4.8 s. 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 s period. Figure 7 shows some of the data that demonstrate that Cen X-3 is an occulting binary system. The bottom portion shows 3 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 s pulses we have also determined that the pulsation frequency is Doppler shifted in phase with the 2.087 day occultation cycle as is shown in the top portion of the figure where the pulse arrival

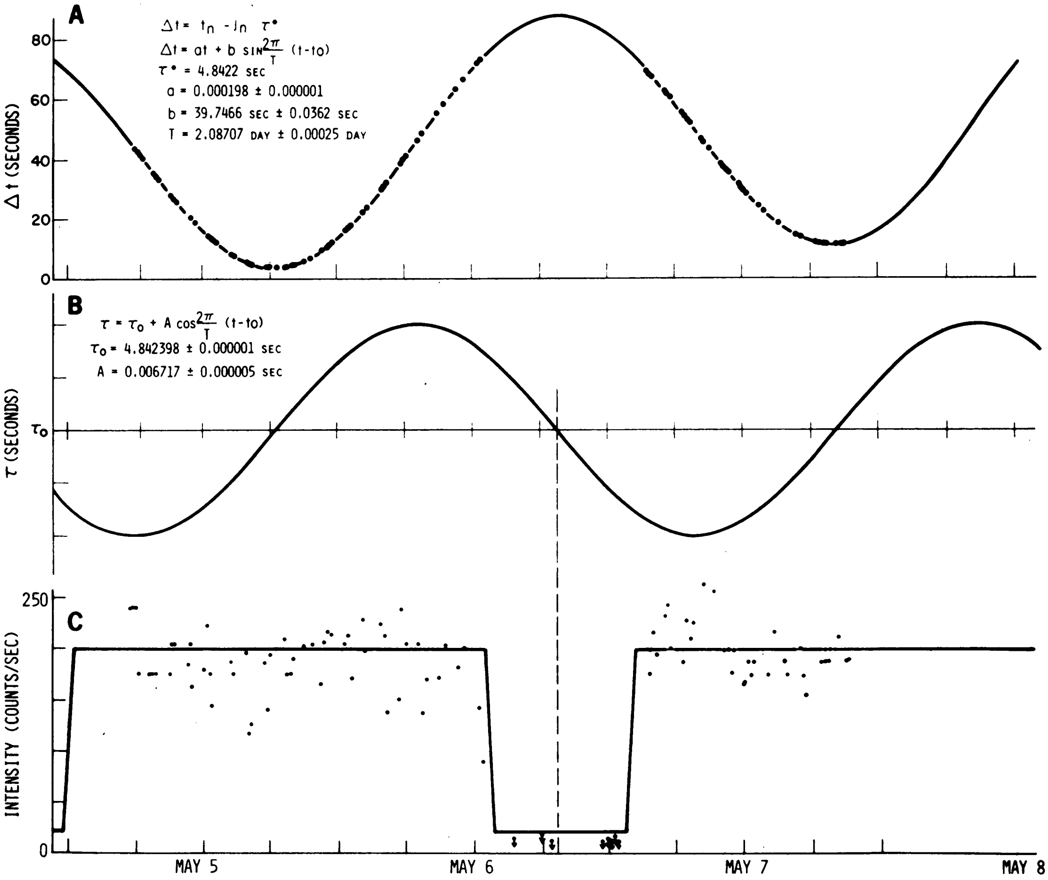

Fig. 7. Bottom: The intensity observed from Cen X-3 (dots) and the light curve predictions for 5–7 May. Top: The difference Δt between the time of occurrence of a pulse and the time predicted for a constant period, plotted as a function of time. A best fit function and the values of the parameters are given. Center: The dependence of the pulsation period τ 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 (Schreier *et al.*, 1972; see caption Figure 6).

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 s^{-1}, 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 8 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 $M_\odot$ and calculations such as those of R. E. Wilson (1972) for close binaries lead to masses on the order of a tenth 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. Figure 9 shows an improved location box for Cen X-3 with an 8 square minutes of arc area. At present there has not been an optical identification of Cen X-3, although several candidates have been suggested including the binary LR Cen which has now been shown not to be the X-ray source.

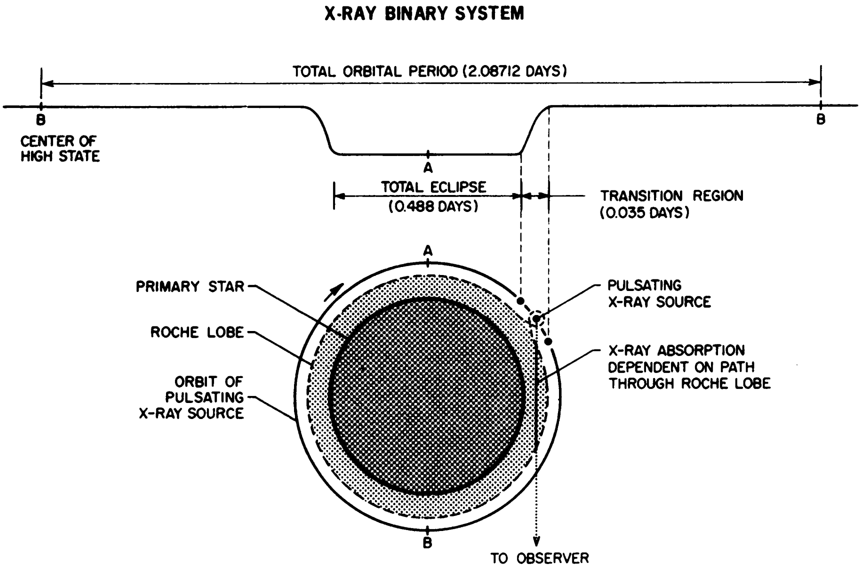

Fig. 8. Schematic representation of occulting binary X-ray system.

Figure 10 shows the pulsating source in Hercules (2U1705+34). This source pulses with a 1.24 s period and as for Cen X-3 is essentially totally pulsed. In Figure 11, we see a schematic representation of the light curve for this source. The heavier lines represent all of the data taken on the source from its discovery in November 1971 through March 1972. The source shows a 1.70017 ± 0.00004 day occultation cycle indicated by the dotted curve with many cycles now observed. The data show a further periodicity. For 9 or 10 days the source is intense and pulsing and can be seen following the 1.70 day occultation cycle. Then for 26 days the source is too weak to be observed. We have now observed 6 cycles of this 35.7 periodicity, the most recent being

Fig. 9. 90% confidence location box for Cen X-3 superimposed on plate taken by Liller and Elliot. During the exposure the plate was oscillated circularly with the 4.8 s period of Cen X-3.

during the past few weeks. Several models have been proposed to explain this 35.7 day cycle; the two currently under consideration are:

(1) A 35.7 day period pulsation of the central object so as to embed the X-ray source in its atmosphere and absorb the X rays for 26 out of every 35.7 days.

(2) Instabilities in the atmosphere of the central star near its Roche lobe. This model assumes accretion onto the X-ray star as the energy source; when the Roche lobe is no longer filled, the energy source is effectively turned off until the atmosphere of the central star again fills the Roche lobe.

For this X-ray source we again observe a Doppler shift of the 1.24 s pulsations in phase with the 1.700 day cycle. We find a projected orbit velocity of 169.2 ± 0.4 km s^{-1}, a projected orbital radius of $(3.95 \pm 0.01) \times 10^{11}$ cm, and a mass function of $(1.69 \pm 0.01) \times 10^{33}$ gm. Since the duration of the occultation is shorter than for Cen

X-3, calculations such as those of Wilson (1972) mentioned earlier, lead to maximum masses from 0.2 to 3.0 $M_\odot$ for the X-ray source and 1.2 to 3.2 $M_\odot$ for the central object assuming 90° inclinations. A search is presently underway for the optical counterpart for this source.

I would also like to point out here that these X-ray measurements of velocities, radii, masses, and pulsation frequencies compare favorably with the precision of most ground based measurements.

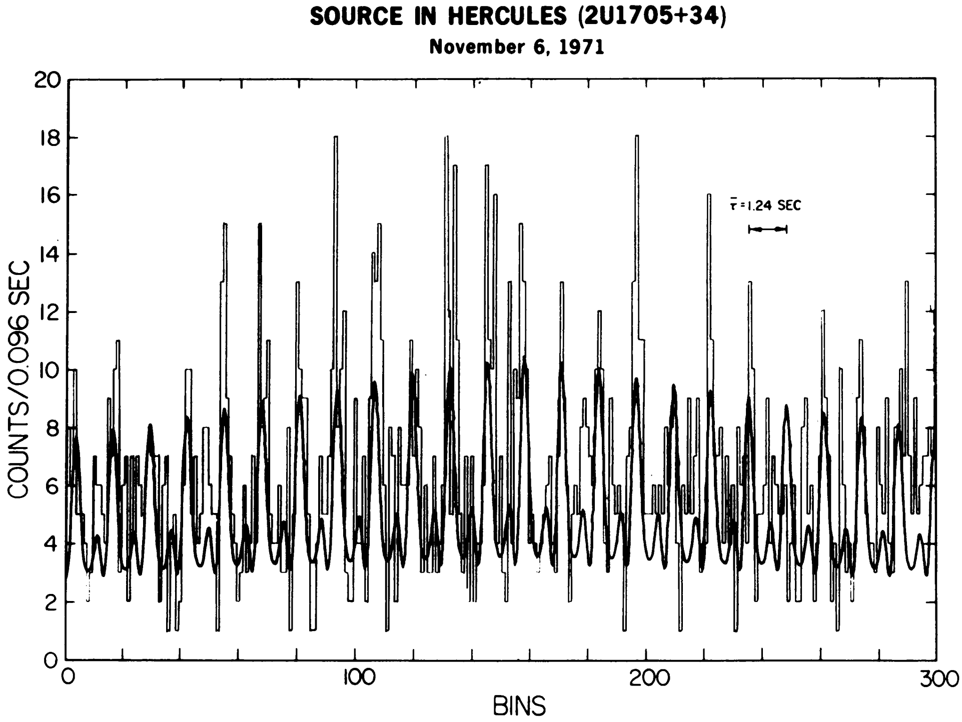

Fig. 10. Counts accumulated in 0.096-s bins from Hercules X-1 during the central 30 s of a 100-s pass on 6 Nov. 1971. The heavier curve is a minimum x^2 fit to the pulsations of a sine function, its first and second harmonics plus a constant, modulated by the triangular response of the collimator (Tananbaum *et al.*, 1972, *Astrophys. J. Letters* **174**, L143.)

6. GX263+3 (2U0900−40)

Still another candidate for identification with a binary system is the X-ray source GX263+3 (2U0900−40). Figure 12 shows the location information for this source; the outer box is the 2U catalog location, the inner box is a 4 sq. minutes of arc location obtained recently using additional UHURU data. The 6.7 magnitude BO supergiant originally suggested by Kellogg and Murray (1971) and by Bradt and Kunkel (1971) for this identification is shown in the center. This star has been studied by Brucato and Kristian (1972) who found it to have a variable velocity suggesting a binary and to be

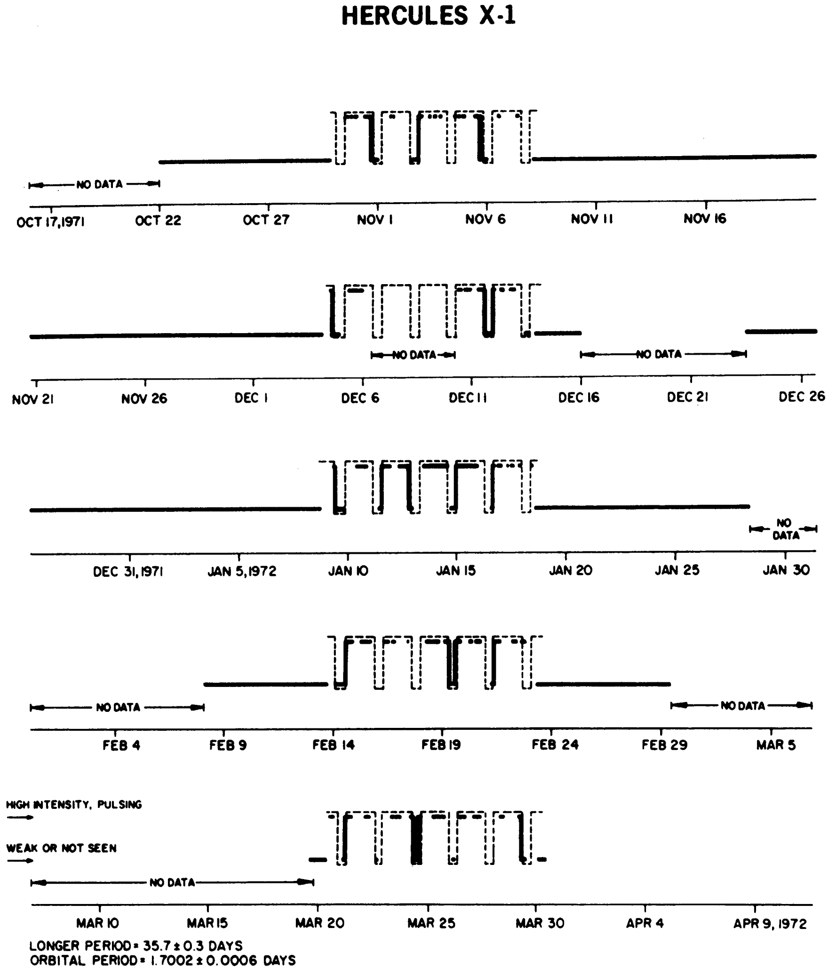

Fig. 11. The heavier line represents schematically the observations of Hercules X-1 as either high intensity pulsed sighting or as weak or not observed sightings. Short term breaks are due to blocking of the source by the Earth or due to dropouts in Quick Look data transmission. Intervals where the satellite was oriented so as not to scan the Hercules source are marked 'no data'. The lighter dashed curve shows a single 1.700-day period fit to all of the observations. Each row in the figure has a duration of 35.7 days and the regular occurrence of the 9-day high intensity pulsed intervals demonstrates the 35.7 day cycle. (Tananbaum *et al.*, 1972 – see caption Figure 10).

at a distance of about 1.3 kpc. Very recently the star was found to be a 7.0 day spectroscopic binary by Hiltner and Osmer (1972) and is reported to have emission lines similar to Cygnus X-1. We are presently observing the source to search for any 7.0 day effects on the X-ray emission.

As an X-ray source, the 2U catalog reported observations of 2U0900−40 ranging from 25 to 75 counts s^{-1}. Analysis of some additional data gives us the results shown in Figure 13 where we have a half day's data with X-ray intensity from 2–6 keV plotted

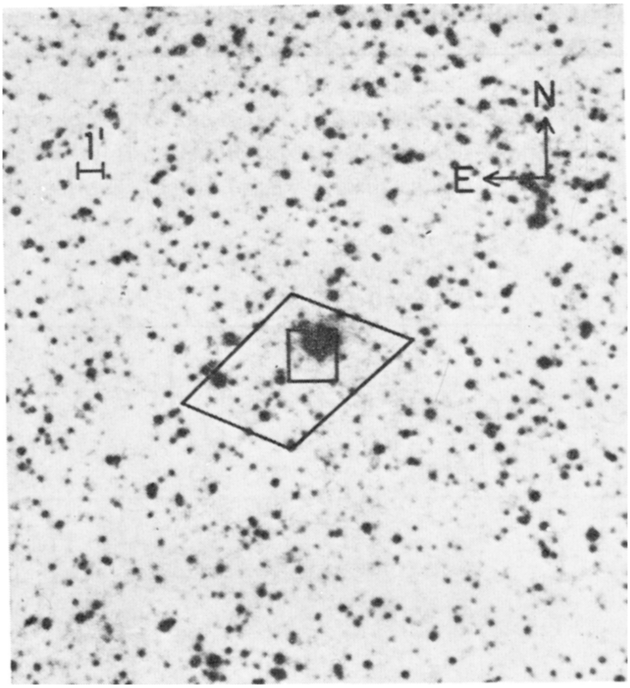

Fig. 12. 90% confidence location box for 2U0900–40 (GX263 + 3). The outer box is the published 2U location and the inner box a more recent determination from additional UHURU data. The 6.7 magnitude BO supergiant suggested for the identification is the bright star shown in the center.

vs. time for this X-ray source. We see that the source intensity changed by a factor of 30 in 2 hr time and that other intensity variations also occurred. We have also studied the energy spectrum for this source and find it variable but very cut off at low energies at the source and very flat. In this respect the source resembles Cen X-3 and Herc X-1. From the optical identification using a distance of 1.3 kpc, we find a 2–20 keV peak luminosity of 8×10^{36} ergs s^{-1}.

We have also looked for faster time scale intensity variations and Figure 14 contains 20 s of data obtained at the flare peak. We see about a 30% intensity pulse over a time of 2 s. Such behavior is observed only when the source is brightest. Attempting to classify this X-ray source I would have to say that the dominant time scale of intensity variability, minutes to hours, is more typical of Sco X-1-like sources, while the range of intensity, 30, and spectral shape are similar to the pulsating sources.

7. Small Magellanic Cloud (2U0115 – 73)

The last source I would like to discuss is the one in the Small Magellanic Cloud (2U0115 – 73). This source has previously been reported by us as variable in intensity (Leong *et al.*, 1971) and in Figure 15 we show 8 days of data obtained in January 1971

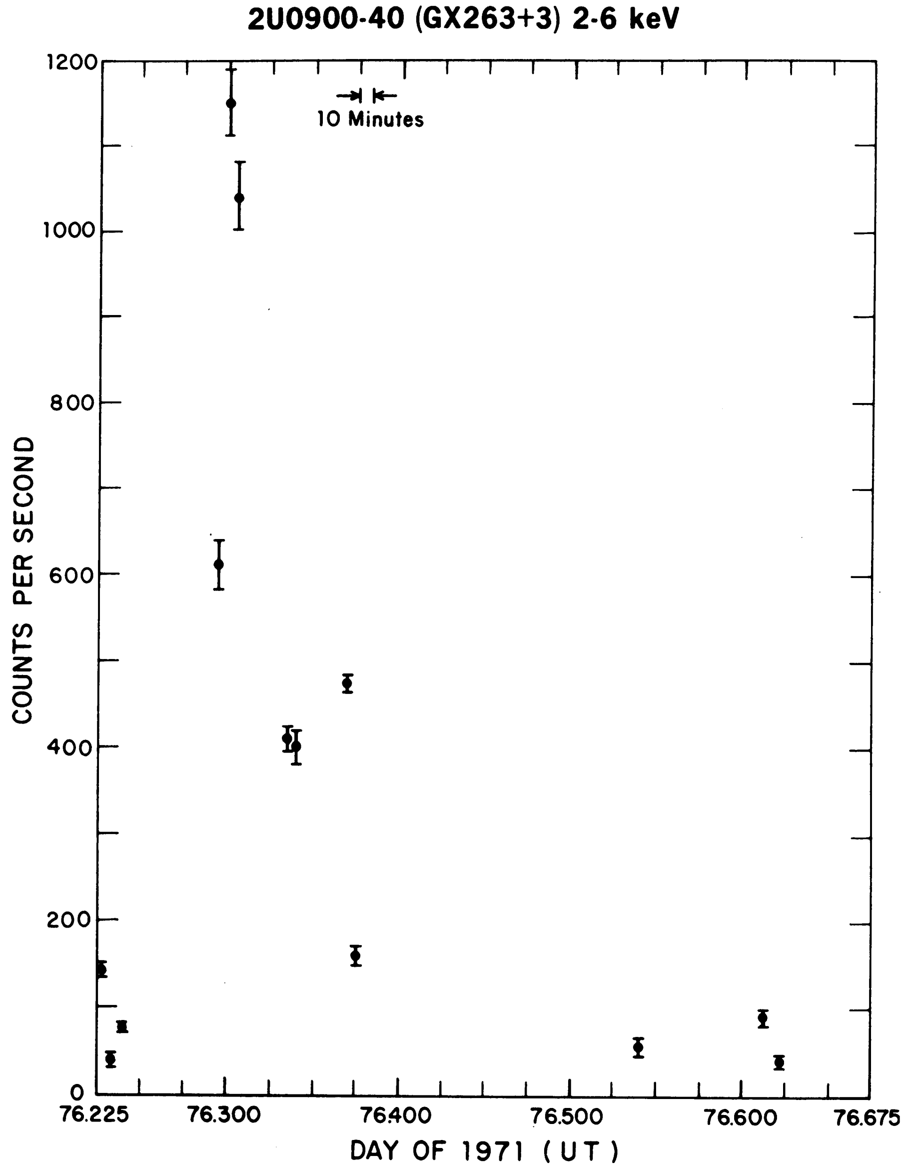

Fig. 13. X-ray intensity for 2U0900−40 plotted as a function of time for ½ day. Data have been corrected for aspect and 1σ error bars are shown.

on this source. Here again the data show highs, lows and transitions, suggesting an occulting system – the period is 3.9 days and the duration of the occultation is 0.6 days. This source is very weak (1/1000 of Sco X-1 in observed intensity) and we can therefore not yet say whether it pulsates on a time scale of seconds. Its spectrum is cut off at low energies at 1.8 keV and a power law fit has an energy index of about 0.15.

In this instance we know the distance to the source, getting a 2–10 keV luminosity of 10^{38} ergs s^{-1} (and using Livermore data (Price *et al.*, 1971) on this source at 40 keV we get $\sim 10^{39}$ ergs s^{-1}). In this respect, the 10^{38} ergs s^{-1} luminosity is comparable to that we found for several of the Sco X-1 like objects towards the center of our own galaxy. Knowledge of the distance to the SMC and thereby the intrinsic source luminosity demonstrates that a binary system can in fact produce luminosities of 10^{38} ergs s^{-1} and that the Sco X-1-like sources are not excluded from being binaries by their high luminosities. The SMC source is also significant since the occultations show that we are observing for the first time in X-rays a stellar system in another galaxy. The source is also interesting because when it is bright it accounts for at least 98% of the 2–6 keV X-ray emission of the SMC.

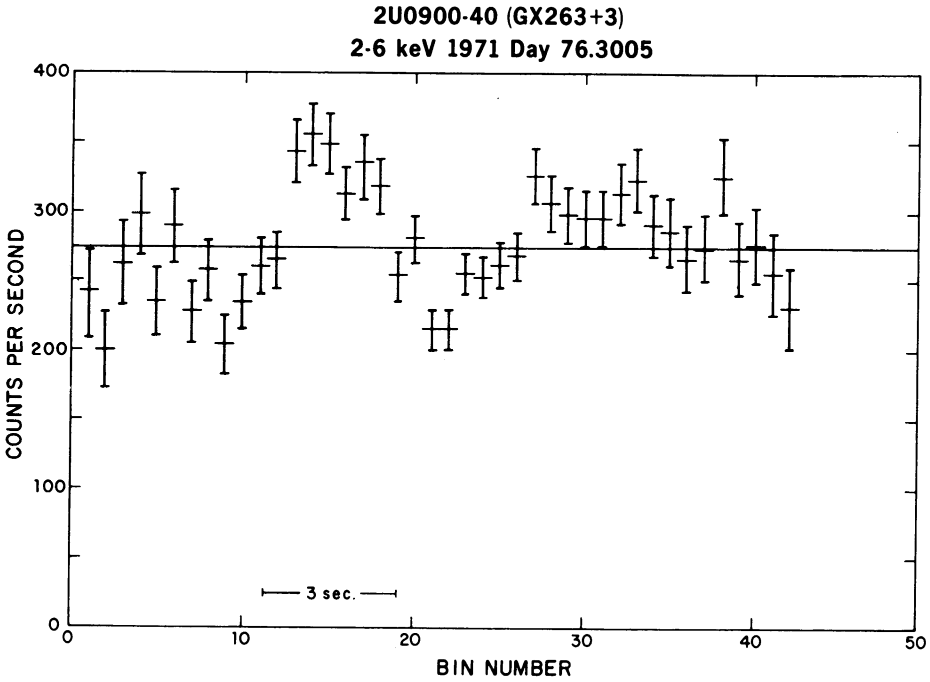

Fig. 14. 20 s of data for 2U0900–40 taken at the peak of the intensity shown in Figure 13. Data have been corrected for the triangular response of the collimator. The solid line shows the average counting level and significant variations are seen.

8. Conclusion

From these results it should be obvious that there is still a wealth of information to be obtained from the detailed UHURU data on individual galactic sources. It seems that the division of the sources into Sco X-1-like and pulsating may not hold up, since the

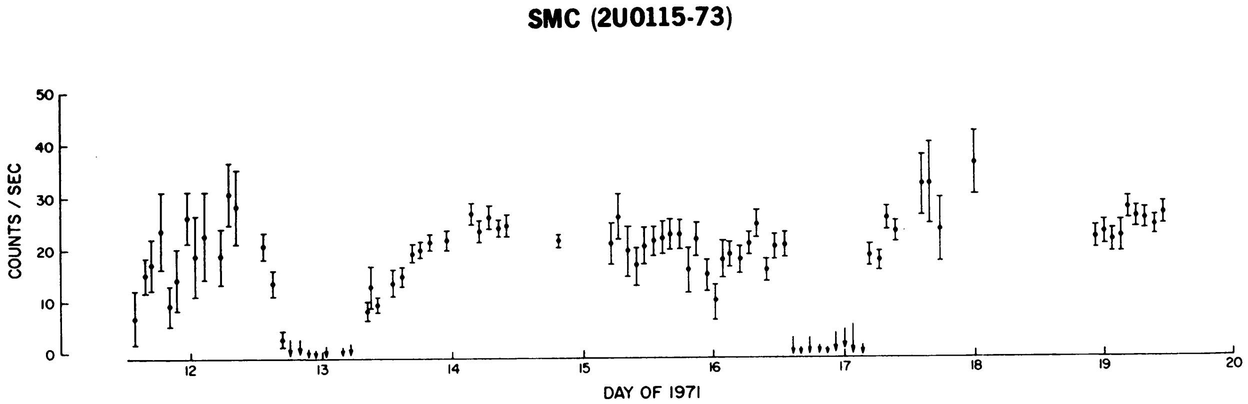

Fig. 15. Light curve for the X-ray source in the Small Magellanic Cloud. The 2–6 keV intensity is plotted for 8 days in January 1971. The data show highs, lows, and transitions suggesting a 3.9-day occulting binary system.

sources GX2 63+3 and SMC seem to have some properties of each class. It is already clear that at least some of the galactic X-ray sources are binary systems and perhaps all of them (except SN remnants) are. Binary models such as those suggested by Pringle and Rees (1972) to be discussed in following papers consider how differences in the nature of the secondary – its mass, radius, magnetic field, spin rate, orbital radius, and in the mass accretion rate could give rise to the variety of X-ray phenomena observed. An important question raised in a recent review by Burbidge (1972) is what makes these few binary systems X-ray sources while most others are not.

Several significant results come from the identification of galactic X-ray sources with binary systems:

- We have an energy mechanism to produce the X-rays – accretion;
- We can determine distances from optical data on the central stars and thereby determine absolute luminosities;
- We can study the final states of stellar evolution – white dwarfs, neutron stars and black holes;
- We can study mass transfer in binaries;
- We can use the X-ray source to probe the central star atmosphere;
- We can determine the masses of both objects in a pulsating binary system if we make an optical identification. The information available is the same as for a double-line spectroscopic binary.

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