

X-Ray Binaries: A Laboratory for Frontier Physics

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Abstract The goal of this paper is to discuss the behaviour of the X-ray binary systems, in order to present to the readers an updated panorama of this important class of X-ray sources. They have in common the binary nature, but rather different characteristics: millisecond pulsations in low mass binary systems, seconds-hundreds seconds pulsations in transient high mass X-ray systems, pulsations limited in a narrow $\sim 6\text{--}12\text{s}$ band in the enigmatic class of systems named anomalous X-ray pulsars. However, all these systems are characterized by a neutron star as collapsed object. A few words will be devoted also to those systems having a black hole as collapsed object. Some comments on radio pulsars-SNRs and X-ray pulsars-SNRs associations will be given too.

Key words: X-ray binary systems: High mass binary systems, Low mass binary systems, Radio pulsars, SNRs/X-ray pulsars association

1 INTRODUCTION

Important observations started early in the past century with the discovery of inexplicable effects — the supernovae. They had been observed in ancient times but it was only with the establishing of the stellar and galactic distance scales that their true enormity was realized, namely the release of $\sim 10^{50}$ erg within a matter of days.

Baade & Zwicky (1934) first suggested that the supernova was the result of the transition from a normal star to a neutron star. The essential point (Zwicky 1939) being that the energy release in such a process is comparable to the change in gravitational potential energy of a star, which collapses from its normal size of $\sim 10^6$ km down to the size of a neutron star of ~ 10 km.

In the 1950s, Burbidge et al. (1957) with their works on stellar nucleosynthesis suggested realistic models of stars prior to supernova explosion. The supernova process was seen as the result of catastrophic change of state occurring in the core of a highly evolved star, e.g. the transformation of an iron core into a helium core. Contrary, Cameron (1958) suggested that this degenerate iron core would collapse to a neutron core through inverse beta decay.

The discovery of the first extra-solar X-ray source — Sco X-1 — (Giacconi et al., 1962) accelerated the studies on neutron stars, until that Zeldovich & Guseinov (1966) suggested the

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presence of an unseen massive companion in a binary system. From that moment, the challenge of X-ray astronomy started and the knowledge of X-ray sources quickly evolved during these last four decades, thanks to a multitude of space-based X-ray experiments on board rockets, stratospheric balloons, and satellites.

In this short review, we would like to discuss the main behaviour of the X-ray binary systems, which form an important group of the whole class of X-ray sources.

2 CLASSIFICATION OF X-RAY SOURCES

A sketch showing the classification of X-ray sources is reported in Fig.1 (updated from Giovannelli & Sabau-Graziati 1993).

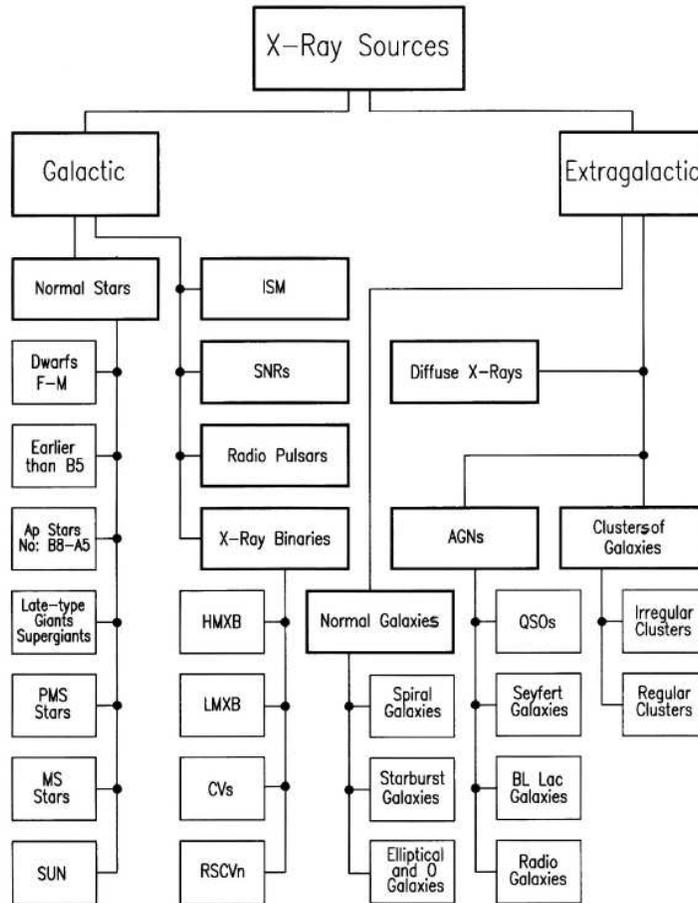


Fig. 1 Classification of X-ray sources (updated from Giovannelli & Sabau-Graziati, 1993).

3 X-RAY BINARIES AND ACCRETION PROCESSES

The trivial definition of X-ray binaries is that they are binary systems emitting X-rays. However it has been largely demonstrated that X-ray binary systems emit energy in IR, Optical, UV, X-ray, Gamma-ray and sometimes they show also valuable radio emission.

Observational evidences suggest that X-rays generate in binary systems because of accretion of matter, coming from the optical companion, onto the collapsed objects. The strong gravitational field of the compact star accelerates the accreting material, which provides the necessary energy for the emitted radiation. The accretion mechanism depends on the equipotential surfaces of the binary system. Figure 2 shows such surfaces for a binary system (Ruffini 1975):

- If the optical star fills its Roche lobe, the matter is flowing through the internal Lagrangian point and approaching the compact star forms an accretion disk around it because of conservation of angular momentum.
- If the optical star is contained within its Roche lobe, the matter accretes onto the compact star via stellar wind of the optical star.

Usually, the mass accretion rate \dot{M} is greater in the first than in the second case.

- It is possible that the flux of mass pushed onto the compact star via stellar wind can form an accretion disk close to the compact star beyond the shock front of the stellar wind. Such a disk is unstable and can sporadically change its configuration, with consequent fluctuations of the torsional momentum of the accreting matter (e.g. Giovannelli & Ziółkowski 1990).

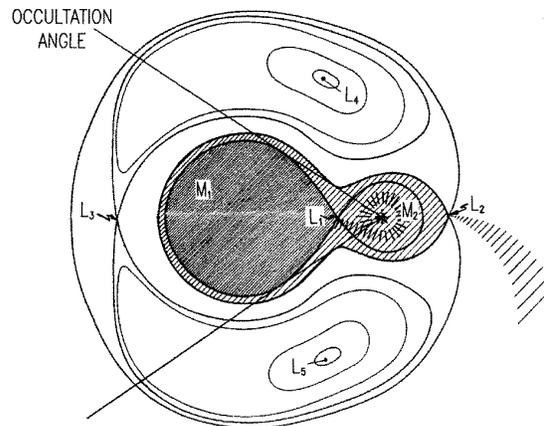


Fig. 2 Roche lobes and equipotential surfaces of a binary system formed by a normal star M_1 and a compact collapsed companion M_2 . L_1, L_2, \dots, L_5 are the Lagrange points of the system (Ruffini 1975).

4 CLASSIFICATION OF X-RAY BINARIES

Following the review of Giovannelli (1991), X-ray binary systems can be divided in different sub-classes:

- The High Mass X-ray Binaries (HMXBs) contain a collapsed object: the secondary star (neutron star or black hole) and an optical companion: the primary star with $M \gg 1 M_{\odot}$. They can be divided in two subclasses:
 - Hard X-ray Transient Sources (HXTSs). Their optical counterparts are Be stars with luminosity classes ranging between V and III, eccentricity of the orbits $0.2 \leq e \leq 0.5$, and orbital periods $P_{\text{orb}} > 10$ d. Their hard X-ray emission has $\overline{kT} \geq 17$ keV and is extremely variable: $L_x \sim 10^{34}\text{--}10^{39}$ erg s $^{-1}$. Their maximum to minimum luminosity ratio is $L_{x\text{max}}/L_{x\text{min}} > 10^2$. With the sensitivities of the first generation detectors, they were not always detectable; this was the reason of their name: transient sources.
 - Permanent X-ray Sources (PXSs). Their optical counterparts are supergiant OB stars (I luminosity class), eccentricity of the orbits $e \simeq 0$, and orbital periods $P_{\text{orb}} < 10$ d. Their hard X-ray emission has $\overline{kT} \geq 9$ keV and is almost constant: $L_x \approx 10^{37}$ erg s $^{-1}$, then $L_{x\text{max}}/L_{x\text{min}} \approx 1$. Also with the sensitivities of the first generation detectors, they were always detectable.

The transfer of mass in both HTXSs and PXSs occurs via stellar wind. The X-ray emission is modulated with the spin period ($0.069 \leq P_{\text{spin}} \leq 1430$ s) of the collapsed objects (neutron stars).

- The Low Mass X-ray Binaries (LMXBs) contain a collapsed object: the primary star (neutron star or black hole) and an optical companion: the secondary star with $M \leq 1 M_{\odot}$ is a late-type star. The transfer of mass from the optical companion onto the collapsed object occurs via Roche lobe overflow. The matter is escaping from the Roche lobe of the optical star through the internal Lagrangian point and forms an accretion disk around the collapsed object.

LMXBs contain:

- X-ray sources in globular clusters.
- Soft X-ray transient sources (SXTSs). They show soft X-ray emission with $\overline{kT} < 10$ keV. In some systems the emission is pulsed (e.g. Her X1, 4U 1626–27, GX1+4). SXTSs show Quasi Periodic Oscillations (QPOs) with periods ranging between ≈ 0.02 s to ≈ 1000 s. At the end of the eighties such QPOs have been observed from about 20 systems (van der Klis 1989). The orbital periods are ranging from 41 minutes to 11.2 days. The X-ray luminosity is in the range $L_x \sim 10^{36}\text{--}10^{39}$ erg s $^{-1}$. With the advent of the new generation satellites of the last decade hundreds LMXBs have been detected as well as the associated QPOs. They are produced in the vicinity of the neutron stars and therefore they are a good probe for the geometrical and physical properties of collapsed objects. Moreover it has been well established that the bulge sources and bursters, considered in the past as a distinct subclass of LMXBs, are on the contrary simply LMXBs.
- Cataclysmic Variables (CVs) in which the optical companion is a low-mass-late-type star and the compact object is a white dwarf. The detected CVs are spread roughly around the solar system at distance of $\approx 200\text{--}300$ pc. Orbital periods are ranging from tens of minutes to about ten hours with the known gap around 2–3 hours. However, the *disrupted magnetic break model* predicts a small number of CVs with orbital periods in such a gap. Indeed, a few SW Sex-like stars have orbital periods just inside the gap. This — together with the values of their magnetic moments, typical of intermediate polars — renders such systems probable precursors of the polar CVs (e.g. Rodriguez-Gil et al. 2002, and the references therein).

The mass transfer in CVs is occurring either via Roche lobe overflow or via accretion columns or in an intermediate way depending on the value of the magnetic field. Typical X-

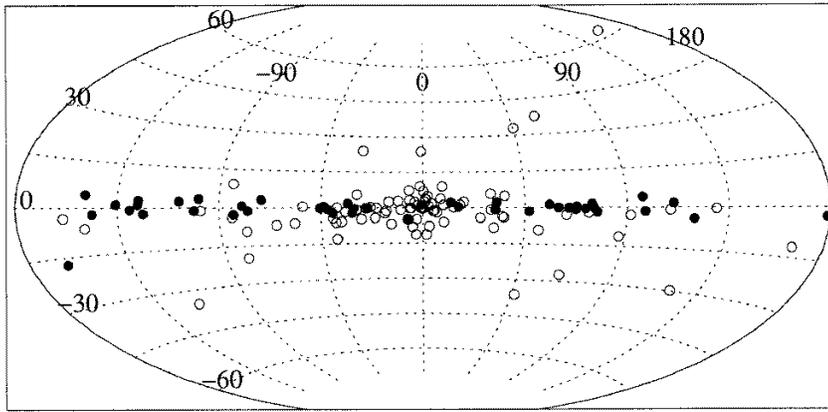


Fig. 3 Distribution of HMXBs (filled circles) and LMXBs (open circles) in the Galaxy. In total 52 HMXBs and 86 LMXBs are shown. Note the significant concentration of HMXBs towards the Galactic Plane and the clustering of LMXBs in the Galactic Bulge (Grimm, Gilfanov & Sunyaev 2002).

ray luminosity is ranging from 10^{32} to 10^{34} erg s^{-1} (e.g. reviews by Giovannelli & Martinez-Pais 1991; la Dous 1993 & 1994; Ulla, Giovannelli & Martinez-Pais 1999).

- RS Canum Venaticorum (RS CVn) type systems, in which no collapsed objects are present and the two components are a F or G hotter star and a K star. Typical X-ray luminosity is ranging from 10^{30} to 10^{31} erg s^{-1} . Usually in the current literature they are excluded from the class of X-ray binaries since historically they were discovered as X-ray emitters only with the second generation of X-ray experiments.
- Anomalous X-ray Pulsars (AXPs). They are X-ray pulsars with properties clearly different from those of the common HMXBs. AXP have spin periods ranging between ~ 6 and ~ 12 s, which are monotonically increasing on timescales of $\sim 10^4$ – 4×10^5 yr. The optical counterparts of AXPs are not known. On the basis of the limits in the optical and IR wavelength regions, the presence of a massive early-type companion star, such as OB super giants or Be stars, can be excluded in AXPs. Moreover, no orbital motion signatures are present in their X-ray light curves. A possible exception is 4U 0142+61, for which Hulleman, van Kerkwijk & Kulkarni (2000) reported the discovery of a faint ($R \sim 25$ mag) blue object in its error box.

From the study of the $\log N - \log S$ and X-ray luminosity function in the 2–10 keV energy range, and the spatial (3-D) distribution of bright, $L_x \geq 10^{34} - 10^{35}$ erg s^{-1} , X-ray binaries in the Milky Way, Grimm, Gilfanov & Sunyaev (2002), in agreement with theoretical expectations and earlier results, found significant differences between the spatial distributions of LMXBs and HMXBs. The volume density of LMXBs peaks strongly at the Galactic Bulge, whereas HMXBs tend to avoid the inner ~ 3 – 4 kpc of the Galaxy. In addition, HMXBs are more concentrated towards the Galactic Plane (scale heights of ≈ 150 pc and ≈ 410 pc for HMXBs and LMXBs, respectively) and show clear signature of the spiral structure in their spatial distribution. The $\log N - \log S$ distributions and the X-ray luminosity functions are also noticeably different. LMXBs have flatter $\log N - \log S$ distribution and luminosity function. The integrated 2–10 keV luminosity of all X-ray binaries in the Galaxy, averaged over 1996–2000, are $\sim 2.5 \times$

$10^{39} \text{ erg s}^{-1}$ (LMXBs) and $\sim 2 \times 10^{38} \text{ erg s}^{-1}$ (HMXBs). Normalized to the stellar mass and the star formation rate (SFR), respectively, these correspond to $\sim 5 \times 10^{28} \text{ erg s}^{-1} M_{\odot}^{-1}$ for LMXBs and $\sim 5 \times 10^{37} \text{ erg s}^{-1} / (M_{\odot} \text{ yr}^{-1})$ for HMXBs. An important consequence of this work is that for an outside observer the integrated emission of our Galaxy is dominated by the 5–10 most luminous sources. Figure 3 shows the distribution of the LMXBs and HMXBs in galactic coordinates.

We know that neutron stars can behave either as the so-called group of radio pulsars or as the so-called group of accreting neutron stars. All neutron stars rotate, but the main mechanisms of rotation are different: the rotation is determined by rotational energy loss in the case of young and old radio pulsars, while the rotation is determined by accretion in the recycled radio pulsars and in the accreting neutron stars. The equilibrium period is determined by the magnetic field intensity and by the mass accretion rate, as: $P_{\text{eq}} \approx 5 \cdot B_{12}^{6/7} \cdot \dot{M}^{-3/7} \text{ s}$. If the accretion rate is at the Eddington limit, the equilibrium period is minimum and expressed by $P_{\text{eq}} \approx 0.7 \cdot B_{12}^{6/7} \text{ s}$. Therefore, roughly speaking for equilibrium periods of $\sim 1 \text{ s}$ and $\sim 1 \text{ ms}$, the magnetic field are $B \sim 10^{12} \text{ G}$, and $B \sim 10^9 \text{ G}$, respectively. The class of radio pulsars contains the youngest pulsars, whose spin periods (33.4–267.4 ms) and derivative spin periods have been measured. Their associated $\log B$ is ranging from 11.96 G to 12.88 G. The radio pulsars contain also the so-called recycled pulsars. These can be sub-divided in three classes depending on their spin periods and $\log B$. The ranges of values of spin periods and $\log B$ characterizing the three classes are: i) 1.6–10 ms and $\log B = 7.88\text{--}9.64 \text{ G}$ for 52 objects, ii) 10–100 ms and $\log B = 8.66\text{--}10.37 \text{ G}$ for 16 objects, iii) 100–536 ms and $\log B = 10.07\text{--}10.83 \text{ G}$ for 12 objects (e.g. Ziółkowski 1997b & 1999). In the class of the 95 accreting pulsars, whose spin periods are ranging from 0.061 to 1413 s, the $\log B$ are ranging from 11 to 12 G. However, a new class of super-strongly magnetized neutron stars ($B \sim 10^{14}\text{--}10^{15} \text{ G}$), namely magnetars, can be considered. The list of candidates contains five soft gamma repeaters (presumably younger magnetars) and eight anomalous X-ray pulsars (older magnetars). Most of magnetars are associated with young supernova remnants and all of them rapidly spin down (on time scale of $10^3\text{--}10^5 \text{ yr}$) (e.g. Ziółkowski 2002). Then it is evident the possibility of classifying the rotating neutron stars in four classes, as shown in Table 1.

Table 1 Classification of the Rotating Neutron Stars (Ziółkowski, 2002).

Class	P_{spin}
RADIO PULSARS	
Newborn	$\sim 10\text{--}100 \text{ ms}$
Recycled	1.6–536 ms
Old ($10^6\text{--}10^7 \text{ yr}$)	$\sim 1,000\text{--}8,400 \text{ ms}$
WEAKLY MAGNETIZED	
ACCRETING NEUTRON STARS	2.5–3.8 ms
STRONGLY MAGNETIZED	
ACCRETING NEUTRON STARS	0.061–1,413 s
MAGNETARS	
Soft γ -ray repeaters	5.16–8 s
Anomalous X-ray pulsars	5.45–11.77 s

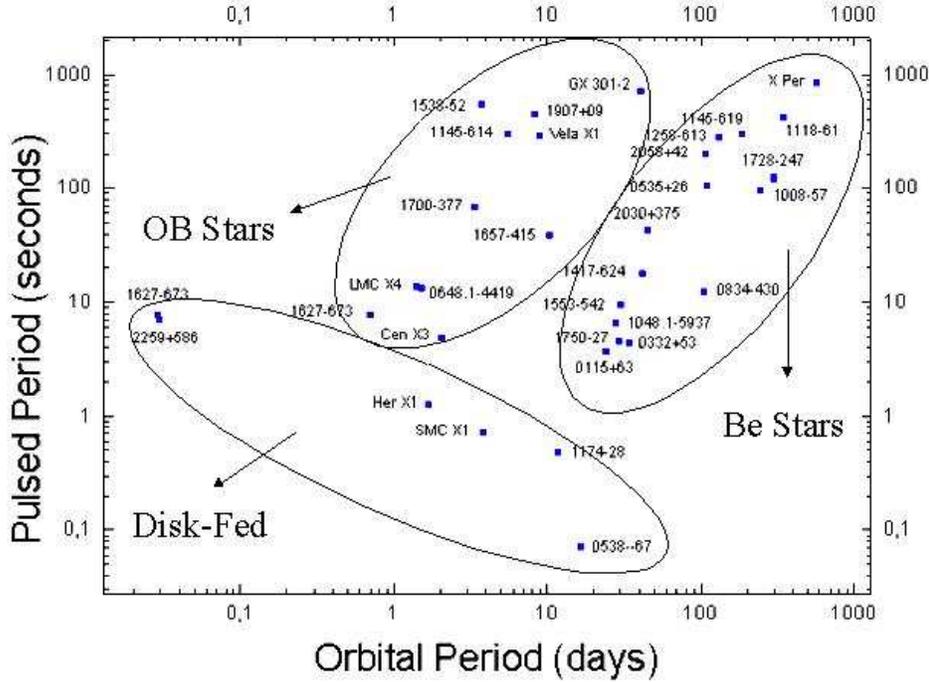


Fig. 4 The dependence of the spin period versus the orbital period of X-ray pulsars (after Giovannelli & Sabau-Graziati 2001, after Corbet, 1984, 1986).

5 HMXBS: MULTIFREQUENCY LABORATORIES

Most of the HMXBs are X-ray/Be systems (see the catalog of Liu, van Paradijs & van den Heuvel 2000), which contains 130 systems with orbital periods ranging from 4.8 hr to 187 d.

Optical emission of HMXBs is dominated by that of the optical primary component, which is not, in general, strongly influenced by the presence of the X-ray source. The behavior of the primary stars can be understood in the classical (or almost) framework of the astrophysics of these objects, i.e. by the study of their spectra which will provide indications on mass, radius, and luminosity. Both groups (PXSs and HTXSs) of HMXBs differ because of the different origin of the mass loss process: in the first, the mass loss process occurs via a strong stellar wind and/or because of an incipient Roche lobe over-flow; in the second group, the mass transfer is probably partially due to the rapid rotation of the primary star and partially to stellar wind and sporadically to expulsions of a casual quantity of matter, essentially triggered by gravitational effects because of periastron passage where the effect of the secondary collapsed star is more marked.

A relationship between orbital period of HMXBs and the spin period of the X-ray pulsars is shown in Fig.4, (Giovannelli & Sabau-Graziati 2001, updated from Corbet, 1984, 1986). It allows to recognize three classes of objects, namely disk-fed systems, wind-fed X-ray/OB systems ($P_{\text{pulse}} \propto P_{\text{orb}}^{4/7}$), and X-ray/Be systems ($P_{\text{pulse}} \propto P_{\text{orb}}^2$).

Most of the systems having a Be primary star are hard X-ray ($kT > 10$ keV) transient sources (HXTS). They are concentrated on the galactic plane within a band of $\sim 3.9^\circ$. The

orbits are quite elliptic and the orbital periods large (i.e. A 0538–66: $e = 0.7$, $P_{\text{orb}} = 16.6$ d (Skinner et al. 1982); A 0535+26: $e = 0.5$ (Finger et al. 1994), $P_{\text{orb}} = 111.0$ d (Priedhorsky & Terrell 1983)). The X-ray flux during outburst phases is of order 10–1000 times greater than during quiescent phases. For this reason, on the contrary, the stars belonging to the first class which do not present such strong variations in X-ray emission, can be named “standard” high mass X-ray binaries. In X-ray/Be systems, the primary Be star is relatively not evolved and is contained within its Roche lobe. The strong outbursts occur almost periodically in time scales of the order of weeks-months. Their duration is shorter than the quiescent phases. During X-ray outbursts, spin-up phenomena in several systems have been observed (i.e. A 0535+26 and 4U 1118–61 (Rappaport & Joss 1981)). The observed spin-up rates during the outbursts are consistent with torsional accretion due to an accretion disk (e.g. Ghosh 1994). So, the formation of a temporary accretion disk around the collapsed object should be possible during outburst phases (e.g. Giovannelli & Ziółkowski 1990).

The values of magnetic field strengths of $10^{11} - 10^{13}$ G in X-ray pulsars are inferred from the pulsations. They require anisotropic in-falling radiation, the cyclotron lines observed in a number of pulsar spectra (Nagase 1989a,b), and the observed changes in pulse period (Ghosh & Lamb 1979; Joss & Rappaport 1984; Prince et al. 1994; Finger & Prince 1997). The strengths of the magnetic field are good probes for the physics of the accretion flow and for the kinetic energy of the in-falling matter converted into radiation. A good estimate of the temperature observed in X-ray pulsars ($T_{\text{eff}} \sim 10$ keV) is coming from the formula $T_{\text{eff}} \sim (\frac{L_x}{\sigma \cdot A_{\text{cap}}})^{1/4}$ keV, where L_x is the X-ray luminosity, σ is the magnetic Thompson scattering cross section, and A_{cap} is the heated polar cap area. However, the pulsar spectra are not blackbody-type; then, in order to understand the emission, an accurate description of the radiating plasma is necessary. Experimentally, the magnetic fields of X-ray pulsars can be determined through the cyclotron lines that can appear in the X-ray spectra. Indeed, in X-ray pulsars, for $B_n \ll B_{\text{crit}} \equiv m^2 c^3 / e \hbar = 4.413 \times 10^{13}$ G, the energy spacing between Landau states reduces to the cyclotron energy $\Delta E \simeq \hbar \omega_B = 12$ keV $\cdot (B/10^{12})$ G, where $\omega_B = eB/m_e$ is the electron cyclotron frequency and assuming the gravitational redshift equal to ~ 1 . Since $kT \leq \hbar \omega_B$ in the atmosphere of X-ray pulsars, electrons will mainly occupied the ground Landau state ($n = 0$) in a one-dimensional distribution. Moreover, the rate of collisional excitation to higher Landau states is much less than the cyclotron radiation rate from excited states; then, the population of the levels may be far from thermal equilibrium, and will be dominated by the radiation field (e.g. Harding 1994). Cyclotron line emission regulates the cooling of the atmosphere: i) for $B > 10^{12}$ G, the electron temperature can be maintained at few times $\hbar \omega_B$; ii) for $B < 10^{12}$ G, the ion temperature is high enough to excite the electron Landau levels via collisions; the electron temperature becomes enough high ($kT_e \approx 10^9$ K) to produce γ -rays. The spectrum from the atmosphere is a Doppler broadened cyclotron line, with practically no continuum contribution from bremsstrahlung.

Thus the detection of absorption line features due to cyclotron resonance scattering (CRSF) in the X-ray spectrum is a definitive method for estimating the strength of magnetic field at the neutron star surface. The first measurements of cyclotron lines from binary systems were obtained by Trümper et al. (1978) from Her X1 and by Wheaton et al. (1979) from 4U 0115+63. From GINGA observations, the CRSFs were discovered in the spectra of several X-ray binaries: Her X1, 4U 0115+63, 4U 1538–52, X0331+53, Cep X4, 1E 2259+586, Vela X1, 4U 1907+09, GX 301–2 (Nagase 1994 and the references therein). The cyclotron resonance energies measured from these nine X-ray pulsars are in the range 7 – 40 keV, corresponding to a magnetic field strength of $(0.6 - 3.5) \times 10^{12}$ G at the neutron star surface, taking the gravitational redshift to be ~ 1 . The luminosities of these nine pulsars were less than 4×10^{37} erg s $^{-1}$ during the observations of the CRSFs. In more luminous X-ray pulsars, such as Cen X3 and SMC X1, such a feature was not observed. A correlation between the fundamental resonance energy (E_B) and the cutoff

energy (E_c) of the power spectrum has been found: $E_B \simeq 2E_c$. The absorption line features are generally broader than the energy resolution of the detectors (proportional counters). In the case of Vela X1 the feature is pulse-phase dependent. The correlation $E_B \simeq 2E_c$ suggests that the cutoff of the spectrum at high energies relates to the cyclotron resonance scattering. Therefore, the cutoff energy could be a good indicator of the cyclotron energy and then of the magnetic field intensity for those pulsars from which the CRSF is not detectable. The scatter in the magnetic field intensity for the known X-ray pulsars is rather small; indeed it is $B = (1 - 4) \times 10^{12}$ G. This is an important track for the investigation on magnetic field evolution of neutron stars. Cyclotron lines have been measured by BeppoSax satellite from several X-ray pulsars, namely Cen X3, 4U1626-67, Her X1, Vela X1, and A0535+26 (dal Fiume et al. 1998). Later cyclotron lines have been found also in other X-ray pulsars (e.g. Orlandini & dal Fiume 2001). A relationship between the cyclotron line energy and the FWHM of the line is present, as shown in Fig.5.

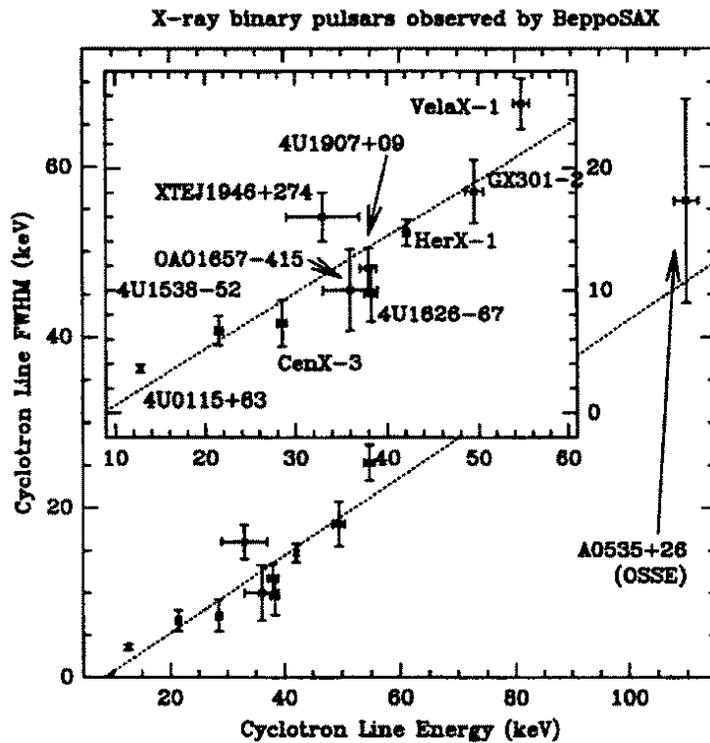


Fig. 5 Cyclotron features FWHM versus centroid energy for several X-ray pulsars (Orlandini & dal Fiume 2001).

One of the most important results obtained with the BeppoSAX came from the observations of the pulsating transient X 0115+63, whose X-ray spectrum showed for the first time four cyclotron harmonic features at 12.74, 24.16, 35.74, and 49.5 keV (Santangelo et al. 1999).

Recently, from the measurements obtained with the RXTE satellite, Coburn et al. (2002), looking at the data base, found all accreting X-ray pulsars showing cyclotron lines in their

spectra. Then, they searched for correlations among the spectral parameters, concentrating on how the cyclotron line energy relates to the continuum and therefore how the neutron star magnetic field influences the X-ray emission. As expected, they found a correlation between the CRSF energy and the spectral cutoff energy. They found also not only that the width of the cyclotron line correlates with the energy, as suggested by theory, but also that the width scaled by the energy correlates with the depth of the feature, as already found by dal Fiume et al. (1998) and Orlandini & dal Fiume (2001) (see Fig.5). Coburn et al. (2002) discussed the implications of these results, including the possibility that accretion directly affects the relative alignment of the neutron star spin and dipole axes. Table 2 shows the pulsar magnetic fields, as they derived, assuming the radius and mass of the neutron star of 10 km and $1.4 M_{\odot}$, respectively and scattering near the surface of the star.

Table 2 Pulsar Magnetic Fields (adapted from Coburn et al. 2002).

X-ray Pulsar	E_c (keV)	B (10^{12} G)
Her X-1	$40.4^{+0.8}_{-0.3}$	4.5
4U 0115+63	$11.6^{+0.2}_{-0.4}$	1.3
Cen X-3	$30.4^{+0.3}_{-0.4}$	3.4
4U 1626–67	$39.3^{+0.6}_{-1.1}$	4.4
XTE J1946+274	$34.9^{+1.9}_{-0.8}$	3.9
Vela X-1	$24.4^{+0.5}_{-1.1}$	2.7
4U 1907+09	$18.3^{+0.4}_{-0.4}$	2.1
4U 1538–52	$20.66^{+0.05}_{-0.06}$	2.3
GX 301–2	$42.4^{+3.8}_{-2.5}$	4.8
4U 0352+309	$28.6^{+1.5}_{-1.7}$	3.2

HMXBs are good targets for a number of measurements in different energy ranges, from the IR to VHE γ -ray, in order to understand many crucial problems on the physics of the collapsed objects and their interactions with the optical companions. For these purposes, two of the most significant energy ranges are the optical and X-ray ones. Simultaneous measurements in these ranges can solve, in a first approximation, most of the still open problems in understanding the physics of the accretion of matter onto collapsed objects, the interactions with the stellar winds from the optical companions, the mechanisms triggering the X-ray emission and outbursts, and others.

In spite of the many space- and ground-based multifrequency experiments and the multitude of excellent-quality data obtained and partially still not analyzed, the question of the nature of the accretion flow to the neutron star and the resultant accretion torque in X-ray/Be binaries is still open. It is amazing that we have so little understanding of the class that forms the majority of known accretion-powered pulsars. A better understanding of the basic properties of the torque due to accretion from stellar winds before we can quantitatively account for the spin behavior of wind-fed sources is essential; while, for the disk-fed sources, it should be important to identify the essential physical processes that determine the magnetic pitch and the spin-down torque.

The X-ray source in HMXBs provides a unique active probe of the winds of massive stars. In fact, the binary system orbits around its center of mass, then our line of sight continuously changes, allowing the map of the distribution of X-ray absorbing gas in the system. Meanwhile, the strong X-ray flux alters the local dynamics of the wind, then it is possible to study the physics of radiatively-driven winds, and thanks to X-ray variability in different time scales, it is also possible to study the dynamics of radiatively-driven winds. Thus, the study of winds provides precious information also on the accretion of matter onto the collapsed objects for systems clearly wind-fed. On the contrary, in the opposite case, in systems where the accretion is completely disk-fed, we do not know completely the dynamics of the Roche lobe overflow process, and in particular the fraction of matter and angular momentum lost from the binary system is still poorly known. And, moreover, wind accretion and Roche lobe overflow are the extreme cases of the same accretion process. Then, an increase of the number of systems deeply studied simultaneously in different energy regions is necessary in order to improve the statistics of the different cases of accretion, from ‘pure’ wind-fed to ‘pure’ Roche lobe overflow.

For this purpose we are rather lucky, since our Galaxy contains a congruous number of HMXBs whose emissions are the highest measurable; this renders such systems the most powerful laboratories to test theories on collapsed objects and plasma physics. In order to go on in such a sense, a change in the philosophy of the experiments is mandatory. Then, a continuous long term monitoring of a ‘few’ systems, representative of homogeneous class of systems, is necessary. In this way it will be possible to clarify what is happening during the different phases in which the physical processes occur. These processes can be influenced by the rotation of the X-ray pulsars, the orbital period of the system, transit time of the matter from the primary to secondary star via wind, or disk, or intermediate, etc.

Moreover, all the obtained results can be scaled to extra-galactic distances and dimensions. The relative facility in performing multifrequency measurements of HMXBs suggests that they can be useful targets even for small satellites. In particular, in the X-ray and optical energy ranges, HMXBs are very suitable targets for experiments like SIXE (Spanish Italian X-ray Experiment) (Giovannelli et al. 1993b, 2001, 2002; Isern et al. 2001) to be launched in small satellites such as the Spanish MINISAT-02.

6 LOW MASS X-RAY BINARY SYSTEMS

The LMXBs class is formed by systems where the optical star — the secondary — is later than type A with a mass $M \leq 1 M_{\odot}$. They can be very old systems with age $\geq 10^9$ yr. In some very evolved systems such a companion can be even a white dwarf. Their spatial distribution is concentrated along the galactic plane, but mostly toward the galactic center: more than half of the known LMXBs are located within 20° of the galactic center (see Fig.3 and section 4).

The optical counterparts in LMXBs are intrinsically faint. Most of the spectra show a few characteristic emission lines superposed to a roughly flat continuum, which is dominated by the emission of an accretion disk around the compact star — the primary. Such an emission is mainly the result of reprocessing of a fraction of the X-rays into optical photons in the disk. The contribution of the secondary star to the total luminosity is generally negligible. The orbital periods of LMXBs range from 11.4 min for 4U 1820–30 (Stella, White & Priedhorsky 1987) and 16.6 d for Cir X-1 (Kaluzienski et al. 1976). The very short period systems ($P_{\text{orb}} < 1$ hr) are expected to have degenerate dwarf mass companions and probably the transfer of mass is being driven by gravitational radiation. The last updated catalog of LMXBs contains 150 systems (Liu, van Paradijs & van den Heuvel 2001).

The importance of low mass X-ray binaries (LMXBs) resides mainly in the fact that they contain neutron stars (or black holes), which are objects of fundamental physical interest. Their

study allows to derive information on the equation of state of high-density matter and to test the general relativity in the presence of very strong field regime.

In LMXBs, matter is transferred from a low mass ($\leq 1 M_{\odot}$) star (the secondary star) to a neutron star (the primary star) via an accretion disk. The X-ray radiation originates from the hot ($\sim 10^7$ K) plasma comprising the inner few 10 km of the flow. This is very close to the neutron star, which has a radius $R_{\text{NS}} \sim 10$ km and a mass $M_{\text{NS}} \sim 1.4 M_{\odot}$. Therefore, the study of the properties of such a flow can provide information about the star.

When the matter is descending into the neutron star's very deep gravitational potential well ($GM_{\text{NS}}/R_{\text{NS}} \sim 0.2c^2$), the temperature of the inner flow increases a lot because of the release of a large amount of gravitational energy. The characteristic velocities near the neutron star are of order $(GM_{\text{NS}}/R_{\text{NS}})^{1/2} \sim 0.5c$. Therefore, the time scale for motion of the matter through the emitting region, namely the dynamical time scale, is as short as $\tau_{\text{dyn}} = (r^3/GM_{\text{NS}})^{1/2} \sim 0.1$ ms for $r = 10$ km, and ~ 2 ms for $r = 100$ km.

Milestones on the study of low mass X-ray binaries (LMXBs) have been the measurements performed with the RXTE and BeppoSAX satellites, which rendered possible to obtain direct information on the properties of these flows at these time scales. Before the beginning of such missions in the middle 1980s, the neutron star (NS) LMXBs were deeply studied with previous experiments on board many satellites (i.e., Einstein, EXOSAT, ROSAT, Ginga). NS in LMXBs display a complex variety of quasi periodic oscillation (QPO) modes in their X-ray flux. One important step in their knowledge was the introduction of X-ray colour — colour diagrams (CDs) (e.g., Hasinger & van der Klis 1989; Schulz, Hasinger & Trümper 1989). Such diagrams resulted extremely useful in the study of correlations between the changes in X-ray spectrum and X-ray timing behaviour of LMXBs. These power spectral variations provided an observational handle of the bright LMXBs, which are galactic X-ray binary systems that in spite of being the brightest and longest known extrasolar cosmic sources had long defied interpretation owing to a lack of diagnostic properties. Several years ago, van der Klis (1989, 1995) reviewed the quasi-periodic oscillations (QPOs) detected in LMXBs, before the discovery of the KHz QPOs, made with the RXTE satellite (Strohmayer et al. 1996; van der Klis et al. 1996). Such a discovery provided experimental evidence of the crude phenomenology, occurring in the vicinity of the neutron stars, as described before.

What is clear in this moment is that, for the first time, rapid X-ray variability phenomena, directly linked with the NS's most distinguished characteristic, namely its compactness, have been detected. This is particularly evident if the phenomena are in some way related to the orbital motion. Indeed, a Keplerian orbital frequency $\nu_{\text{K}} = P_{\text{orb}}^{-1} = (GM_{\text{NS}}/4\pi^2 r_{\text{K}}^3)^{1/2}$ of 1200 Hz around a $1.4 M_{\odot}$ NS as seen from infinity corresponds to an orbital radius $r_{\text{K}} = (GM_{\text{NS}}/4\pi^2 \nu_{\text{K}}^2)^{1/3}$ of 15 km directly constraining the equation of state of the bulk nuclear-density matter, and only just outside the general-relativistic marginally stable orbit (van der Klis 2001). Whatever the model, for the first time one has to seriously worry about general-relativistic effects in describing the observable dynamics of the physical systems.

In the Ph.D. thesis of Wijnands (1999) and in his short review (Wijnands 2001), and in van der Klis (2001), millisecond phenomena in X-ray binaries have been deeply discussed.

6.1 X-Ray Sources in Globular Clusters

With the HRI detector of the Einstein observatory it was possible a survey of 30 globular clusters with luminosity $L_{\text{x}} > 10^{34} \times d_{10}^2 \text{ erg s}^{-1}$ (d_{10} is the distance in units of 10 kpc), and with the IPC detector it was possible to reach a luminosity limit $L_{\text{x}} \geq 10^{33} \times d_{10}^2 \text{ erg s}^{-1}$ and to observe 32 clusters. Such X-ray sources were identified since a long time as objects extremely interesting because of their resemblance with the bright galactic X-ray sources (Canizares 1975;

Grindlay 1978), and moreover the clusters were identified as X-ray burst emitters (Grindlay et al. 1976).

Surveys of the dozen brightest ($L_x \geq 10^{36} \text{ erg s}^{-1}$) X-ray sources in globular clusters have shown that they are very similar to the LMXBs found in the rest of the Milky Way. They show X-ray bursts and lack of coherent pulsations in their persistent emission (Hertz & Wood 1985; Parmar, Stella & Giommi 1989; Verbunt et al. 1995). The presence of type I bursts indicates the presence of accreting NSs rather than BHs in the luminous systems, which are considered similar to the galactic X-ray burst sources. However, their formation is more efficient by a factor of ~ 200 in globular clusters than in the Galaxy itself.

The importance of the study of X-ray sources in globular clusters resides in the fact that their distances are determined independently through main-sequence modelling and other methods (e.g. Carretta et al. 2000). Therefore, a more accurate values of luminosity than that typical for galactic LMXBs can be achieved. Moreover, the cluster reddening can be measured, so providing an independent estimate of low energy absorption. Finally, the mean cluster abundances can be determined, allowing any dependence of X-ray properties on abundance to be examined.

We do not want to enter in more details, since X-ray sources in globular clusters have been reviewed by Frank Verbunt in this workshop (Verbunt & Bassa 2003).

6.2 Soft X-Ray Transients

Soft X-ray transients (SXTs) constitute a subclass of LMXBs and are characterized by low accretion rates. Non-steady mass transfer onto the compact object causes sporadic and sometimes repetitive large X-ray and optical outbursts, which usually last for several months, when the X-ray luminosity can increase up to a factor of 10^7 (van Paradijs & McClintock 1995). SXTs are located in the galactic plane with a distribution similar to that of LMXBs (van Paradijs & White 1995). The presence of SXTs in globular clusters is of particular interest due to their possible evolutionary link with recycled milli-second pulsars (MSPs). It is possible that some of the dim ($L_x \leq 10^{34} \text{ erg s}^{-1}$) X-ray sources in globular clusters are SXTs in quiescence (e.g., Verbunt et al. 1994). For an alternative explanation see e.g., Grindlay (1994). A long review on SXTs is that by Campana et al. (1998). Briefly, contrary to persistent LMXBs, SXTs emit a significant flux of X-rays only during the outbursts, which are separated by long intervals of quiescence (much longer than the duration of outbursts). Their outbursts are very strong so that the systems in such conditions are the brightest sources in the X-ray sky. The decline from an outburst is slow: the duration can be of order a few months.

The luminosity during a typical outburst approaches the Eddington limit and the X-ray emission is dominated by thermal emission from the hot inner part of the accretion disk around the collapsed object. Most of the the optical contribution during outbursts is due to reprocessing of X-rays in the outer regions of the accretion disk. Typical luminosities at outbursts are of $\sim 10^{37} - 10^{38} \text{ erg s}^{-1}$, but sometimes they can reach $\sim 10^{39} \text{ erg s}^{-1}$ (Tanaka & Lewin, 1995). Therefore, during outbursts the SXTs are similar to the persistent LMXBs both in X-ray and optical behaviour. The total luminosity is dominated by the emission of the accretion disk. When the SXT is returning to the quiescence, its optical emission reveals the presence of the optical companion. This is the unique possibility of directly detect the characteristics of the secondary among the class of the LMXBs. However, for instance in cataclysmic variables, which can be considered LMXBs having as primary a white dwarf, such a detection is possible (e.g., Martinez-Pais et al. 1994).

During quiescence, the X-ray luminosity is strongly dependent on the nature of the compact star. For neutron star systems, this luminosity is of $\sim 10^{38} \text{ erg s}^{-1}$, while for black hole systems it can be as small as $\leq 10^{31} \text{ erg s}^{-1}$ (e.g., van Paradijs, 1998 and references therein). Narayan, Garcia, & McClintock (1997) argued that this difference can be explained only if the accretion

inner disk around the collapsed object of quiescent SXTs is advective. Bisnovatyi-Kogan, (1999) discussed the accretion disk theory from the standard model until advection. A general and exhaustive discussion on such a kind of disk is reported by Bisnovatyi-Kogan & Lovelace (2001).

The discovery of an accreting NS with a 2.49 ms spin period in the soft X-ray transient SAX J1808.4–3658 (Wijnands & van der Klis 1998), whose orbital period is $P_{\text{orb}} = 2.01$ hr (Chakrabarty & Morgan 1998) had important consequences for many aspects of our understanding of LMXBs and their evolution. One of these aspects is the tight limit one can place on the neutron star radius, which in turn has significant implications for the equation of state and possible mass of this compact star.

Most of the SXTs contain black holes, while persistent LMXBs contain neutron stars.

The soft components in the spectra of systems with BHs and NSs are qualitatively the same (i.e. same functional form), except for significantly lower characteristic temperatures in the BH systems, being typically the colour-temperature $kT \leq 1.2$ keV, when the X-ray luminosity is $L_x \sim 10^{38}$ erg s⁻¹ (Ebisawa et al. 2001). Sunyaev & Revnivtsev (2000) suggested a possible way of distinguishing between systems hosting a BH and a weakly magnetized NS based on their power spectra: NS systems can show significant power above ~ 300 Hz, while BHCs do not.

We believe that it is necessary to analyze wider samples of NSs and BHCs before to definitively state firm conclusions.

6.3 Microquasars (Black Holes in Binary Systems)

A microquasar (micro-QSO) is a galactic X-ray binary with radio jets. Microquasars constitute a small subclass of LMXBs, which show sporadic ejection of matter at apparently superluminal velocities. In these binaries of stellar mass the three basic ingredients of quasars are found: a black hole, an accretion disk heated by viscous dissipation, and collimated jets of high-energy particles. But contrary to quasars, where the masses of the black holes are several million of solar masses, in microquasars the black holes are only a few solar masses; the accretion disks in microquasars reach thermal temperatures of several millions degrees instead of several thousands degrees in quasars, and the relativistic particle ejected can travel up to distances of a few light years only, instead of several million light years as in radio galaxies (e.g. Mirabel & Rodriguez 1998). For a review see Mirabel & Rodriguez (1999) and for an update panorama the book *Microquasars* (Castro-Tirado, Greiner & Paredes 2001).

Microquasars are the ideal laboratories for the comprehension of the mechanism of relativistic jets and its relation with the accretion flow onto a black hole, traced by the brightness and fast variability in X-ray energy regions. Since such binaries are galactic, then close by us, and bright at many wavelengths, multifrequency observations, possibly simultaneous, can allow to obtain a lot of information on all the fan of processes occurring in accreting binaries with jets and the possibility of extrapolating the results, with some caution, to quasars. Indeed, the characteristic dynamical times in the flow of accreting matter onto a black hole are proportional to its mass, the events developing in time scales of minutes in microquasars could correspond to similar phenomena with duration of thousand years in a quasar of $\sim 10^9 M_{\odot}$, like for instance 3C 273. Therefore, phenomena that we cannot observe in quasars because of their long duration can be observed in microquasars now very easily, thanks to the new generation experiments usually having high time resolution, high spectral and flux sensitivities, and high angular resolution.

The list of known galactic micro-QSOs contains ten objects, which are all LMXBs with the exception of Cyg X-1. They are shown in Table 3, where the mass function of the binary system and the masses of the collapsed object and the optical companion are reported too (Blandford & Gehrels 1999; Filippenko et al. 1999; Casares 2001). In addition, there are several

more objects that are possible candidates for being included into the list (e.g. Ziółkowski 1997a, 2001; Casares 2001 and the references therein).

Table 3 Black holes in the Milky Way Galaxy (Blandford & Gehrels, 1999; Filippenko et al. 1999; Casares, 2001)

Source Name	Identification	Companion	f(M)	M_{Opt} (M_{\odot})	M_{BH} (M_{\odot})
Cygnus X-1	HD226868	O9.7 Iab	0.24	24–42	11–21
GS2023+338	V404 Cyg	K0 IV	6.26	~ 0.6	10–15
GS2000+25	QZ Vul	K3 – K5 V	4.97	~ 0.7	6–14
H1705–250	V2107 Oph	K3	4.86	0.3–0.6	6.4–6.9
GROJ1655–40	N Sco 1994	F6 IV	3.24	2.34	7.02
A0620–00	V616 Mon	K3 – K5 V	3.18	0.2–0.7	5–10
GS1124–68	GU Mus	K3 – K4 V	3.10	0.5–0.8	4.2–6.5
GROJ0422+32	V518 Per	M2 V \pm 2	1.21	~ 0.3	6–14
4U1543–47		A2 V	0.22	~ 2.5	2.7–7.5
GRS1009–45	N Vel 1993	K8 V \pm 2	3.17	~ 0.6	4.4

Following the current definitions, a macroquasar (macro-QSO) is an AGN, such as 3C 273, with a giant black hole of mass of $\sim 10^7 - 10^9 M_{\odot}$ as main source of energy emission. Its characteristics are very similar to those of microquasars. A discussion on the analogies between macroquasars and microquasars can be found in, e.g., Giovannelli & Sabau-Graziati (2001).

Thanks to these analogies, a possible easier line of investigation for understanding the physics of quasars is that of investigating micro-QSOs, since they are typically ~ 100 times brighter than macro-QSOs, as seen from the Earth, and the corresponding variability time scales are $\sim 10^6 - 10^8$ times shorter than in macro-QSOs.

The question of possible connection between rapid rotation and the highly relativistic nature of the jets remains open. Also the mechanism of the jet acceleration remains still unknown, although efforts have been done by many authors (e.g., Li, Miller & Colgate 1997; Kirk 1997; Ostrowski 1997, 1999, 2000).

Looking far into the future, a most compelling test of General Relativity is the promise of a phenomenon that is believed to happen quite often in the Universe: the merging of two black holes, which occurs most often when two galaxies collide. The final cataclysm is accompanied by a powerful burst of gravitational radiation, which could be an impressive test of Einstein's theory.

7 ANOMALOUS X-RAY PULSARS

In the last few years a new class of X-ray binaries has been recognized. They are X-ray pulsars with properties clearly different from those of the common HMXBs. These pulsars were recognized to present several characteristics similar to those of LMXBs, and for this Stella, Mereghetti & Israel (1996) suggested that this new group of pulsars constitutes a subclass of the LMXBs, characterized by lower luminosities, higher magnetic fields and smaller ages than non-pulsating LMXBs. They tentatively called the systems of this new group Very Low Mass X-ray Binaries (VLMXBs). Soon after these objects have been called Anomalous X-ray Pulsars (AXPs) (Mereghetti & Stella, 1995; van Paradijs, Taam & van den Heuvel, 1995) and this is now the current accepted name.

Review papers on this topic are those by Mereghetti (2001a,b). A general review on accretion powered pulsars is that by Becker (2000). AXPs have spin periods ranging between ~ 6 and ~ 12 s, contrary to the larger spread of those of HMXBs ($0.069 - few \times 10^3$ s). Spin periods of AXPs are monotonically increasing on timescales of $\sim 10^4 - 4 \times 10^5$ yr. Six AXPs are currently known and three of them are associated with SNRs (Mereghetti 2001a). Association of X-ray pulsars and SNRs have been claimed since 1993 by Giovannelli's group (Giovannelli et al. 1993a, c, 1994; Giovannelli & Sabau-Graziati 2000, 2001). The nature of AXP as neutron stars is supported by their P_{spin} and \dot{P}_{spin} . However, the corresponding rotational energy loss ($\sim 10^{45} \Omega \dot{\Omega}$ erg s^{-1}) is not sufficient to power the luminosity of the AXP, typically $10^{34} - 10^{36}$ erg s^{-1} . This poses problems in understanding the accretion processes in these objects: e.g. binary models assuming weakly magnetized neutron stars ($B \sim 10^{11}$ G) rotating close to their equilibrium period. This requires accretion rates of $a few \times 10^{15}$ g s^{-1} , which is consistent with the luminosity of AXPs (Mereghetti & Stella 1995). Alternatively, the AXPs could involve isolated neutron stars accreting matter from a residual accretion disk (Corbet et al. 1995; van Paradijs, Taam & van den Heuvel 1995; Ghosh, Angelini & White 1997); AXPs result from the common envelope evolution of massive close X-ray binary systems. The formation of an accretion disk around an isolated neutron star could be possible through the falling material coming from the progenitor star after the supernova explosion (Chatterjee, Hernquist & Narayan 2000).

Models based on strongly magnetized neutrons stars ($B \sim 10^{14} - 10^{15}$ G) have been developed in the last decade just in order to explain the behaviour of the Soft Gamma-ray Repeaters (SGRs) (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). SGRs are transient very short (< 1 s) events, characterized by a relatively soft bursts, peaked at $\sim 20 - 30$ keV, with super-Eddington luminosity. Up to now only four (maybe five) SGRs are known (see reviews of Hurley 2000a, b). Recent measurements of the spin-down rates of SGRs and AXPs have been interpreted as evidence of very strong magnetic fields at the collapsed object poles, roughly two orders of magnitudes greater than those of the "normal" X-ray pulsars. However, this problem is one of the hottest in the modern astrophysics. Indeed, for instance, Dar & De Rújula (2003) argue that, instead, the observations support the hypothesis that SGRs and AXPs are neutron stars that have suffered a transition into a denser form of nuclear matter to become, presumably, strange stars or quark stars. Internal heat and slow gravitational contraction long after this transition can power both their quiescent X-ray emission and their star quakes, which produce 'soft' gamma ray bursts.

8 RADIO PULSARS-SNRs AND X-RAY PULSARS-SNRs ASSOCIATIONS

A workshop on *The Relationship between Neutron Stars and Supernova Remnants* was held in Elba Island (Italy) on June 1998. The proceedings (Bandiera et al. 1998) reported the status of the art, at that time, on this important problem. Indeed, how pulsars born and if they are isolated or lie in binary systems, and what is the ratio between the number of isolated pulsars and the number of pulsars in binary systems still constitute open problems. Attempts in determining associations among pulsars and SNRs have been done by several authors in the cases of isolated pulsars (e.g., Kaspi 1998; Helfand 1998), AXPs (e.g. Mereghetti 1998), and X-ray pulsars in binary systems, including AXPs (Giovannelli et al. 1993a, c; 1994; Giovannelli & Sabau-Graziati 2000a, 2000b, 2001).

It has been demonstrated that such associations exist; this proves theories predicting formation of pulsars by SN explosions in collapsing isolated progenitors or SN symmetric or asymmetric explosions in binary-system progenitors. Isolated pulsars are the remnants of a SN explosion of a collapsing isolated progenitor, or of a SN explosion in a binary-system progenitor with

disruption of the binary system itself. Pulsars in low and high eccentricity binary systems are the remnants of symmetric or asymmetric SN explosions, without the disruption of the binary nature of the systems.

In the latter two cases, a neutron star is orbiting around an early-type supergiant, giant or main sequence star.

This kind of association is very useful not only for the point of view of the evolution of binary systems, but also for calibrating the ages of the binary systems and associated SNRs: their ages must be of course the same. This allows to make a check of the theories of the evolution of binary systems, the braking of the pulsars and the development of a SNR after the explosion. Evolutionary theories of SNRs are mainly based on their radio behavior, while evolutionary theories of binary systems are mainly based on their optical and X-ray behavior. Therefore, so different methods of sounding so different cosmic objects are a powerful tool of cross-checking a lot of astrophysical problems.

Lipunov (1998) reviewed the problem of the population synthesis of binary radio pulsars (with white dwarfs, neutron stars, B-stars, and planets) including different assumptions about anisotropy during the formation of neutron stars. Binary pulsars statistics strongly depends on the initial kick velocity (w) of newborn neutron stars. Results of his calculations demonstrated that the distribution of pulsars's high space velocities is in large contradiction with the binary pulsars zoo. Therefore, the best coincidence between observations and calculations at $w \sim 100 - 200 \text{ km s}^{-1}$ indicates the need for a small natal kick velocity, as was previously shown by Kornilov & Lipunov (1984). This fact has been indirectly corroborated by Giovannelli et al. (1993a,b) who found a kick velocity of the X-ray pulsar A 0535+26 and its Be companion HDE 245770 (Flavia' star) — which is the best studied X-ray/Be system, deeply discussed in the review paper by Giovannelli & Sabau-Graziati (1992) — $w \sim 160 \text{ km s}^{-1}$, being such a system associated with the SNR S147.

The number of coincidences between SNRs (220) and galactic X-ray pulsars (88) found by Giovannelli & Sabau-Graziati (2001) — on the base of circumstantial proofs, namely positions, distances, and ages — is 41, being the associations due to chance coincidence equal to 6. This demonstrates that X-ray pulsars in binary systems, as well as isolated, can originate from SN explosions. A better knowledge of the distances and ages of the objects of both classes could facilitate the search for direct experimental evidences of such associations, that indeed recently they are coming out for several objects, like commented by the latter authors. This number of coincidences, however, represents a lower limit to the actual number of associations between X-ray pulsars and SNRs, since some of the oldest SNRs, associated with the slowest pulsars are not visible any more; moreover, some sources in very crowded regions, such as the Galactic Center, has been removed in order to avoid uncertain associations: e.g. the four transients 1,2,3 and 4 discovered by GINGA (Koyama et al. 1989) Furthermore, some X-ray pulsars can have left the apparent radius of the remnant, which is, however, energy dependent and difficult to be determined. It is also possible that some SNRs have not yet been recognized.

However, for determining directly most of the proposed associations, future proper motion and multifrequency studies are needed, both for SNRs and X-ray pulsars samples.

9 CONCLUSIONS

In this paper we have discussed some of the interesting problems connected with the X-ray binary systems, following the most popular accepted classification, essentially based on the mass of the optical companion: high-mass and low-mass binary systems. We have not discussed RS CVn-type systems, which are X-ray binaries, but with two optical stars as components, and CVs, which are also LMXBs, but with a white dwarf instead a neutron star as compact object.

We want to remark that observations of QPOs in LMXBs lead to a global picture that for the first time provides information on the innermost regions of an accretion disk. As already noted by several authors, LMXBs are very similar to CVs: one just has to replace the central white dwarf by a neutron star. The formalism of the accretion process is the same for the two cases; the only difference we must introduce is the dimension of the neutron star, whose magnetosphere is small enough to allow to the disk to reach much smaller inner radius and therefore much higher temperature. As consequence, radiation pressure can become important in the inner part of accretion disks around neutron stars, contrary to CVs.

What is important to remark is that, for the first time, rapid X-ray variability phenomena, directly linked with the NS's most distinguished characteristic, namely its compactness, have been detected.

The measurements of cyclotron lines from binary systems have provided a direct method of measuring the magnetic field intensity on the surface of neutron stars. The width of the cyclotron line correlates with the energy, as suggested by theory, and the width scaled by the energy correlates with the depth of the feature. One of the implications of these results is the possibility that accretion directly affects the relative alignment of the neutron star spin and dipole axes. A wider sample of systems must be measured in order to refine the results.

A better understanding of the basic properties of the torque due to accretion from stellar winds before we can quantitatively account for the spin behavior of wind-fed sources is essential; while, for the disk-fed sources, it should be important to identify the essential physical processes that determine the magnetic pitch and the spin-down torque. Wind accretion and Roche lobe overflow are the extreme cases of the same accretion process. Then, an increase of the number of systems deeply studied simultaneously in different energy regions is necessary in order to improve the statistics of the different cases of accretion, from 'pure' wind-fed to 'pure' Roche lobe overflow.

Finally, thanks to the analogies among macroquasars and microquasars, a possible easier line of investigation for understanding the physics of the former objects is that of investigating the latter, since they are typically ~ 100 times brighter than macro-QSOs, as seen from the Earth, and the corresponding variability time scales are $\sim 10^6 - 10^8$ times shorter than in macro-QSOs.

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DISCUSSION

FRANK VERBUNT, The period gap may be just an artefact from one type of variability at periods above 4 hr and another below 3 hr. If one looks at unbiased samples, e.g. AM Her & DQ Her systems, the period gap is not significant.

FRANCO GIOVANNELLI, I agree. I remember your paper (Verbunt, F., 1997, MNRAS **290**, L55) in which you suggested that the period gap was no longer significant, as well as those of Wickramasinghe, D. T & Wu, K. (1994, Ap&SS **211**, 61) and Wheatley (1999, MNRAS **274**, L51). However, the *historical* gap is still used in the literature (e.g. Howell, S. B., Nelson, L. A. & Rappaport, S., 2001, ApJ **550**, 897), and I have shown an histogram of Pablo Rodriguez-Gil, where some SW Sex systems lies just inside, as well as some other systems, such as 1RXS J1016.9–4103 ($P_{\text{orb}} = 122.3$ min) (Vennes, S., Ferrario, L. & Wickramasinghe, D., 1999, ASP **157**, 143). And this is just to show the lack of the *historical period gap*.