# PART III

# ACCRETION OF MATTER AND X-RAY SOURCES

# BINARY X-RAY SOURCES

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**Abstract.** The observational data concerning binary X-ray sources is reviewed, with emphasis placed on Her X-1, Cen X-3 and Cyg X-1. In particular, the evidence for the identification of Cyg X-1 as a black hole is discussed.

## 1. Introduction

With the advent of orbiting X-ray observatories, such as UHURU, X-ray astronomy has entered an era of exciting new astronomical discoveries. In particular, with respect to galactic X-ray astronomy, the discovery of pulsating X-ray sources in binary systems by UHURU, has given us a powerful new tool with which to study the physical processes occurring in stars near the end point of their stellar evolution.

Long before many of the results, I will be discussing, had been obtained, Zel'dovich and Novikov (1964) had suggested that condensed stars could be found as X-ray sources accreting matter from binary companions.

The first indication that some X-ray sources might be associated with collapsed stars was provided by the first optical studies of compact galactic sources. The spectrum of Sco X-1 (Sandage *et al.*, 1966) was found to be similar to that of an old nova. It is well known that such objects are close mass exchange binaries containing a collapsed (probably white dwarf) companion (Kraft, 1964). Shortly thereafter, Burbidge *et al.* (1967), reported evidence for the binary nature of Cyg X-2. These observations suggested an attractive model for X-ray sources: matter lost from the primary star in a close binary would accrete onto a compact object, releasing $\sim 1$–10 keV of gravitational potential energy per particle in the case of a white dwarf, $\sim 100$ MeV per particle in the case of neutron stars, and black holes. The thermalization of this energy, either by shock waves or by viscous heating in a disk, would produce a hot gas which would emit X-rays. In this way, X-ray luminosities in the range $10^{36}$–$10^{38}$ erg s$^{-1}$ could be explained by modest accretion rates in the range $10^{-8}$–$10^{-10}$ $M_{\odot}$ yr$^{-1}$. This idea was pursued by Cameron and Mock, Shklovsky, Prendergast and Burbidge in papers published in 1967–1968. However, further observations of Sco X-1 and Cyg X-2 failed to show definite evidence of binary motion. Thus, for a time the possibility that compact X-ray sources could be binaries decreased in popularity. A number of other models, based for the most part on analogy with pulsars, were proposed, and the picture became somewhat muddled. Then in 1971 a dramatic breakthrough in our understanding of compact X-ray sources was achieved as a result of observations by the X-ray satellite, UHURU. Two periodically pulsating X-ray sources, Cen X-3 and Her X-1, were discovered. The observation of eclipses and a Doppler variation in their period conclusively established their binary nature

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on the basis of X-ray data alone. Today, as a result of combined radio, optical and X-ray observations, we can make a fairly convincing case that all compact X-ray sources not associated with supernova remnants are associated with mass transfer binaries containing a collapsed star. Perhaps, most significant of all, in the case of Cyg X-1, X-ray astronomy has furnished the strongest evidence yet for the existance of a new class of objects, black holes.

The work by Kippenhahn and his associates, and by Paczyński, has shed considerable light on the evolutionary tracks that may lead to the formation of the type of binary systems which the X-ray observations seem to require (Paczyński, 1971). It was shown that in the evolution of short period binary systems, there exists the possibility of obtaining systems in which a collapsed star is accompanied by a massive companion which overflows it s lobe of the zero velocity surface. Detailed computations were carried out by van den Heuvel and Heise for Cen X-3 (van den Heuvel, 1972). They follow the evolution of a system containing stars of mass 16 $M_{\odot}$ and 3 $M_{\odot}$ and $\tau = 3$ days. Using the evolutionary track of Paczyński, they find a descendant system containing 15 $M_{\odot}$ and 4 $M_{\odot}$ with a period of 1.53 kays. Assuming a supernova explosion ejecting 3.5 $M_{\odot}$, and assuming that the system remains bound, they are left with a 15 $M_{\perp}$ star accompanied by a 0.5 $M_{\perp}$ neutron star with a period of about 2 days. It should be pointed out that several assumptions on the conservation of angular momentum and total mass for the system, as well as on the details of the explosion are made in the computation. Colgate has pointed out the difficulties of retaining a bound system through the supernova event and has questioned whether neutron stars can be found in binary systems at all (Colgate, 1968). It is not my intention to deal in detail with evolutionary questions which will be more adequately covered by other authors in Session 66, except to point out that the existence of an X-ray emitting phase appears to be a required stage in the evolution of massive stars in short period binaries, rather than an oddity.

Apart from the insight that the discovery of such systems gives us on the evolution of stars, the finding of compact objects in binaries presents us for the first time with the opportunity to investigate their properties in detail. Thus, the possibility exists in the case of Her X-1 and Cen X-3 that a precise determination of mass could be obtained, as in the case of double line spectroscopic binaries. In this case, the velocity of one component is derived by X-ray measurements and of the other by conventional spectroscopic techniques in the optical. If these objects are indeed neutron stars, a statistical analysis on several such systems will give us an important indication of the possible upper limits on their mass. Also, the detailed study of the changes in orbital period and pulsation periods which are observed in X-rays will greatly improve our understanding of matter loss processes from the system, changes in moments of inertia of neutron stars and the nature of their physical state (Lamb, 1972; Baker, 1973). The detailed analysis of X-ray absorption features, will permit us to understand the gas dynamics in the system. Finally, the discovery and subsequent study of black holes is of great significance for general relativity, a point vigorously made by Wheeler and Ruffini (1971).

In this survey of X-ray binaries, I will not attempt to expand on the points above. I will simply endeavor to bring to your attention the wealth of information which is rapidly being uncovered by X-ray observations.

## 2. Her X-1

The best studied of the binary X-ray sources is Her X-1. As we will see, many of the observational phenomena for Her X-1 can be clearly explained in terms of a rotating neutron star orbiting in a binary system, although some of the complex features of this system are not yet fully understood. The view that Her X-1 is a neutron star is by no means generally accepted. Models based on differentially rotating degenerate dwarfs have recently been suggested; and the proponents of vibrating degenerate dwarf have not yet conceded. Without going into the merits of the models, I have adopted the neutron star point of view as a means of more conveneintly describing the data. If, indeed, degenerate dwarfs with masses of 1.4 $M_\odot$ can rotate or pulsate at 1.24 s, then the alternate models are at least plausible although no detaled computation to explain the details of the observations has, to my knowledge, yet been carried out.

If we start from the simplest X-ray observations, we find that Her X-1 shows periodic occultations with a 1.7 day period. Figure 1 shows the 2–6 keV X-ray intensity, as observed by UHURU, varying from a high of 100 counts $s^{-1}$ to a level below the limit of UHURU's detectability of a few counts $s^{-1}$. The transitions between the high intensity state and eclipse take a time less than 12 min. Data for 3 adjacent occultation cycles in July 1972 are shown in the figure, which also shows that the X-ray eclipse lasts for 0.24 days. Figure 2 from Forman *et al.* (1972), shows the optical behavior of Hz Herculis in the summer of 1972 and on plates from the 1940's. The 1.7 day optical variations in phase with the schematically represented X-ray eclipses of Her X-1 make certain the identification of the star with the X-ray source. The optical variations are interpreted in terms of a binary in which the central star has a hot side facing the X-ray source and heated by the X-ray emission with temperatures of order 10000 K for the hot side and 6000–7000 K for the cooler side. Recent papers, such as those of Wilson, Joss *et al.*, and Rucinski, have considered the various detailed models which are required to reproduce the shape of the observed optical variations.

The first X-ray observations of Her X-1 also showed another regular feature. The source pulses periodically with a 1.24 s period. This behavior is illustrated in Figure 3, where the lighter histogram shows 30 s of 2–6 keV counting rate data accumulated in 0.096 s bins, the highest time resolution available with UHURU. The heavier curve is a minimum $X^2$ fit to the pulsations of a sine function plus two harmonics.

Since Her X-1 undergoes regular eclipses, it should not be surprising that its 1.24 s pulsing shows a regular Doppler pattern. As the X-ray source orbits its binary companion, the pulses appear closer together (shorter period) as the source comes out of elipse and approaches us and the pulses appear farther apart (longer period) as the source heads towards eclipse and moves away from us. This behavior allows us to measure directly and precisely very many of the parameters of the Her X-1 system.

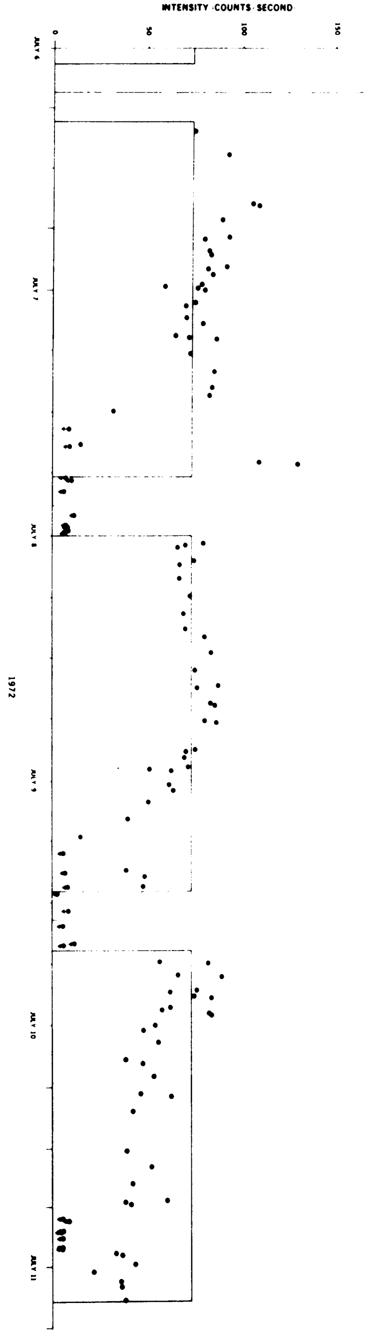


Fig. 1.

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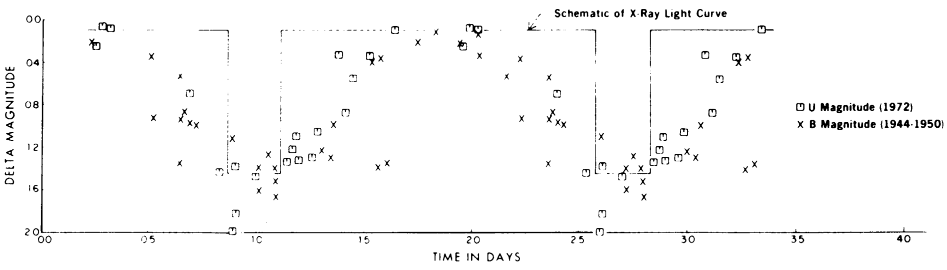


Fig. 2. Hz Herculis optical observations folded 1.70015 days.

The Doppler curve is indicated in Figure 4, where in the bottom half, we have replotted the intensity data from the first Hercules figure and in the top half, we have shown the time difference between the time of arrival of a pulse and the time predicted for a constant period plotted versus time. As can be seen from the figure, the arrival time of the pulse is delayed 13.2 s at the center of the occultation and is 13.2 s early at the center of the high state.

The delay time of 13.2 s is a direct measure in light seconds of the radius of the orbit of the X-ray star about the center of mass of the binary system as projected into the observing plane. Most importantly, the presence of the sinusoidal Doppler curve confirms the picture of the X-ray source orbitting in a binary system as first suggested by the regular eclipse.

Table I contains a summary of the observed parameters of the Hercules X-ray system – the average pulsation period $\tau$, the half-amplitude of the period variation

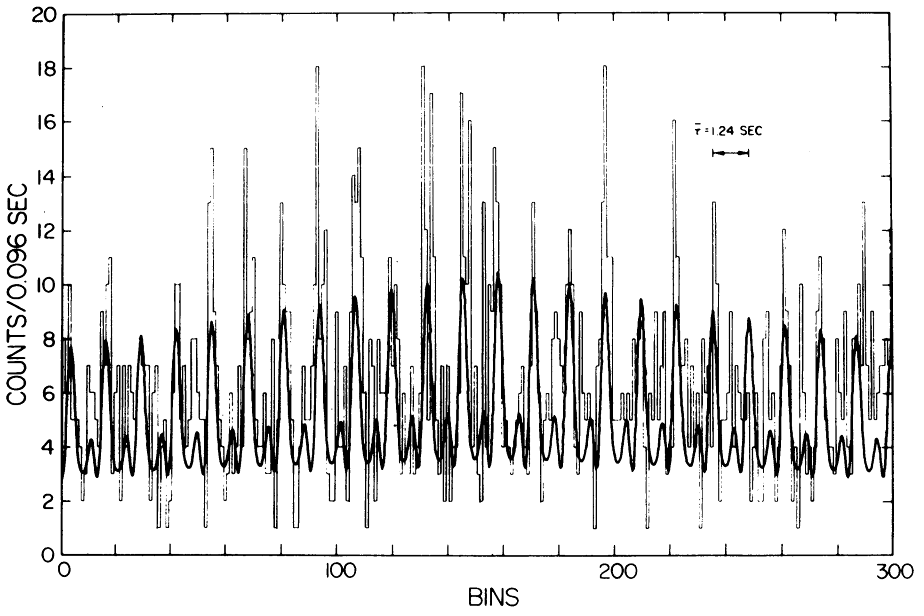


Fig. 3. Source in Hercules (2 U 1702+35). November 6, 1971.

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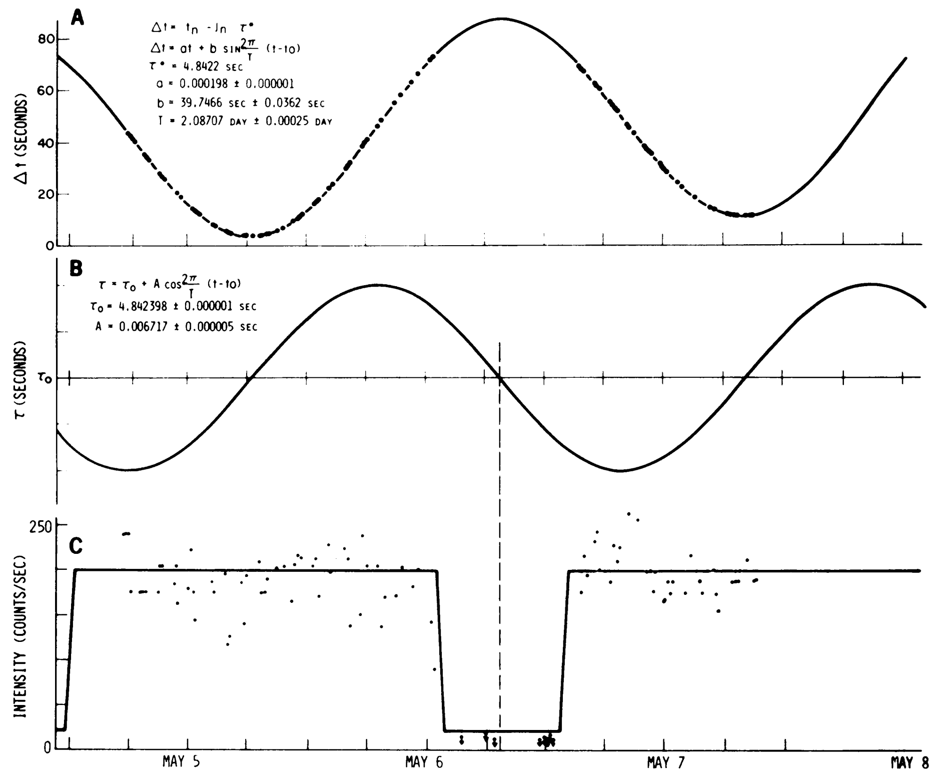


Fig. 4.

TABLE I

PARAMETERS OF HERCULES X-1

| | |
|---|---|
| Observed Parameters | |
| $\tau$ (average heliocentric pulsation period in seconds) | $1.2378206 \pm 0.0000001$ (Jan. '72) |
| $\Delta\tau$ (half-amplitude of period variation in seconds) | $0.0006979 \pm 0.0000003$ |
| T (orbital period in days) | $1.70017 \pm 0.00001$ |
| $\phi_T$ (phase of eclipse: low center) | UT 1972 Jan. $13.0772 \pm 0.0003$<br>UT 1972 Jul. $6.1897 \pm 0.0004$ |
| Derived Parameters | |
| $\epsilon$ (eccentricity) | $\leq 0.05$ |
| $v \sin i = (\Delta\tau/\tau)\, c$ (km s$^{-1}$) | $169.0 \pm 0.1$ |
| $r \sin i = (T/2\pi)\, v \sin i$ (cm) | $(3.95 \pm 0.01) \times 10^{11}$ |
| $M_2^3 \sin^3 i/(M_1+M_2)^2 = (2\pi/T)^2 (r \sin i)^3/G$ (grams) | $(1.69 \pm 0.01) \times 10^{33}$ |

$\Delta\tau$, the orbital period $T$, and the phase of the eclipse center $\phi_T$. In addition, four paramaters are derived from the measured quantities under the model of a binary system in an orbit with an inclination angle $i$ to observer ($i=90°$ corresponds to the observer being in the plane of the orbit of the binary system). The first derived parameter is the eccentricity of the orbit of the binary and from the good quality of the sine fit to the pulse arrival times is determined to be less than 0.05. This result justifies the assumption of a circular orbit which can be used to derive the projected orbital $v \sin i$, the projected orbital radius about the center of mass $r \sin i$, and the mass function of the system $(M_2^3 \sin^3 i)/(M_1+M_2)^2$ where $M_1$ is the mass of the X-ray star and $M_2$ the mass of the occulting star.

We should point out that the value of the period $T$ given in the table is the heliocentric value determined in January 1972. We have now determined the pulsation period for 14 times from December 1971 through March 1973. These data are shown in Figure 5 with corrections for all significant motions applied. The figure shows the heliocentric period vs time. Significant changes are clearly occurring but the picture is quite complex. From January 1972 to August 1972 the period decreased by $5\frac{1}{2}$ $\mu$s, from September 1972 to October 1972, the period increased by about 3 $\mu$s, and then from October 1972 to March 1973, the period decreased by $3\frac{1}{2}$ $\mu$s.

The fact that the X-ray period shows a net decrease of 6 $\mu$s over $1\frac{1}{4}$ yr rules out

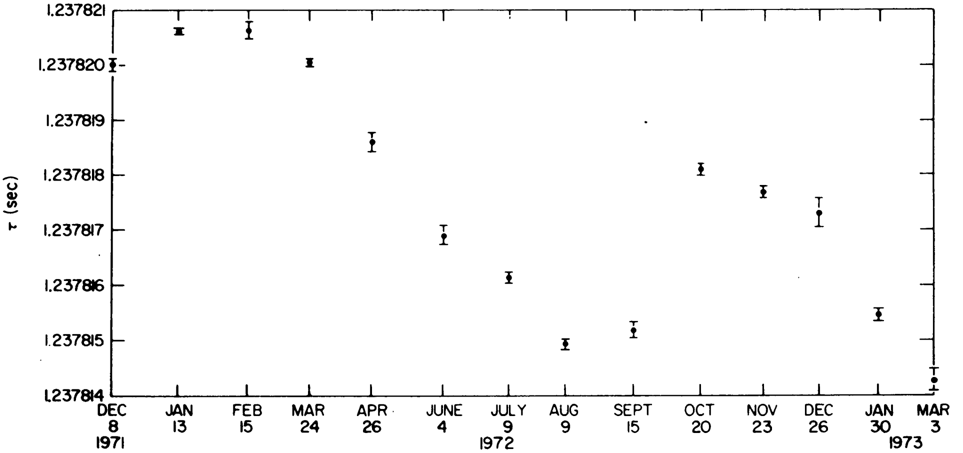


Fig. 5. Her X-1, pulsation period $\tau$ vs time.

models such as have been applied to radio pulsars and the Crab Nebula pulsar, in which a rotating neutron star slows down (period increases) at a rate approximately equal to that required to supply the energy emitted as radiation.

Since Her X-1 is a member of a binary system, we turn to accretion as the most likely energy source with the rotation of a neutron star still providing the clock mechanism. Although accretion models are extremely complicated, a few general statements may be appropriate. Material can be accreted radially if it has insufficient angular momentum for centrifugal forces to halt its free fall. However, for close binary systems accreting matter is likely to have so much angular momentum that it cannot fall directly onto the compact object. In this case, the matter will form a disk composed of material which gradually spirals inward and transfers its angular momentum to the compact star. The accretion problem has been studied by Zel'dovich and Novikov (1971), Prendergast and Burbidge (1968), Shvartsman (1971), Pringle and Rees (1972), Ostriker and Davidson (1972), Lamb *et al.* (1973), and Shakura and Sunyaev (1973). Most relevant to the X-ray results on the speeding up of Her X-1, both Pringle and Rees, and Lamb *et al.* predict that matter being accreted will transfer angular momentum to the star thereby speeding it up with the predicted changes being of the same order that we have observed for Her X-1. The models can explain the more complicated picture now presented on the change of the period with time on the basis of changes in the rates of matter transfer.

Distances determined from optical data imply an X-ray luminosity from $10^{36}$ to $10^{37}$ erg $s^{-1}$ although this could decrease by a factor of 10 by accounting for the limited solid angle that the pulsed source fills. The accretion process is capable of producing at least $10^{38}$ erg $s^{-1}$ and therefore is capable of producing the observed luminosity. As already described in the last table, the mass function of Her X-1 is 0.85 solar masses. One of the most important quantities to determine is the mass of the X-ray source itself which might yield the first direct measurement of the mass of a neutron star. The mass function derived from the Doppler shift of the X-ray pulsation period gives one equation involving $M_1$, $M_2$ and $\sin i$. There are several approaches that can be followed at this point. The simplest conceptually is to determine the velocity of the central star about the system center of mass from visible light and spectroscopic observations. Further the spectral typing of the central star allows its mass to be determined, in principle. These two additional results then determine with the X-ray data $M_1$, $M_2$ and $i$. Alternatively, the detailed shape of the optical eclipse can be used to determine the system parameters. These areas of effort are still the subject of much discussion and debate on the interpretation of the observed radial velocities, although preliminary results, such as those of Crampton and Hutchings, who obtain $1.4 \pm 0.4\ M_\odot$ for the X-ray star, agree with the numbers obtained below.

Another technique that can be used to estimate the masses involved uses the X-ray data alone. One equation relates the size of the Roche lobe of the primary to the separation of the stars and their masses. A second expression relates the radius of the occulting object, the separation of the binary components, the inclination angle $i$, and the phase angle of the occultation duration, a measured quantity. Using these equations requires us to relate the radius of the occulting region to the size of the Roche lobe and this is where some difficulty lies. Among others, Wilson has argued that the sharpness of the eclipse transition requires so large a density gradient that the radius of the occulting region cannot be larger than the Roche lobe. Ruffini, on the other hand, argues that the radius of the occulting region must be larger than the Roche lobes since the star is losing mass. Depending upon which inequality is correct, we can calculate a range of allowable masses for each value of $i$. If we assume, as is likely, that $R \approx R_L$, we obtain a value of $M_1$ and $M_2$ for each possible $i$, and some results of such a calculation are tabulated in Table II. For example, at an inclination of 85°, assuming the radius of the occulting region is equal to the size of the Roche lobe, determines a mass of 1.99 solar masses for the central star and 1.04 $M_\odot$ for the X-ray source.

TABLE II

HERCULES X-1 MASS ESTIMATES - X-RAY DATA ONLY

Assumes $R_{occulting} = R_{Roche\ lobe}$

| Inclination Angle | Mass X-Ray Star | Mass Central Star |
|---|---|---|
| 90° | 1.19 | 2.09 |
| 85° | 1.04 | 1.99 |
| 80° | 0.74 | 1.78 |
| 75° | 0.45 | 1.56 |
| 60° | 0.09 | 1.47 |
| 45° | 0.03 | 2.46 |
| 30° | 0.04 | 6.8 |

The observations of Her X-1 show further structure in the X-ray intensity vs time. For 10 or 11 days, the source is intense and pulsing and can be seen following the 1.70 day occultation cycle. Then for 24 days the source is too weak to be observed.

Figure 6 shows the detailed X-ray intensity data, corrected for aspect, observed during the high states in January, March and July, 1972. Each dot represents a single spin of the satellite across the source. Two types of error bars are shown in the figure; the statistical error bar is determined from counting statistics and is the appropriate error bar to apply locally when considering variability. The larger error bar is dominated by the aspect correction and must be applied when comparing data taken on different days since the satellite is normally maneuvered once per day.

In addition to the fluctuations observed within a day, there are other features that stand out in this figure. First, we see that the source turns on rather abruptly. The intensity then increases rapidly to a maximum level and stays near this level for several days. The intensity then decreases rather smoothly for several days until the source is not detectable. Recently, the X-ray experiment on Copernicus has detected X-ray emission from Her X-1 during a time in which it was predicted to be in the off part of the cycle. We first established the 35 day cycle from observations of 5 cycles from November 1971 until March 1972; 4 of which the source was monitored with coverage on 67 out of 96 days occurring between high states. On all of these 67 days, as well as a number of additional scattered days of observation, the source was not detected

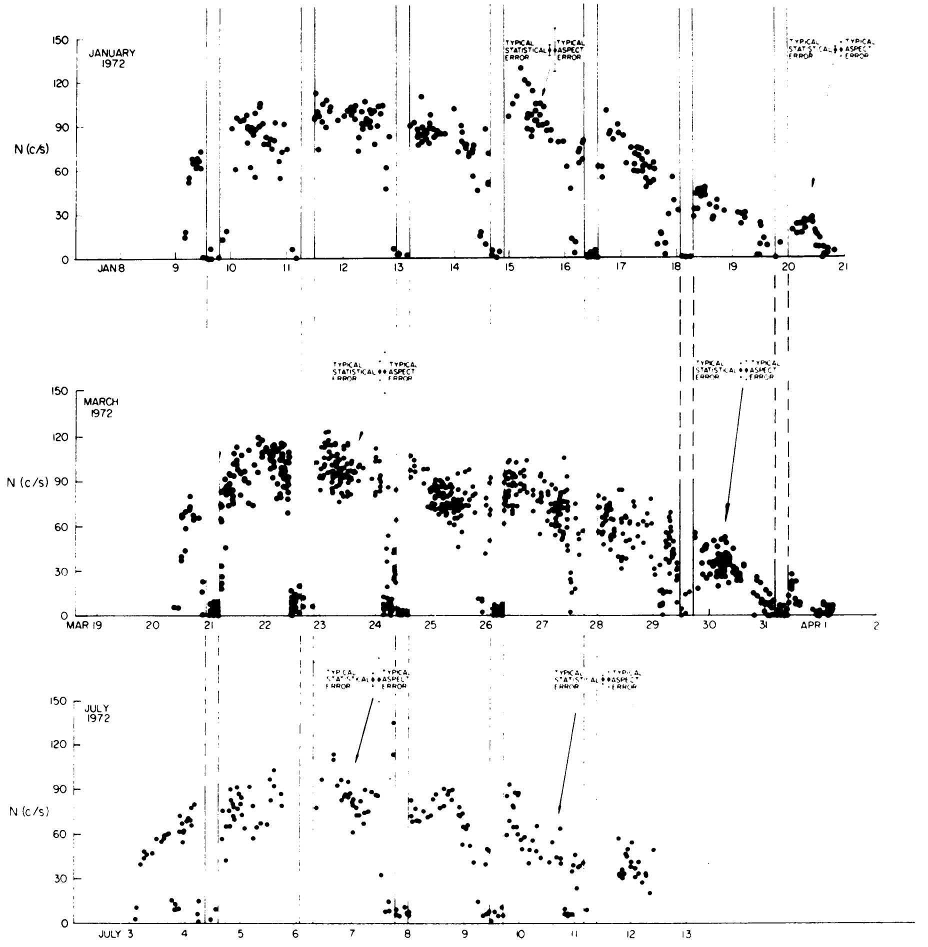


Fig. 6.

above background, thereby indicating the rarity of events, such as detected by Copernicus and possibly by the Livermore group in a May 1971 rocket flight.

In Figure 7 (top half) we have used the sharpness of the high state turn on to look at the time of occurrence of the 35-day cycle. We have plotted the time of the turn-on minus an integer *34.85. The first several points lie on a straight line whose slope indicates the 35.7 day periodicity first reported. Other points lie on lines with slopes corresponding to 34.85 day and 34.0 day periods, while a few points are scattered off the lines. While the turn-on data definitely do not show a strict periodicity, we should note that all of the points are within one eclipse cycle of the average 34.85 day cycle chosen. Thus, while there appears to be an underlying clock, it just does not seem to keep time precisely except on the average.

This may be understood, perhaps, by considering the bottom half of Figure 7 where we have plotted the turn-on times as a function of 1.7 day orbital phase. We should note that the range of phase indicated in this plot, as well as the error bars in the upper half of the figure, represent absolute limits on the uncertainty in turn-on times. We see that the turn-ons cluster at two phases: around phase 0.2 and 0.7. An earlier analysis suggested that all of the turn-ons could be consistent with two very well defined times, but as more data have been analyzed, we find that while the turn-ons do cluster near phases 0.2 and 0.7, there are some that definitely do not overlap.

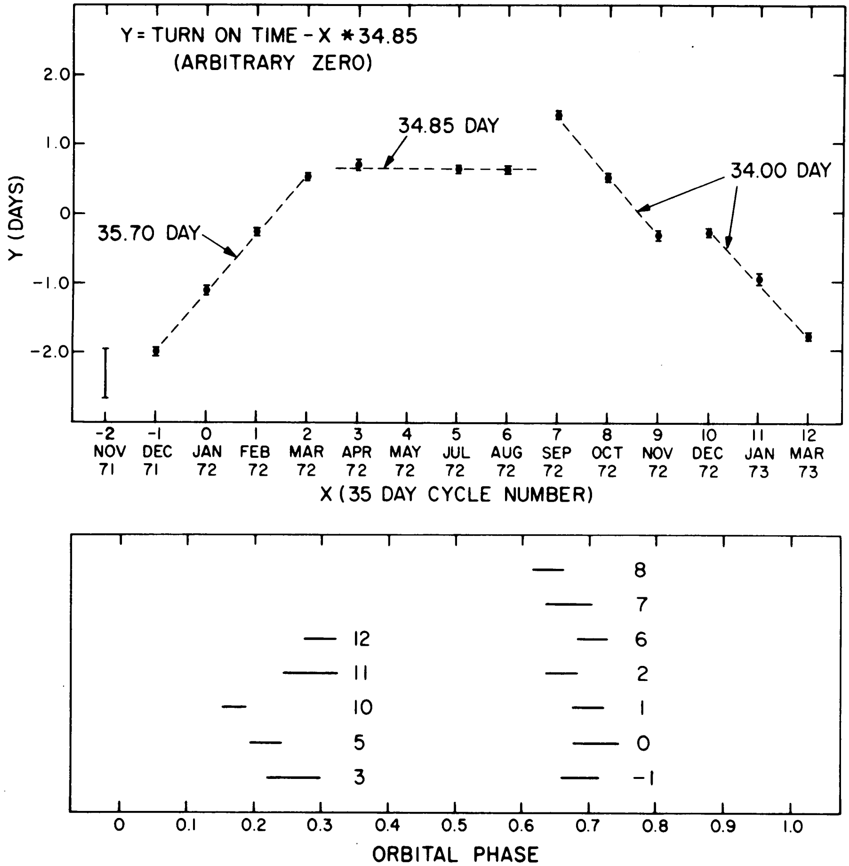


Fig. 7. Her X-1 35-day turn on.

The simplest model for the 35 day cycle is torque-free precession of an oblate spheroid neutron star first described by Brecher. If this is the case, then the 35 day cycle of Her X-1 is a reflection of conditions in the interior of the neutron star. For example, Pines, Pethick, Lamb and Shaham have shown that the model works only if the neutron star has a solid core. This model has been modified by Pines and co-workers to explain the sudden onset of the 'on' state by a triggering effect of the accreting material piling up at the Alfvén surface until the precession angle becomes such that acretion onto one or the other of the magnetic pole regions is no longer

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prevented. By assuming that the accumulated disk of matter acreted during the off state is thickest near the inner and outer Lagrange points, Pines and co-workers explain the turn-ons at phases near 0.25 and 0.75 as occurring at the locations at which the X-rays can most easily 'burn' through the disk and first be seen. Further detailed work is, of course, necessary to fully evaluate this model and to see if further details of X-ray absorption by streaming gas, such as the dips described by Giacconi *et al.* (1973a), and the complicated optical behavior can be explained by the model.

## 3. Cen X-3

We now turn our attention to Cen X-3. Figure 8 shows this source pulsing with a

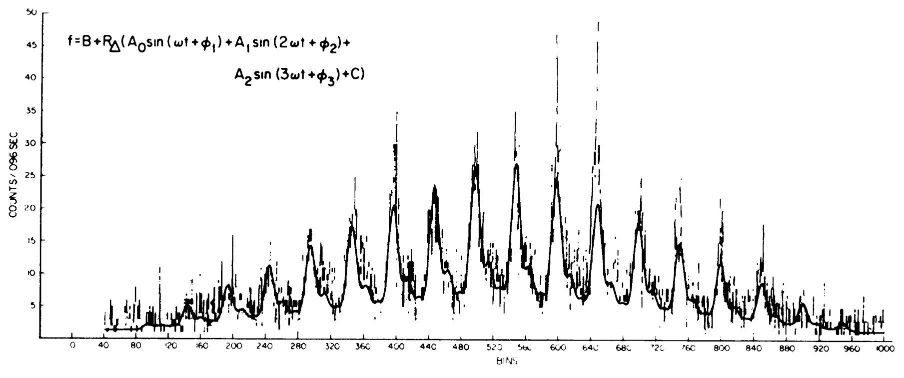


Fig. 8. Cen X-3 (2U 1119–60). May 7. 1971.

4.8 s period. The lighter histogram is again the 2–6 keV intensity observed with UHURU in 0.096 s bins and the heavier curve is a fit to the data. Figure 9 shows that, as for Her X-1, this source undergoes regular occultations and that the 4.8 s pulse period is Doppler shifted in phase with the eclipses. One difference from Her X-1 is that Cen X-3 does not exhibit a regular 35-day cycle, but as is shown in Figure 10, has times when it is intense and pulsing, and other times when it is seen weakly (if at all), and still other times when it alternates erratically between a high state and a low state. The data in the figure cover the $2\frac{1}{2}$ yr time over which UHURU has operated. There are no clear cut regularities in the highs and lows – no single period comes close to fitting all the observations. The data suggest that typical high states may last for around 4 months and typical low states for around 2 months; but exceptions are almost the rule.

In Figure 12a we have plotted several heliocentric 4.8 second periods observed for Cen X-3. The changes in period are so great that error bars are smaller than the dots representing the data points. The period decreased by 1.1 ms from January to May 1971, decreased by 0.2 ms from May to July, decreased by 0.25 ms from July to December 1971, decreased by 1.3 ms from December 1971 to September 1972 and increased by about 50 $\mu$s from September to October 1972.

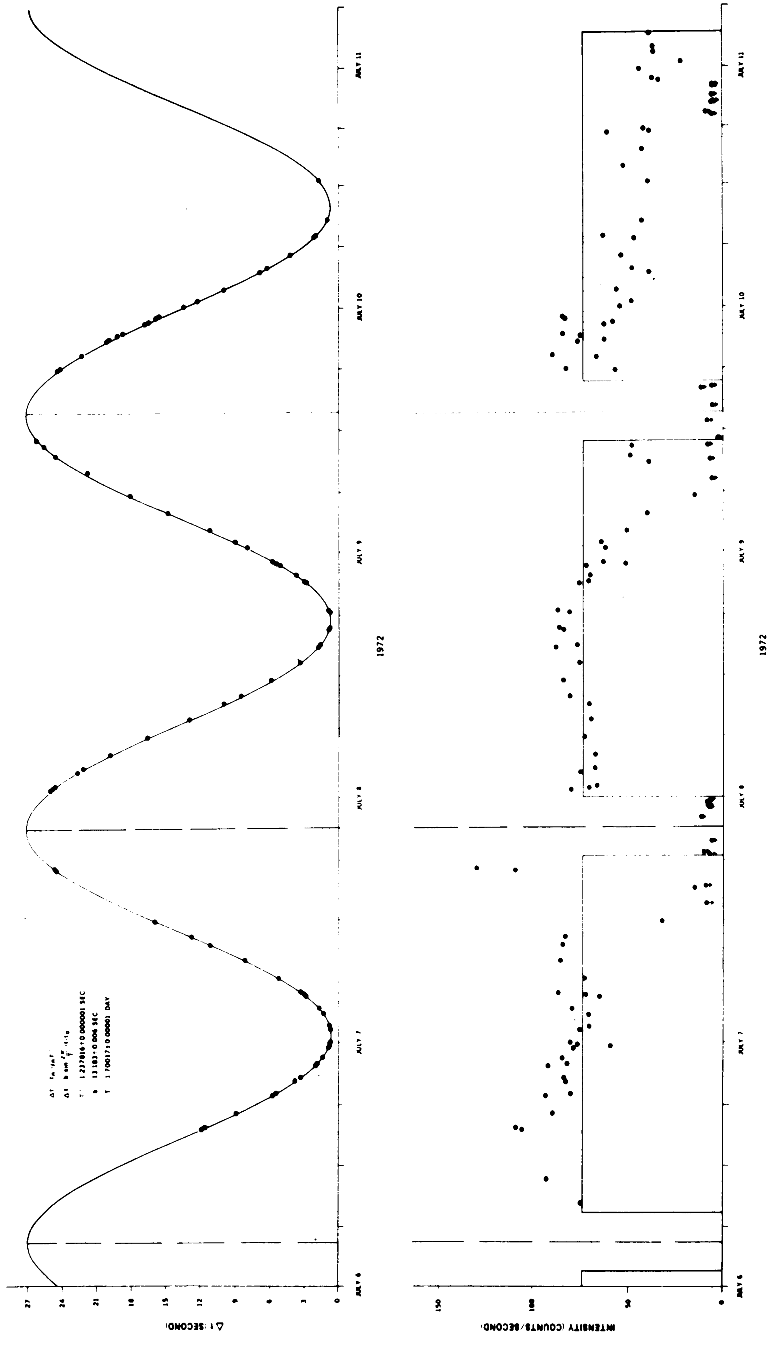
JULY 6
JULY 7
JULY 8
JULY 9
JULY 10
JULY 11
1972
Δt (SECOND)
INTENSITY (COUNTS/SECOND)

Fig. 9.

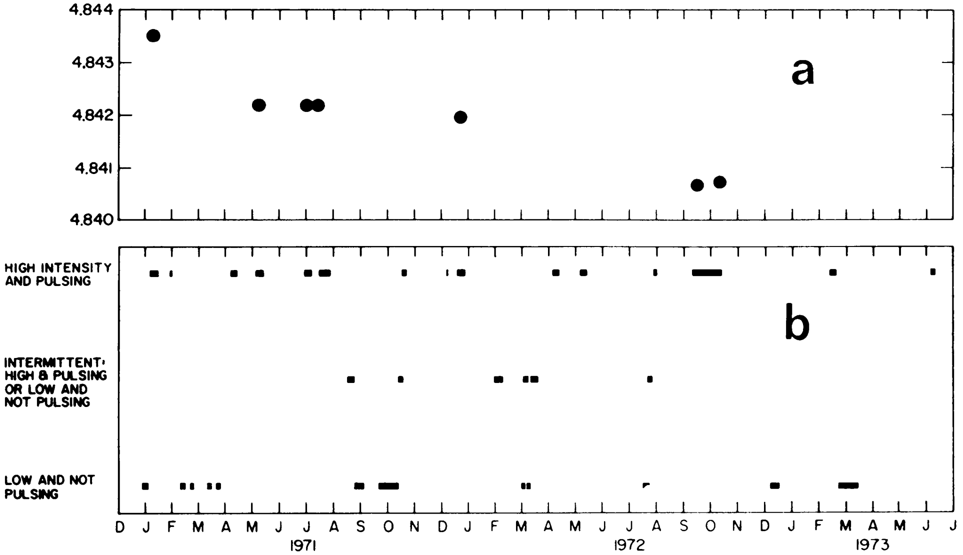


Fig. 10. (a) Cen X-3, pulsation period vs time. (b) Cen X-3, intensity vs time.

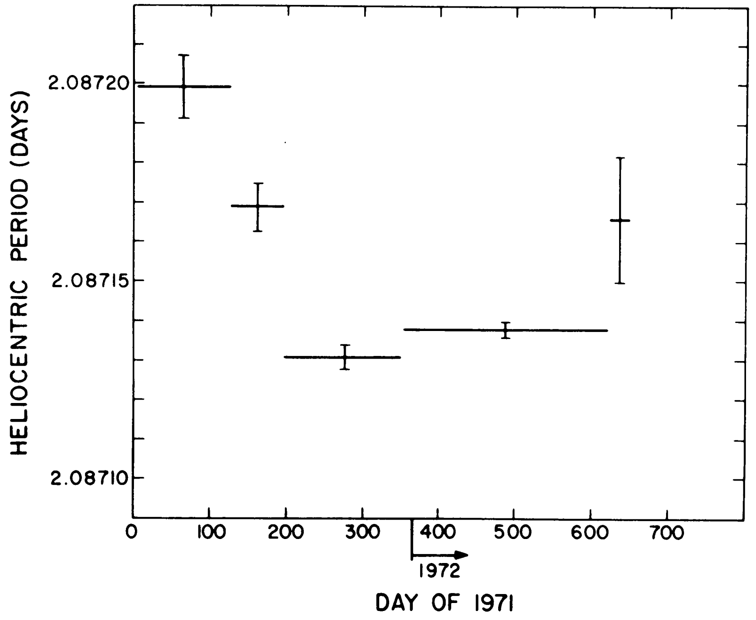


Fig. 11. Orbital period of Cen X-3 (averaged over indicated bxselines).

One additional piece of evidence in the Cen X-3 picture is shown in Figure 11, where we plot the two day orbital period of Cen X-3 vs time. The first few data point indicate that the orbital period is decreasing at a rate consistent with mass loss

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from the primary at a rate of $\sim 10^{-5}$ solar masses per year. However, additional data have shown that the orbital period is increasing with time. Liller has recently found a 14th mag. optical counterpart for Cen X-3, although the identification requires small changes in the presently observed X-ray period to fit the data on old plates. Changes that are required are of the order of the changes observed in the X-ray orbital period so at present the identification seems likely to be correct.

The dissimiliarities of their detailed behavior notwithstanding, Her X-1 and Cen X-3 seem to fit well in a model where accretion occurs on a magnetic, rotating neutron star of small mass 0.2 to 1.4 $M_{\odot}$. The observational data regarding Cyg X-1 seem, however, to require a different model.

## 4. Cyg X-1

The discovery of short X-ray pulsations from Cyg X-1 has been certainly one of the most significant achievements of the UHURU orbiting observatory with regard to galactic X-ray sources. This discovery stimulated a wealth of X-ray observations on periodic and non-periodic pulsating X-ray sources which resulted in the discovery of Her X-1, Cen X-3, and many of the binary sources we are presently studying. It also stimulated a concentrated effort in identifying the radio and optical counterparts of the object, whose detailed study has led to the conclusion that the Cyg X-1 system contains a black hole. Due to the importance of this finding and to the rapidly accumulating evidence strengthening this conclusion, I believe it is useful to review some of the experimental results and discuss more of the argument involved in reaching it.

Cyg X-1 has been observed in some of the earliest surveys in X-ray astronomy. In 1966, a survey of the Cygnus region (GR 67a) resulted in the first accurate location determinations for Cyg X-1, Cyg X-2 and Cyg X-3. As a result of this survey, the optical candidate for Cyg X-2 was found. No candidate objects could be found for Cyg X-3 or Cyg X-1. The energy spectra of the Cygnus sources were also measured. The spectrum of Cyg X-1 covering the range from 1 to 80 keV was measured by many observers from balloons and rockets. It appeared to have a flat power law spectral shape ($E^{-\alpha}$) with $\alpha = 0.7$, thus rather similar to the one found in the Crab Nebula. It was considered puzzling that while the source was not too different in intensity and spectral form from the Crab Nebula source, no evidence of radio emission could be found with a limit of 1/500 of Crab radio flux. Since at the time we only knew of 2 types of X-ray sources, Sco X-1-like and supernovas, this was considered evidence for a different type of X-ray emitter. How truly different was not revealed to us until December, 1971, when the UHURU X-ray observatory detected the existence of X-ray pulsations from Cyg X-1 (Oda *et al.*, 1971; Figure 12).

Figure 13 contains data already reported in the literature (Schreier *et al.*, 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

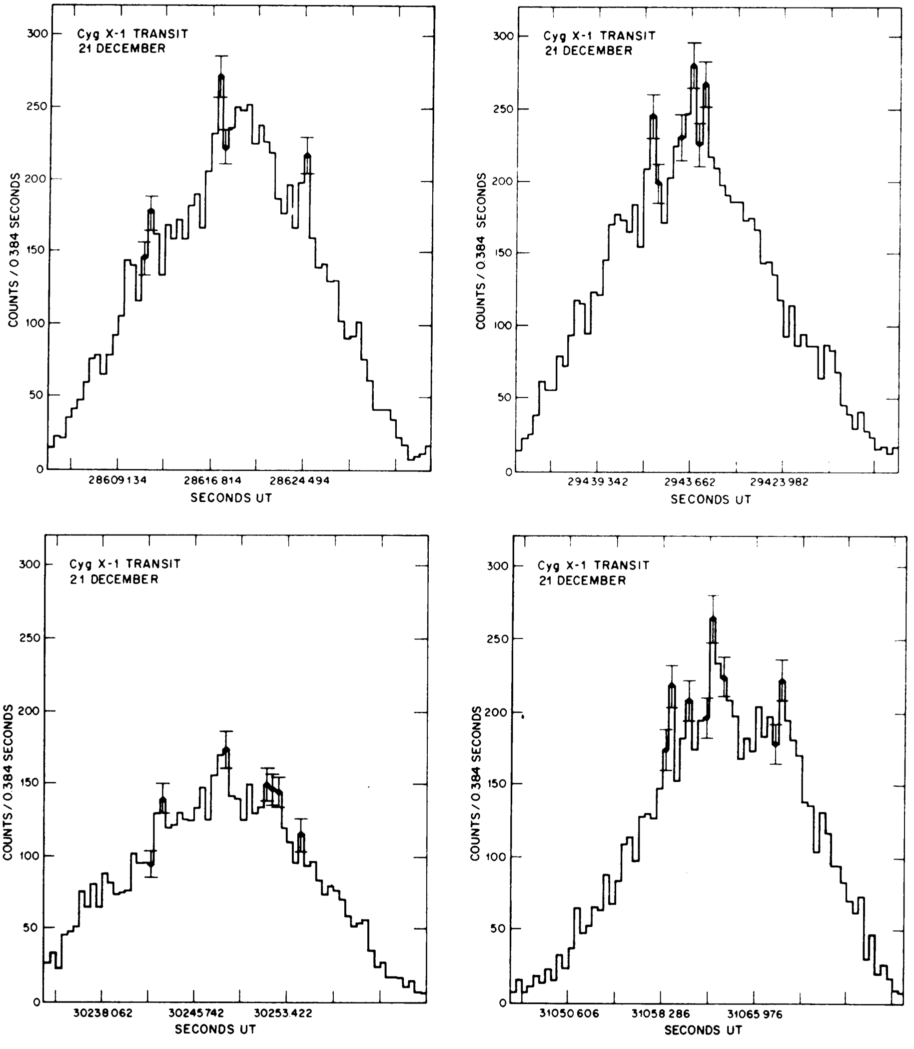


Fig. 12.

scientists at MIT (Rappaport *et al.*, 1971a), Goddard Space Flight Center (Holt *et al.*, 1971) and NRL (Shulman *et al.*, 1971) compels us to consider a source region of $10^9$ cm or less.* Figure 14 shows the X-ray location obtained from an MIT rocket flight and from UHURU which led to the discovery of a radio source 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 Cyg X-1 with the 5.6 day spectroscopic binary system HDE 226868. The central object of this system is most likely a 9th mag. B0 supergiant and conservative mass estimates for the primary lead to a mass in excess of several $M_\odot$ for the unseen

* See note added in proof, p. 178.

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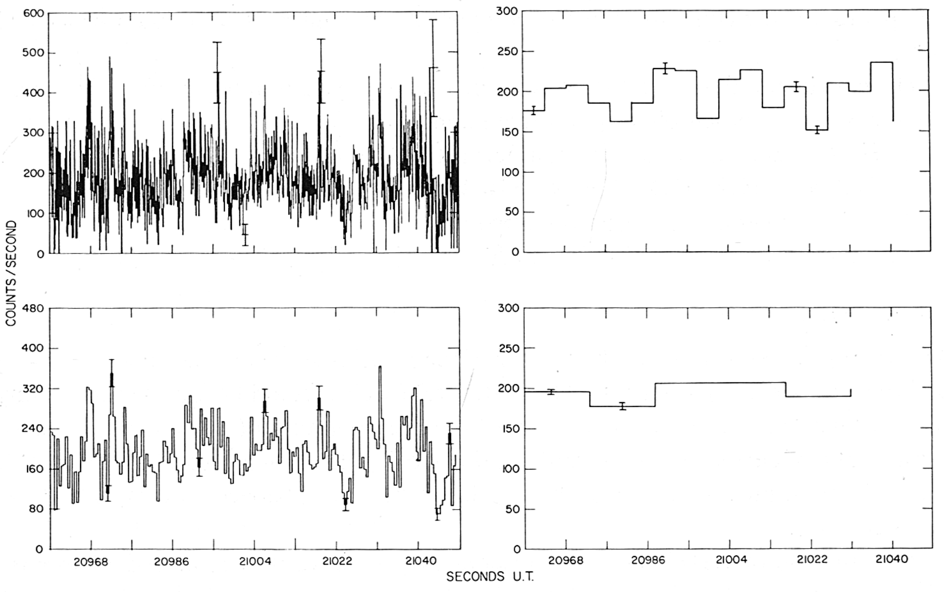


Fig. 13.

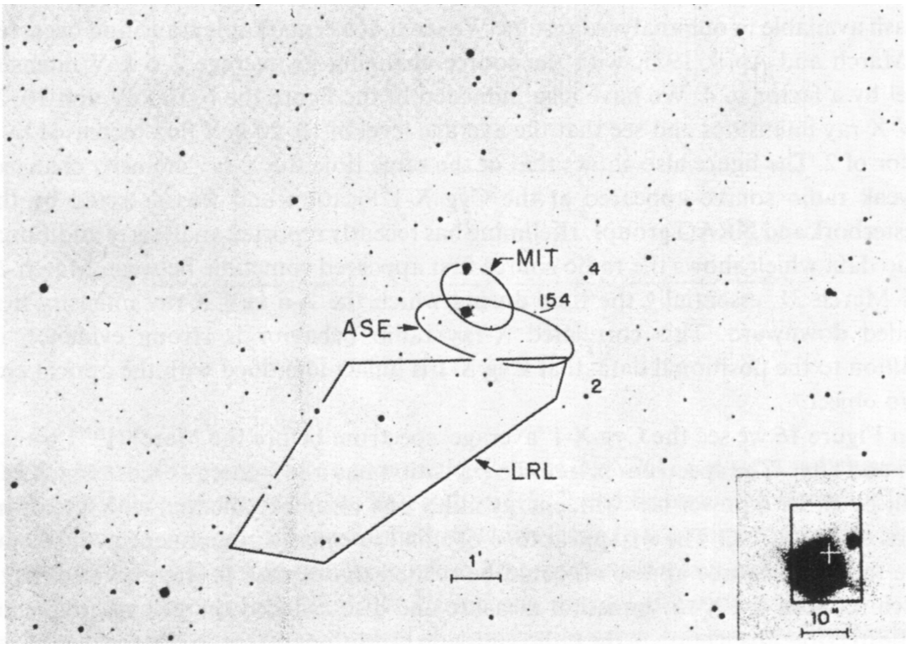


Fig. 14.

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companion. If the companion is the compact X-ray source, then it could be a black hole.

The conclusion that Cyg X-1 consists of a binary system in which one of the stars is a black hole is based then upon three main points:

(1) HDE 226868 is the optical counterpart of Cyg X-1,

(2) The mass of the HDE 226868 $\geqslant 20\ M_{\odot}$, and

(3) The X-ray emitting object is compact.

I will consider the three points in order.

### 4.1. Identification

The identification is based on first order of the positional coincidence between X-ray and optical object (1′), Figure 14. No evidence, however, could be found in the Uhuru data at high X-ray energies (2–10 keV) of the binary nature of the system. Since the positional coincidence between radio and optical yields much greater accuracy (1″), we have attempted to establish a correlated behavior between radio and X-ray emission.

With the use of UHURU as an observatory, we have now analyzed 16 months of data on Cyg X-1 which are shown in Figure 15. 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 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. Hjellming has recently reported analysis of additional radio data which shows the radio source first appeared sometime between March 22 and March 31, essentially the time during which the 2–6 keV X-ray intensity first headed downward. This correlated X-ray radio behavior is strong evidence, in addition to the positional data, that Cyg X-1 is in fact identified with the optical and radio object.

In Figure 16 we see the Cyg X-1 'average' spectrum before the March 1971 transition and after. The spectrum before the transition has a low energy excess which can be fit by either a power law with energy index of 4 or an exponential with a temperature of $11 \times 10^6$ K. The disappearance of this low energy component at the same time the radio source appeared, could be related to decrease in the plasma density which reduced the X-ray emission measure and also reduced the plasma frequency or the free-free absorption of the radio emission. Additional evidence for the identification has been reported by Sanford (1973) on the basis of Copernicus satellite data. He reports that a decrease of soft X-ray emission from Cyg X-1 was detected at Phase 0 of the 5.6 period of several occasions. Such low energy X-ray behavior would prove conclusively the identification.

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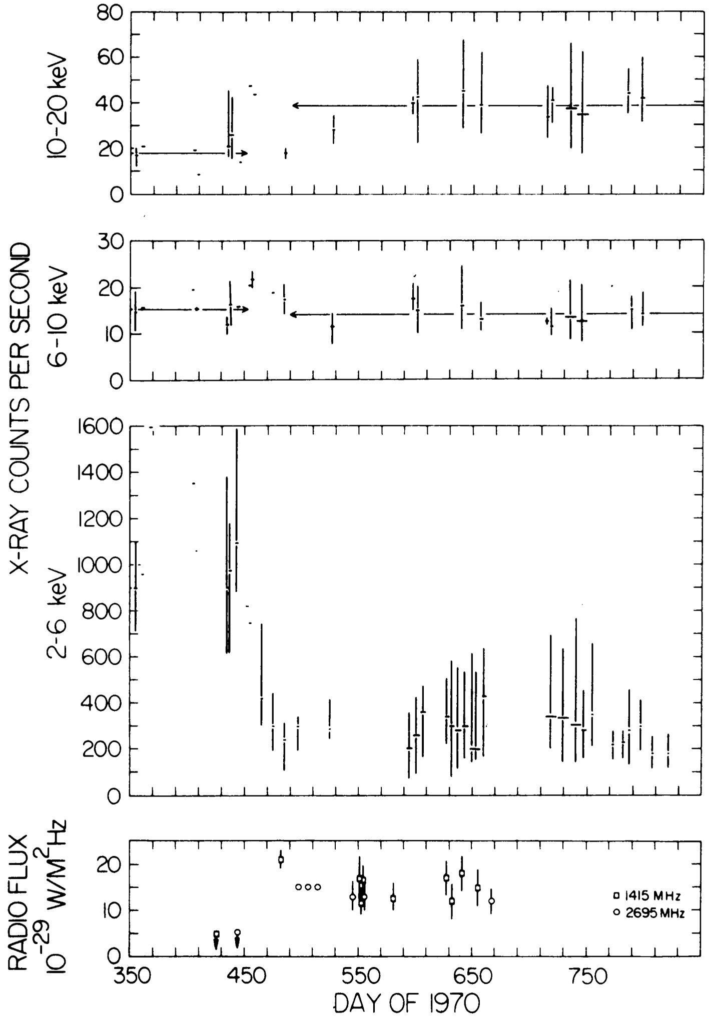


Fig. 15. Cyg. X-1.

### 4.2. Mass of HDE 226868

On the basis of the arguments given above, the HDE 226868 system is believed to be the optical counterpart of Cyg X-1. Bolton (1972) and Brucato and Kristian (1972) derived spectroscopically a mass function which leads to a minimum mass of about 5 $M_{\odot}$ for the X-ray emitting secondary star. This conclusion was based on the assumption that the primary star of HDE 226868 is a normal B0Iab supergiant of more than 20 $M_{\odot}$ according to the spectral characteristics given, for instance, by Walburn (1973). Paczyński (1972) and Trimble *et al.* (1973) criticized this assumption. Indeed a spectrum gives only information on the effective temperature and the surface gravity of a star. Trimble *et al.* (1973) gave a model of a low mass star which is in full agreement with the observed spectral type. Paczyński pointed out that the strong

X-ray flux from the secondary might alter the appearance of the observable spectrum of a star. Four recent papers have addressed these criticisms. One paper by Bolton (1973) used mass function as determined from the absorption line velocities, the HE II 4686 emission line velocities and the distance derived from interstellar red-

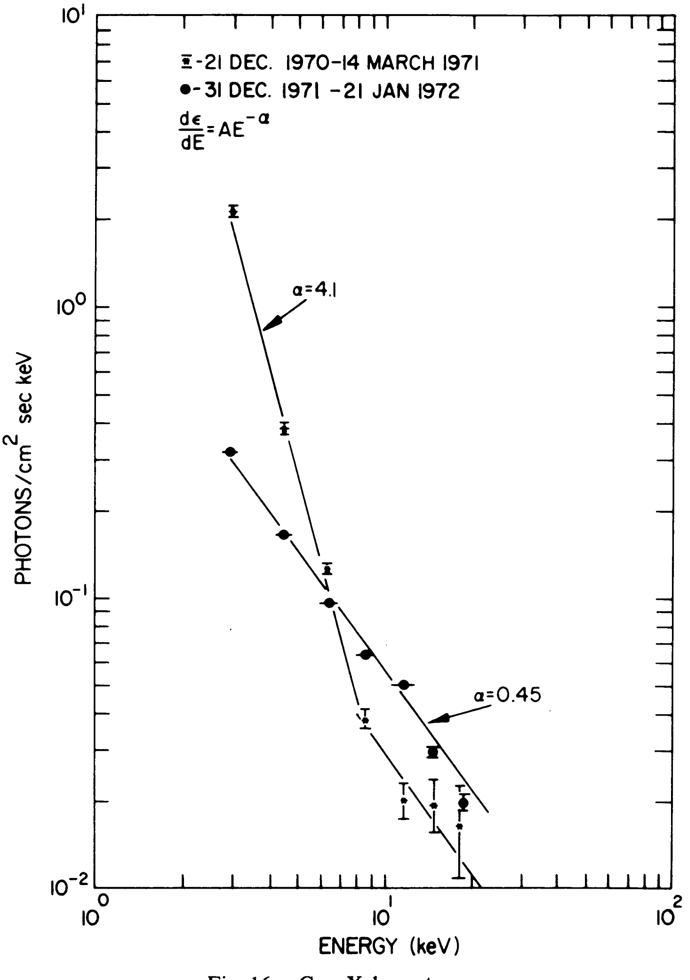


Fig. 16. Cyg. X-1 spectra.

dening and the equivalent width and velocity of the interstellar K line to determine values of 20 $M_\odot$ for the primary, 13 $M_\odot$ for the secondary, 2.2 kpc for the distance, and an inclination angle of 26°. Cherepashchuk (1972) used the absorption line velocities, the HE II emission line velocities with some allowance that the emission region may not belong to the X-ray star, but may lie between the two stars, and the photoelectric observations showing 0.07 mag. changes due to a tidally distorted system. Taking into account limb darkening and the gravity darkening, and assuming that the primary fills its Roche lobe, they determined a primary mass between 10.7

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and 22 $M_\odot$, a secondary mass between 7.8 and 17 $M_\odot$, and a distance as large as 5 kpc. They appear to have neglected any interstellar absorption effects and have, therefore, overestimated the distance. Mauder (1973) used the absorption line velocities, the possible distances allowed by the observed reddening (and absence of a bright infrared source which could be produced by an absorbing circumstellar shell), the absence of any substantial reflection effects as demonstrated by the photoelectric observations, the X-ray to visible light energy ratio, and the photoelectric observations. Assuming that the star cannot be any larger than its Roche lobe, he determines a self-consistent set of parameters that gives a distance of 2 kpc, a primary mass of 25 $M_\odot$, and a secondary mass between 6.0 and 7.3 $M_\odot$. Most importantly, Margon *et al.* (1973) have recently determined the extinction of 50 stars in the field immediately surrounding Cyg X-1 and find $Av/d = (1.3 \pm 0.2)$ kpc$^{-1}$. Since $Av = 3.3$ for HDE 226868, this leads to a distance estimate for Cyg X-1 of $2.5 \pm 0.4$ kpc, in agreement with the spectroscopic modulus for a B09 star. I also understand that Kraft will report on a refined determination of distance which agrees with the above result.

In addition, the recent study of Sanduleak 160 reported by Liller and by Hiltner *et al.* (1973), seems to me to lend much strength to these arguments. Sanduleak No. 160 (13.2 mag. star) had been suggested as the optical counterpart of SMC X-1, the occulting binary X-ray source in the Small Magellanic Clouds. No doubt exists about the identification of this source since the period of the X-ray occultations and of the visible light star coincided. The companion star is reported as B01 according to Webster *et al.* (1972). Liller (1972) has pointed out that if one derives a value for the absolute visual magnitude of the star following Keenan (1963), one finds $-6.2$ and $-5.6$ for the $M_v$ of stars of spectral type B0Ib and B0II. This is in excellent agreement with the value of $M_v$ derived using the distance modulus of SMC of 18.8 mag. and the observed visual magnitude. The absolute value computed in this manner is of 6.0. Thus, for at least this case of SMC X-1, the presence of a strong X-ray source in the system has not altered the spectral appearance of the companion sufficiently to cause substantial errors in determining the mass from spectroscopic data alone. It should be noted that in SMC X-1 the ratio between X-ray and visible light emission is considerably greater than in Cyg X-1. In fact, the heating effects of SK 160 by SMC X-1 are clearly seen in the light curves obtained by Petro *et al.* (1973) for SK 160 while no such effect has been clearly established for Cyg X-1. Therefore, it appears that the effect of the X-ray flux on the primary is not important for the system containing SMC X-1 and should, therefore, be even less important for the system containing Cyg X-1.

It appears to me that the distance of Cyg X-1 has been clearly established to be greater than 2 kpc, that its luminosity and its mass are those consistent with a B0 supergiant and that, therefore, the value of a mass greater than 6 $M_\odot$ for the X-ray source has also been firmly established.

### 4.3. Compact nature of the source

The rapidity of X-ray intensity variations leaves little doubt that the size of the X-ray emitting region is less than $10^9$ cm. This can be used as an argument to imply that the entire star on which the X-ray emission is taking place is compact. This argument depends only on the assumption of an accretion model, and the validity of the Eddington limit.

It seems to me that additional evidence comes from the lack of any observable contribution to the visible light emitted by the system from the 6 $M_\odot$ star. For a main sequence star one could predict that approximately 3% of the light from the system should arise from the object due to its intrinsic luminosity. A similar value would be due to reflection of the light from the primary.

No evidence is observed in the light curve for the presence of such a star and Bolton (1973) has placed a limit of 1% of the total luminosity on its continuum contribution. A weaker upper limit on any line emission arising from the secondary is of order of 15%.

In conclusion, there appears to be strong evidence that Cyg X-1 consists of a binary system containing a B0 supergiant of 20 or 30 $M_\odot$, and a compact source of 6 $M_\odot$. This is the strongest evidence to date for the existence of black holes. I would like to mention that perhaps even more convincing evidence for the existence of such systems will come from the discovery and study of other similar objects. Two, in particular, appear for different reasons as candidates for this search. The first is, of course, the SMC X-1 source. In this case, there appears to be no doubt about the identification and distance of the source and consequently about the mass of the primary. Petro et al point out in a recent paper that from an analysis of the optical photometry and X-ray eclipse duration, the mass ratio is found to be 0.28, $i = 79°$, and $P = 3^{d}\!.89206$. On this basis of a mass of 20 $M_\odot$ for SK 160, the mass of SMC X-1 is 5.6 $M_\odot$. Confirmation of this result requires precise radial velocity measurements which unfortunately have not yet been made. The source is too weak to allow determination of short time variability (0.1–10 keV). However, variability in the time scale of minutes to months is observed.

The source already mentioned previously, Cir X-1, is potentially quite interesting from this point of view. It appears to exhibit the same rapid non-periodic pulsations as Cyg X-1 (Figure 17). Its position is quite well known (0.0002 sq deg) (Figure 18). No bright star appears to be present within the error box brighter than 15 mag. We have some indication of high and low states, however, which may have corresponding visible light variations and might aid in the identification. Also, there appears to be some tentative evidence in the X-rays for a binary occulting behavior. The period would be quite long, $\sim 12$ days. If an optical counterpart could be found on the basis of either of these effects, among the stars in the error box, further analysis of this system might prove quite interesting, in that although the X-ray emission characteristics closely resemble those of Cyg X-1, the companion star appears to be quite dim and therefore of significantly lower mass than HDE 226868. Under these conditions, if the accreting object is a massive compact object, large radial velocities should be observed for the companion. Most of the mass of the binary system in this case would reside in the compact object.

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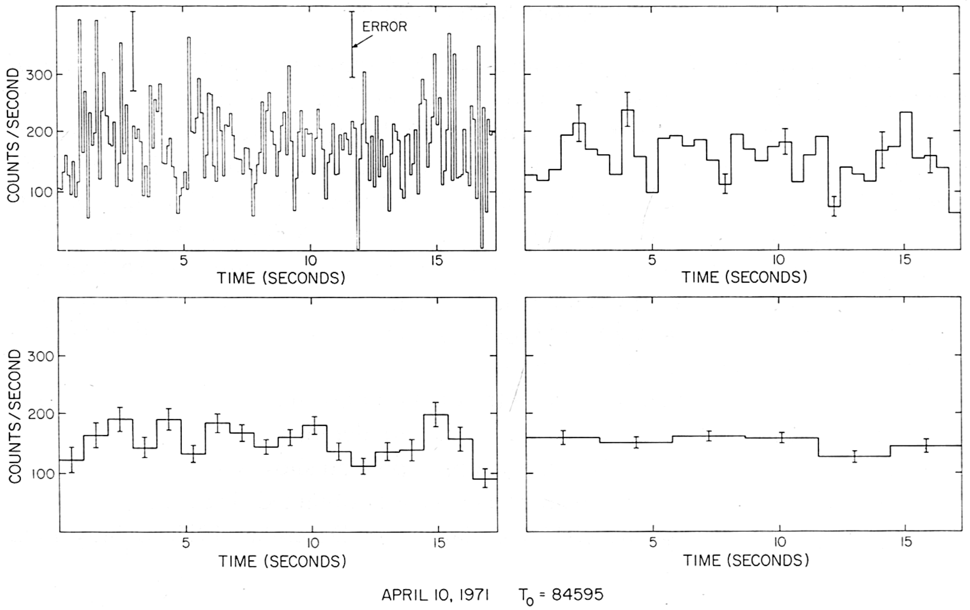


Fig. 17. 3U 1516 – 56.

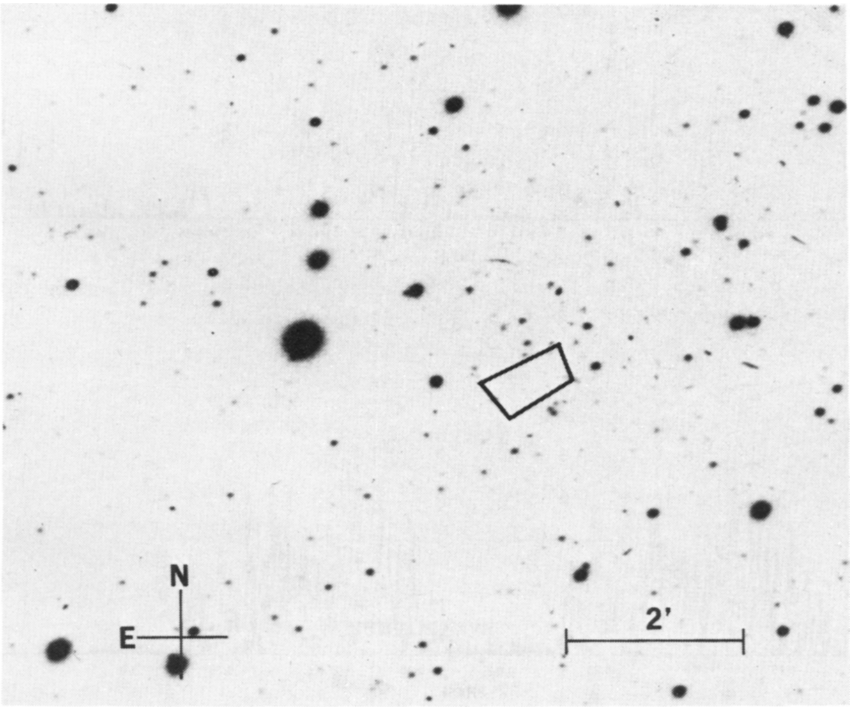


Fig. 18. Location of 3U 1516 – 56.

## 5. Other Binary Sources

The discovery of Her X-1, Cyg X-1 and Cen X-3 raises naturally the question of whether most other galactic sources also can be associated with binaries.

At present we have some 6 X-ray sources we believe are associated with binaries on firm grounds. They are: Her X-1, Cen X-3, Cyg X-1, 2U 1700 − 37, 2U 0900 − 40, SMX-1. With the exception of Cyg X-1, all other sources exhibit an eclipsing behavior. Cyg X-3 exhibits a periodic 4.8 h intensity variation in X-rays, with a factor of 2 maximum to minimum intensity. A strong variable radio source at the Cyg X-3 location was observed to exhibit enormous flares in September 1972. At the location of the radio source a periodically varying IR source was recently detected by Neugebauer *et al.* exhibiting sharp occultations.

The next several figures show some of the data on known eclipsing X-ray binaries. In particular, Figure 19 shows the data used to demonstrate that 2U 1700 − 37 eclipses with a 3.4 day period. Data in the upper portion show seven days of data in May 1972 from which the approximate period was obtained. Data in the bottom half of the figure are all of the UHURU data from December 1970 to May 1972

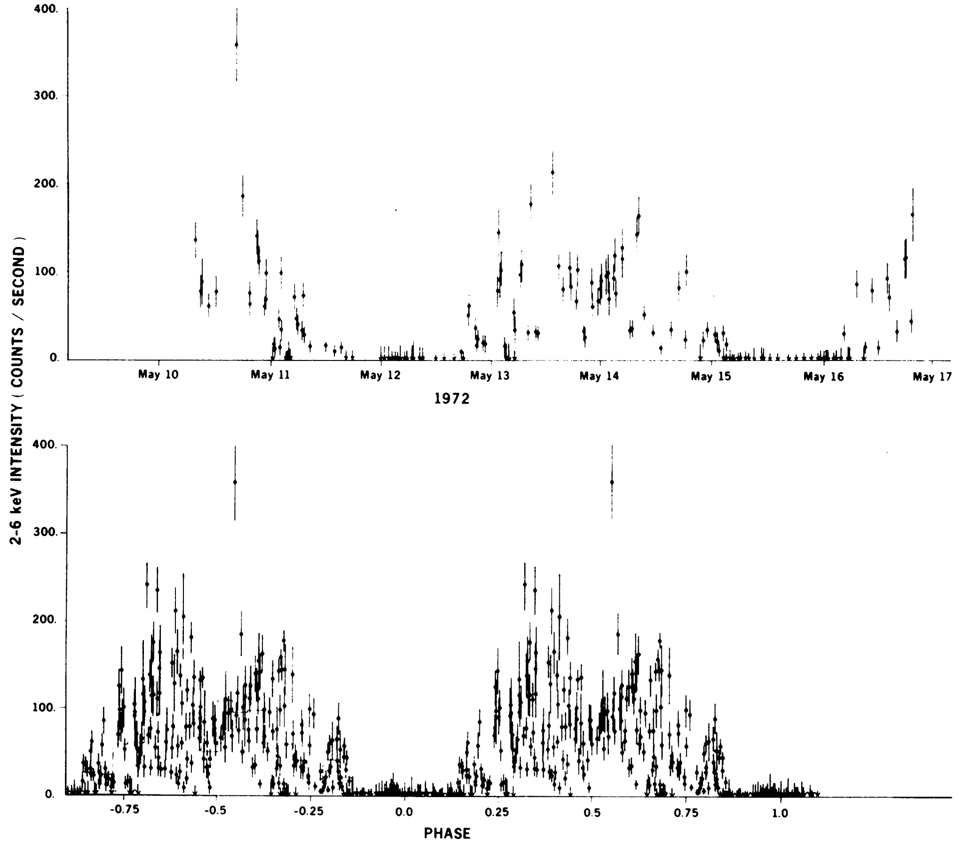


Fig. 19.

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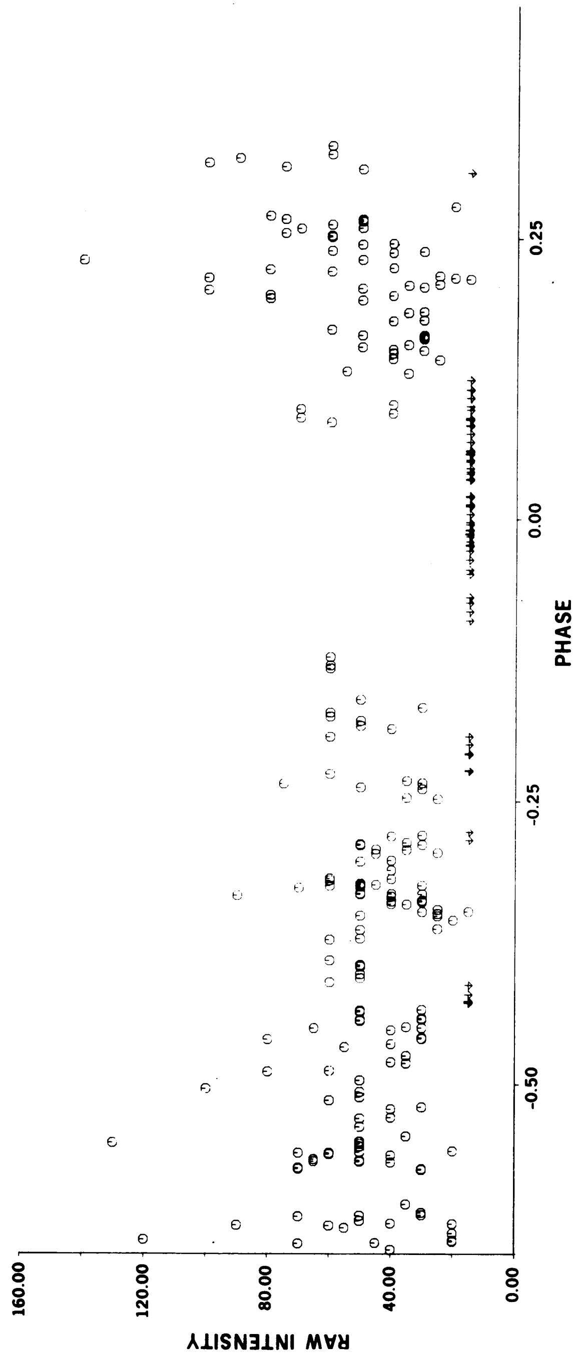


Fig. 20. 172 U 0900 − 40. Data folded with 8.96 day period (May–June 1972).

folded with a 3.412 day period. Figure 20 shows the UHURU observations of 2U 0900−40 folded with an 8.95 day period. The determination of this period was considerably complicated by the complex, erratic variability that the source undergoes. In particular, times of low intensity at phases other than eclipse are observed, although with no regular pattern. This type of behavior obviously greatly complicates the search for new eclipsing X-ray binaries. Figure 21 shows the UHURU data on the X-ray source in the Small Magellanic Cloud obtained in January and June 1971, showing the source eclipses with a 3.9 day period.

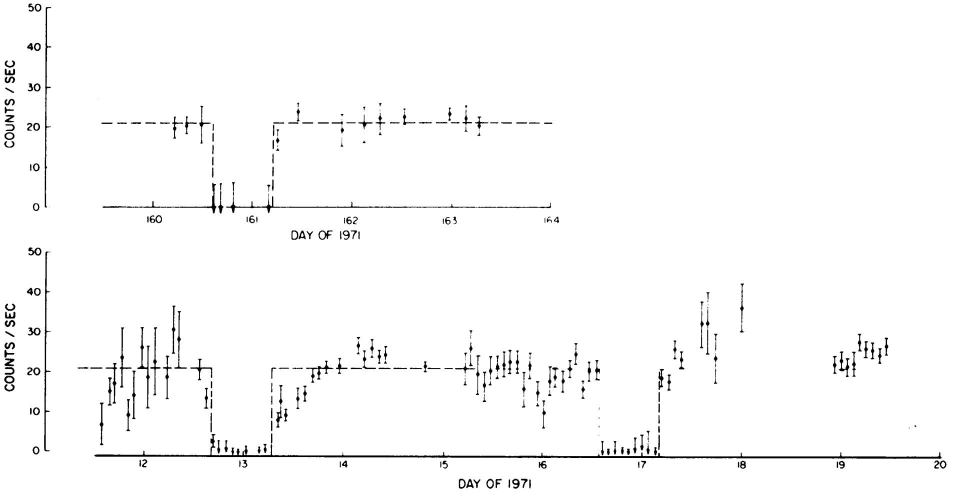


Fig. 21. SMC X-1 (2U 0115−73).

Table III summarizes much of the data on established X-ray binaries. The first column names the 6 sources; the second column gives the binary period (the period for Cyg X-1 is deduced from the behavior of its optical counterpart), the third column describes the short term variability observed in all 6 sources – (SMC X-1 is too weak to detect 0.1 to 1 s pulsations with UHURU), the fourth column names the optical candidate to which the candidate for Cen X-3 should now perhaps be added; the fifth column estimates the distance from the optical data; and the last column gives the peak observed X-ray luminosity from 2–10 keV (the luminosities range from $10^{36}$ to $10^{38}$ erg $s^{-1}$), close to the Eddington limit at which radiation pressure should limit mass flow and thereby luminosity.

Typical counting spectra for these 6 binary sources are shown in Figure 22. Notice the deficit in counts for 5 of the 6 sources in the lowest energy channels. The only source without a substantial low energy cutoff is the only one which does not eclipse – Cyg X-1. We interpret this as being caused by the presence of much material in the orbital plane of the mass transfer binary systems. Systems which eclipse are observed at inclinations near the orbital plane, where much of the material of the system presumably lies, thus giving rise to the observed absorption. Cyg X-1 is presumed to be observed from above the orbital plane and hence little obscuring material is

## TABLE III

CHARACTERISTICS OF X-RAY BINARIES

| Source | Binary Period (Days) | Short Term Variability | Optical Candidate | Distance (kpc) | Peak Luminosity (2-10 keV ergs/sec) |
|---|---|---|---|---|---|
| Cyg X-1(2U1956+35) | 5.600 ± 0.003 from optical. Not observed in X-ray. | Quasi-periodic pulsations as short as 50 millisec. | HDE226868 | 2 | $1 \times 10^{37}$ before transition<br>$3 \times 10^{36}$ after transition. |
| Cen X-3 (2U1119-60) | 2.08712 ± 0.00004 | 4.842 sec pulsations | None | ? | ? |
| Her X-1 (2U1702+35) | 1.700167± 0.000006 | 1.23782 sec pulsations | HZ Her | 5.8 | $1 \times 10^{37}$ |
| 2U1700-37 | 3.412± 0.002 | Non-periodic pulsations as short as 0.1 sec | HD153919 | 1.7 | $3 \times 10^{36}$ |
| 2U0900-40(GX263+3) | 8.96 ± 0.05 | Non-periodic pulsations on times of secs | HD77581 | 1.3 | $4 \times 10^{36}$ |
| SMC X-1(2U115-73) | 3.8927 ± 0.0010 | Non-periodic pulsations on times of mins | Sanduleak 160 | 61 | $3 \times 10^{38}$ |

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along the line of sight. The fact that intensity variation appear to be a prevalent characteristic of the X-ray sources in binary systems makes it very difficult to establish the existence of eclipsing behavior. It is also clear that only a few of the sources even if they are in binary systems will have appropriate orbital inclindations to allow us to observe eclipses.

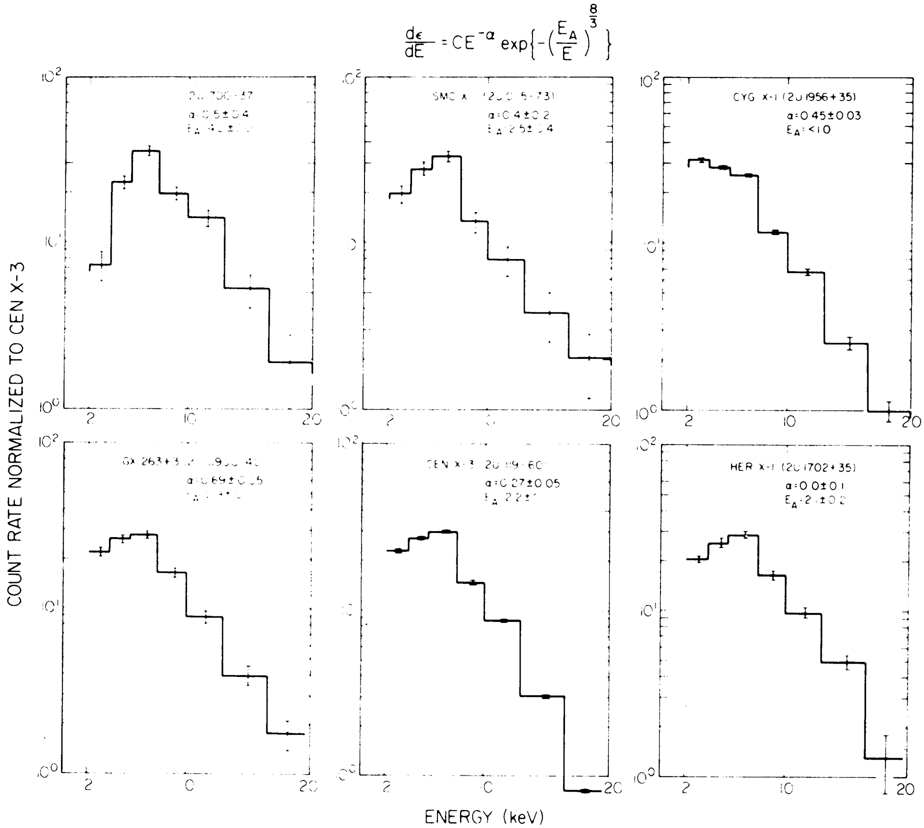


Fig. 22. Binary source spectra.

We have, therefore attempted to establish other criteria to aid us in determining how many of the strong galactic sources could be binaries.

The criteria of large intensity variations and substantial low energy cutoffs were used in selecting the 9 candidates for first study as possible new eclipsing binaries. While no new binaries have been observed definitely, the data in Figure 23 indicate the situation with Cir X-1 (3U1516−56). The data on this source were examined for possible periodicities less than 15 days and a period of 12.29 days was obtained. However, due to the erratic behavior of the source and the fact that it has not been possible to observe the source continuously for several periods, we regard this result as tentative. Figure 23 shows the data folded with a 12.3 day period and we see there is about $\frac{3}{4}$ of a day with no high intensity sightings. As we earlier mentioned with

2U 0900 − 40 there are many additional low points, as well as a large scatter, showing the extreme variability of this source. All of this contributes to the difficulty in obtaining a period and thereby confirmation as a binary. Given the very small location error box for this source, and its intrinsic interest, we hope that optical astronomers may succeed in finding an optical counterpart.

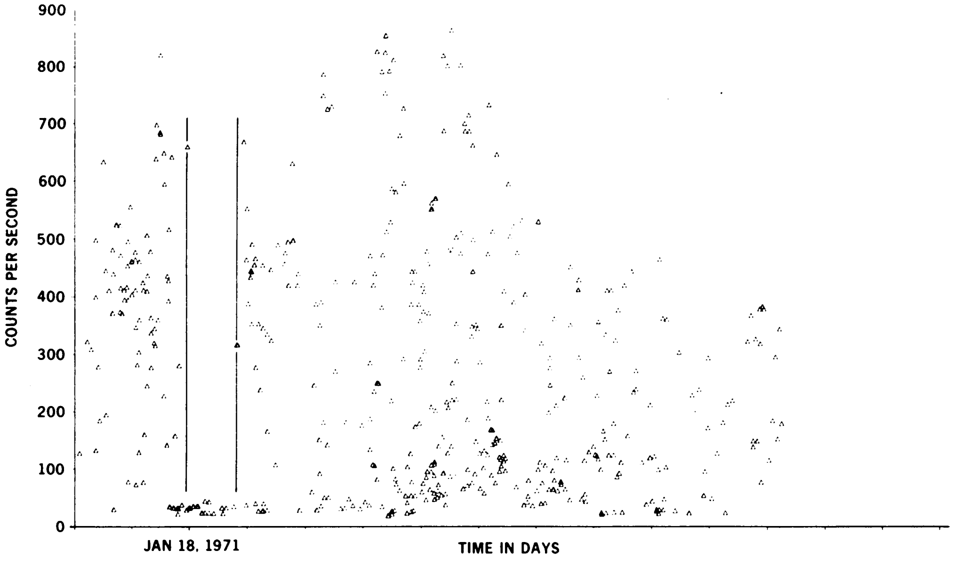


Fig. 23. Cir X-1, data folded with 12.29 days.

In view of the limited success of this approach, we have begun a systematic search for short and long term variability, adopting the point of view that compactness is a necessary, if not sufficient, criterion for establishing the binary nature of the sources. Although this work is just beginning, I would like to report some preliminary results that have been obtained by our group and primarily by Christine Forman Jones.

## 5.1. Long term variability

In the first table (Table IV) a compilation of the day-to-day variability of the strongest among the known 161 X-ray sources that comprise the 3U Catalog is given (Giacconi *et al.*, 1973). We have divided the sources into two intensity classes, the 44 sources greater than 35 counts $s^{-1}$ and the 10 sources between 20 and 35 counts $s^{-1}$ (sources fainter than 20 counts $s^{-1}$ have insufficient counting statistics to be considered for this purpose). Before proceeding to examine this sample for variability, we eliminate known extragalactic sources (NGC 1275 and Virgo Cluster), known supernova remnants (the Crab and Cas A), and the known extended source at our Galactic Center. This leaves 40 and 9 sources in the two categories, respectively. Of the 40 sources brighter than 35 counts $s^{-1}$, 36 are found to vary in average intensity on different days (1 day to several months apart) in the 3U Catalog. Additional study

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has shown that 3U 1636−53 and 3U 1728−24 also vary in intensity, leaving only 3U 1735−44 (for which we have parts of 4 days of data) and 3U 1822−00 at 37 counts $s^{-1}$ as not variable. Based on past experience, 3U 1735−44 might be found to vary as more data become available, although another possibility is that this source could correspond to a supernova remnant with weak, extended, non-thermal

TABLE IV

DAY-TO-DAY VARIABILITY OF 3U SOURCES

161 SOURCES IN 3U CATALOG

| | I > 35 COUNTS/SEC | 35 ≥ I ≥ 20 |
|---|---|---|
| TOTAL SOURCES | 44 | 10 |
| KNOWN EXTRAGALACTIC | 1 (NGC 1275) | 1 (VIRGO) |
| KNOWN SUPERNOVA | 2 (CRAB, CAS A) | |
| KNOWN EXTENDED | 1 ( GAL. CENTER) | |
| TOTAL REMAINING | 40 | 9 |
| VARY IN 3U CATALOG | 36 | 3 |
| VARY FROM FURTHER STUDY | 2 | |
| NOT PRESENTLY KNOWN TO VARY | 2 (3U 1735-44 <I>=210 3U 1822-00 <I>=27) | 6 |
| KNOWN BINARIES | 6* | 1 |
| CANDIDATES UNDER STUDY AS POSSIBLE ECLIPSING BINARIES | 9 | |

*INCLUDES CYG X-1 WHICH DOES NOT ECLIPSE IN X-RAYS AND CYG X-3

radio emission yet undetected. As for 3U 1822−00 a factor of two variability could easily have gone undetected given the source intensity of 37 counts $s^{-1}$, as is also suggested by the absence of detected variability in 6 of the 9 sources with intensity between 20 and 35 counts $s^{-1}$. This is apparently the boundary at which the UHURU instrument becomes limited in sensitivity. Thus, our data are consistent with the view that all sources exhibit large variations of intensity on the scale of days. These results have been obtained by comparing the average intensity of the sources from one sighting to the next.

### 5.2. Short term variability

We can now examine each individual sighting in order to study the short time scale variability (0.1 to 1 s) of the more intense galactic sources. Table V is a table summarizing the status of this survey. The table starts with the 2 periodically pulsing sources – Cen X-3 and Her X-1, and 4 sources already reported by us in the literature as pulsating but with no evidence for regular, persistent periodicity. Then, we list 8 sources newly found to pulsate and 4 more which probably pulsate. The results

TABLE V

SHORT* TIME SCALE VARIABILITY OF 3U SOURCES

PERIODIC VARIATIONS

1. CEN X-3 (3U1118-60)
2. HER X-1 (3U1653+35)

PREVIOUSLY REPORTED AS PULSATING

3. CYG X-1 (3U1956+35)
4. 3U1700-37
5. CIRC X-1 (3U1516-56)
6. GX263+3 (3U0900-40)

NEWLY FOUND TO PULSATE

7. 3U1636-53
8. GX9+1 (3U1758-20)
9. GX349+2 (3U1702-36)
10. SERPENS X-1 (3U1837+04)
11. 3U1820-30
12. GX3+1 (3U1744-26)
13. GX5-1 (3U1758-25)
14. GX340+0 (3U1652-45)

PROBABLY PULSATE

15. CYGNUS X-3 (3U2030+40)
16. GX13+1 (3U1811-17)
17. CYGNUS X-2 (3U2142+38)
18. 3U1658-48

NO EVIDENCE FOR LARGE PULSATIONS

19. GX17+2 (3U1813-14)
20. GX9+9 (3U1728-16)
21. 3U1630-47
22. 3U1705-44
23. SCO X-1 (3U1617-15) - shows ~ 5% variations in 1 SEC

STUDIED BUT TOO WEAK TO DRAW CONCLUSIONS

24. 3U1702-42
25. 3U1822-00
26. 3U1727-33
27. 3U0115+63
28. SMC X-1 (3U0115-73)

*SHORT – → TYPICALLY LESS THAN 1 SECOND AND OFTEN ON TIMES OF 0.1 SECOND.

are obtained by means of a $X^2$ analysis of the intensity fit to individual passes of durations from 2 to 100 s and refer to non-periodic variations. Not all passes exhibit a statistically significant $X^2$, but for the sources numbered 7 to 14 there are sufficient passes with large enough $X^2$ to conclude the sources do pulsate (at least some of the time). For sources 15–18, not enough data have yet been analyzed, but preliminary indications strongly suggest the existence of pulsations. In the case of Cyg X-2, variations of at least 25% in less than 1 s are observed on one occasion.

For the other sources, 7 to 18 in the table, variability is often observed on times of 0.1 s – the best time resolution available with UHURU and with amplitudes that are consistent with 50% changes in intensity. What we have not yet done is determine quantitatively the characteristic time and amplitude of the variability – if such categorization should prove significant – or the fraction of the time that the source is active. Sources 19–23 in the table were studied in a number of passes and have not yet demonstrated large amplitude, short time scale variations, although all have been observed to vary on times of days or less.

The last 5 objects in the table are sources whose intensity is too low to allow us to draw any conclusions from our analysis. Although this survey has not yet been completed and we cannot yet give a quantitative description of the characteristic time scales and amplitude of the variation, yet the above results allow us to conclude that essentially all of the strong galactic X-ray sources with the exception of supernova remnants are variable and many of them appear to vary on times less than 1 s, indicating source regions of $10^{10}$ cm or less.

It may well be that the variety of X-ray behavior we observe is caused by combinations of the various parameters which a binary system with a compact secondary may exhibit, starting with the nature of the secondary, its magnetic field, the mass transfer rate, and the inclination angle to the observer, to name a few. We hope that the survey for eclipsing X-ray sources, the study of the X-ray light curves of the 40 or so brightest sources, the search for short time scale variability, and the searches for optical counterparts presently underway, will contribute to our understanding of the physical processes taking place at the source and perhaps allow us to answer, in at least a statistical sense, the question of the binary nature of all of the galactic X-ray sources and to begin to understand the complicated variety of behavior exhibited. In the near future with the advent of orbiting X-ray telescopes, such as the one planned for the HEAO-B mission of NASA, it will become possible to extend the study of sources of $10^{36}$–$10^{37}$ erg $s^{-1}$ intrinsic luminosity to 30 Mpc. It is our hope that this will greatly expand the number of sources we will be able to investigate in detail, and make it possible to give a substantial contribution to our understanding of the properties of objects near the end point of stellar evolution.

**Note added in proof.** It has recently been reported by a group at Goddard Space Flight Center (Rothschild *et al.*, 1973) that during a rocket experiment in which Cyg X-1 was observed with high time resolution ($\sim 300$ $\mu$s) for a period of 100 s, large amplitude variations occurring in times of the order of 1 ms were observed. This report confirms the analysis performed by Oda *et al.* (1973) on the rocket experiments by the MIT group (Rappaport *et al.*, 1971b). This finding further strengthened the conclusion about the compact nature of the Cyg X-1 source.

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