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COMPACT X-RAY SOURCES[1]

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ABSTRACT

Compact X-ray sources are one of the most varied and exciting systems to the present astronomy community. In this paper, I present a review of the accretion disks which have a vital role in mass transfer to these compact objects such as white dwarfs, neutron stars or black holes. I then explain some properties of X-ray binaries such as LMXBs, HMXBs, QPOs, etc. I went into the detail of systems of compact objects rather than that of themselves.
Subject headings:

1. INTRODUCTION

An X-ray binary is a system consisting of a compact object (a neutron star or a black hole) which accretes gas from a more ordinary star or a white dwarf. In this accretion process, gas from that ordinary star becomes trapped in the strong gravitational field of the compact object and forms an in-spiraling accretion disk around it.

X-ray binaries constitute the brightest class of X-ray sources in the sky. Because X-ray binaries are so bright, that they were the first X-ray stars to be discovered by the astronomers using very simple X-ray detectors launched into space in the 1960s.

2. ACCRETION VIA ACCRETION DISKS

An accretion disk (Figure 1) is a structure formed by material falling into a gravitational source. In an X-ray binary (hereafter XRB), a compact star accretes material from its companion. The gravitational potential energy of this material is converted to kinetic energy and eventually to radiation and this gives rise to the increased observed luminosities. In an XRB the compact component which accretes material is the X-ray emitter and called the "primary"; the donor star is called the "companion".

As the radius of the compact object gets smaller the energy that can be formed from the accretion gets larger. This is as a result of the amount of gravitational potential energy of the infalling material increases while the radius of the compact object decreases.

The viability of accretion as an energy source that is conversion of gravitational potential energy to radiation relative to the other mechanisms such as nuclear processes, depends on how large the "efficiency factor", η, can be made. The potential energy of a mass m, at a distance R from a central source of mass M is

$$U = \frac{GMm}{R}. \tag{1}$$

The rate at which the potential energy of infalling material can be converted to radiation is given by

$$L_{acc} \approx \frac{dU}{dt} = \frac{GM_\star}{R_\star}\frac{dm}{dt} = \frac{GM_\star \dot{M}}{R_\star}, \tag{2}$$

where $M_\star$ and $R_\star$ are the mass and the radius of a star respectively, and $\dot{M}$ is the accretion rate (i.e., mass crossing radius per unit time). In this equation we assume that all the kinetic energy of the accreted matter is converted to radiation at $R_\star$. Efficiency is defined as the conversion of mass to energy for different sources, so the energy available from a mass M is $E = \eta M c^2$. The rate at which energy is emitted by the nucleus ($L = dE/dt$) gives us the rate at which energy must be supplied to the nuclear source by accretion,

$$L_\star = \eta \dot{M} c^2, \tag{3}$$

e.g., neutron stars convert accreted mass to energy with an efficiency of

$$\eta = \frac{L_\star}{\dot{M}c^2} \sim 0.1 \tag{4}$$

compared with 0.007 for thermonuclear fusion. An accreting neutron star emits radiation mostly in the range of 1 keV - 50 MeV (Frank et al. 1985). An estimate for the upper limit to the luminosity of these sources can be found by equating the outward force on electron-proton pairs with the gravitational force.

The outward radiation force on a single electron is obtained by multiplying by the cross-section for interaction of the photon;

$$F_{rad} = \sigma_e \frac{L}{4\pi c r^2}\hat{r} \tag{5}$$

where σ_e is a constant of Thompson scattering cross-section and $\hat{r}$ is a dimensionless unit vector in the radial direction. The gravitational force acting on an electron-proton pair by a central mass M

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[1] High Energy Astrophysics Lecture, End of Term Paper

is;

$$F_{grav} = -\frac{GM(m_p + m_e)}{r^2}\hat{r} \approx -\frac{GMm_p}{r^2}\hat{r} \qquad (6)$$

where m_e, the mass of the electron can be ignored due to its small mass compared to the m_p, mass of the proton. The inward gravitational force acting on the gas must be balanced or exceed the outward radiation force if the source is to remain intact, so it is required that

$$|F_{rad}| \le |F_{grav}| \qquad (7)$$

$$\frac{\sigma_e L}{4\pi c r^2} \le \frac{GMm_p}{r^2} \qquad (8)$$

$$L_E \le \frac{4\pi G c m_p}{\sigma_e} M. \qquad (9)$$

This equation is known as the "Eddington Limit" and can be used to establish a minimum mass, the "Eddington Mass", M_E, for a source of luminosity. Therefore the resulting luminosity will be

$$L_E = \frac{4\pi G c m_p}{\sigma_e} M \approx 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) ergs^{-1}. \qquad (10)$$

If the luminosity exceeds this value the radiation pressure from the source overcomes the gravitational force and the accretion stops (Audley 1997).

FIG. 1.— Artist's impression of an accretion disk. Matter falling on to a compact star via an accretion disk

2.1. Mass Transfer

The mass transfer could occur by two mechanisms. a) Capture of the companion star's stellar wind or b) overflow of Roche lobe. These two mechanisms shown in figures 2 & 3 respectively, and basically these figures display the extreme cases. However the difference between these two cases is not distinct for companions that come close to filling their Roche lobes. Because of the presence of the accreting object, the stellar wind will be expanded along the line of centers, forming a tidal stream that flows through the L_1 point (Petterson 1978), (Blondin et al. 1991).

Interestingly, in Roche lobe overflow, an accretion disk is required to reduce the specific angular momentum of the transferred matter before it can accrete onto the compact object, however, in the case of wind accretion, an accretion disk may not be required depending on the orbital angular speed of the accreting object.

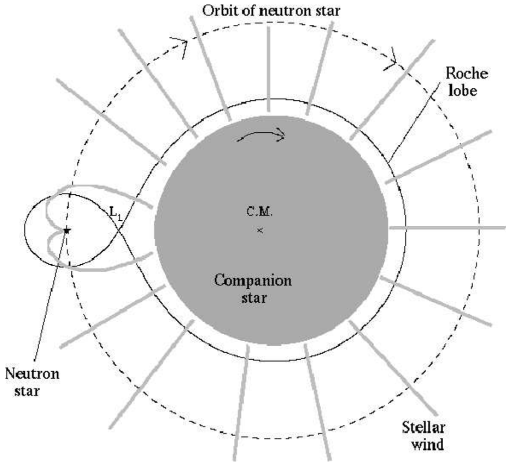

FIG. 2.— Mass-transfer in an X-ray binary by wind accretion

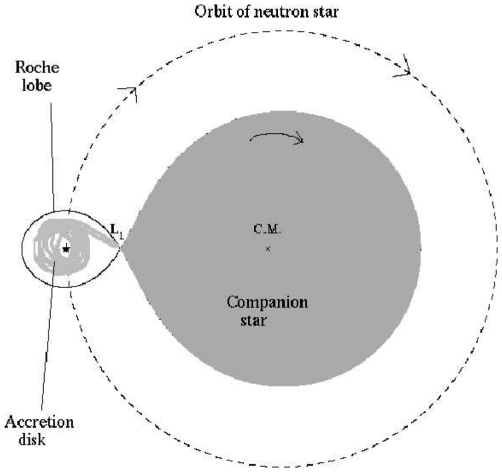

FIG. 3.— Mass-transfer in an X-ray binary by Roche lobe overflow

According to Frank et al. (1985) we can verify that an accretion disk should form in the case of Roche lobe overflow. The specific angular momentum of the material spilling through the L_1 point is essentially $d^2\omega$, where d is the distance from the accreting object to the L_1 point and ω is the orbital angular speed.

In order to accrete onto the compact object this matter must shed angular momentum. The flow can lose energy through shocks but it is difficult for it to lose angular momentum. Then the accreting matter will initially settle into the lowest energy orbit consistent with its specific angular momentum. If the matter flow has lost no angular momentum since passing through the L_1 point, this will be a circular orbit with radius

$$R_{\rm circ} = \frac{d^2\omega}{V_\Phi} \tag{11}$$

where

$$V_\phi = \sqrt{\frac{GM_\star M_\odot}{R_{\rm circ}}} \tag{12}$$

is the tangential velocity. Viscous interactions will cause the plasma to spread out and form an accretion disk. If the accreting star is a white dwarf, a neutron star, or a black hole, $R_{\rm circ}$ will be larger than the stellar radius, allowing an accretion disk to form. $R_{\rm circ}$ will also be smaller than the primary's Roche lobe radius which is

$$R_L = \frac{0.49}{0.6 + q^{2/3}\ln(1+q^{-1/3})} \tag{13}$$

where q is the ratio of the masses of the accreting star and the companion, $q \equiv \frac{M_\star}{M_c}$ using the Eggleton (1983) approximation.

3. PROPERTIES OF X-RAY SOURCES

The primary factors that determine the emission properties of an accreting compact object are;

i) Whether the central object is a black hole or a neutron star,
ii) If it is a neutron star, the strength and geometry of its magnetic field,
iii) The geometry of the accretion flow from the companion, whether it is a disk or spherical accretion,
iv) The mass of the central object,
v) The mass accretion rate.

The first three factors determine whether the emission region is the small magnetic polar cap of a neutron star, a hot accretion disk surrounding a black hole, a shock heated in a spherical inflow, or the boundary layer between an accretion disk and a neutron star. And the last two factors influence the overall luminosity, spectral shape and time variability of the emission.

According to (Pringle and Rees 1972), (Davidson and Ostriker 1973) and (Lamb et al. 1973), a neutron star with a strong magnetic field ($\approx 10^{12} G$) can disrupt the accretion flow at some hundreds of neutron star radii and funnel material onto the magnetic poles. But if the magnetic field of the neutron star is relatively weak ($< 10^{10} G$), the disk might touch or come very close to the surface of the neutron star. The energy released from the inner accretion disk and the boundary layer between the disk and the neutron star will dominate the emission (Mitsuda et al. 1984). If the central object is a black hole, the X-rays come from the inner disk and are the result of viscous heating (Shakura and Sunyaev 1973b,a).

4. X-RAY BINARIES

Any binary star systems contain two stars that orbit around their common center of mass. X-ray binaries are made up of a normal star and a collapsed star which can be a white dwarf, neutron star, or a black hole. The X-ray emission is a result of accretion of gaseous material from the companion on to the compact star.

There are two main types of X-ray binaries: Low-Mass X-ray Binaries (LMXBs) where the companion star has a mass less than or equal to 1 $M_\odot$, and High-Mass X-ray Binaries (HMXBs) which have a companion that has a mass of over 10 $M_\odot$. This criteria comes from Bradt and McClintock (1983) who based their classification scheme on the ratio of X-ray to optical luminosity. For a HMXB;

$$\frac{L_\star(2-10\ \mathrm{keV})}{L_{\rm opt}(3000-7000\ \text{Å})} \gtrsim 10 \tag{14}$$

Briefly, in HMXBs, material is transferred via a strong stellar wind from a massive O- or B-type star to the compact object, however, in LMXBs, the lower mass stars do not have strong stellar winds.

4.1. Low-Mass X-ray Binary Systems LMXBs

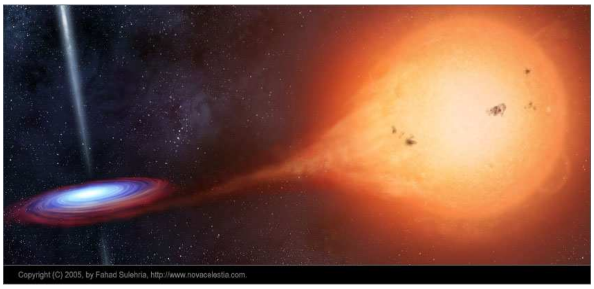

Fig. 4.— Artist impression of an LMXB. Image Courtesy: novacelestia.com

If the companion star is later than type A, then the system is called a Low-Mass X-ray Binary, where Low-Mass represents the mass of the companion star which is similar to or less than that of the Sun. Also in some very evolved systems the companion can be a white dwarf. In this case X-rays are seen only if the two stars are very close to each other so the normal star fills its Roche Lobe (Figure 5). When this happens material is squeezed off the normal star by the intense gravity of the compact object. The brightest part of the LMXBs is the accretion disc of matter falling down onto the compact object. Most of the radiation output of LMXBs is through X-rays, and a small fraction of the light is visible light, which makes LMXBs faint in visible wavelengths (Bradt and McClintock 1983).

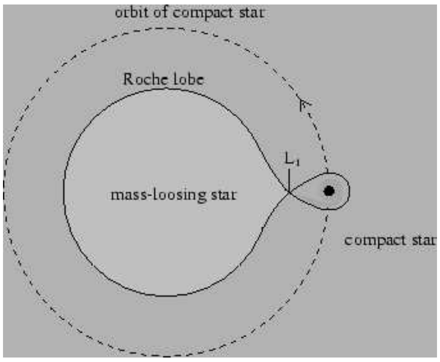

FIG. 5.— Schematic picture of low-mass X-ray binary system. The mass-losing star has expanded and overflows its Roche lobe. The gas flows through the inner Lagrange point, L_1, and and accretes onto the compact object through an accretion disk. Image Credit: Pountanen, J., Stockholm Observatory

The LMXB systems can have very short binary periods and the shortest binary period known belongs to the X-ray binary 4U 1820-30 (Figure 6) located in the globular cluster NGC 6624 with an orbital period of $P_0 = 0.19$ hr (ROSAT Data Release). The orbital periods of LMXBs range from ten minutes to hundreds of days.

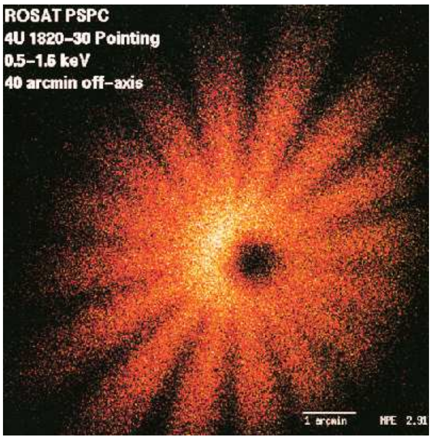

FIG. 6.— Image of 4U 1820-30 from the ROSAT telescope

When the system is viewed from the side, the companion star will get in the way, and cause an eclipse. This results in the X-ray source turning off for a few minutes. The eclipses tell us the orbital period. See Figure 7 for the light curves of two LMXB systems. X 1822-371 has a partial and broad X-ray eclipse, whereas EXO 0748-676 displays narrow, but almost total eclipse combined with irregular variations. If these are smoothed out (as would be the case if the inclination were slightly higher) then the two light curves are remarkably similar. The irregular variations of EXO 0748-676 are simply due to structure on the edge of the disk occasionally obstructing our view of the central X-ray source. In 2A 1822-371 the central source is never visible at all (the inclination is higher) and so the eclipse is of an extended X-ray region, making the light curve smooth.

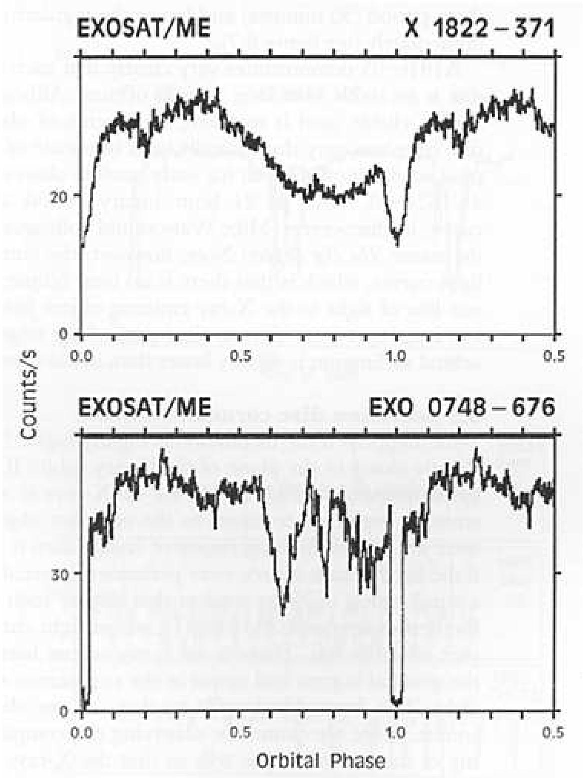

FIG. 7.— EXOSAT light curves of 2A 1822-371 and EXO 0748-676. Each shows 1.5 orbital cycles for clarity, with phase 0 defined as mid-eclipse. Image Credit: Parmar et al. (1986)

Also seen in EXO 0748-676 is lots of dipping activity which usually preceeds the eclipse. These dips are caused by the splash of material from the companion star, where it hits the accretion disk.

4.2. High Mass X-ray Binary Systems HMXBs

FIG. 8.— Artist impression of an HMXB. Image Courtesy: novacelestia.com

HMXBs are systems containing a massive blue O or B class giant star ($M > 10 M_\odot$) whose optical/UV luminosity may be comparable to, or greater than, that of the X-ray source (Conti 1978; Petterson 1978). These systems are also called Massive X-Ray Binaries (MXRBs). In these systems X-ray heating is minimal, with the optical properties dominated by the companion star.

In such binaries, the massive companion produces a substential stellar wind removing between 10^{-6} and 10^{-10} $M_\odot$ yr^{-1} with a thermal velocity up to 2000 km s^{-1} in its evolution. The wind is so powerful that sufficient material is being blown in all directions, and is easily captured by the compact star to form an accretion disk. At the inner edge of the disk, gaseous material is rubbed violently to high temperatures due to the strong gravity and this will generate heat to power the X-ray source.

The orbital separation is generally wider than in a typical LMXB because the companion is much larger. The periods of HMXBs range from 4.8 hours to 187 days and mostly determined from pulse arrival time analysis and/or the detection of the eclipses. Most Be-star systems have longer periods of several tens or hundreds of days whereas supergiant systems have relatively shorter periods. The supergiant systems typically are eclipsing and show extreme intensity and absorbtion variability on all timescales. The shorter orbital period systems have circular orbits, whereas the longer period systems show some eccentricity.

In HMXBs the companion is generally highly evolved and dominates the optical emission. Tidal distortion of the companion can cause ellipsoidal variations in the optical light curve. These happen partly because the observer will see different parts of the distorted companion at different angles as it rotates. The optical light curve can also be affected by X-ray heating and light from an accretion disk. According to van Paradijs and McClintock (1995), by modelling the ellipsoidal variations it is possible to determine how close the companion comes to filling its Roche lobe. If the strong wind of the companion is not highly ionized it may be driven by the absorption of UV photons which is called a "line-driven wind". If the wind material is highly ionized it will be transparent to UV radiation and another driving mechanism such as X-ray heating may be involved. The dominant ionization mechanism is photoionization due to the X-ray luminosity which may be as high as $\sim 10^{38}$ erg s^{-1}.

As a result of the HMXBs having heavier companions they tend to be younger than LMXBs. The HMXBs are Population I objects and therefore are concentrated in the Galactic plane. In contrast, LMXBs tend to be Population II objects and their spatial distribution shows no preference for the Galactic plane, although they tend to be concentrated towards the Galactic center (Audley 1997).

4.2.1. Magnetic Properties

There is strong circumstantial evidence that the magnetic fields of some neutron stars do decay. These invariably happen to be neutron stars which have a binary history. Bhattacharya and Srinivasan (1995) in (Lewin and Livingston 1995) suggest evidence to support this. For example, from the fact that accreting neutron stars in HMXBs pulsate, it can be concluded that they must have strong magnetic fields; accretion is collimated towards the polar cap by the magnetic field, and the modulation of the X-ray intensity is due to the rotation of the neutron star. In contrast, neutron stars in LMXBs with very few exceptions do not pulsate, and this is understood in terms of their magnetic fields being several orders of magnitude smaller than their counterparts with massive companions. Since the neutron stars in HMXBs are relatively young compared to those in LMXBs, it is natural that the magnetic fields of neutron stars in binaries do decay.

4.2.2. Stellar Winds

The O and B stars in HMXBs have enourmous stellar winds that modify the properties of X-ray sources. The X-ray emission from the compact object must propogate through the wind and will undergo absorption. If the wind is inhomogeneous, then variations in absorption may occur. In LMXBs the natural stellar wind from the companion is less important, although a radiation driven wind caused by the X-ray illumination of the companion may be present in some systems (Tavani and London 1993).

When the OB star does not come close to filling its Roche lobe, the X-ray properties are determined by the wind of the star and its interaction with the compact object. These tend to be lower luminosity systems, typically less than 10^{36} erg s^{-1}. In systems where the star is close to filling its critical Roche lobe, which tend to be more luminous systems, the gas stream dominates the accretion flow and a disk forms around the neutron star. If the companion is out of synchronous rotation with the orbit, the gas stream will trail behind the compact object and escape the system (Savonije in Lewin and van den Heuvel (1983)).

4.2.3. Evolution of HMXBs

The evolution of binary systems is determined by three timescales. The time for the system to come to hydrostatic equilibrium is quite short compared to the other two timescales. The thermal and Kelvin-Helmholtz timescale is

$$t_{\text{th}} = 3 \times 10^7 \left(\frac{M_\odot}{M_c}\right)^2 \text{years.} \tag{15}$$

The nuclear timescale is

$$t_{\text{nuc}} \approx 10^{10} \left(\frac{M_\odot}{M_c}\right)^{\frac{5}{2}} \text{years.} \tag{16}$$

This is the timescale for hydrogen core burning to take place in the star at $\sim 10^7$ K, leading to the formation of a helium core. Figure 10 displays a possible scenario for the formation of a HMXB (van den Heuvel and Heise 1972).

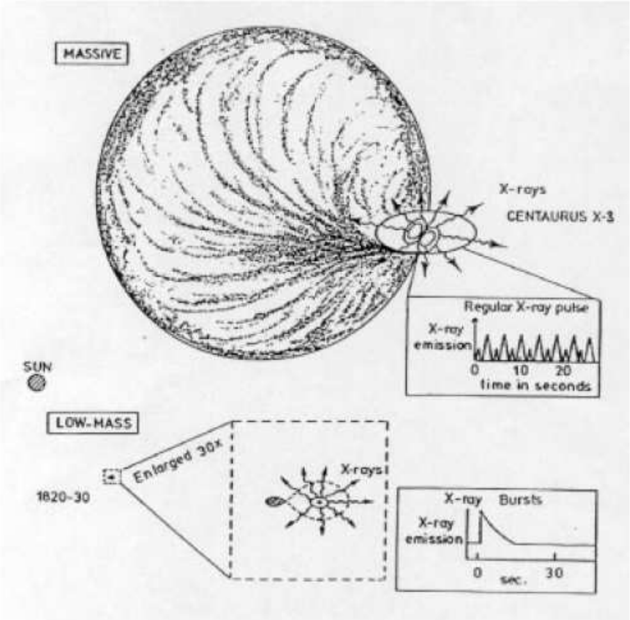

FIG. 9.— Comparison of two binaries, LMXB 4U1820-30 and HMXB Cen X-3 Image Credit: Hameury 2000, Ecole CNRS de Goutelas XXIII

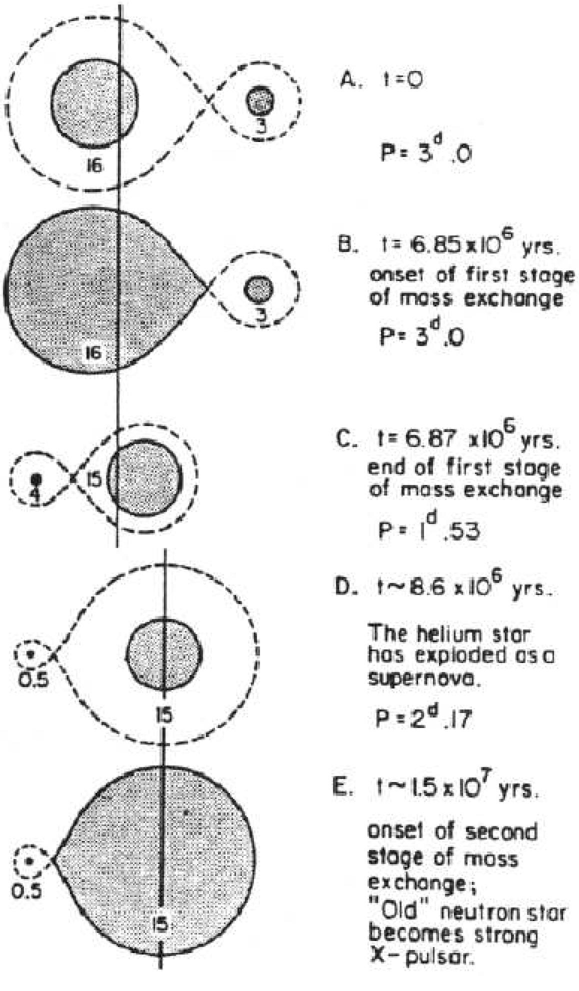

FIG. 10.— Possible scenario for the formation of a HMXB (van den Heuvel and Heise 1972). The center of mass of the system is represented by the vertical lines.

The compact object must have been a more massive star earlier in the history of the binary star system, since it evolves faster than the other star. During its final stages it seperates the outer layers of hydrogen, helium and carbon which can partly be captured by the other star. At the end of the massive star's life it blows off as a supernova and leaves behind this compact object, which is most likely a neutron star or a black hole.

Then starting up a mass transfer will cause the orbital separation and period to decrease, causing the companion's Roche lobe to shrink (Frank et al. 1985). In a close HMXB, tidal forces can be important, as these can cause the neutron star's orbit to be circularized a few million years after the supernova that created it. Once the orbit is circularized, a tidal instability can set in if the ratio of orbital to spin angular momentum is less than 3. In this case the orbit will decay on a timescale of $\sim 5 \times 10^5$ years and the neutron star will spiral into the companion's atmosphere. When the companion leaves the main sequence, it will overfill its Roche lobe and mass transfer will occur on the thermal timescale $t_{\rm th}$. The primary star will quickly spiral in, resulting in an LMXB comprising the primary neutron star and the He core of the companion. The companion may later undergo a supernova explosion, either disrupting the system or forming a binary pulsar system (Audley 1997).

It should also be noted that if the massive star has not entered a red-giant phase, where it has swollen significantly, the compact object has to be really close to be able to rip off gas and create an accretion disk, especially if the compact object is a white dwarf or a neutron star.

5. OTHER FEATURES OF SOME X-RAY BINARIES

Apart from the main classification of HMXB and LXMB, some X-ray binaries are also characterized by different features, in the following objects.

5.1. Quasi-Periodic Oscillators - QPO

In the accretion process, as the matter falls toward the compact object, it emits X-rays. Sometimes the emitted X-rays are pulsed, or modulated and the pulse period is found to be exactly the same as the spin period of the neutron star. Another type of pulsation, so called Quasi-Periodic Oscillations which were found by Strohmayer et al. (1996) shows that the average period of the oscillations varied as the overall X-ray brightness of the source varied (Figure 11). The brighter the source was in X-rays, the shorter the QPO period. It was theorized that this modulation of X-rays was due to the difference in frequency between the matter's orbital period around the compact object and the spin period of the compact object. This difference, called the beat frequency, would explain the 6 - 20 Hz Quasi-Periodic Oscillations.

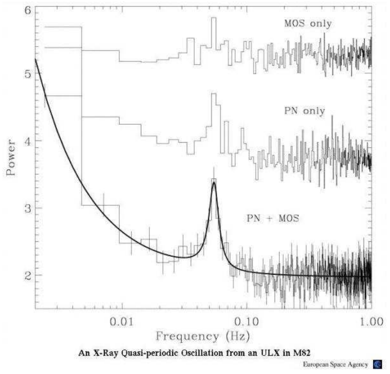

FIG. 11.— An X-ray Quasi-Periodic Oscillation from an ULX in M82. Image courtesy of ESA/XMM-Newton

QPOs are also divided to some sub-categories which are

i) Normal (Low Frequency QPOs) which have frequencies up to 100 Hz

ii) High Frequency QPOs which are also known as kHz QPOs (Figure 12)

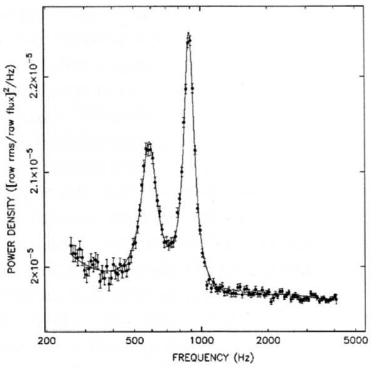

FIG. 12.— kHz QPO Image Credit: Van der Klis (2000)

iii) Burst Oscillations which do not occur in every burst and result from anisotropic burning on the surface and the rotation of the neutron star, they are also close to the neutron star frequency (Figure 13)

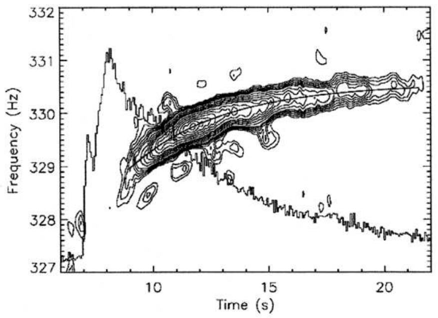

FIG. 13.— Burst Oscillation Image Credit: Van der Klis (2000)

iv) Z-shape sources which are typical among the strong, non-bursting, non-pulsating galactic center sources that have luminosities at approximately the Eddington limit and the magnetic fields of $\sim 10^9$ G (Figure 14).

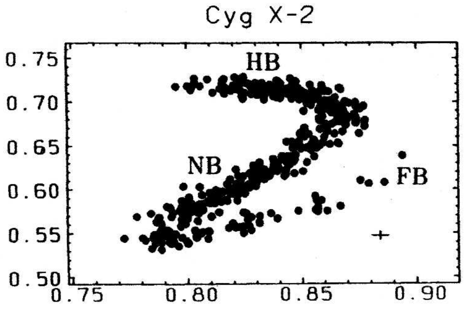

FIG. 14.— Z-shape sources Image Credit: Vanderklis (1989)

v) Atoll Shape Sources are in contrast to the Z-shape sources, their pattern is characteristic of X-ray bursters, with luminosities of only 1% of Eddington luminosity, and magnetic field strengths about ten times lower. (Figure 15)

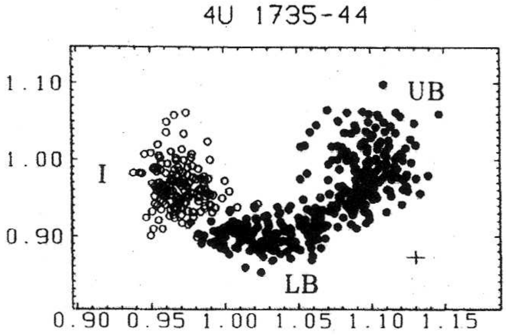

FIG. 15.— Atoll shape sources Image Credit: Vanderklis (1989)

The formation of the QPOs are still debated and the most developed model to account for kHz QPO is the "sonic point model" of Miller et al. (1996). This model follows the detailed trajectories of blobs of gas leaving the inner edge of the accretion disk around a neutron star and spiraling down to the neutron star surface, taking into account the effects of general relativity. The gas spirals inward supersonically and collides with the surface of the neutron star.

5.2. X-ray Binary Pulsars

The primary distinguishing property of X-ray binary pulsars is their extremely intense magnetic field, which are around $\sim 10^{12}$ Gauss, that restricts the mass of the X-ray emission to the polar cap region. The offset magnetic dipole in these systems produces a unique pulse profile as the neutron star rotates on its spin axis (Figure 16). As seen in the figures the pulse profile is quite variable as a function of energy.

There are around 30 well studied X-ray binary pulsar systems in the Milky Way. They are in orbits with binary periods ranging from 0.029 to 187.5 days and their spin periods range from 0.025 to 840 sec (Wijnands and van der Klis 1998). The companion stars in these systems span the widest range of possible types, from stars much less massive than our Sun to supergiants. A prominent sub-group among the X-ray binary pulsars has Be-star companions. These systems tend to be wider, often eccentric orbits and show transient episodes of accretion, most probably triggered by sudden mass outflows by the Be-companion. The X-ray luminosities for these systems range from 10^{36} - 10^{38} ergs s^{-1} (Cominsky 1998).

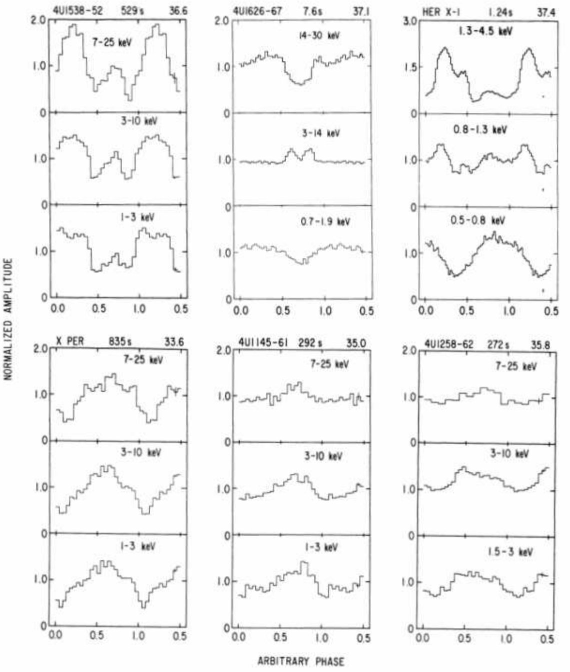

Fig. 16.— The pulse profiles as a fuction of phase and energy for 6 different X-ray binary pulsars (White et al. 1983).

6. CONCLUSIONS

The X-ray astronomy missions are largely supported by the astronomical community nowadays and within the next years researches will find many new types of objects at the X-ray regime and some of the formation theories might be changed fundamentally. This review about the "Compact X-ray Binaries" was gathered mainly from the fundamentally accepted papers, and debates were not included.

7. APPENDIX

7.1. X-ray Emission Mechanisms

X-ray astronomy is a major branch of astronomy which has the range of 0.1 Angstroms to 100 Angstroms, or 100 eV to 100 keV. X-ray emission is expected in sources which contain an extremely hot gas at temperatures from a million to hundred million Kelvins. That is generally in objects that their the atoms and/or electrons have a very high energy. Briefly, X-rays originate in the following astronomical mechanisms;

i) The hottest plasmas in the furthest reaches of the universe

ii) The most energetic events and shocks produced by such events as distant supernova explosions

iii) The very high electric and magnetic fields that can accelerate electrons to very high energies releasing X-ray photons

iv) Compact objects, such as white dwarfs, neutron stars or black holes, the release of the energy source of gravitational energy, which comes from gas heated by the fall in the strong gravitational field of such objects.

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