X-ray Binaries

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The first detection of a cosmic X-ray source different from the Sun occurred accidentally when making measurements with a sounding rocket. The source was located in the Scorpio constellation, and was called Sco X-1. During the following years many similar rocket experiments were carried out, leading to the discovery of some 30 point sources of X-rays in the Milky Way, as well as outside our Galaxy. Resolution was very poor, and the sources could not be located to a precision better than half a degree, which made optical identification almost impossible.

In 1970 the first X-ray satellite was launched, officially named SAS-1, Small Astronomical Satellite, but better known under the name UHURU, when several hundred X-ray sources were discovered. A map showing their relative brightness as represented by the size of the dots, is reproduced in Fig. 1. It shows clearly a clustering of the X-ray sources along the galactic plane, near the galactic centre.

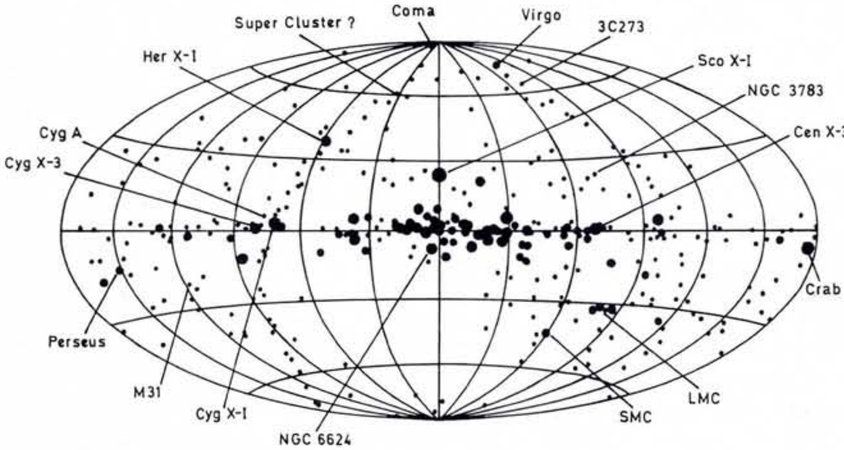
Detailed observations revealed that the X-ray emission is generally variable although in many cases the variations are extremely regular. A source in the Centaurus constellation, Cen X-3 was observed to show regular pulses, with an on and off periodicity of 4.84 s, the flux also varying with a period of 2.1 days. From this particular behaviour it was concluded that Cen X-3 is a binary system, and that the X-rays are produced near the surface of a rapidly rotating object which thus emits a rapidly spinning beam, comparable to the light beam of a lighthouse. In addition the X-ray source is periodically eclipsed by its stellar companion shutting off the source for about one quarter of the longer period.

In 1966 the X-ray spectrum of Sco X-1 was shown to be similar to that of an old nova. Novae are binaries in which one of the components is a normal star and its companion a white dwarf. So it was suggested that the X-ray source of Sco X-1, could possibly be a white dwarf. Such an explanation was just feasible also for the pulsar Cen X-3 because although an ordinary star would be destroyed if it were to rotate at a period of a few seconds, a white dwarf would survive. However the discovery by Jocelyn Bell (1967) of a still faster spinning pulsar, CP 1919 with a pulse period of 1,33 s, and then the extreme example in the Crab nebula, spinning at 30 times per second indicated that even white dwarfs would be torn apart through centrifugal force, and that pulsars had to be more compact objects, neutron stars or black holes.

One of the X-ray sources discovered by UHURU revealed a particularly enigmatic behaviour. Unlike the other X-ray sources, Cyg X-1 shows variations in X-ray intensity of differing time scales, one of them as small as a few milliseconds. In 1971 it was identified optically with a luminous star whose spectrum showed Doppler shifts consistent with it being a member of a binary with an orbital period of 5.6 days. The compact star is not a pulsar and the curious flickering emission seemed more characteristic of an accreting black hole than a neutron star. Moreover whilst the mass of the companion is estimated at 25 $M_\odot$, the compact object is at least 9 $M_\odot$, well over the upper limit for the mass of a neutron star (estimated at 3-5 $M_\odot$). This object is so far the best evidence we have for the existence of a black hole.

Evidence has since built up to suggest that most binary X-ray sources contain neutron stars and a fraction of the pulsating sources (members of a well defined class of strong sources with relatively hard X-ray spectra) are associated with young, luminous stars. These are known as Type I sources. In another category are the strong galactic sources of soft X-rays with continuous emission and a different spatial distribution. These are known as Type II sources and include objects belonging to globular clusters and to the bulge of the galaxy.

Fig. 1 — A map of the Galaxy with the X-ray sources indicated. The brightness of the sources is proportional to the size of the dots. (Smithsonian Astrophysical Observatory).



Mechanism for the Production of X-rays

In a binary system, matter expelled by the luminous star is gravitationally accreted by the compact star by mass transfer or is guided by the field lines towards the magnetic poles, generally by the stellar wind. At the surface of the compact object, *e.g.* a neutron star, extremely large magnetic fields may be present and these are not necessarily aligned with the rotation axis. Matter hits the surface of the neutron star with extremely high velocities, releasing a huge amount of kinetic energy which is converted into radiation in the hard X-ray range or even in the gamma region, which is then converted through repeated scatterings into softer X-rays. Details of the process are not very well known although the energetic balance of the accretion process is consistent with the observed X-ray luminosities of the order of 10^{29} to 10^{30} J/s.

Types of X-ray Binary

Type I — Massive X-ray Binaries

This group can be divided into two sub-groups with different characteristics.

The "standard" systems are permanent sources, *i.e.* the X-rays have a regular periodicity and the optical light output displays the ellipsoidal variations, characteristic of the tidal distortion provoked by the dark orbiting compact star. The optical companion nearly fills its Roche volume (outside which its gravi-

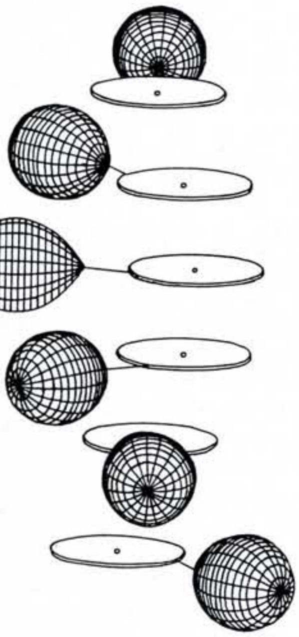
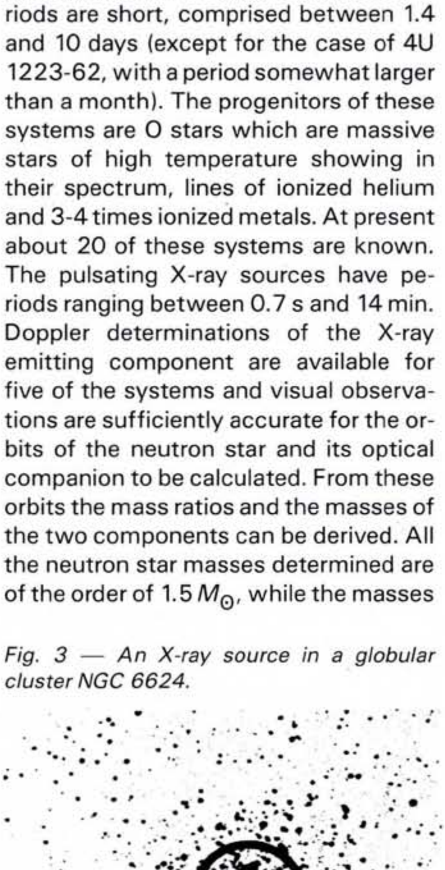


Fig. 2 — A cataclysmic variable (CV) or an X-ray burst source (XRB): a low mass star plus a white dwarf (in a CV) or a neutron star (in an XRB) with a disk.

tational field is no longer dominant), and the system shows regular eclipses. Periods are short, comprised between 1.4 and 10 days (except for the case of 4U 1223-62, with a period somewhat larger than a month). The progenitors of these systems are O stars which are massive stars of high temperature showing in their spectrum, lines of ionized helium and 3-4 times ionized metals. At present about 20 of these systems are known. The pulsating X-ray sources have periods ranging between 0.7 s and 14 min. Doppler determinations of the X-ray emitting component are available for five of the systems and visual observations are sufficiently accurate for the orbits of the neutron star and its optical companion to be calculated. From these orbits the mass ratios and the masses of the two components can be derived. All the neutron star masses determined are of the order of 1.5 $M_{\odot}$, while the masses of their optical companions range from 20 through 30 $M_{\odot}$.

Fig. 3 — An X-ray source in a globular cluster NGC 6624.



The second sub-group comprises the Be-X-ray sources in which the optical companions are rapidly rotating B stars, stars of lower temperature which show in their spectrum lines of neutral helium and hydrogen. The Be variety are characterised by showing strong emission lines, *i.e.* brighter than the background. They do not fill their Roche volumes, X-ray eclipses are almost absent and there are no regular ellipsoidal light variations. Their masses are lower than those of the standard massive X-ray binaries lying in the range of 10 to 20 $M_{\odot}$. The X-ray flux from a number of objects belonging to this group is not constant, but shows bursts, and such objects are as a result, called "transients".

Type II — Low Mass X-ray Binaries

The second group covers the low mass sources with softer spectra ($T < 8 \times 10^7$ K), generally not pulsating and mostly situated near the galactic centre or in globular clusters. Several are bursters, first discovered in September 1975 with the ANS, the Astronomical Netherlands' Satellite. The X-ray intensity increases by several orders of magnitude within a second, followed by a decrease over tens of seconds. Since the first burster discovered belonged to a globular cluster it was believed at the beginning that the burst phenomenon was confined to globular clusters sources, but later on a multitude of bursters were found outside globular clusters, in the bulge of the galaxy. The dominant source of light in these low mass systems is probably the accretion disk (see Fig. 2), the disk shaped volume of matter accreted from the mass-expelling companion which is not itself visible.

From a spectral analysis of the X-ray bursts we can, assuming that we are observing the black body emission from the surface of a cooling object, derive a radius for the X-ray emitter of about 10 km. This means that we are probably dealing with a neutron star. The energy emitted in the form of bursts is only 1% of the steady X-ray emission, comparable to the ratio of the energy derived from helium burning to the energy released by accretion. Hydrogen accreted by a non magnetic neutron star fuses immediately to helium whereas the helium fuses only in flashes. The time profile of the computed flashes agrees well with that of the X-ray bursts. The similarity of the bulge sources and the globular clusters suggests that they form one single class with the same origin and the same evolutionary pattern. Moreover the optical spectra associated with burst sources are similar to those of the X-ray binary Sco X-1 which has a flaring behaviour over seconds or minutes and which shows a blue continuum with the Balmer emission lines, and emission lines of He II (4686 Å), N III, C III (4640 Å). This is turn resembles the spectra of accretion disks in cataclysmic variables (see below). The low luminosity of the companion and the short period (0.78 d) suggest that the non-compact star is a red dwarf, comparable to the non-visible component of the bursters.

The large X-ray luminosities of the Type II sources also indicate that the systems contain a neutron star or a black hole rather than a white dwarf and we can exclude black holes because eight out of the 13 sources found in globular clusters and many of the sources around the galactic centre are X-ray bursters which would require far too high a density of black holes.

The foregoing arguments lead therefore to the conclusion that the Type II sources are close binary systems consisting of an old neutron star, accompanied by a low mass red dwarf of the order of 1 $M_{\odot}$, which is filling its Roche lobe. A part of the matter expelled by this red dwarf is accreted by the compact star.

Within these Type II systems we can distinguish two groups: Globular Clusters and Galactic Bulge sources.

a) Globular Cluster Sources

The incidence of X-ray sources in globular clusters (Fig. 3) is rather high, 13 sources in 125 clusters, a much higher density than the average in the Galaxy. In Andromeda we find 19 sources in 270 observed globular clusters compared with 90 sources in the whole Galaxy. This suggests that the conditions for the formation of binaries containing a neutron star are more favourable in globular clusters than in the rest of the Galaxy.

Because of the high densities occurring in globular clusters (10^5-10^6 stars per pc^3) the formation of binaries by close encounter, and the subsequent capture has a higher probability than elsewhere in the Galaxy. Moreover as the relative velocities of the stars are low, relatively little energy has to be dissipated for a first encounter to lead to capture. The most plausible explanation then for the high occurrence of X-ray binaries in globular clusters is that given by Sutantyo (1975) *i.e.* they were formed by capture of a normal star by a neutron star.

Since single stars in the range of about 4-50 $M_{\odot}$ eventually become collapsed objects, one may expect that in globular clusters, during the first 10^8 years of their formation, thousands of neutron stars would have been produced, of which a certain fraction would have left the cluster (about 90%), but a significant number would remain. Their masses exceed the average stellar mass, so they would have sunk to the core thus increasing the stellar density and hence the collision probability. However, the escape velocity from a globular cluster is of the order of 10 km/s only and the neutron star that is created in binaries that are radio pulsars are known to receive at their birth runaway velocities of the order of 100 km/s, probably from the explosion of the most evolved component and disruption of the binary system. The neutron stars with low velocities are the final products of single stars.

So we are led to the conclusion that those stars that started their evolution as binaries in globular clusters have become single stars by disruption of the system, and have left the cluster, while the neutron stars that had a single star as progenitor remain in the cluster and can later capture a companion and so become a low mass X-ray binary.

b) Galactic Bulge Sources

The stars in the galactic bulge have larger velocities than those in globular clusters, and moreover the stellar density is much lower; capture is thus unlikely. However it has been found that carbon-oxygen white dwarfs near their Chandrasekhar limit may collapse to neutron stars, and it appears that this is also the case for O-Ne-Mg white dwarfs in close binaries. The systems will generally remain bound and after a few billion years, due to gravitational radiation and magnetic braking, the stars will have come close enough for the non-collapsed object to overflow its Roche lobe, after which mass transfer starts. In this way the system becomes a low mass X-ray binary.

The neutron star is already old at the moment it becomes an X-ray source. The magnetic field has decayed, and the source may become an X-ray burster.

Evolution of X-ray Binaries

Type I Sources

An evolutionary scenario for X-ray binaries was proposed by van den Heuvel and Heise in 1972. The idea, now generally accepted, is that a massive close binary, consisting of two luminous stars, evolves into an X-ray source by mass exchange and through a final explosion, produces the compact object. Computations to evaluate this scenario in detail have been made by the author and one of his collaborators, J.P. de Greve. Examples with the relevant time scale are presented in Figs. 4 and 5. The massive stars evolve, from zero age mass sequence (ZAMS), into a Wolf-Rayet system, consisting of a helium star and a massive companion. Several tens of such systems are known, and are easily recognized by their extremely strong emission lines. Later on the smaller star becomes a supernova [1]) and explodes producing the neutron star. The orbital period of the system changes due to the changing masses of the components.

At a more advanced stage (not shown) the massive star also fills its Roche lobe, and loses matter. The period of the system is reduced drastically, and the neutron star spirals in. In this way a second X-ray stage can be initiated, forming a binary with a very short period, like Cyg X-3. Finally the secondary also explodes and two separate neutron stars result.

After the first supernova explosion, the system remains bound since it is the less massive star which is exploding.

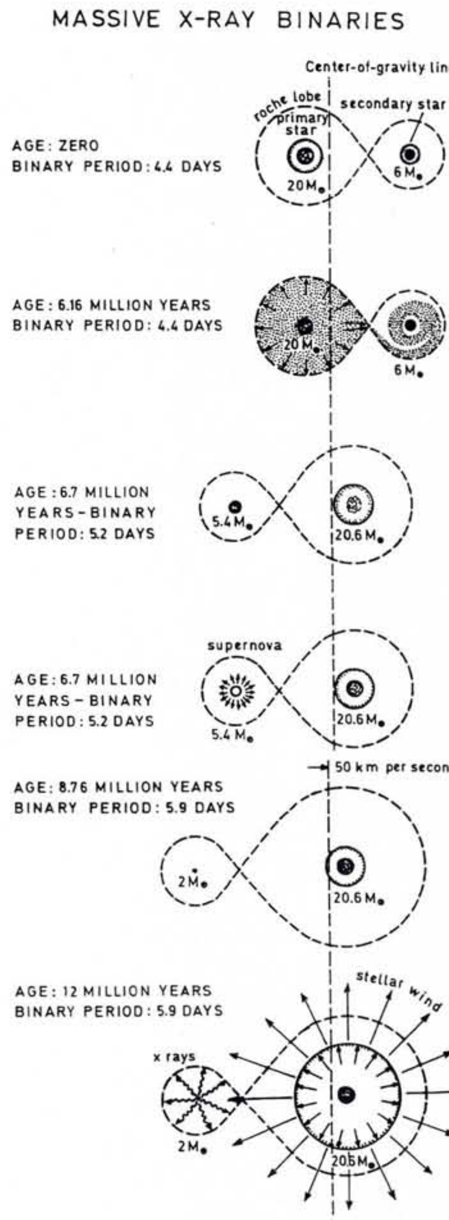
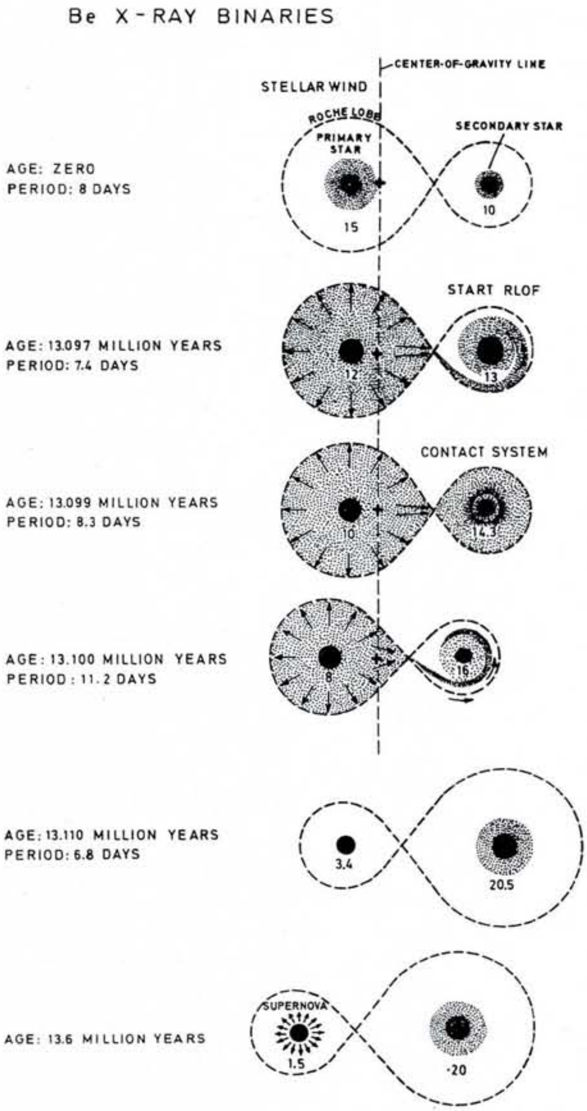


Fig. 4 — Evolution of standard massive X-ray binaries.

The second explosion however has a greater probability of disrupting the system although in a few rare cases, the system remains bound, and two neutron stars remain together in a binary pulsar with a very short period, of the order of hours to a couple of seconds. An example of such a binary pulsar is PSR 1913+16 with an orbital period of 7.75 h and a pulse period of 0.059 s.

Type II — Low Mass X-ray Binaries

Low mass zero age main sequence binaries evolve (Fig. 6) through a phase of mass transfer into systems comprising a helium, or a carbon-oxygen white dwarf and a main sequence companion, with periods in the range of about two hours. At this stage the binary is called a cataclysmic variable as the stars show



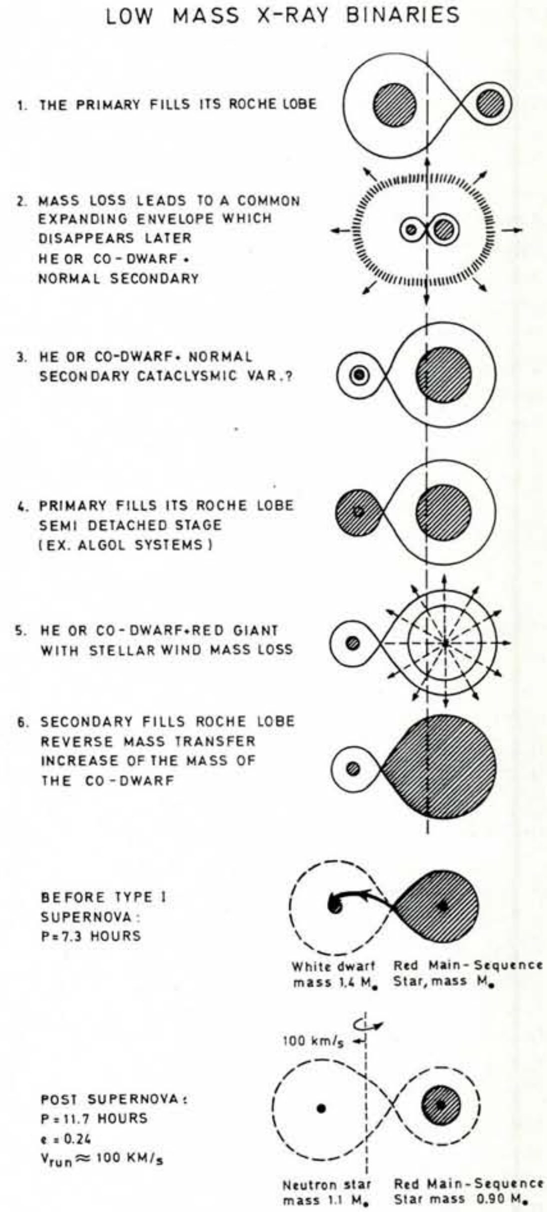


Fig. 5 — (Above) Evolution of a Be X-ray binary.
Fig. 6 — (Right) Evolution of a low-mass X-ray binary.

increases in brightness, reach peak luminosities in a short time and then very slowly return to their former brightness. An accretion disk is present around the white dwarf component (Fig. 2).

Gravitational radiation and magnetic braking decrease the distance between the two components, and when the distance has become small enough, the Roche lobe of the companion, that meanwhile has evolved towards the red giant state, has become so small that the star overflows this critical surface, and mass transfer towards the white dwarf occurs.

As a consequence of the accreted matter, the white dwarf mass becomes larger than the Chandrasekhar limit, and evolves into a neutron star, either in a soft way, or by a supernova explosion. Due to gravitational braking the magnetic field decays, and the system can become a burster.

Final Remarks

X-ray astronomy, as well as gamma-ray astronomy has opened a completely new field, and gives access to an extremely interesting laboratory where we can observe matter under conditions which on Earth are non-existent. We can look at stars during the final stages of their evolution and matter under conditions previously unknown. We can observe systems emitting enormous quantities of extremely high energy, systems emitting gravitational radiation, and in this way spinning down, *i.e.* decreasing their period.

A few years ago, cosmic ray physicists detected gamma rays showing a 4.8 h periodicity, coming from the direction of the X-ray source Cyg X-3 and, at the beginning of 1985, neutrinos apparently emitted by the same source (as the periodicity was 4.8 h) were detected by scientists carrying out an experiment in a salt mine, 500 m below Lake Erie when Cyg X-3 was below the horizon. In a proton decay experiment, muons again with a periodicity of 4.8 h were detected, triggered it is thought by showers produced by particles coming from Cyg X-3 and impinging on the Earth and its atmosphere. Although the results still require confirmation, they seem more than interesting. High energy gamma rays from other X-ray sources have also been detected, from Herculis X-1, Vela X-1, and from an X-ray source in the Large Magellanic Cloud, LMC X-2. It is evident that in the coming years particle physicists as well as astrophysicists will be turning their attention to these fascinating binary systems.

REFERENCE

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