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EVOLUTION OF X-RAY ASTRONOMY

Bruno Rossi

Department of Physics and Center for Space Research
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

ABSTRACT

The evolution of X-ray astronomy up to the launching of the Einstein Observatory, proceeded through the following major steps. (1) The discovery in 1962 of an extrasolar X-ray source, Sco X-1, orders of magnitude stronger than astronomers believed might exist; it turned out to belong to a class of previously unknown galactic objects, the X-ray stars. (2) The identification of a strong X-ray source with the Crab Nebula. (3) The identification of Sco X-1 with a faint, peculiar optical object. (4) The demonstration that X-ray stars are binary systems, each consisting of a collapsed object (a neutron star, occasionally a black hole) accreting matter from an "ordinary" star. (5) The discovery of X-ray "bursts." (6) The discovery of exceedingly strong X-ray emission from active galaxies, quasars and clusters of galaxies. (7) The demonstration that in these the principal X-ray source is a hot gas filling the space between galaxies.

Keywords: X-Ray Astronomy, Binary System, Supernova, Active Galaxy, Quasar, Cluster

1. THE EARLY HISTORY

1.1 The Discovery of the First Extrasolar X-ray Source

In the fall of 1959 a decision was made at American Science and Engineering, Inc. (ASE) - a young Cambridge company - to start a major effort aiming at the discovery of X-rays from celestial sources other than the Sun. At that time, I was acting as a consultant for ASE, as were, among others, George Clark and Stan Olbert. Riccardo Giacconi, who had recently joined the company, took charge of the program.

Despite the obvious potential interest of a search for extrasolar X-ray sources, extrasolar X-ray astronomy had been essentially ignored in the early planning of the national space program. Only one group, that of Herbert Friedman at the Naval Research Laboratory (NRL), had made some attempts at detecting X-rays from sources outside the solar system. The results had been negative or ambiguous. (Friedman informed me later that the NRL group was engaged in a development program of X-ray detectors to be used in an exploratory work in extrasolar X-ray astronomy.)

The reason for the low priority given to extrasolar X-ray astronomy was, of course, that all astronomical information available at that time led to the conclusion that any conceivable X-ray source located outside the solar system was extremely unlikely to produce a signal strong enough to be detected, except by instruments far beyond the state of the art.

These predictions did not deter us from our efforts; instead we decided to follow two lines of attack.

The first was the development of an instrument many orders of magnitude more sensitive than existing X-ray detectors, capable of detecting the very weak X-ray fluxes expected to originate from extrasolar X-ray sources. To actually produce such an instrument was a very difficult task. It was not enough to improve existing technologies; what was needed was an entirely new approach. The breakthrough came with Giacconi's suggestion to concentrate on a small area detector X-rays from a point source that are incident upon a large collecting area, by making use of total external reflection of X-rays under grazing incidence. The end product was the X-ray telescope, an image-forming device having a very fine angular resolution and a very high sensitivity.

It was clear from the beginning that the development of such a novel instrument as the X-ray telescope would require many years. In fact, the first X-ray telescope suitable for extrasolar X-ray astronomy was launched only in 1978 aboard the HEAO-2 satellite (the Einstein Observatory); although smaller versions had been used previously, in observations of the Sun in X-rays.

The second line of attack had a more modest aim; namely to improve the thin-window gas counters used for solar X-ray astronomy, so as to enhance as much as possible their sensitivity.

We knew, of course, that these detectors would not even approach the sensitivity needed to observe the predicted fluxes from extrasolar sources. On the other hand, we felt that, by looking at the sky with X-ray detectors substantially more sensitive than those used previously, we were entering an entirely unexplored territory, where things unpredictable might be encountered. Which is exactly what happened.

Work on the improvement of thin-window X-ray counters, extending over a period of about two

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years and carried out to a great extent by Frank Paolini, a scientist in Giacconi's group, produced X-ray detectors about 100 times more sensitive than those used previously in solar X-ray astronomy.

The first successful flight with such instruments took place on June 18, 1962. This historic flight detected an extraordinarily strong X-ray source located outside the solar system. The same flight also produced evidence of a diffuse X-ray background (Ref. 1). (For the history, the "official" purpose of this rocket flight was an attempt to detect fluorescent X-rays from the moon.)

Some early skepticism about our discovery was soon dispelled by further observations of the ASE group (Ref. 2) and of the NRL group (Ref. 3). Moreover, the NRL observations, carried out with a collimated detector, succeeded in locating the X-ray source more precisely than the ASE experiment had done, placing it in the constellation of Scorpio. Hence the name of Sco X-1 by which this source became known. The same observations also produced evidence for a second source in the constellation of Taurus, in the general direction of the Crab Nebula.

It was clear, of course, that sounding rockets had serious limitations as platforms for astronomical observations, the most serious being the short useful observation time (a few minutes). Consequently, soon after the discovery of the first extrasolar X-ray sources, a proposal for an X-ray satellite was presented to the National Aeronautics and Space Administration (NASA) by Giacconi and his team. It took many years before this project materialized. In the meantime, however, substantial progress was achieved despite the limited facilities available to X-ray astronomers.

1.2 Progress in the Pre-Satellite Period (1962-1970)

Let me begin with the technical developments.

a) The early free-spinning rockets were gradually replaced by pointing rockets; i.e., by rockets whose detectors could be pointed in a specified direction, or made to sweep slowly across a specified band of the sky.

b) In 1964 George Clark introduced the use of high-flying balloons. Using scintillation counters as well as gas counters, high-flying balloons gathered important data concerning celestial X-rays with sufficiently high energy to traverse the uppermost layers of the atmosphere.

c) In 1965, Minoru Oda, then a guest of MIT, invented a novel kind of collimator, the so-called modulation collimator, which became an essential component of many future rocket (and satellite) instrumentations (Ref. 4). Without entering into details of its operation, I shall just mention that the modulation collimator combines two most desirable features, that are mutually exclusive in the conventional collimators, i.e., a wide field of view and a fine angular resolution.

d) Great progress was made in the development of the grazing incidence telescope during the 1960s. This telescope, aboard rockets and as one of instruments of Skylab, yielded a large number of impressive and highly informative X-ray images of the Sun.

Turning next to the observational results, I would like to mention, in the first place, that by 1970, i.e., by the end of the pre-satellite period, about 40 discrete X-ray sources had been discovered. Their celestial distribution showed a strong concentration along the galactic equator, a clear indication that most of them were galactic objects.

As soon as the existence of extrasolar X-ray sources became established, efforts were directed toward discovering their optical and/or radio counterparts. The first identification - a milestone in the history of X-ray astronomy - was achieved by the NRL group in 1964 (Ref. 5). I already mentioned that previous observations by the same group had detected an X-ray source in the general direction of the Crab Nebula, the remnant of the supernova observed the year 1054. A lunar occultation of this nebula, which took place on July 7, 1964, provided the opportunity to determine whether this source was, in fact, coincident with the Crab. The NRL group succeeded in launching a rocket equipped with X-ray detectors at the beginning of the occultation. They found that the X-ray flux dropped gradually to zero as the visible nebula was being occulted, which proved conclusively not only that the Crab Nebula was indeed the source of the observed X-rays, but also that this particular source was appreciably extended, with a diameter of several arc minutes.

The discovery of an X-ray emission by the Crab Nebula was followed by the identifications of a few additional X-ray sources with supernova remnants. Some of the identifications were fairly certain, others were tentative. The characteristic feature of these sources was their finite angular dimensions, ranging from a few minutes of arc for the younger remnants to a few degrees for the older remnants. The great majority of the X-ray sources, however, did not coincide with supernova remnants. They appeared as point-like "stars" and for this reason they became known as "X-ray stars."

The optical identification of X-ray stars proved to be more difficult than the detection of X-ray sources in supernova remnants. The first and only firm identification of an X-ray star achieved in the pre-satellite era was that of Sco X-1, in 1966 (although, shortly thereafter, another possible identification, that of Cyg X-2, was proposed). The identification of Sco X-1, still another landmark in the history of X-ray astronomy, was the result of the collective efforts by two X-ray teams [at ASE and at the Massachusetts Institute of Technology (MIT)] and of two teams of optical astronomers (at the observatory of Tokyo and at the Palomar Observatory (Refs. 6,7). The optical counterpart of Sco X-1 was found to be a 13th magnitude star (see Figure 1), with very peculiar properties. Its optical emission exhibits a most unusual flickering activity. The spectrum has a large blue and ultraviolet excess. Both the optical and the X-ray emissions are highly variable. At all times the X-ray luminosity is about 1000 times greater than the optical luminosity.

An important property of X-ray stars was established during the early years of X-ray astronomy. Most, perhaps all of them, undergo strong temporal variations, with time scales ranging from minutes to years. The first evidence of long-term variation was found by the NRL group in the

X-ray star Cyg X-1. The first striking example of short-time variations was an X-ray flare of Sco X-1 observed in 1967 during a balloon flight, by Walter Lewin and his associates at MIT (Ref. 8).

Extreme cases of variability were two transients, Cen X-2 and Cen X-4, observed in 1967 and 1969 by an Australian group (Ref. 9) and by a group at the Los Alamos Scientific Laboratories (Ref. 10) respectively. These sources flared up at places where previous surveys had failed to detect any X-ray source; for some time they outshone most other sources and then gradually faded, becoming again unobservable after several months.

Finally, I wish to recall that already in the early years of X-ray astronomy evidence was obtained for powerful X-ray emission by some extragalactic objects. In 1966 the NRL group reported the observation of an X-ray source in the Virgo cluster, tentatively assumed to be coincident with the radio galaxy M-87 (Ref. 11). In 1970 the same group found evidence of X-ray emission by the radio galaxy Cen A (Ref. 12); in 1969 and 1971 respectively the X-ray group at the Lawrence Radiation Laboratory detected X-ray emission from the Large and the Small Magellanic Clouds (Refs. 13,14).

In parallel with the progress of observational X-ray astronomy, active interpretative work was in progress.

Only in the case of the Crab Nebula a clear understanding of the X-ray emission mechanism was achieved.

As is well known, the optical and radio emissions of this object are due to a synchrotron process. Since the X-ray spectrum appeared to be the more or less natural continuation of the optical spectrum, it was natural to assume that the X-ray emission was due to the same process; and this, in fact, became the prevailing view, although the possibility of other emission processes were suggested. Anticipating a result obtained several years later, I wish to mention that the synchrotron mechanism was definitely confirmed in 1976 by Novick's group at Columbia University (Ref. 15); by means of an X-ray polarimeter mounted on the OSO-8 satellite, this group showed that the X-rays from the Crab Nebula are polarized; polarization, of course, is a characteristic feature of the synchrotron radiation.

There remained the problem of the origin of the high energy electrons responsible for the synchrotron process. Let me remind you that the lifetime of relativistic electrons in a magnetic field is inversely proportional to their energy. Electrons of the energy needed to produce visible light via the synchrotron process, in the magnetic fields likely to exist in the Crab Nebula, have a lifetime comparable with the age of the nebula itself. Therefore, before the discovery of the X-ray emission, one could assume that the electrons were somehow generated in the initial explosion. But the electrons needed to produce X-rays had much higher energies, and correspondingly shorter lifetimes. It was thus necessary to assume that an electron accelerator was even now at work in the Crab Nebula. The problem was to identify this accelerator.

The answer came in the late 60's, with the discovery of a 33 milliseconds pulsar within the Crab Nebula by David Staelin and Edward Reifenstein of MIT; presumably the collapsed residue of the supernova explosion (Ref. 16).

Like only another pulsar (the Vela pulsar), the Crab pulsar has a spectrum extending up to the gamma-ray region. [X-rays from the Crab pulsar were observed first by G. Fritz and his coworkers at NRL (Ref. 17), and shortly thereafter by Hale Bradt and his coworkers at MIT (Ref. 18)]. Pulsars are believed to be rotating magnetized neutron stars. There is little doubt that the Crab pulsar is responsible for the acceleration processes needed to sustain the population of high energy electrons in the nebula. No satisfactory theory of these processes has yet been developed; but the identification of the electron accelerator with the pulsar appears to be supported by the following energy argument. The Crab pulsar was found to be slowing down gradually, the pulsation period increasing by one part in 2400 per year. The corresponding loss of rotational kinetic energy turns out to be close to the total radiation energy emitted by the Crab. This coincidence strongly suggests that the radiation energy of the Crab is indeed derived from the rotational energy of the pulsar.

Not much progress was made, in the pre-satellite era, in the interpretation of the X-ray emission by supernova remnants other than the Crab Nebula. The observational data were scarce and of limited accuracy. They did show, however, that the X-ray spectra are generally softer than that of the Crab, suggesting a thermal radiation rather than a synchrotron radiation.

Turning next to Sco X-1 and the other X-ray stars, as late as 1970 their structure and emission mechanism were still obscure. Crude spectral measurements appeared to indicate that the bulk of the X-ray emission (in the range from ~1 to ~10 keV) was thermal bremsstrahlung by plasma clouds with temperatures of several tens million degrees. However, in the case of Sco X-1, for example, the presence of a high-energy tail and of optical emission lines were evidence of a complex structure.

Several hypotheses were proposed to explain the peculiar properties of X-ray stars; one of the basic problems being the very large energy supply needed to power the X-ray emission. One of the suggested models was the so-called accretion model according to which X-ray stars were close binary systems, each consisting of a condensed object (a white dwarf, a neutron star, a black hole) and of an "ordinary" star. Matter would accrete from the "ordinary" star to the condensed component, releasing a large amount of gravitational energy which, in some way or another, was changed into thermal energy (see, e.g. Ref. 19). While this model had many atrractive features, it lacked any observational support, because no evidence had been found for a binary nature of X-ray stars. Moreover, there were serious doubts that a binary system could survive the supernova explosion of one of its components, which was deemed necessary for the generation of a collapsed object.

2. THE X-RAY SATELLITES

The launching, on Dec. 7, 1970, of SAS-1, the first in the NASA series of Small Astronomical Satellites and the first satellite devoted to X-ray astronomy, was a turning point in the history of this field of science. Named Uhuru, it had been conceived by Giacconi, who had supervised the construction (at ASE) of its scientific payload (see Figure 2). This consisted of two thin-window counters mounted back to back, and pointing perpendicularly to the spin axis.

Many additional satellites were launched in the following years, some devoted entirely to X-ray astronomy, some instrumented to carry out X-ray observations as part of a more comprehensive astronomy program. A partial list appears in Table 1. In these satellites, with the exception of HEAO-2, practically all X-ray observations were performed by instruments essentially similar to those employed previously in rocket and balloon experiments; i.e., by large-area, thin-window, collimated photon counters. Modulation collimators, operated in various manners, were widely used. By their means, angular resolutions on the order of 20 arc seconds were often achieved. Occasionally, some grazing incidence concentrators were also employed. As in many rocket missions, star sensors provided aspect determination. The output signals of the X-ray detectors and of the star sensors were telemetered to ground.

Satellites provided X-ray astronomers with far superior observational facilities than had been previously available. An essential feature of Uhuru and of the subsequent satellites was aspect control (an extension of the previous pointing device of rockets), which could be used, on command from the Earth, to cause the X-ray detectors to sweep slowly and repeatedly over a chosen band of the sky, and/or to point steadily, for long periods of time, in a chosen direction. This feature resulted, as expected, in a large increase of sensitivity. Less predictable was the fact that the long (intermittent or continuous) observation of individual X-ray sources would play an essential role in discovering the nature of these sources.

The launching in November 1978 of HEAO-2 (No. 2 in the NASA series of the High-Energy Astronomical Observatories) was another step of fundamental importance in the development of observational X-ray astronomy.

As I already mentioned, HEAO-2 carries a grazing incidence telescope, the first to be used for extrasolar X-ray astronomy. Conceived by Giacconi and developed over an 18 years period, it has a sensitivity almost 1000 times greater than that of detectors flown on previous satellites. Its angular resolution (about 2") is comparable to that of ground-based optical telescopes.

This telescope has produced a wealth of new and most important results. I understand that these will be presented by Dr. Murray. Here I shall focus on the most significant findings of satellites equipped with the conventional thin-window gas counters.

One of the purposes of the early satellites was to discover weak X-ray sources and to determine, with some accuracy, their position. This purpose was achieved with great success already by Uhuru. The final Uhuru catalogue contains 339 sources. Their celestial distribution is shown in Figure 3 (Ref. 20). For comparatively bright sources, this map is still the most complete available to date. Many of the sources in the Uhuru map were identified optically on the basis of positions accurate to a few arc minutes or better. The clustering of the stronger sources along the galactic equator, already noted on the basis of the much more meager sample available in the pre-satellite era, was confirmed. Moreover a crowding of sources around the galactic center became evident. Obviously most of these sources are galactic objects. However, a nearly spherical distribution of weak sources is now clearly seen; most of these sources are distant galaxies.

3. BINARY X-RAY STARS

3.1 Discovery of the Binary Nature of Cyg X-1 and Cen X-3

While the detection by Uhuru of a large number of new X-ray sources was an important achievement, of even more fundamental significance were the results concerning individual sources. Among these results two stand out. The first, in galactic X-ray astronomy, is the discovery of the binary nature of X-ray stars. The second, in extragalactic X-ray astronomy, is the discovery of X-ray sources in clusters of galaxies, the demonstration that these sources have finite dimensions (Ref. 21) and that the X-radiation originates, not in the individual galaxies, but in a hot gas cloud filling the space between the galaxies of the cluster.

Here I shall discuss the first of these two findings. In view of the great importance of the discovery of binary X-ray emitters, a chronological account of the events which led to this discovery has some interest.

This discovery resulted from the observations of two X-ray stars, Cyg X-1 and Cen X-3.

Cyg X-1 is one of the brightest X-ray sources in the sky. It has a very unusual spectrum, much harder than the average spectrum of X-ray stars. Since the early days of X-ray astronomy, efforts were made to discover its optical counterpart, but those efforts had not been successful.

One of the early observational programs of Uhuru was an attempt to reduce the uncertainty in the position of Cyg X-1 and, hopefully, to achieve an optical identification. While these observations were going on (in December 1970 and January 1971), Oda in collaboration with scientists of the ASE group discovered very rapid fluctuations in the X-ray emission of Cyg X-1; an unusual and puzzling feature (Ref. 22).

In the meantime, Uhuru's observations produced a new position for Cyg X-1 accurate to about 20 square minutes of arc (Ref. 23). Soon afterwards, a rocket experiment by the MIT group further improved the positional accuracy, reducing the area of uncertainty to little more than 1 square minute of arc (Ref. 24).

In June 1971 (the date refers to the time when the results were submitted for publication), within this area of uncertainty, Braes and Miley and Hjellming and Wade observed a weak radio source which they tentatively identified with the X-ray source Cyg X-1 (Refs. 25,26). This identification received final confirmation in 1972 from the observation of correlated changes in the X-ray and radio fluxes (Ref. 27).

In July 1971, a group of optical astronomers reported that many observers had noted the presence of a supergiant, HDE-226868, near the radio source and had suggested that it may be associated with the X-ray source (Ref. 28). The authors, however, expressed strong doubts about this conclusion. But, shortly thereafter, Murdin and Webster presented convincing evidence for the identification, based largely on the very small positional error (30 arc seconds) of the radio source (Ref. 29). Just on the basis of positional coincidence between the X-ray source, the radio source and the supergiant, they argued that the three objects were most likely one and the same celestial body. Interestingly, they thought that "the X-ray source may be a companion to the supergiant rather than identical to it;" perhaps the first tentative indication (other than the consequence of the still highly hypothetical accretion model) that Cyg X-1 may be a binary system.

Later in 1971, still stronger evidence for the identification was produced by Wade and Hjellming who verified the nearly perfect spatial coincidence between the supergiant and the radio source, after having now reduced the positional error for the latter to less than 1 arc second (Ref. 30).

In the meantime Webster and Murdin in Nov. 1971 and, independently, Bolton in Dec. 1971 reported observational results of great significance, showing that the optical spectral lines of HDE-226868 displayed the characteristic Doppler shifts of spectroscopic binaries. These observations were one more corroboration of the proposed identification. Moreover, they proved that the supergiant was part of a binary system (Refs. 31,32). The authors pointed out that the X-rays almost certainly originated from the unseen partner (no double set of periodically Doppler shifted spectral lines were observed), and that this object must be a collapsed star.

From accurate Doppler curves (see Figure 4), it was possible to obtain information on the orbital elements. In particular, it was found that the orbital period was 5.6 days.

Meanwhile, the discovery of the fast fluctuations in the X-ray emission of Cyg X-1 had prompted a search of a similar phenomenon in other X-ray stars. The first X-star selected for this study was Cen X-3, whose X-ray emission was known to be highly variable. Early observations by means of Uhuru, which were reported in May 1971, revealed that the X-ray emission of Cen X-3 was indeed pulsed. However these pulsations, unlike those of Cyg X-1, were periodic, with a period of about 4.8 sec. Moreover, sudden transitions were observed between states of high intensity and states of low intensty. Also the pulsation period was found to undergo small changes (Ref. 33).

In January 1972, after collecting a substantial amount of data, and having developed an effective method of analysis (illustrated below), the Uhuru scientists recognized that the observational results inevitably led to the conclusion that the X-ray source in Cen X-3 was part of a binary system, with an orbital period of 2.87 days (Ref. 34). The variations in the pulsation frequency were the result of a Doppler effect due to the orbital motion of the source. The periodic obscurations of the X-ray flux were eclipses of the X-ray source by the binary companion. (This was optically identified by Krzeminski in 1974, and turned out to be a supergiant.)

Thus, within a short time, the binary nature of two, quite different X-ray stars, Cyg X-1 and Cen X-3, became firmly established.

The Uhuru group presented the data obtained from the observations of Cen X-3 in the form shown in Figure 5. The dots on the upper curve A are the differences between the measured delays of the pulses, relative to a fixed time, and the "nominal" delays computed as if all pulse intervals had some constant value ($T = 4.8422$ in the figure); note the remarkable small scattering of the points. Curve B is the differential of curve A, and represents (apart from a constant) the pulsation period, as modified by the Doppler effect. Graph C represents (schematically) the time variation of the intensity, and clearly shows the occurrence of an eclipse. This is centered at superior conjunction, where the motion of the X-ray source is perpendicular to line of sight, and therefore the Doppler shift is zero, in agreement with curve B. (Note that the sinusoidal shapes of curve A and B signify a circular orbit.)

3,2 High-Mass X-ray Binaries

In the following years, a number of additional pulsing X-ray binaries, similar to Cen X-3, were discovered [the first being Her X-1, discovered by means of Uhuru (Ref. 35)]. About 17 such binaries are known today. Their energy output varies from about 10^{36} erg/sec to about 10^{38} erg/sec. (For comparison, the total luminosity of the Sun at all wavelengths is 2×10^{33} erg sec^{-1}.) Their periods range from 0.7 sec to 835 sec. Samples of the pulse shapes of 14 pulsators are shown in Figure 6.

The discovery that some at least of the X-ray stars are binary systems provided crucial support for the view that X-ray stars are powered by accretion, a view which soon became generally accepted. As I already noted, this assumption implies that the accreting partner of the binary system is a collapsed object; i.e., a white dwarf, a neutron star or a black hole. The fast pulsations supply confirming evidence of the very small dimensions of the X-ray source.

There remained the question as to which of the three possible collapsed objects was actually present in the X-ray stars.

Let us consider first Cyg X-1.

In their paper, reporting the evidence for the binary nature of this X-ray star, Webster and Murdin as well as Bolton estimated a minimum value for the mass of the collapsed partner, on the basis of the optical data. They found values which appeared to be higher than the upper limit for the mass of a white dwarf or a neutron star, and, cautiously, advanced the hypothesis that the collapsed object may be a black hole (W. and M.: "It is inevitable that we should speculate that [the collapsed object] may be a black hole." B.: "This raises the distinct possibility that the secondary is a black hole.")

Since then, the conclusion that Cyg X-1 contains a black hole has been reinforced by more accurate estimates of the mass of the collapsed object (see, for example, Ref. 36). It has also survived alternate tentative interpretations of the observational data, invoking a complex structure of Cyg X-1.

I may add that the very unusual spectrum and the peculiar occurrence of very rapid fluctuations in the X-ray emission strongly suggest that the collapsed objec in Cyg X-1 is different from the collapsed objects in the pulsing binaries which, as we shall presently see, have been identified with neutron stars.

In conclusion, the observational data concerning Cyg X-1 are certainly the most convincing direct evidence for the existence of black holes in our galaxy so far available; but whether this evidence should be regarded as decisive, is a matter still subject to debate.

Turning next to the pulsing X-ray binaries, we can, in the first place, rule out black holes as the collapsed objects because black holes are not capable of producing the observed extremely regular pulsations. White dwarfs can be ruled out in the case of the X-ray stars with pulsation periods of the order of one second (Her X-1, SMC X-1), simply because white dwarfs cannot rotate that fast without being disrupted by centrifugal forces; nor, it turns out, can they vibrate with such high frequencies in the extremely stable manner observed. There are other reasons, valid also for most of the slower pulsators, which strongly speak against white dwarfs. One of them is the unreasonably large rate of accretion that would be needed to produce the observed X-ray fluxes, because of the fact that the potential well created by a white dwarf is about 1000 times less deep than that created by a neutron star. [Actually, theoretical arguments have shown that accretion onto a white dwarf cannot produce intrinsic X-ray luminosities greater than a few times 10^{36} erg sec^{-1} (Refs. 37, 38,39)]. Another very convincing argument is based on the fact that the pulsation frequencies of most X-ray pulsators for which sufficiently accurate measurements are available have been found to increase gradually over periods of years. The observed rates of increase are quite consistent with estimates of the torques exerted by the accreting material on the collapsed objects, if these are assumed to be neutrons stars; they are much too large, however, if the collapsed objects are assumed to be white dwarfs. The reason, of course, is that the moments of inertia of white dwarfs exceed by many orders of magnitude those of neutron stars (Refs. 40,41).

In conclusion, there is practically no doubt that the collapsed objects in the pulsing X-ray stars are neutron stars. The observed pulsations are explained as due to the rotation of these stars. This implies that the X-ray source is not axially symmetric with respect to spin axis; magnetic fields are supposed to be responsible for this asymmetry; I shall return to this point later.

In most cases, pulsing X-ray stars have been optically identified. The optical counterparts are generally found to be O or B stars, often in the giant or supergiant luminosity class. The optical counterpart of Her X-1 is an F star with a mass equal to a small multiple of one solar mass. There is one pulsing X-ray star (3U 1627-27) with a mass of only a small fraction of one solar mass; I shall discuss this object later in some detail.

It may be worth mentioning, at this point, that often an optical identification, initially suggested by positional coincidence, has been confirmed unequivocally by the observation of the light curve of the optical candidate. Light curves are periodic variations of the light flux in phase with the orbital motion of the neutron star. They may be produced by two effects. The first effect is heating and consequent bulging of that portion of the ordinary star which faces the X-ray emitting partner. The second effect is a tidal effect, i.e., a deformation of the ordinary star by the gravitational field of the partner. This effect causes the star to acquire the shape of an ellipsoid, which rotates in phase with the orbital motion. Heating effects tend to produce a single light maximum at inferior conjuction; tidal effects tend to produce two light maxima at quadrature.

Summarizing the results presented above, we arrive at the following picture.

There exists a class of X-ray stars consisting of binary systems, each formed by a collapsed object and a nuclear-burning, heavy (usually very heavy) ordinary star. In one case, among those reported to date, the collapsed object is (probably) a black hole; in all other cases it is a neutron star. To distinguish these from other X-ray stars we may want to call them high-mass X-ray binaries. In these objects, matter gradually accretes onto the collapsed partners from the atmosphere of the ordinary star. Since the collapsed partner has a mass similar to that of the Sun, but much smaller dimensions, it creates a deep well of gravitational potential. Falling into this well, the accreting matter releases a large amount of gravitational energy. This energy is somehow converted into thermal energy; thus a very hot, ionized, plasma is produced, whose thermal bremsstrahlung lies in the spectral range of X-rays. Most neutron stars are believed to be strongly magnetized and in a state of fast rotation. The accreting plasma is guided by the magnetic field lines toward the magnetic poles. The result is an X-ray source unevenly distributed over the surface of the neutron star and in its lower atmosphere. Rotation of the neutron star, then, produces the observed pulsations. Absorption and scattering in the surrounding gases govern the details of the pulse shapes. (Magnetization of the neutron stars originally hypothesized to explain the pulsations, has since been confirmed by the observation of a cyclotron line in the X-ray spectrum of Her X-1; see Ref. 42).

Until now, our discussion has been of a qualitative nature. It will be appropriate to add here some simple quantitative arguments.

Let us consider first the luminosity of X-ray stars.

It is well known that the luminosity of a source powered by accretion of infalling plasma is subject to the condition that the force exerted on the plasma by the radiation pressure not exceed the gravitational attraction by the accreting body.

In the case of a plasma of pure hydrogen, we obtain the limiting luminosity value L_E (the so-called Eddington limit) by equating the force exerted on a proton by the gravitational field to the force exerted on an electron by the radiation pressure. An elementary computation yields:

$$L_E = \frac{4\pi c\ GM}{\sigma_T} \tag{1}$$

where $G = 6.668\times10^{-8}$ dyn $cm^2 g^{-2}$ is the gravitational constant, $m_p = 1.67\times10^{-24}$ g is the proton mass, $\sigma_T = 6.7\times10^{-25}$ cm^2 is the Trompson cross-section and M is the mass, in grams, of the accreting body.

With the numerical values of the constants, and expressing the mass of the accreting body in terms of the mass of the Sun, $M_\odot$ (= 2×10^{33} g) we obtain:

$$L_E = 1.25\times10^{38} \frac{M}{M_\odot} \text{ erg sec}^{-1} \tag{2}$$

It is interesting to note that the luminosity of X-ray stars often approaches, in some cases seemingly exceeds, the Eddington limit. Of course, a variety of causes may result in appreciable deviations of the upper luminosity limit from the Eddington limit, as given by Eq. (2). The numerical coefficient in this equation is computed for the case of pure hydrogen. Substantial admixture of heavier elements would increase the value of L_E. Moreover the computation of L_E assumes symmetric inflow, an assumption hardly justified in the presence of a magnetic field. Also no account has been taken of the possible presence of forces other than those due to the gravitational field and the radiation pressure (such as might be exerted by the magnetic field on the moving plasma).

Let us turn next to the measurement of the parameters which characterized the binary system.

The parameter which is most easily derived from the observations in the orbital period T. This may be determined from the eclipses (when present), from the optical light curves, from the Doppler curves of the X-ray pulsations.

Knowledge of T makes it possible to estimate with fair accuracy the overall dimensions of the system.

In the case of circular orbits, an elementary computation yields the equation:

$$\frac{m_x + m_{op}}{(a_x + a_{op})^3} = \frac{1}{G}\left(\frac{2\pi}{T}\right)^2 \tag{3}$$

where m_x and m_{op} are the masses of the neutron star and of the optical partner respectively, and a_x, a_{op} are the radii of their orbits in the center of mass system. One can show that Eq. (3) is valid also in the case of elliptical orbits if a_x and a_{op} are interpreted as the major semiaxes.

With the numerical values of G, with the total mass of the system, m_x and m_{op}, expressed in terms of the solar mass, $M_\odot$, and with $a_x + a_{op}$ expressed in terms of the solar radius the solar radius, $R_\odot$ (= 6.955×10^{10} cm) Eq. (3) yields:

$$\frac{a_x + a_{op}}{R_\odot} = 4.2\left(\frac{m_x + m_{op}}{M_\odot}\right)^{1/3} T_d^{\ 2/3} \tag{4}$$

where T_d is the orbital period in days. The total mass of the system, $m_x + m_{op}$, can always be estimatee approximately; Since Eq. 4 contains only its cubic root, its exact value is of no consequence. Therefore, the exactly measurable quantity T_d is sufficient to determine a fairly accurate value for the quantity $a_x + a_{op}$, a quantity which represents the dimensions of the binary system, exactly in the case of circular orbits, approximately in the case of elliptical orbits.

The Doppler effect of the X-ray pulsations, which can be measured with great accuracy, is a very important source of information.

To begin with, the shape of the Doppler curve provides information on the eccentricity of the elliptical orbit of the neutron star. [It is found that persistent pulsing X-ray stars, like Cen X-3, have nearly circular orbits. Transients, like A0535+26 (see below), have highly elliptical orbits.]

From the Doppler curves one can also derive an accurate value for the major semiaxis of the neutron star orbit in the center of mass system, a_x, projected onto the line of sight, i.e., for the quantity $a_x \sin i$, where i is the inclination angle of the orbit (angle of the plane of the orbit with the plane of the sky).

Newtonian mechanics, then, yields the equation:

$$\frac{m_{op}^{\ 3} \sin^3 i}{(m_x + m_{op})^2} = \left(\frac{2\pi}{T}\right)^2 \frac{(a_x \sin i)^3}{G} \tag{5}$$

(the derivation is quite elementary in the special case of circular orbits).

The function:

$$f = \frac{m_{op}^{\ 3} \sin^3 i}{(m_x + m_{op})^2}$$

contains only accurately measurable quantities. Known as the <u>mass function</u>, it is an important ingredient for the evaluation of the parameters of the binary system. As one can immediately see, it represents a lower limit for the mass of the ordinary star.

The mass functions and other quantities belonging to five among the best known X-ray pulsing X-ray stars are presented in Table 2 (see Ref. 43).

Clearly the measurements discussed so far are not sufficient to determine all parameters of the binary systems. For this purpose one must make use of other pieces of information, derived from X-ray and optical observations, most of which are of limited precision. These informations include the duration of the X-ray eclipses, the Doppler effect of the optical spectral lines, the estimate (from the theory of stellar structure) of the mass of the optical partner.

The most interesting parameter of our binary systems is the mass of the neutron star. Theory predicts that this mass cannot exceed a certain critical value at which the nuclear forces and the Fermi pressure of the neutrons are no longer capable of withstanding self gravitation, and the neutron star collapses into a black hole. There still is some uncertainty about the exact value of the theoretical limiting mass. Neutrons in a neutron star are more closely packed than nucleons in an ordinary nucleus; therefore their interaction cannot be determined from laboratory measurements, but must be estimated from an extrapolation of the data provided by experiments in nuclear physics. However it is generally believed that the limiting mass of neutron stars is near 2 solar masses, in any case less than 3.

The complex problem of how to use the observational data to obtain the most accurate values of the binary parameters (and, in particular, of the masses of the collapsed objects) was carefully examined by Yoram Avni of the Weizmann Institute, by John Bahcall of the Institute for Advanced Studies in Princeton, and jointly, by Saul Rappaport and Paul Joss of MIT (Refs. 44, 36, 45). Rappaport and Joss applied the methods developed in these studies to five X-ray binaries stars for which the most useful data were available. The analysis produced values of the neutron star masses, accurate to about 30% (see Figure 7). None of the mass values thus found contradicts the theoretical predictions concerning the maximum value of a neutron star mass. It is of some interest to note that the observational data are consistent with the view that all neutron stars have the same mass (equal to 1.4±0.2 solar masses) but, of course, do not prove that this is so. (It may be noted, that the most accurate determination of the mass of a neutron star came from the data concerning the binary radio pulsar PSR 1913+16. Analysis by Joseph Taylor and coworkers gave: $m = (1.3 \pm 0.15)\ M_{\odot}$).

To provide some concrete feeling for the geometry of high-mass X-ray binaries, Figure 8 shows (schematically) the trajectories of the neutron stars in seven such objects, estimated from available observational data.

Returning to the accretion process, let me stress that this is a very complex phenomenon. It has been the subject of many elaborate theories, which cannot be discussed here in any detail. These have been reviewed by Frederick Lamb of the University of Illinois and by Vytenis Vasyliunas of the Max-Planck-Institut für Aeronomie (Refs. 46, 47). Basic to all theories is the structure of the gravitational field of a binary system, which may or may not be modified by centrifugal forces, depending on whether or not the atmospheric gases of the donor star partake of the rotational motion of the two stars around their common center of mass. In either case, the equipotential surfaces in the vicinity of the two stars have practically spherical shapes. With increasing distance, they become elongated and eventually join at a point, called the <u>inner Lagrangian point</u>. The two portions of this singular equipotential surface are the so-called <u>Roche lobes</u>, shown in Figure 9. Their dimensions depend on the distance between the two partners and on their mass ratio. Beyond the Roche lobes the equipotential surfaces envelope both stars.

Some stars, such as the optical counterpart of Her X-1, have normally stationary atmospheres, which are prevented from escaping by the gravitational forces. The situation is changed when a star belongs to a binary system. In the course of its evolution away from the main sequence, its atmosphere expands; eventually it will fill the Roche lobe and spill, across the Lagrangian point, into the potential well of the partner. This, in fact, is supposed to happen in the case of Her X-1.

Other kinds of stars, such as the O and B stars (particularly those in the giant and supergiant luminosity classes) are supposed to have atmospheres which expand continuously into space, generating a stellar wind. It is thought that, in this case, accretion occurs through the capture by the neutron star of a small fraction of the stellar wind. It seems, however, that often even in the presence of a stellar wind, the dense portion of the atmosphere of the optical star fills all or a large portion of its Roche lobe. In this case the occulting object coincides at least approximately with the Roche lobe. Since the duration of the eclipse depends on the dimensions of the occulting object, and since the dimensions of the Roche lobes depend on the ratio m_X/m_{op}, the identification of the occulting object with the Roche lobe of the optical partner furnishes still another useful relation between the parameters of the system.

Whether accretion occurs via a stellar wind or via overflow of a Roche lobe, the accreting matter, in general, will have a certain angular momentum with respect to the neutron star. Therefore it will not reach the neutron star directly; it is generally believed that it will remain temporarily trapped in an <u>accretion disk</u>, rotating around the neutron star with Keplerian velocity, until, in some way or another, the angular momentum is dissipated.

A few of the X-stars classified as high-mass X-ray binaries on the basis of their optical identifications were found not to exhibit pulsations. It is believed that, except, of course, for Cyg X-1, these X-ray stars are systems similar to the pulsing binaries. Absence of pulsations can be explained by the assumption that the neutron stars are weakly magnetized, or that their gyration and magnetic axes are coaligned.

I already mentioned the early findings that most X-ray stars undergo large intensity variations. This is true, in particular, for X-ray stars classified as high-mass X-ray binaries. Here, presumably, changes in the accretion rate and/or in the absorption by the plasma cloud surrounding the neutron star are responsible for the observed changes of flux.

I also mentioned a striking phenomenon, noted in the early work on X-ray astronomy, namely the occurrence of <u>transients</u>. Transients, at first, were believed to form a class of objects intrinsically different from other X-ray stars. This view was abandoned following the discovery of some X-ray stars which, except for their transient behavior (Table 3), are entirely similar to the high-mass X-ray binaries (or to the low-mass X-ray binaries to be discussed later). The current view is that in some binary systems, intrinsically similar to the persistent X-ray emitters, accretion occurs only on rare, widely separated occasions, possibly because of episodic enhancements in the activity of the optical partners, and therefore in the accretion rates.

3.3 <u>The Bulge Sources (Low-Mass Binaries)</u>

For some years, after the discovery of the binary nature of Cyg X-1 and Cen X-3, the interest of

X-ray astronomers remained focussed on the high-mass X-ray binaries. However it was already clear that not all, in fact not even most, X-ray stars were objects of this kind. The clearest example of an X-ray star different from a high-mass binary was Sco X-1, the only X-ray star optically identified before Uhuru. Certainly Sco X-1 did not contain a massive, luminous star, as shown by the fact that, for Sco X-1, the ratio of X-ray to optical luminosity is about 1000, many orders of magnitude greater than the same ratio for the high-mass X-ray binaries.

Actually, since the early days of X-ray astronomy, evidence had been produced for the existence of two different families of X-ray stars (see, e.g., Ref. 48). The evidence was based on the celestial distribution of the sources, on their intrinsic luminosity, and on their X-ray spectrum.

One family consisted of X-ray stars clustered around the galactic center. They came to be known as the "galactic bulge sources." This turned out to be a misnomer, for X-ray sources, physically similar to those clustered around the galactic center, are found also outside the galactic bulge. Still I shall continue, temporarily, to use this expression with the understanding that by "bulge source," or "bulge-type source," I mean a source with properties similar to those of the sources in the galactic bulge, but not necessarily located in the bulge.

The second family of X-ray stars was composed of sources contained in a thin disk around the galactic equator; these were called initially "disc sources." By the early 70's it had become clear that the disc sources were, for the most part, high-mass X-ray binaries. But the nature of the bulge sources was still uncertain.

As late as 1975 the only firm optical identification of a bulge-type source was that of Sco X-1, obtained, as we have seen, in 1966 with a rocket experiment; although Uhuru had reinforced the tentative optical identification of a second bulge-type source (Cyg X-2) suggested by Giacconi and his collaborator on the basis of rocket observations.

Only with the launching of satellites capable of very precise positional determinations it became possible to initiate a systematic search for the very weak optical counterparts of bulge sources. Parituclarly productive in this observational program was the SAS-3 satellite, whose scientific payload was designed and developed by Clark and his associates at MIT. Accurate positions of several X-ray sources, leading to their optical identification, were also obtained by means of the satellite HEAO-1 (Ref. 49). A comprehensive list of positions and identifications was published by Hale Bradt and his associates at MIT (Ref. 43). Figures 10a and 10b illustrate the identifications of a high-mass binary and of a bulge-type source.

All optical counterparts of bulge sources turned out to be remarkably similar to the optical counterpart of Sco X-1. Their optical luminosity is very small (from one part in 100 to one part in 10,000 of the X-ray luminosity; whereas for the high-mass X-ray binaries the corresponding ratio ranges from 1000 to 1/10). Their spectra are dominated by a flat continuum, which implies a strong blue and ultraviolet excess, when compared with the spectra of ordinary stars. Generally there are no absorption lines, such as those produced by the atmospheres of ordinary stars, but emission lines are usually detected. Typical prominent features are the He $\lambda 4686$ line and the $\lambda\lambda 4640$-4650 complex.

Bulge-type sources have, on the average, a greater intrinsic X-ray luminosity but a softer spectrum than the high-mass X-ray binaries. None of the bulge sources shows eclipses. Only one of them (4U1627-67) exhibits pulsations. Like the high-mass X-ray binaries, bulge source undergo strong temporal luminosity changes. Several cases of transient behavior have been observed.

The question concerning the nature of the bulge sources has not yet been answered with the same degree of confidence as that concerning the nature of the high-mass X-ray binaries. The prevailing view is that bulge sources, too, are binary systems formed by collapsed objects accreting matter from non-degenerate partners. The latter, however, are thought to be very low-mass, nuclear-burning dwarfs ($m < M_{\odot}$) rather than high-mass ($m > M_{\odot}$) stars. Most likely, the collapsed objects are neutron stars, although, at this time, one cannot rule out the possibility that, in some cases, they may be white dwarfs or black holes.

I should point out that, until now, evidence of a binary nature is available only for very few bulge-type sources. The belief that all of these X-stars are binary systems rests upon the as yet unproven assumption that all bulge sources are similar objects. An additional argument is the difficulty of finding an alternate credible model for these sources. (The suggestion that some of them may be collapsed objects immersed in small dense clouds of interstellar matter runs counter accepted astronomical views, and predicts a much higher low-energy cut-off in the X-ray spectrum than is observed).

Presented below are the observational data supporting the binary model for some bulge-type sources.

3.3.1 Direct optical observation of the non-degenerate partner. Optical observations, which, in the case of high-mass binary X-ray stars, provide direct evidence for the presence of non-degenerate objects and therefore for the binary nature of the systems, do not afford the same kind of evidence in the case of bulge sources. Here one finds that the visible objects, although very faint, still have a greater luminosity than non-degenerage dwarfs (and a very different spectrum). It is thus practically certain that most of the optical emission is a secondary effect, due, presumably, to the heating of an accretion disk by the X-ray flux.

The predominantly secondary origin of the optical emission rules out, in general, the possibility of establishing the nature and the very existence of a non-degenerate component by means of optical observations. This possibility, however, exists, at least in principle, in the case of X-stars exhibiting transient behavior.

Five transient bulge-type sources were studied in detail (see Table 4). In all these cases, the sudden appearance of a "new" X-star was accompanied by the sudden strong increase in the luminosity of an optical object coincident with the

X-star (see Ref. 50) and Figure 11). In three cases (Cen X-4, A0620-00 and Aquila X-1) optical astronomers succeeded in measuring the spectra of the exceedingly faint optical objects that were left behind after the extinction of the X-ray sources. These spectra were found to be those characteristic of K-dwarfs, leaving little doubt that the three transients were binary systems, with K-dwarfs as the non-degenerate components.

3.3.2 Optical light curve. A periodicity, probably related to an orbital motion, has been observed in the optical emission of Sco X-1 (not, however, in the X-ray emission). The period is 0.787 days.

3.3.3 4U1627-67. The study of this object - the only pulsing bulge source detected to this date - has been most illuminating. The pulsations (7.68 sec period) were discovered in the SAS-3 records. However, extensive search for a Doppler effect of the pulsations gave negative results. From a critical discussion of all available evidence, the conclusion emerged that, if the binary model is correct, 4U1627-67 must be a very compact system consisting of a collapsed object, almost certainly a neutron star, accreting matter from a dwarf star of not more than a few tenths of one solar mass (Ref. 51). Subsequently J. Middleditch and his collaborators at the Lawrence Radiation Laboratory of the University of California, Berkeley, produced convincing proof of the binary model by showing that the power density spectrum of the optical pulsations contains clear evidence of an orbital motion with a period of only 2490 sec (Ref. 52). This means that the separation of the two binary partners is less than one half the solar radius (see Eq. 4). Thus the optical data, confirming the conclusions derived from previous X-ray observation, show that 4U1627-67 is an exceedingly compact binary system.

At this point one may reverse the argument and inquire if the assumption that all bulge sources are binary systems runs against any observational evidence. One difficulty is the total absence of eclipses. The small masses of the non-degenerate partners, and the consequent small dimensions of their Roche lobes, make eclipses unlikely, but not to the extent needed to explain why not a single one has been observed among a fairly large sample of bulge sources. Thus it appears that, in order to salvage the binary model, special selection effects must be invoked. One interesting suggestion has been advanced by Mordechai Milgrom of the Weizmann Institute (Ref. 53). He argued that, since the occulting object is very small, eclipses will occur only if the observer is very close to the orbital plane of the neutron star. In this case, the X-ray emission may be obscured by an accretion disk whose median plane coincides with the orbital plane, and the X-ray star may escape detection.

If, as it appears most likely, the bulge sources are binary systems, it will be appropriate to rename them "low-mass X-ray binaries," in line with the nomenclature adopted for the other family of X-ray stars discussed previously.

3.4 Bursting X-ray Stars

Great interest has aroused in recent years the discovery of a peculiar kind of temporal variations, which seems to be typical of low-mass X-ray binaries. These variations, known as bursts, are charaterized by a sudden increase in the X-ray flux, which, in a few seconds or less, reaches a peak of about 10^{38} erg sec^{-1}, comparable to the flux of the strongest persistent sources, and is followed by a more or less regular decay, with an energy-dependent time constant in the range from several seconds to several tens of seconds.

The first burst sources (or "bursters") were discovered, independently, in 1975, by Jonathan Grindlay and John Heise, using the ANS satellite (Ref. 54), and by Richard Belian, Jerry Conner, and Doyle Evans using the 5B Vela military satellite (Ref. 55). Intensive studies by Walter Lewin, George Clark, Jeffrey Hoffman and their associates at MIT using the SAS-3 satellite and by Jean Swank and her associates at GSFC using the OSO-8 satellite are responsible for much of our present knowledge concerning these sources (see review paper in Ref. 56).

About thirty bursters are known today. With one exception, the bursts from a given source follow each other at intervals of hours or days. Sometimes the time intervals between bursts are nearly constant or change regularly with time. Sometimes they are completely irregular. Periods of activity alternate with periods of quiescence.

The exception is the so-called "Rapid Burster," discovered by Walter Lewin and his associates, which produces sequences of bursts separated by time intervals of only seconds or minutes (see Ref. 57 and Figure 12). The same scientists noted characteristic differences between these bursts and those produced by the "slow" bursters; to emphasize these difference, the latter bursts were called type 1 bursts, and the former type 2 bursts.

Crude measurements of pulse-height distributions suggest that both types of bursts have black-body spectra. However, in the type 1 bursts, the temperature appears to decrease during the decay, whereas no significant temperature change is seen to occur during the evolution of the type 2 bursts. If indeed the radiation process is black-body emission, from the temperature (as given by the spectrum), and the total X-ray flux it is possible (assuming a distance of about 10 kpc for the burster) to compute the dimensions of the emitting area. It is probably significant that these dimensions turn out to be of the order of those of a neutron star (about 10 km in radius).

Some bursters lie in globular clusters. The majority, however, are isolated objects and appear to coincide with persistent X-ray stars. Of these, six have been identified with optically faint objects; five of them exhibit the characteristic blue color of low-mass binaries, while the spectral character of the sixth is obscured by strong interstellar reddening. This is a strong indication that only low-mass binaries are capable of producing bursts.

The burst mechanism has not yet been clarified with certainty. Following earlier suggestions by several scientists, in particular by Laura Maraschi and Alfonso Cavaliere of the Milano University (Ref. 58), that bursts may be caused by thermonuclear flashes, Paul Joss made a detailed quantitative analysis of the nuclear reactions that might occur at the surface of an accreting neutron star (Ref. 59). This analysis produced a model which involves accretion of hydrogen by the neutron star, non-explosive thermonuclear reactions changing hydrogen into helium, explosive thermonuclear reactions changing helium into heavier elements. Bursts of type 1 would be the manifestation of these thermonuclear flashes. This model has attractive features although, I understand, meets with some difficulties.

Turning to the Rapid Burster, a key observational result was the discovery by MIT scientists using SAS-3 that, in addition to type 2 bursts it, too, produced type 1 bursts, separated by long time intervals (Ref. 60). This result suggests that the Rapid Burster is not intrinsically different from the slow bursters, except that in the Rapid Burster, for reasons unknown, accretion occurs in spurts rather than continuously; the spurts manifest themselves as type 2 bursts, while the less frequent type 1 bursts would be produced by the same thermonuclear flashes supposed to be responsible for the bursts in the slow bursters.

Since 1978, a program has been under way, aiming at the observation of the optical bursts which are expected to accompany the X-ray bursts.

Several simultaneous otpical/X-ray bursts were observed during 1978 and 1979 (see Ref. 61 and Figure 13). The program is continuing, with the Japanese X-ray satellite Hakucho playing a major role.

An important observational result has been the time delay between the X-ray and the optical bursts. In all cases, the optical burst was found to be delayed by a few seconds with respect to the optical burst. This delay is evidence that the optical burst is due to a reprocessing of the X-ray burst. The delay, then, represents the difference in travel time between the direct X-rays and the reprocessed optical radiation. Its magnitude shows that reprocessing occurs at a distance of the order of a few light seconds from the source of X-rays. This means that it occurs mostly in some matter surrounding the neutron star, presumably an accretion disk, rather than at the surface of a non-degenerate companion. Probably the optical emission by persistent low-mass binaries is also due to the reprocessing in an accretion disk of the X-radiation originating from the neutron star.

3.5 The Problem of the Origin of X-ray Stars

No definitive answer has yet been given to the problem of the origin of X-ray stars. What follows is a brief account of the prevailing views on this matter. It is based largely on a review article by Edward Van den Heuvel of the Astronomical Institute of the University of Amsterdam (Ref. 62), whose work on this subject has been particularly illuminating.

The non-degenerate partners of the high-mass X-ray binaries are massive, population I stars. These stars are short-lived (~10^7 years). Therefore the rate of production of the high-mass X-ray binaries must be large. High-mass X-ray binaries are believed to originate from compact binary systems, each consisting of two nuclear-burning stars, one of which, after receiving mass from its binary partner, has reached the development stage where a supernova explosion takes place, leaving behind a fast rotating, highly magnetized neutron star. The large mass of the other partner prevents the binary system from being disrupted by the explosion.

The non-degenerate partners of the low-mass X-ray binaries, instead, are population II stars. The galactic distribution of the low-mass X-ray binaries, showing a concentration in the galactic bulge, confirms this view. So does the comparatively large abundance of low-mass X-ray binaries in globular clusters, which are formed by population II stars. Unlike the high-mass X-ray binaries, the low-mass X-ray binaries are long lived (about 10^8 years). Therefore a small rate of production is sufficient to maintain the present population. (Of course, both for the high-mass and for the low-mass binaries, the X-ray active period may well be shorter than the life of the binary itself.)

A low-mass X-ray binary cannot be produced by the supernova explosion of one of the partners of a pre-existent non-degenerate binary system, because the gravitational field of the surviving non-degenerate dwarf could not prevent the disruption of this system. It has been pointed out by Clark that a likely production process of the low-mass X-ray binaries located in globular clusters is the capture of non-degenerate dwarfs by neutron stars. Because of the large density of population II stars in globular clusters, the frequency of occurrence of this process appears to be sufficient to explain the observed abundance of low-mass X-ray binaries in such clusters.

It seems unlikely that a similar capture process may account for the production of low-mass binaries outside globular clusters, where the star density is much smaller. As originally suggested by Gursky, these X-stars may represent the end product of the evolution of binary systems formed by a non-degenerate dwarf and a white dwarf. Matter accretes from the non-degenerate dwarf to the white dwarf. As a consequence, the mass of the latter increases gradually, until it reaches the maximum allowed mass of the white dwarfs, at which point the white dwarf collapses into a neutron star.

Unlike neutron stars in the high-mass X-ray binaries, those in the low-mass X-ray binaries are, on the average, very old. It is therefore quite possible that they may have dissipated their magnetic field; which could provide a natural explanation for the nearly complete absence of pulsations among this group of X-stars.

4. GALACTIC X-RAY SOURCES DIFFERENT FROM X-RAY STARS

While the most striking achievement of the satellite observations prior to the launching of Einstein was the discovery of the binary nature of X-ray stars and the understanding of their behavior, important results were also obtained concerning X-ray sources other than X-ray stars.

4.1 Supernova Remnants

To the supernova remnants detected as X-ray emitters in the pre-satellite years, several new ones were added by observations with counter-equipped satellites. Evidence was produced showing that, at least in the older remnants, the bulk of the X-radiation originates from a thin shell of hot plasma immediately behind the shock front which separates interstellar gas from the fast-expanding cloud generated by the supernova explosion. The interpretation of the X-ray emission as a thermal bremsstrahlung received definitive confirmation by the observation, in several remnants, of a spectral feature at about 7 keV, which is interpreted as line emission of highly ionized iron. [This feature was first detected in the Cas A remnant by a rocket-borne experiment carried out by the group at GSFC (Ref. 63)].

4.2 X-rays from Optically Known Galactic Objects

A small number of "exotic," comparatively near-by stars and star systems, known to optical astronomers before the beginning of X-ray astronomy, were found to be sources of X-rays, mostly of soft X-rays, with luminosities much greater than the X-ray luminosity of the Sun, but smaller than those of the weakest X-ray stars. (Clearly, they were the tip of an iceberg, whose exploration had to wait for the launching of the Einstein observatory.)

Included in this group are objects of the following classes:

4.2.1 Dwarf novae. Binary systems in which a degenerate, non-magnetic dwarf accretes matter from a late-type, nuclear-burning star, filling its Roche lobe; both a soft (< 1 keV) and a medium energy (up to ~ 10 keV) spectral components have been observed. Typical X-ray luminosities are on the order of 10^{32} erg sec^{-1}, but occasional large bursts occur, with peak X-ray luminosities as large as 10^{38} - 10^{39} erg sec^{-1}.

4.2.2 AM Her binaries (magnetic dwarf novae). Binary systems similar to dwarf novae, except for the presence of a strong magnetic field, which is supposed to cause the white dwarf to be locked-in with the orbital motion, and to produce an accretion column. The X-ray spectrum of some members of the group contain both a soft and fairly hard (up to about 30 keV) components. It is believed that the former is black-body radiation from the base of the accretion column, the latter (when present) is thermal bremsstrahlung from the column itself X-ray luminosities up to ~ 10^{34} erg sec^{-1} have been observed. Orbital motions produce periodicities both in the optical and in the X-ray emission.

4.2.3 Stars with hot coronae (RS cVn systems). Rapidly rotating, main sequence or subgiant stars, in binary systems, whose exceptionally hot coronae (T ~ 10^7 °K) produce abundant soft X-rays, presumably by thermal bremsstrahlung. It has been suggested that tidal interaction with the binary companion might be responsible for the heating. Their X-ray luminosities (in the low-energy range) are mostly between 10^{30} and 10^{33} erg sec^{-1}.

4.2.4 Hot white dwarfs. White dwarfs with very high surface temperatures. Two objects of this class (HZ43 and Sirius B) were found to be X-ray emitters. The observed soft X-rays appear to be black-body radiation. The luminosities are on the order of 10^{32} erg sec^{-1}.

4.2.5 Flare stars. Cool stars producing frequent optical flares with risetimes of seconds and decay times of minutes. Two flare stars (UV Ceti and YZ Canis Minoris) have been observed to produce X-ray flares.

4.2.6 Algol. A rather anomalous X-ray source, which does not fit into any of the categories listed above. It seems to be a triplet. Both soft and medium energy X-rays have been observed. The production mechanism is not yet well understood.

5. EXTRAGALACTIC X-RAY SOURCES

Substantial advances occurred also in extragalactic X-ray astronomy, which, in the pre-satellite era, had barely begun. [See a review paper by Pounds and Fabian, Ref. 64, which contains an extensive bibliography].

By 1978, about 100 extragalactic X-ray sources had been detected, most of them by means of Uhuru, Ariel-5, SAS-3, HEAO-1. They include:

(a) One "normal" galaxy," Andromeda (in addition to the two Magellanic clouds), with an X-ray luminosity similar to that of our own galaxy; i.e. a small multiple of 10^{39} erg sec^{-1}.

(b) Between 40 and 50 active galaxies (Seyfert galaxies, Radio galaxies, High Excitation Emission Lines galaxies), with X-ray luminosities orders of magnitude greater than normal galaxies (2-10 keV luminosities mostly in the range from about 10^{42} to about 10^{46} erg sec^{-1}).

(c) 7 BL Lac Objects; ill-understood objects, characterized by a point-like or very compact appearance; spectral lines absent or very weak, strong radio emission, strong polarization of optical and radio emission, bright nucleus, extreme variability; 2-10 keV X-ray luminosities in the range from about 10^{43} to about 10^{46} erg sec^{-1}.

(d) Three quasars, namely the bright, comparatively near-by quasar 3C 273 and two quasars discovered through the optical examination of two faint X-ray sources detected and accurately located by SAS-3. Their 2-10 keV X-ray luminosities are on the order of 10^{44} - 10^{46} erg sec^{-1}.

(e) About 40 clusters of galaxies, with 2-10 keV X-ray luminosities in the range from about 10^{43} to about 10^{46} erg sec^{-1}.

Active galaxies were found to have exceedingly bright nuclei at all wavelengths. It is interesting to note that in active galaxies and quasars the X-ray and γ-ray luminosity may exceed the luminosity at all other wavelengths. It was noted that the galactic nuclei are similar to quasars, and it was suggested that quasars may be bare nuclei of active galaxies. Strong temporal variations had been observed in some active galaxies and some quasars, with time scale ranging from hours, to days, to years (see below).

Undoubtedly, quasars and their close relatives, active galactic nuclei, are among the most interesting and puzzling celestial objects. Basic to any attempt at establishing their structure and interpreting their behavior is some information on the sizes and the masses of these objects.

Radio observations by means of the Long Baseline Interferometer have placed an upper limit of several times 10^{-4} arc sec to the angular dimensions of some galactic nuclei. With a typical distance of about 10 Mpc., this angular size corresponds to a linear size on the order of 10 parsec.

Much more stringent upper limits were derived from the temporal variations of the luminosity. It seems that one can safely assume that the time scale of a variation cannot be smaller than the time of traversal of light through the source. The upper limit set by this condition will not be invalidated by a possible reverberation of the radiation due to scattering in the medium surrounding the source, an effect which can only lengthen the observed time scale and cause an over-estimate of the size of the source.

The fastest variation published so far is a flare exhibiting an order of magnitude change of flux in 730 sec, observed by the CFA group on the Seyfert galaxy NGC4151 by means of Uhuru (Ref. 65). However, to measure, indeed to even establish the existence of such a short event in a very faint source, is a very difficult task. (The authors themselves appear to have some doubts about the reality of the effect). On the other hand, variations with time scales on the order of one day appear to be well established. Observations, by means of Ariel 5, of 28 active galaxies have detected, among a number of variations with longer time scales, one flare with a time scale of about one day in MKN 421, and one sudden increase of flux, with a time scale of about 1/2 day in the quasar 3C 273 (Ref. 66). The maximum size compatible with this time scale is about 1.3×10^{15} cm, i.e., less than 1/1000 of one light year, a very short dimension indeed on a galactic scale.

For an estimate of the mass of an active nucleus or a quasar we are on less solid ground than for the estimate of the size. The simplest method is based on the criterion of the Eddington limit (Eq. 2) to the observed luminosity. In the case of 3C 273, for example, $L_x \approx 10^{46}$ erg $\sec^{-1}$. By requiring that $L_x \lesssim L_E$, we obtain for the mass M the condition $M \gtrsim 10^5 M_\odot$. As I already cautioned, the straightforward application of the Eddington limit to obtain a minimum value for the mass is a risky procedure. Therefore this minimum value might well differ, even by an order of magnitude, from that quoted above. Nonetheless, it is certain that 3C 273 (and undoubtedly the other quasars and active nuclei as well) have truly enormous masses. That these masses are contained in as small volumes as indicated by the occurrence of fast variations, justifies the wide spread belief that quasars and active nuclei may contain supermassive black holes. If this is so, the emission from these objects may be powered by accretion to the black holes from the surrounding matter.

Early in the history of X-ray astronomy clusters of galaxies had emerged as a prominent class of extragalactic X-ray sources. I already mentioned that X-ray observations played a prominent role in establishing the physical nature of these systems; I noted that records (obtained by Uhuru) had shown that the X-ray emitting regions in the Perseus and Coma clusters extend through the volumes of the clusters (Ref. 21). I also noted that observations (by means of the Ariel 5 satellite) had shown that the X-radiation of the Perseus cluster originates not from the individual galaxies but from a hot gas ($T \approx 10^7 - 10^8$ K) filling the cluster's volume. The latter result was established by the detection of the same 7 keV spectral feature, due to line emission of Fe XXIV-XXVI, which had been found in the spectra of supernova remnants (Ref. 67). This observation also proved that the gas in the clusters is not primordial but, presumably, has been processed in supernova explosions.

6. THE DIFFUSE RADIATION

The diffuse radiation, already detected in the early rocket flights, was investigated more thoroughly by means of satellites.

One important result was that below 1 or 2 keV this radiation is very patchy and therefore, presumably, of galactic origin (perhaps arising from the residues of very old supernova clouds). At higher photon energies, instead, the background appears to be isotropic, a strong argument in favor of its extragalactic origin.

Clearly, what is seen as a diffuse radiation by any given instrument, arises, in part at least, from faint sources which are not resolved by that particular instrument. The question remains whether all of the diffuse extragalactic radiation can be accounted for in this manner, or whether a substantial fraction of it originates in the space between galaxies. In the latter case the most likely production process is thermal bremsstrahlung by a hot gas filling intergalactic space. An answer to this question is of great cosmological significance, for the total mass of the necessary gas may come near to the mass needed to "close" the Universe, i.e., to prevent the Universe from expanding indefinitely.

Results bearing on the problem of the nature of the diffuse radiation have been obtained from spectral measurements by means of the satellite HEAO-1 (Ref. 68). Important data have also been produced recently by the Einstein telescope. By virtue of its high sensitivity, this instrument is capable of detecting much fainter X-ray sources than had been observed before, thereby pushing further down the upper intensity limit of discrete sources whose cumulative effect is undistinguishable from a true diffuse radiation.

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Summing up, we find that observations with counter-equipped rockets and satellites have provided a solution, rather complete in its essential features of the problem concerning the nature and the mode of operation of X-ray stars. Much remains to be done to fill in important details; one may anticipate that collimated counters will continue to be the basic tool for these investigations.

The counter technique has played an essential role in the development of X-ray astronomy not only in the study of X-ray stars, but also in the study of X-rays from other sources (X-rays from supernova remnants, from "known" galactic objects, from extragalactic sources; diffuse X-rays). However, in connection with many important observational problems encountered in this latter field, the grazing-incidence telescope, with its high sensitivity, its fine angular resolving power and its image-forming capability offers opportunities unmatched by other instruments. Therefore, as far as this aspect of X-ray astronomy is concerned, a detailed discussion of early results, stopping short of the recent observations by means of the Einstein telescope, would be rather pointless. Since a presentation of Einstein's data is not part of my assignment, I shall stop at this point.

TABLE 1

Partial list of X-ray astronomy satellites (not included are the Air Force sponsored satellites nor the USSR satellites). Satellites marked with a star were devoted entirely to X-ray astronomy.

Spacecraft	Launch date	Organization	Principal Investigators and some other participants
*SAS-1 (Uhuru)	Dec. 12, 1970	NASA	R. Giacconi (American Science and Engineering)
OSO-7 (Orbiting Solar Observatory No.7)	Sept. 29, 1971	NASA	G. Clark, H. Bradt, H. Schnopper, W. Lewin (Center for Space Research Massachusetts Institute of Technology)
Orbiting Astronomical Observatory C (Copernicus)	Aug. 21, 1972	NASA	R. Boyd (University College, London)
Astronomical Netherland Satellite No.1 (ANS-1)	Aug. 30, 1974	Netherland Agency for Aerospace and NASA	A. Brinkman (Space Research Lab., Utrecht); H. Gursky (Center for Astrophysics, Harvard University); H. Schnopper (Center for Space Research, Massachusetts Institute of Technology)
*U.K. 5 (Ariel 5)	Oct. 15, 1974	U.K. Science Research Council and NASA	R. Boyd (University College, London); H. Elliot (Imperial College); K. Pounds (University of Leicester); S. Holt (Goddard Space Flight Center)
*SAS-3	May 7, 1975	NASA	G. Clark, H. Bradt, H. Schnopper, S. Rappaport, W. Lewin (Center for Space Research, Massachusetts Institute of Technology)
OSO-8 (Orbiting Solar Observatory No.8)	June 21, 1975	NASA	E. Boldt (Goddard Space Flight Center); W. Kraushaar (University of Wisconsin); R. Novick (Astrophysics Laboratory, Columbia University)
*High Energy Astronomical Observatory No.1 (HEAO-1)	Aug. 12, 1977	NASA	H. Friedman (Naval Research Laboratory); E. Boldt, (GSFC) and G. Garmire (Caltech) jointly; H. Gursky (CFA) and H. Bradt (MIT) jointly; L. Peterson (U. of Calif., S. Diego) and W. Lewin (MIT) jointly

TABLE 1 (Continued)

Spacecraft	Launch date	Organization	Principal Investigators and some other participants
*High Energy Astronomical Satellite No.2 (HEAO-2, Einstein)	Nov. 13, 1978	NASA	R. Giacconi (Center for Astrophysics, Harvard University); G. Clark (Center for Space Research, Massachusetts Institute of Technology); E. Boldt (Goddard Space Flight Center); R. Novick (Astrophysics Lab., Columbia University); H. Tananbaum, Center for Astrophysics, Harvard University)
*CORSA-B (Hakucho)	Feb. 21, 1979	Inst. Space Aeron. Sci., U. of Tokyo	M. Oda (University of Tokyo)
*U.K. 6 (Ariel 6)	June 2, 1979	U.K. Science Research Council	R. Boyd (University College, London) K. Pounds (University of Leicester)

TABLE 2

Properties of Some High-mass X-ray Binaries

τ = pulsation period; T = orbital period, d = approximate distance; L_x = approximate x-ray luminosity (~2 to ~10 keV); L_x/L_o = approximate ratio of x-ray to optical luminosity (Ref. 43).

	Companion Spectral type	τ (sec)	T(days)	$a_x \sin i/R_\odot$	$f/M_\odot$	d(kpc)	L_x(erg/s)	L_x/L_o
Cen X-3 4U1119-60	O giant	4.84	2.087	17.15	15.5	∿ 8	$\sim 10^{37}$	∿0.05
Her X-1 4U1656+35	F	1.24	1.700	5.69	0.85	∿ 5	$\sim 10^{37}$	∿10
Vela X-1 4U0900-40	B supergiant	283	8.966	48.40	18.93	∿ 1	$\sim 2\times10^{36}$	$\sim 3.\times10^{-3}$
SMC X-1 4U0115-73	B supergiant	.714	3.892	23.04	10.84	∿ 65	$\sim 6\times10^{38}$	∿1.2
4U1538-52	B supergiant	529	3.73	23.79	13.0	∿ 7.	$\sim 4\times10^{36}$	∿0.01

TABLE 3

High-mass X-ray Transients (Ref. 43).

	A1118-61	A0535+26	4U0115+63
Date	Dec. 1974	April 1975 Seven further outbursts from 4/75 to 4/76	Dec. 1977 Previous outburst in '71
Optical object	Be star ?	Be star	reddened B star
Pulsation period (sec)	405	104	3.61
Orbital period	?	months?	24d
L_x/L_o	∿ 2	∿ 0.1	∿ 2

TABLE 4

Low-mass X-ray Transients

	A0620-00 (Monoceros Nova)	A1524-61 (Triang. Austr. Nova)	H1705-25 (Nova Ophiuchi)	3U1908-00 (Aquila X-1)	Cen X-4
Date	August 1975 Previous outburst (optical) 1917	November 1974	Fall 1977	recurrent; ∿ once a year	July 1969 May 1979
Max. X-ray Intensity	≃ 50 Crab	≃ Crab	≃ 3 Crab	≃ Crab	≃ 35 Crab ≃ 4 Crab
L_x/L_{opt} at max.	∿ 150 (Ref. 69)	∿ 200 (Ref. 69)	∿ 100 (Ref. 70)	∿ 500	∿ 40 (Ref. 50)

7. ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Figure 1. Photograph of the region of the sky containing Sco X-1, reproduced from the Palomar Sky Survey print. The X-ray source was found to lie in one or the other of the two rectangles (1' x 2' in size). The optical counterpart of Sco X-1 (arrow) is a 13th magnitude object (Ref. 6).

Figure 2. Scientific payload of Uhuru (Ref. 71).

Figure 3. The X-ray map of the sky, in the range of photon energies 2 to 6 keV, according to the fourth Uhuru catalogue. (Ref. 20).

Figure 4. Doppler curve of a spectral line of the supergiant HDE-226868, the optical counterpart of Cyg X-1 (Ref. 32).

Figure 5. Cen X-3 observational data showing the Doppler effect on the pulsations and one eclipse; see text (Ref. 34).

Figure 6. Pulse profiles of nine pulsing X-ray stars. The pulsation periods are indicated (Ref. 72).

Figure 7. Values of the neutron star mass derived from measurements on five high-mass X-ray binaries and one pulsar (Ref. 45).

Figure 8. Orbits of neutron stars in seven high-mass X-ray binaries (schematic). Masses of the non-degenerate partners are indicated; 4U0115-63 is a transient (Ref. 45).

Figure 9. The Roche lobes of a high-mass X-ray binary. L is the inner Lagrangian point; the cross indicates the center of mass of the system (Ref. 73).

Figure 10. (a) Optical identification of the high-mass X-ray binary GX301-2; parallelogram: error box from measurements of Uhuru; larger circle: preliminary SAS-3 error box; smaller circle: final SAS-3 error box; the optical partner is the bright star at the center of the SAS-3 circles.

(b) Optical identification of the bulge-type source 2S 1627-673; the optical partner is the faint "peculiar" star No. 4 within the SAS-3 error circle; all other stars within this circle have the appearance of "ordinary" stars (Refs. 74, 75, 76).

Figure 11. Optical observation of the X-ray transient Cen X-4; (a) faint optical object detected before the X-ray outburst; (b) bright optical object observed after the X-ray outburst (Ref. 50).

Figure 12. Eight typical sequences of bursts from the Rapid Burster (Ref. 57).

Figure 13. Simultaneous X-ray and optical bursts from a low-mass X-ray binary (the object at the center of the white circle; Ref. 61).

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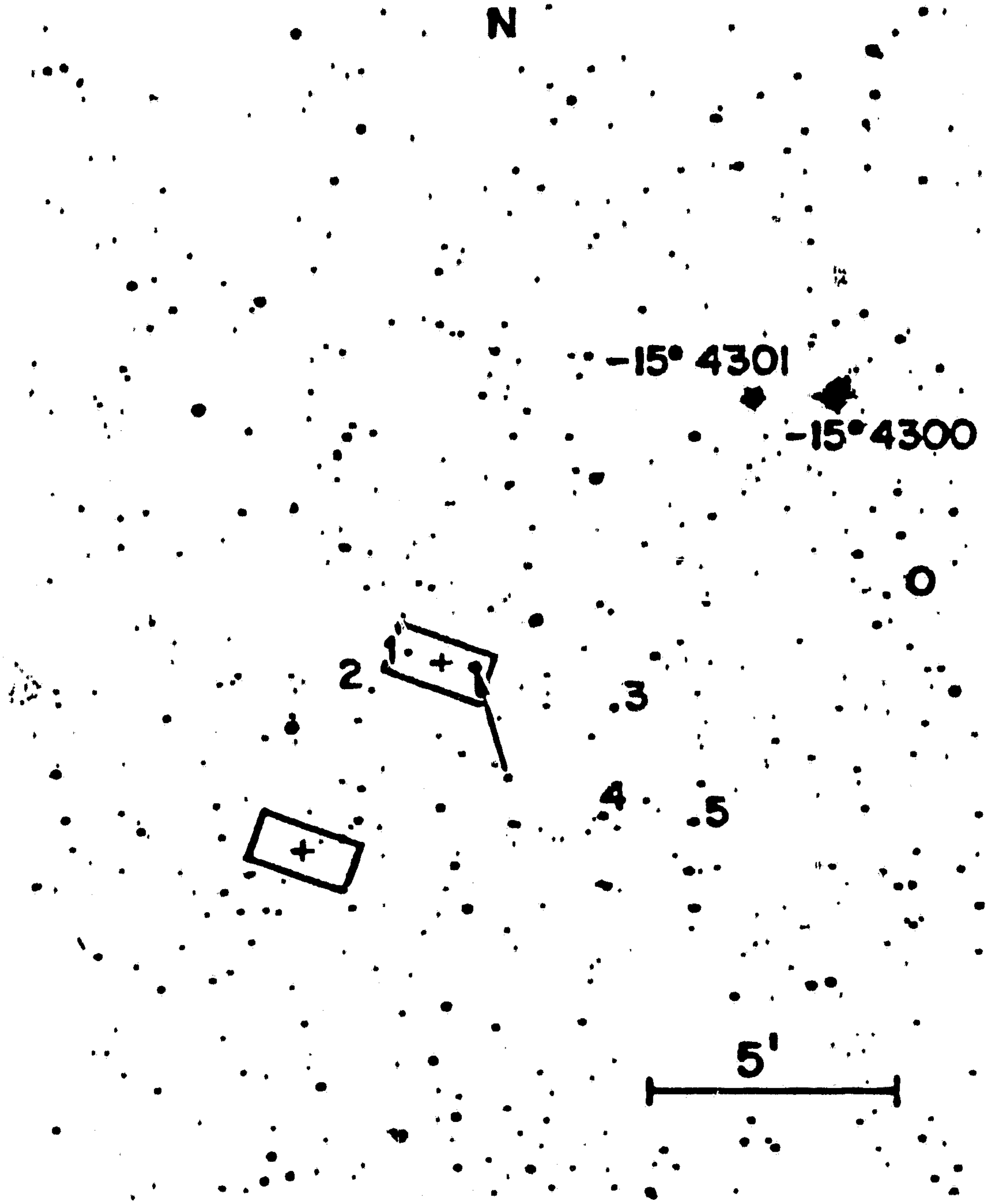

Fig. 1

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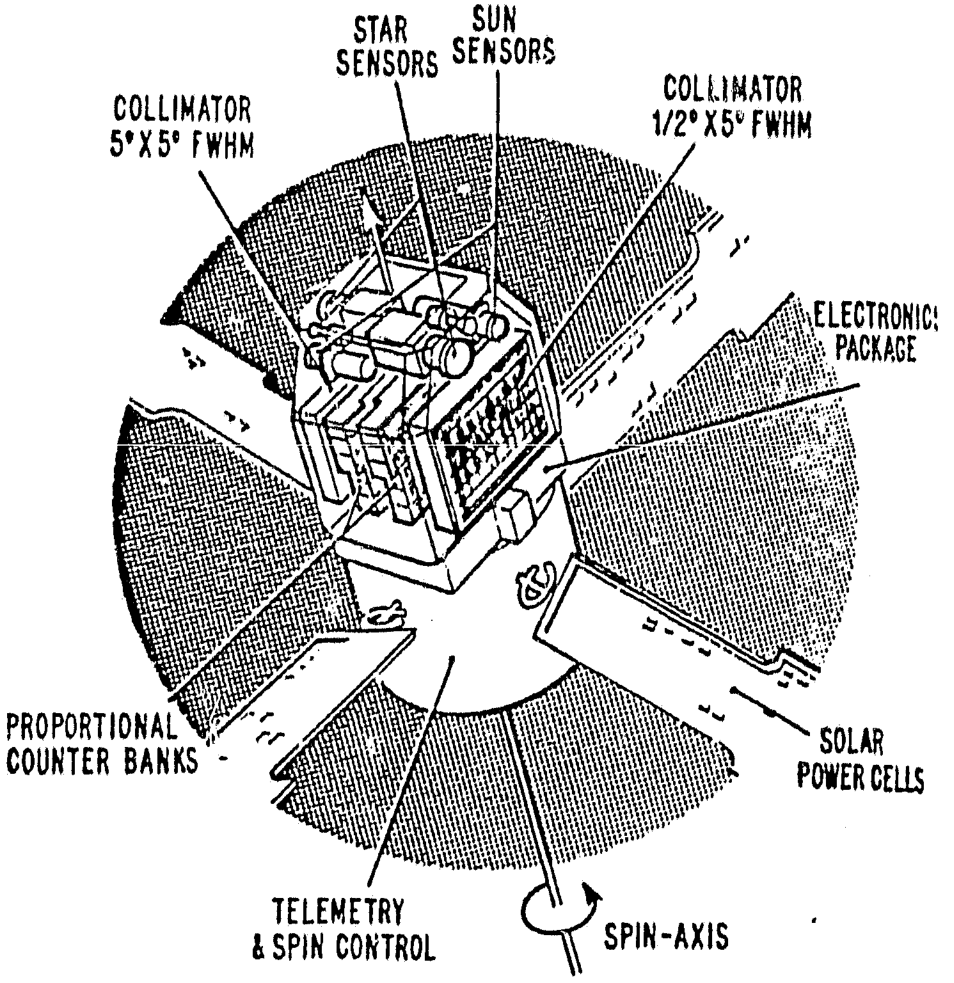

Fig. 2

THE FOURTH UHURU CATALOG

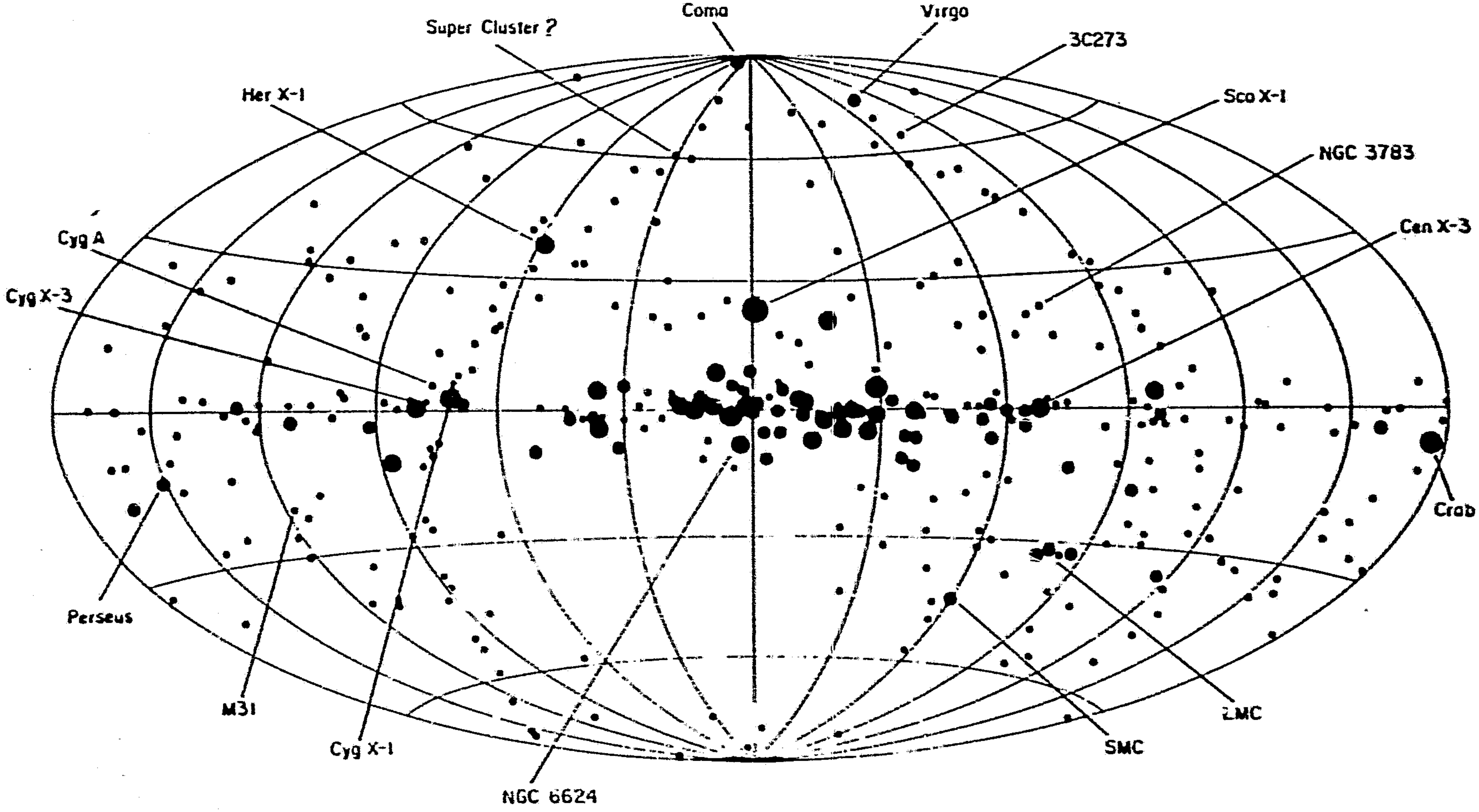

Fig. 3

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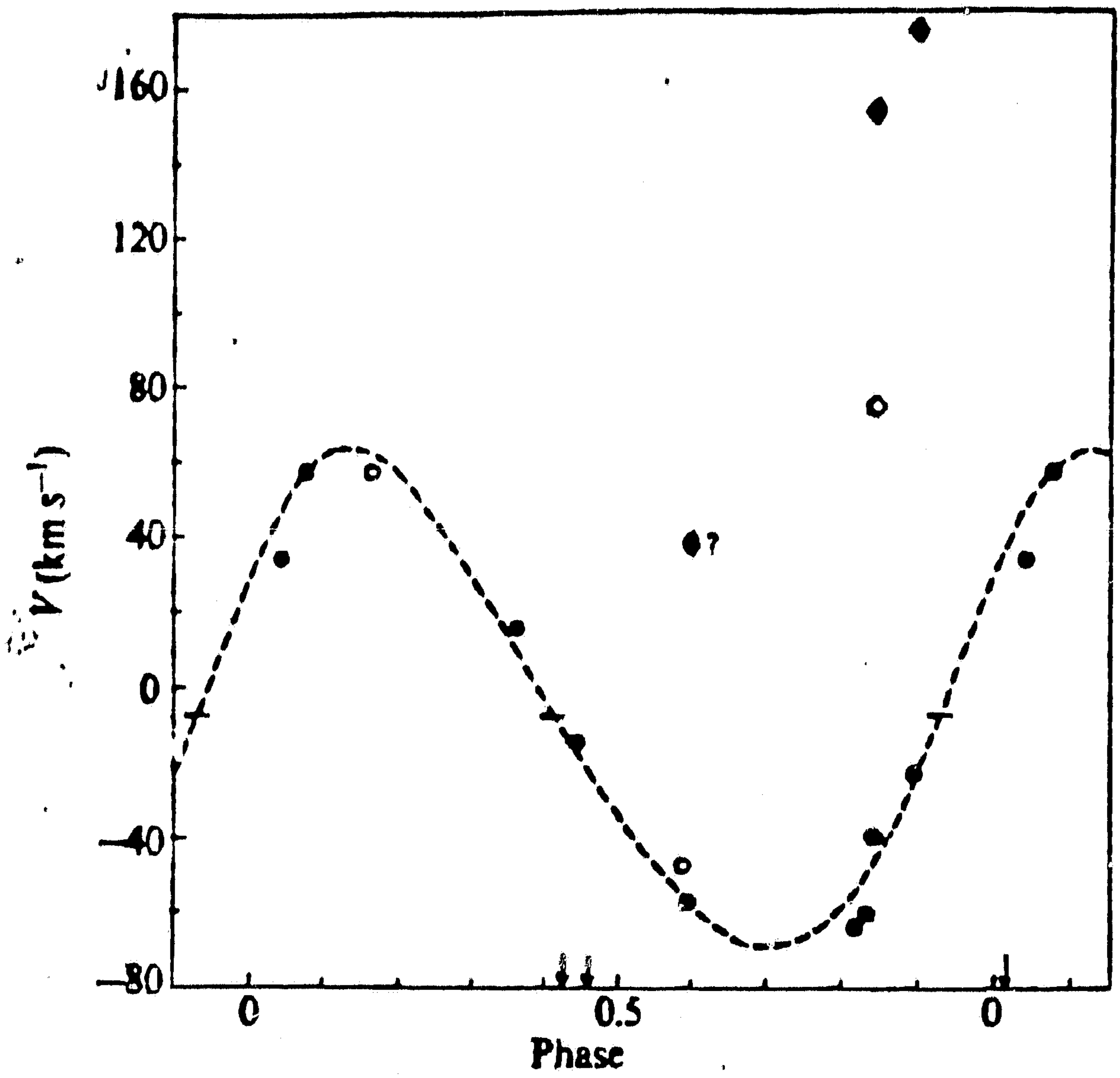
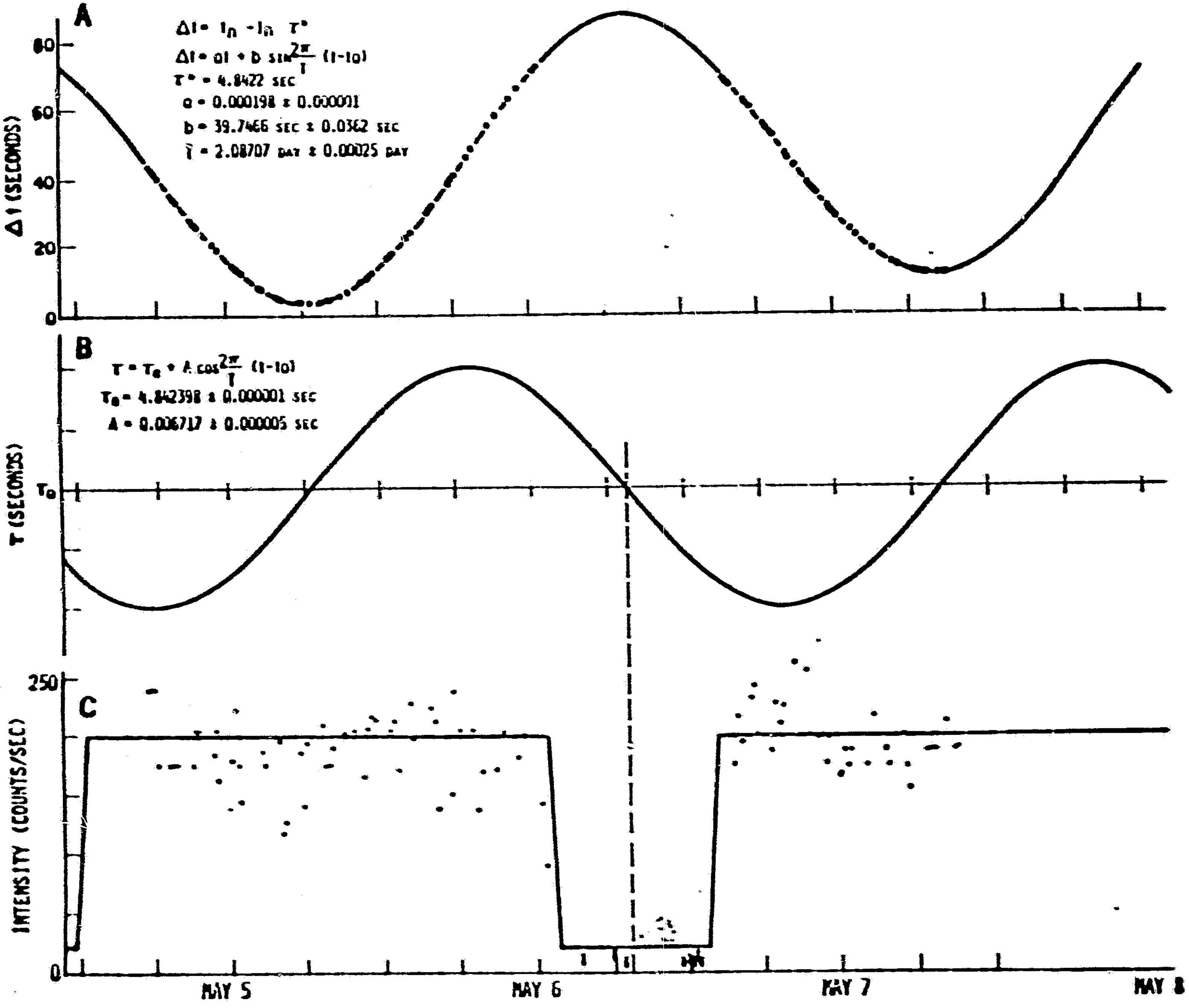


Fig. 4


A
Δt = tn - tn τ*
Δt = at + b sin 2π/T (t-to)
τ* = 4.8422 sec
a = 0.000198 ± 0.000001
b = 39.7466 sec ± 0.0362 sec
T = 2.08707 day ± 0.00025 day
Δ t (SECONDS)
80
60
40
20
0
B
τ = τo + A cos 2π/T (t-to)
τo = 4.842398 ± 0.000001 sec
A = 0.006717 ± 0.000005 sec
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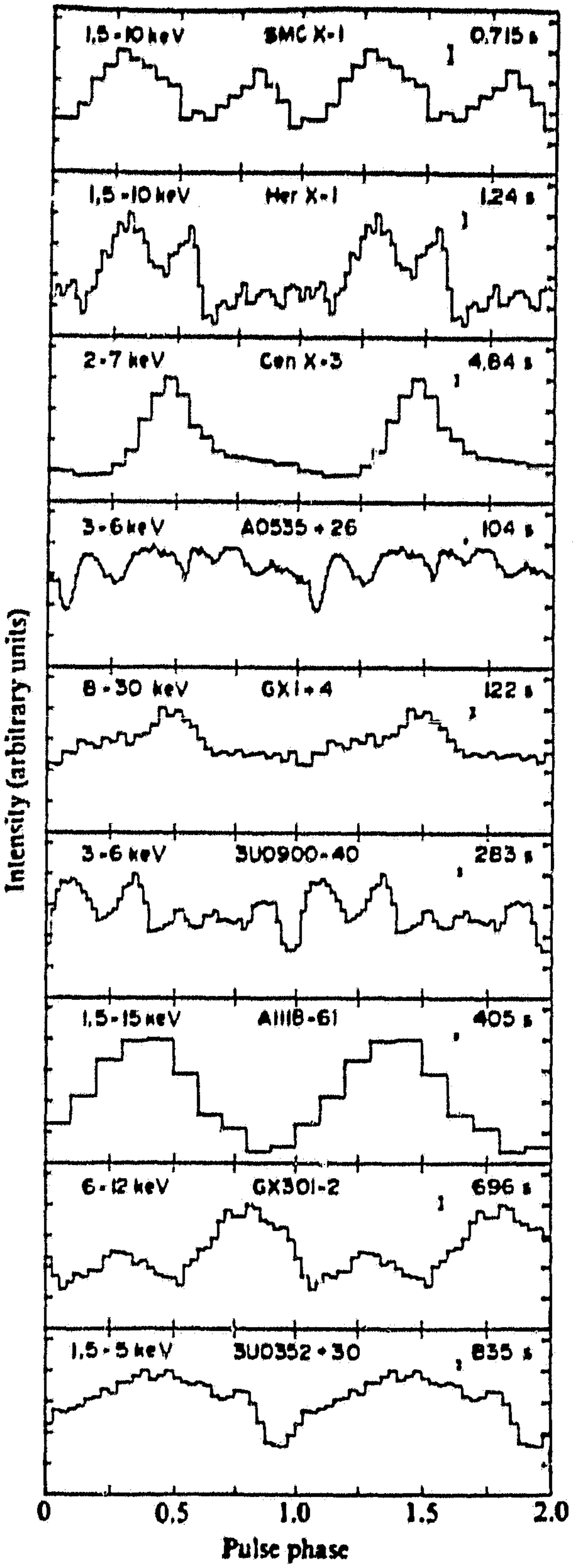
MAY 6
MAY 7
MAY 8

Fig. 5


1.5-10 keV
SMC X-1
0.715 s
1.5-10 keV
Her X-1
1.24 s
2-7 keV
Cen X-3
4.84 s
3-6 keV
A0535+26
104 s
8-30 keV
GX1+4
122 s
3-6 keV
3U0900-40
283 s
1.5-15 keV
A1118-61
405 s
6-12 keV
GX301-2
696 s
1.5-5 keV
3U0352+30
835 s
Intensity (arbitrary units)
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1.5
2.0
Pulse phase

Fig. 6

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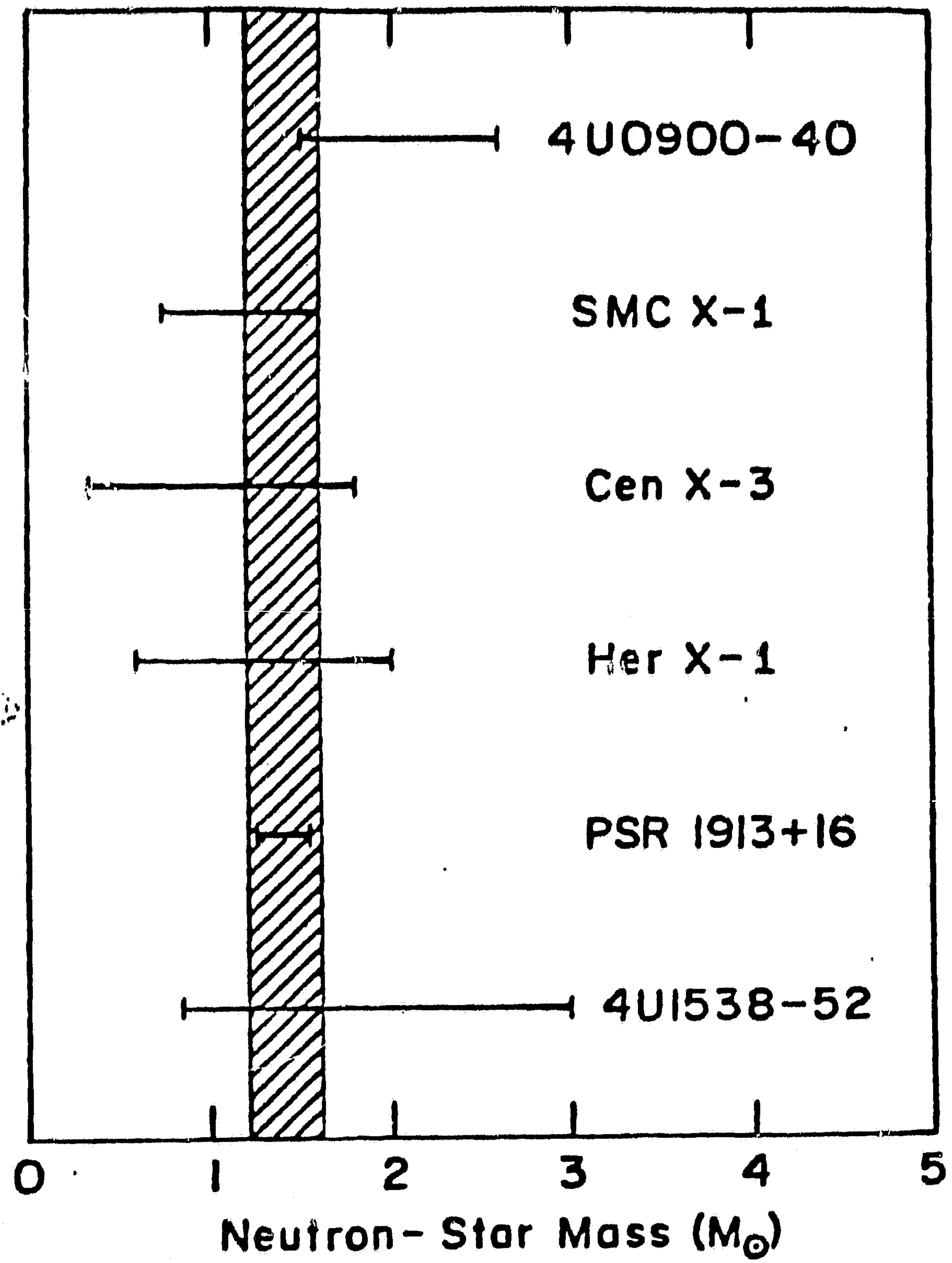

Fig. 7

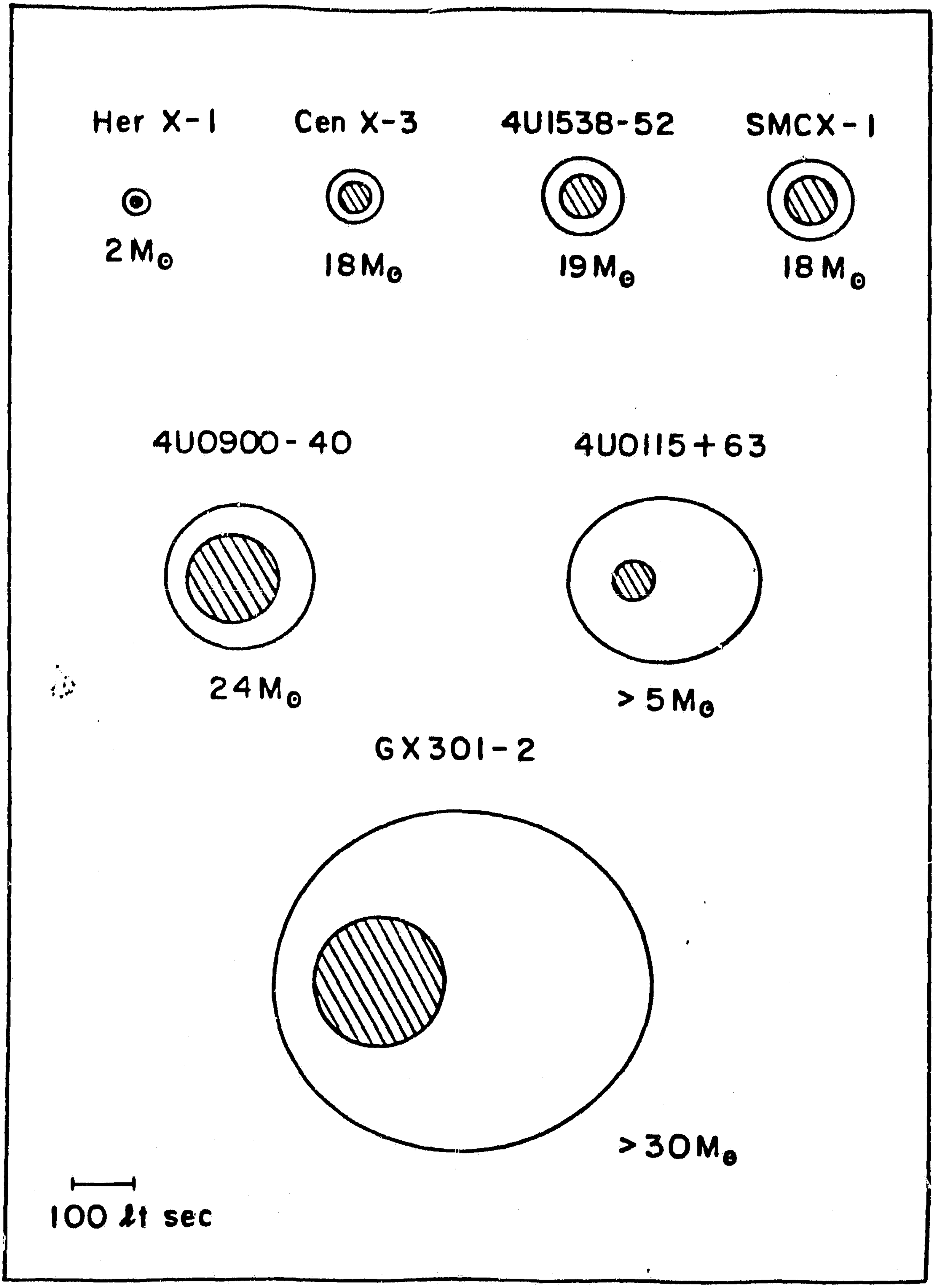
Her X-1
Cen X-3
4U1538-52
SMCX-1
2 M☉
18 M☉
19 M☉
18 M☉
4U0900-40
4U0115+63
24 M☉
> 5 M☉
GX301-2
> 30 M☉
100 lt sec

Fig. 8

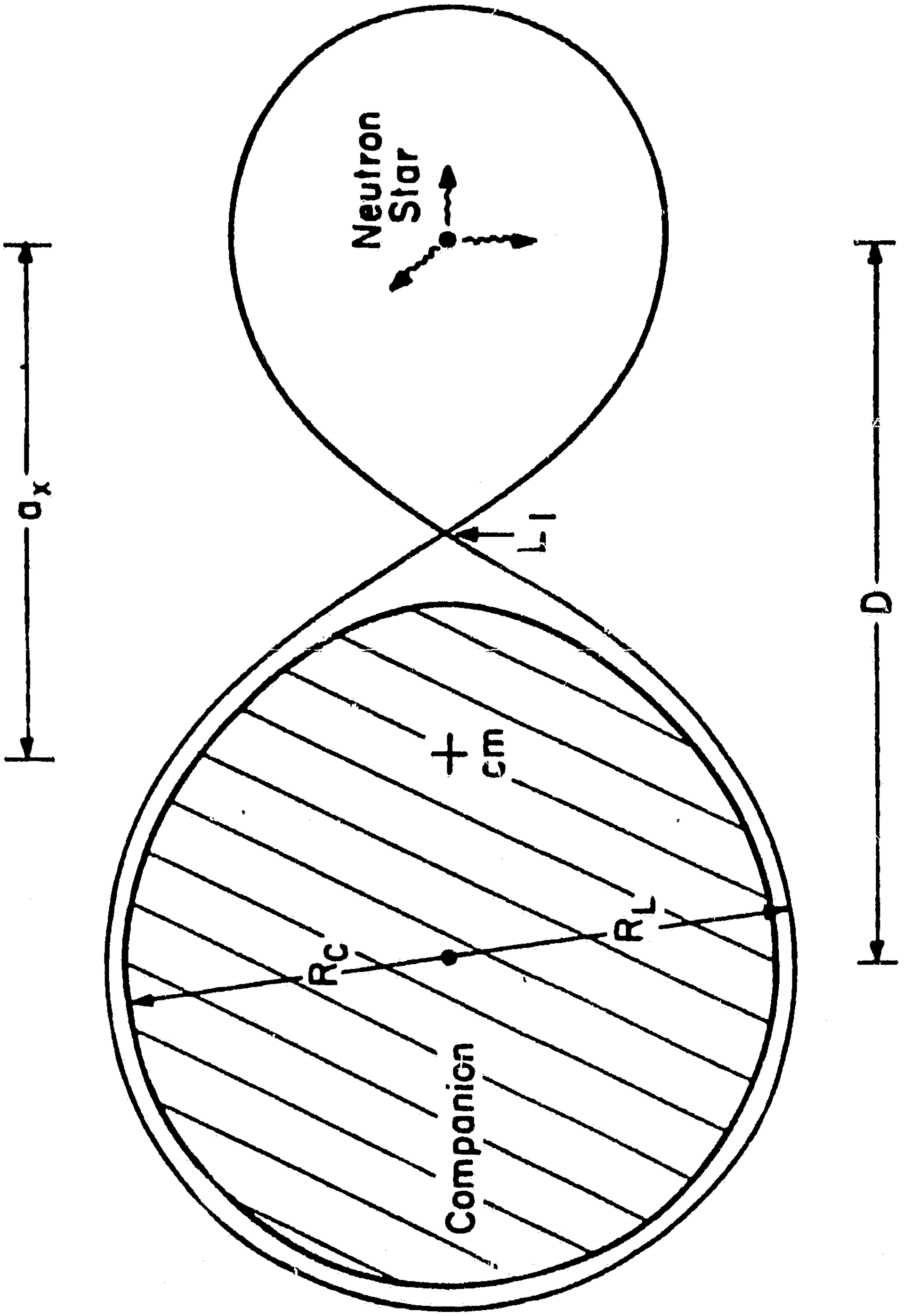

Fig. 9

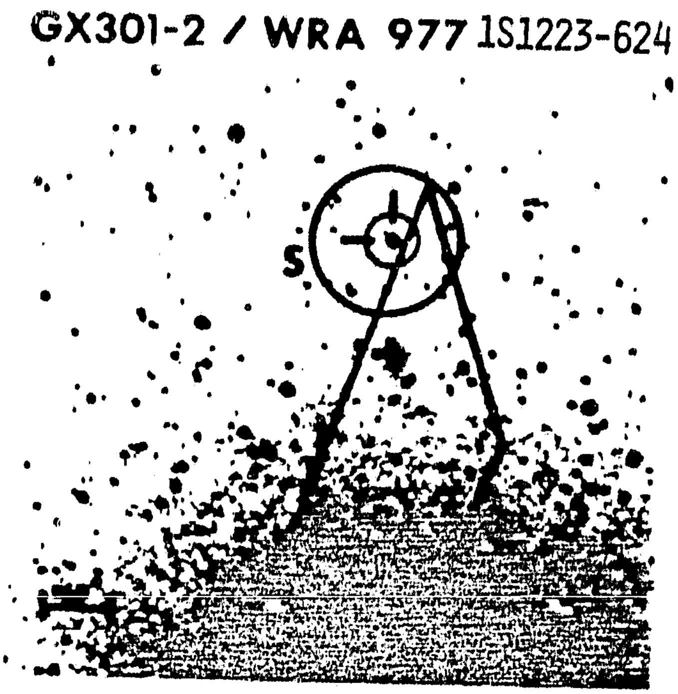

Fig. 10a

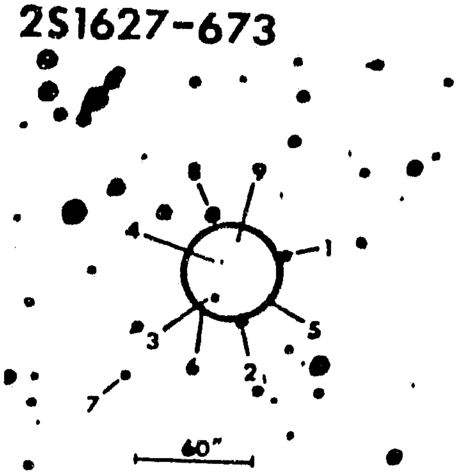

Fig. 10b

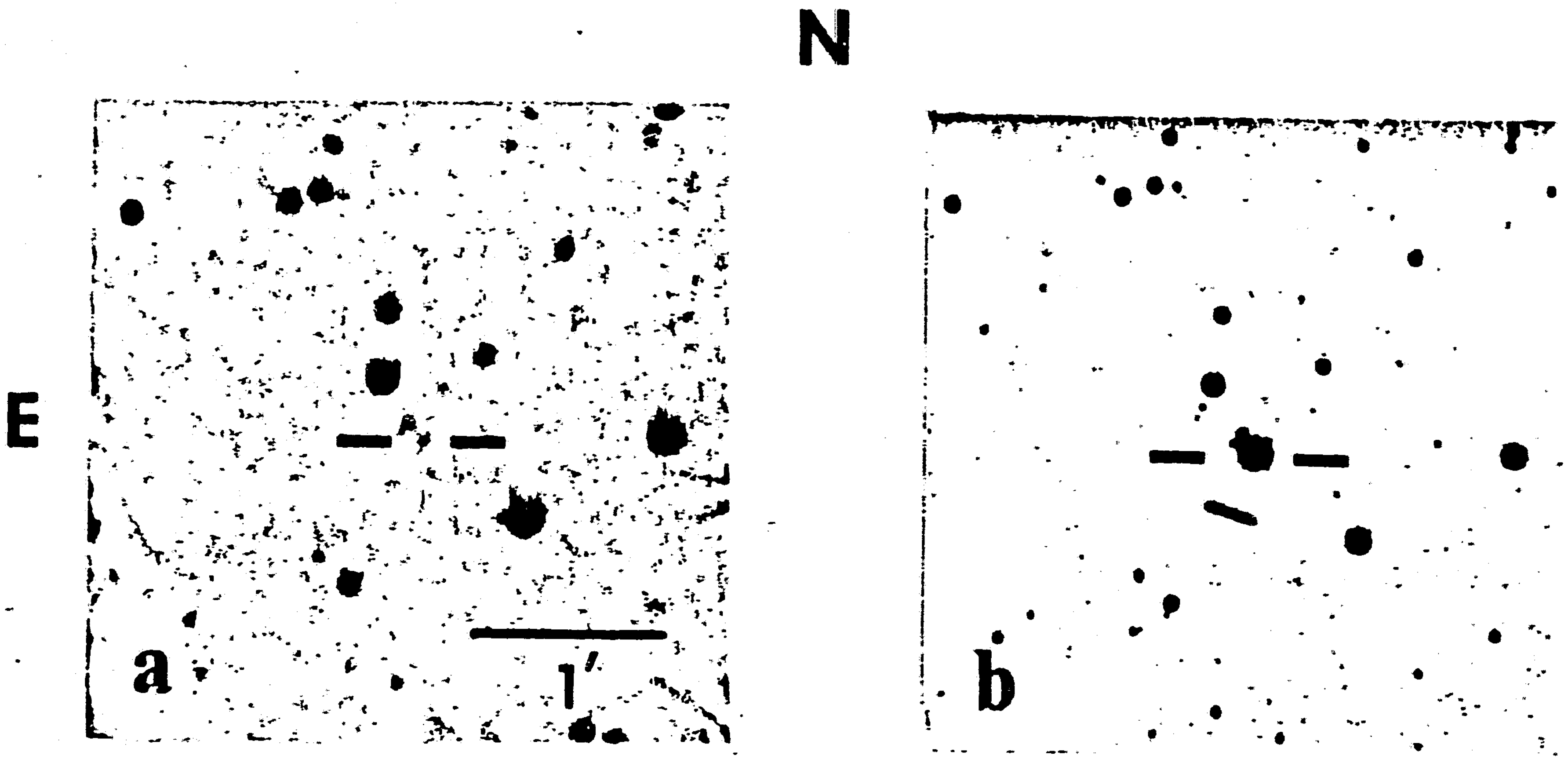

Fig. 11

ORIGINAL PAGE IS
OF POOR QUALITY

SAS-3 OBSERVATIONS OF RAPIDLY REPETITIVE X-RAY BURSTS FROM MXB 1730-335

24-minute snapshots from 8 orbits on March 2/3, 1976

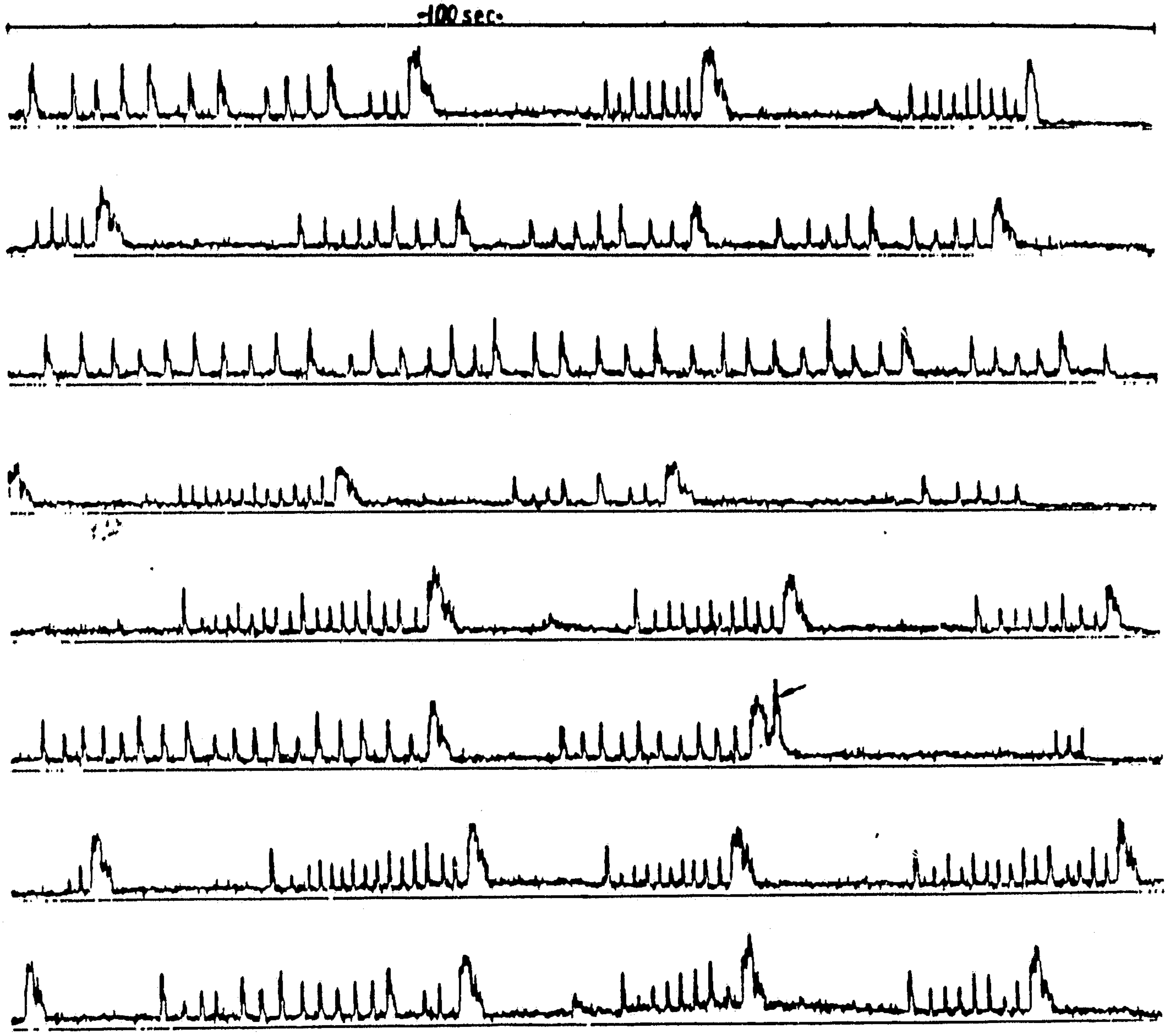

Fig. 12

ORIGINAL PAGE IS
OF POOR QUALITY

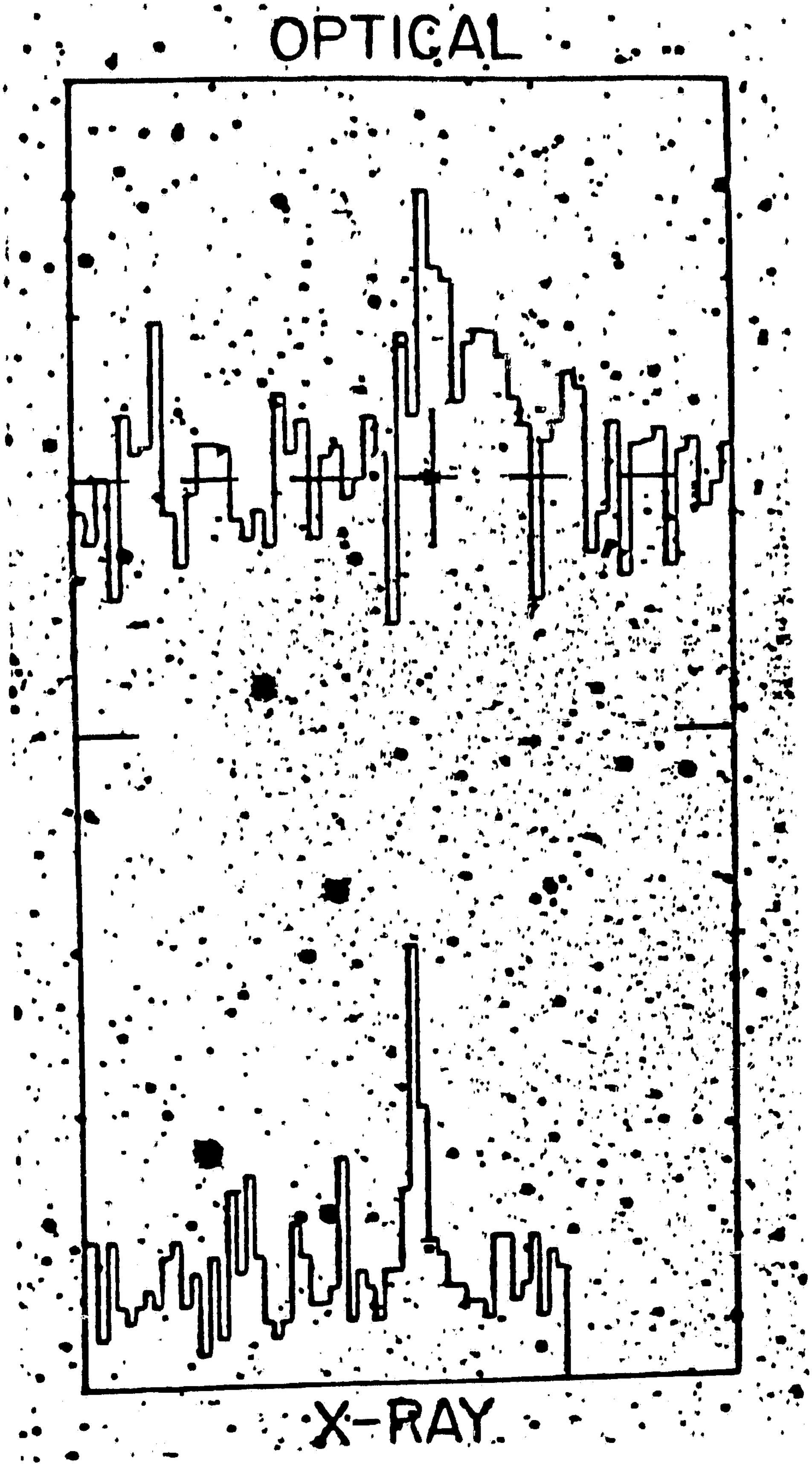

Fig. 13