X-RAY BINARIES

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ABSTRACT. A brief tutorial description of X-ray binaries is given. Different classes of objects such as low and high mass X-ray binaries, Be/X-ray binaries, X-ray pulsars, X-ray bursters, atoll/Z sources, black hole candidates in X-ray binaries, recycled pulsars and galactic microquasars associated with X-ray binaries are discussed.

1. Introduction

In this review I shall briefly describe X-ray binaries. They fit very well the topic of our conference, since they are truly multifrequency objects. They are well observed in radio, infrared, optical, ultraviolet, X-ray and gamma-ray regions of the electromagnetic spectrum. Few years ago we believed to observe them also as VHE-UHE emitters. Now, we are not so sure. I shall briefly return to this point at the end of my talk.

1.1. What are X-ray binaries?

An X-ray binary is a close system of two stars, one of which is transferring matter to the companion. The transfer might take the form of a stellar wind or of a stream from the L_1 point (due to overflow of the critical Roche lobe). The companion must be compact enough, so that the infalling matter radiates in X-ray spectral region (see below). In this talk we shall limit our discussion to strong X-ray binaries (X-ray luminosity $> 10^{34}$ erg/s), which requires the compact component to be either a neutron star or a black hole. So, for our purposes, an X-ray binary is composed of an optical component (or a "normal" star) and of an X-ray component (or a "compact object" which must be a neutron star or a black hole).

1.2. Accretion luminosity

The matter attracted by a neutron star or a black hole is falling down an enormous well of gravitational potential and is accelerated to extremally high velocities. The free-fall velocities at the region where the kinetic energy can be thermalized and radiated away (near the surface of a neutron star or the last stable orbit around black hole) are of the order of half of the velocity of light. Therefore, accretion on a very compact object is a very efficient way of releasing energy (much more efficient than nuclear reactions). The accretion luminosity can be estimated as:

$$L_{accr} = \frac{GMm}{R} \tag{1}$$

where M is the mass of the compact object, R the distance of the region of energy release from the center of the compact object and m the accretion mass flux. Using typical parameters, we find from (1) that L_{accr} is $\sim 0.15mc^2$ for a neutron star and $\sim (0.1 - 0.3)mc^2$ for a black hole (depending on its state of rotation). Let us remind that for the most efficient nuclear reaction only 0.007 of the rest mass is changed into energy. Using convenient units, we can replace (1) with

$$L_{accr} \approx 1.3 \times 10^{36} \dot{m}_{16} \left(\frac{M}{M_\odot}\right) \left(\frac{R}{10km}\right)^{-1} erg/s \tag{2}$$

where $\dot{m}_{16}$ is mass flux in units of 10^{16} g/s. Accretion luminosity cannot be larger than certain critical value at which the gradient of radiation pressure balances the gravity at radius R. Higher luminosity would force the outflow of the matter and, at least partially, block the accretion. This critical value (so called Eddington luminosity) is given by

$$L_{Edd} \approx 2.5 \times 10^{38} \left(\frac{1}{1 + X_H}\right) \left(\frac{M}{M_\odot}\right) ergs/s \tag{3}$$

where X_H is the hydrogen content of the accreted matter. The observations confirm that in most X-ray binaries the accretion luminosity does not exceed the Eddington limit. In few cases it seems to be by a factor of few too large. However, taking into account that, most probably, accretion is not spherically symmetric (as was assumed in deriving the limit given by (3)) the discrepancy does not exceed the accuracy of our estimates.

1.3. The temperature of radiation from the accreting matter

This temperature depends on the place and the conditions of thermalizing the infalling matter kinetic energy. Most of the energy is released close to the compact object. Let us assume that it happens at distance R from the center. The lowest temperature of radiation is obtained in an optically thick case if all released energy is emitted as a spherically symmetric black body radiation from a sphere of radius R. This temperature is equal to:

$$T_{min} = \left(\frac{L_{accr}}{4\pi R^2 \sigma}\right)^{1/4} \tag{4}$$

The highest temperature is obtained in an optically thin case if kinetic energy of an accreted proton - electron pair is thermalized and directly radiated away. In this case we have:

$$T_{max} \approx \frac{GMm_p}{3kR} \tag{5}$$

where m_p is the mass of proton. Making the estimate for the surface of a typical neutron star and assuming that L_{accr} is at Eddington limit, we obtain from (4) and (5) that $T_{min} \approx 10^7$ K (which corresponds to energy ~ 1 keV) and $T_{max} \approx 5 \times 10^{11}$ K (which corresponds to energy ~ 50 MeV). This range of energy corresponds to X-rays and soft gamma-rays.

The reader is refered to a review by Brinkmann (1987) for a more detailed discussion of physics of accretion in X-ray binaries.

1.4. Variability of X-ray radiation

The observed variability can be classified into three classes:
regular - pulses and orbital effects,
semi-regular - bursts and QPOs (quasi-periodic oscillations),
chaotic - low frequency noise and high frequency noise.
We shall briefly describe these phenomena while discussing the relevant types of X-ray binaries.

1.5. Classification of X-ray binaries

More than two hundreds of galactic X-ray binaries are known at present. Depending on the mass of the optical component they belong to one of two distinct groups: massive X-ray binaries (HMXB, 74 objects) and low mass X-ray binaries (LMXB, 135 objects). 38 X-ray binaries contain X-ray pulsars (33 in HMXB and 5 in LMXB). 30 X-ray binaries contain black hole candidates (26 in LMXB and 4 in HMXB). 42 X-ray binaries contain X-ray bursters (all of them in LMXB). 17 X-ray binaries contain objects called atoll sources and Z sources. The last two groups (bursters and atoll/Z sources) are not mutually exclusive: some bursters are simultaneously atoll or Z sources. This schematic classification of X-ray binaries is shown in Fig. 1.

In the next sections we shall briefly describe different types of X-ray binaries and different objects found in these systems. The reader is refered to an excellent book *X-Ray Binaries* by W.H.G. Lewin, J. van Paradijs and E.P.J. van den Heuvel (eds.) for a detailed description of all types of objects and for a comprehensive bibliography.

1.6. Low mass vs high mass X-ray binaries

Here we shall compare the basic characteristics of two classes of X-ray binaries.

1. The nature of the optical component. It is a low mass ($M \leq 2M_\odot$) star (usually a K - M type dwarf) in low mass systems. In the second group it is either a massive Be star ($M \geq 5M_\odot$) or an OB supergiant ($M \geq 15M_\odot$).

2. X-ray spectrum. It is relatively soft ($\sim$ few keV) for low mass systems and rather hard (≥ 15 keV) for the high mass systems.

3. Optical luminosity. For low mass systems it is very low ($L_x/L_{opt} \sim 100-1000$, most of the optical output is provided not by a "normal" star but by an accretion disc around the compact component). High mass systems are very bright optically ($L_x/L_{opt} \leq 1$).

4. Distribution in the Galaxy. Low mass systems are concentraced towards galactic center (like an old disc population); many of them are found in globular clusters. The

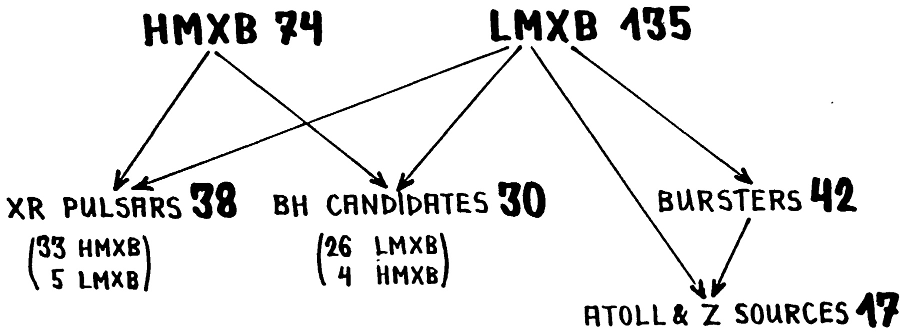

Fig. 1. Schematic classification of X-ray binaries.

massive systems are concentraced in the galactic plane and especially in spiral arms (like the young stellar population).

5. The mode of mass transfer. In low mass systems it has a form of a stream from L_1 point (the optical component fills its Roche lobe). In high mass systems the matter for accretion is supplied mostly in the form of stellar wind.

1.7. Two classes of high mass X-ray binaries

High mass X-ray binaries (HMXB) can be further divided into two groups, depending on the nature of the optical component. One of these groups is called Be/X-ray binaries, the other - OB supergiant X-ray binaries.

Below is a brief comparison of their basic properties.

1. In the first group the optical component is a Be star. In the second group it is usually an OB supergiant.

2. The orbits of Be/X-ray binaries are elliptical with substantial eccentricities - usually $e \geq 0.3$. In other systems orbits are usually circular.

3. In the first group the orbital periods are rather long - between 12 and 580 days. In other systems they are almost always shorter than 10 days.

4. In Be/X-ray binaries the optical components (Be stars) are not substantially evolved and they are much smaller than their Roche lobes. In other systems optical components (OB supergiants) are substantially evolved (they are overluminous or undermassive) and they approximately fill their Roche lobes.

5. In the first group the mechanism of accretion operates due to stellar winds and/or episodic mass ejections from Be component. In other systems it operates due to stellar winds and/or Roche lobe overflow.

6. In the first group the X-ray emission has distinctly transient nature with rather short active phases (a flaring behaviour). In other systems the emission is rather permanent, although it may be strongly variable.

Table 1

Be/X-Ray Binaries

Name	P_{pulse} [sec]	P_{orb} [d]	e	Opt. Sp.
2S 0114+65		11.59	0.16	B0.5 IIIe ?
E 0236+61		26.45		B0e
A 0538-66	0.069	16.66	0.4-0.8	B2 IIIe - B7 IIe
4U 0115+63	3.61	24.31	0.34	Be
V 0332+53	4.38	34.25	0.31	Be
1E 1048-59	6.44			Be
2S 1553-54	9.26	30.6	< 0.09	Be
2S 1417-62	17.6			Be
EXO 2030+37	41.8	46.0	0.31	Be
Cep X-4	66.25			Be ?
A 0535+26	103.4	110.3	0.47	O9.7 IIIe
GX 304-1	272	132.5		B2 Vne
4U 1145-61	292	187.5	> 0.6	B1 Ve
A 1118-61	405			O9.5 III-Ve
4U 0352+30	835	580 ?		O9.5 III-Ve
RX J0147+61	1413			B5 IIIe

NOTE: e = eccentricity, Opt. Sp = optical spectrum.

At present, we know 74 high mass X-ray binaries. Only 16 of them are Be/X-ray binaries. However, in fact, the first group is probably much more numerous than the second. The unfavorable statistics is due to the fact that almost all Be/X- ray binaries are transient X-ray sources with rather short active states, so that we see only small part of them. The list of known Be/X-ray binaries and some of their parameters are given in Table 1.

2. X-Ray Pulsars

In great majority of massive X-ray binaries, the X-ray components are seen as confirmed or suspected X-ray pulsars. The phenomenon of X-ray pulses is explained by rotation of a strongly magnetized accreting neutron star. Due to presence of strong magnetosphere,

Table 2

Binary X-Ray Pulsars

Name	P_{pulse} [sec]	P_{orb} [d]	Name	P_{pulse} [sec]	P_{orb} [d]
1E 1024.0-5732	0.061		EXO 2030+37	41.8	46.0
A 0538-66	0.069	16.66	Cep X-4	66.25	
1612-52	0.069		GS 1839-04	81.1	
SMC X-1	0.71	3.89	GRO J1008-57	93.5	
Her X-1	1.24	1.70	A 1845-024	94.8	
4U 0115+63	3.61	24.31	A 0535+26	103.4	110.3
V 0332+53	4.38	34.25	A 1833-076	111	
Cen X-3	4.84	2.09	GX 1+4	122	304 ?
1838-0301	5.45		4U 1230-61	191	
1E 1048-59	6.44		GX 304-1	272	132.5
1E 2259+586	6.98	0.027	Vela X-1	283	8.96
4U 1626-67	7.7	0.029	4U 1145-61	292	187.5
4U 0142+614	8.69	0.017	1E 1145.1-6141	297	
2S 1553-54	9.26	30.6	A 1118-61	405	
GS 0834-430	12.3	110	EXO 1722-363	413	
LMC X-4	13.5	1.40	4U 1907+097	438	8.38
2S 1417-62	17.6		A 1540-53	529	3.73
GRO J1948+32	18.7		GX 301-2	697	41.4
GS 1843+009	29.5		4U 0352+30	835	580 ?
OAO 1657-415	37.7	10.4	RX J0147+61	1413	

the accretion is possible only on small areas in the vicinity of magnetic poles. As a result, X-ray emission is beamed. This beaming together with rotation leads to the observed X-ray pulses (lighthouse effect). The basic properties of X-ray pulsars: (1) strong magnetic field ($B \sim 10^{11} - 10^{13}$ Gs); (2) hard X-ray spectrum ($kT \geq 15$ keV, this is an effect of concentration of accretion on small areas); (3) rotation at so called equilibrium periods (see below), the observed periods range from 0.07 sec to 1413 sec; (4) presence of an accretion disc (permanent or temporary) around neutron star.

The list of known binary X-ray pulsars is given in Table 2.

2.1. The accretion gate mechanism

We shall discuss the accretion gate mechanism for Be/X-ray binaries, since these systems are the best laboratories in which this mechanism is demonstrated. However, the mechanism is quite general and operates also in majority of other X-ray pulsars (although with much longer on and off states).

The accretion gate mechanism operates due to changes in the mass flux of matter falling on the magnetosphere of the neutron star. The size of the magnetosphere is determined by the instantaneous balance between the magnetic pressure and the dynamic pressure of the infalling matter. Therefore the magnetosphere changes its size. When the flux of the infalling matter decreases, the magnetosphere expands. When the flux increases - the magnetosphere gets sqeezed. For example, the magnetosphere of a neutron star travelling along an elongated orbit around a Be star is much smaller at periastrón than at apoastron. We have strong reasons to believe that neutron stars in Be/X-ray binaries, similarly as most of other X-ray pulsars, are rotating at so called equilibrium periods (Ziolkowski 1980, 1985; Joss and Rappaport 1984, Stella et al. 1986, Giovannelli and Ziolkowski 1990, and references therein). The equilibrium period is defined as a period at which the outer edge of magnetosphere (at Alfven radius) rotates with the Keplerian velocity. At this period the accelerating accretion torque and the braking propeller torque should balance each other and the period, in the first approximation, should be constant. For a given magnetosphere (i.e. for a given magnetic field strength) the equilibrium period depends mainly on the mass flux of the infalling matter (because it determines the size of the magnetosphere which is assumed to corotate with the neutron star). This relation is given as:

$$P_{eq} \sim B^{6/7} \dot{M}_{-3/7} \tag{6}$$

where B is the magnetic field strength and $\dot{M}$ is the mass flux (Davidson and Ostriker 1973, van den Heuvel 1977, Lamb 1977). Returning to our neutron star on an elongated orbit, we see that its instantaneous equilibrium period varies along the orbit as it tracks the variable mass flux. At periastron P_{eq} is much smaller than at apoastron. As a result, we find that in a typical situation $P > P_{eq}$ ("slow" pulsar) at periastron but $P < P_{eq}$ ("fast" pulsar) at apoastron. It means that at periastron the accretion gate is open and the pulsar (neutron star) is accelerated, while at apoastron the accretion gate is closed and the pulsar is braked. The real rotation period P will adjust itself so that the action of the accretion torque along the inner part of the orbit and the braking torque along the outer part, integrated over the full orbital cycle, will cancel each other. Therefore the statement that X-ray pulsars in Be/X-ray binaries rotate at equilibrium periods should be read as "equilibrium periods averaged over orbital cycle (or, in fact, over many orbital cycles, beccause of the intrinsic variability of a Be star)". One should remember, however, that along the orbit (except for two points) the real rotation period P substantially differs from the instantaneous value of P_{eq} and, therefore, the pulsar is always, either "fast" or "slow".

2.2. Two states of an X-ray pulsar

The previous paragraph leads us to the picture of two possible states of an X- ray pulsar in a binary system:

(1) Accretor

This state typically occurs when $P < P_{eq}$. Since the velocity of the outer edge of magnetoshere is smaller then the Keplerian velocity, there is no centrifugal barrier. The matter can approach the neutron star and get accreted (accretion gate open). Due to accretion taking place, the neutron star is a strong X-ray emitter and also experiences a substantial spin-up of its rotation (due to large angular momentum of the matter in the accretion disc which is a typical supply of the matter being accreted). The characteristic properties of the accretor state are therefore: (1) "slowness" of the pulsar ($P < P_{eq}$), (2) strong X-ray emission, (3) rapid spin-up.

(2) Propeller

This is a typical state when $P > P_{eq}$. In this case the velocity of the outer edge of magnetosphere is larger than the Keplerian velocity and there exist a centrifugal barrier against accretion. The matter that would like to get accreted is rather expelled by the magnetosphere acting as a propeller (Illarionov and Sunyaev 1975, Davies et al. 1979). The accretion gate is closed. Only marginal amount of matter can get accreted and so the X-ray luminosity is low or undetectable. However the neutron star loses rotational energy because its magnetospheric propeller has to work on the infalling matter to get it expelled and so it experiences a slow-down of its rotation. The characteristic properties of the propeller state are therefore: (1) "fastness" of the pulsar ($P > P_{eq}$), (2) low or undetectable X-ray emission, (3) significant spin- down.

2.3. A 0535+26/HDE 245770 - a "canonical" example of an accretion gate mechanism at work

The best studied case of centrifugal gate (accretion gate) mechanism at work is the binary A 0535+26/HDE 245770. The comprehensive and very detailed description of this system is given by Giovannelli and Sabau Graziati (1992). Here we shall give only a very brief summary focused on the operation of an accretion gate. The system consists of a neutron star known as an X-ray pulsar A 0535+26 and a Be star known as HDE 245770. The X-ray pulsar has a pulse period 103 s. It orbits the Be star on an elongated orbit with eccentricity $e = 0.47$ and orbital period $P_{orb} = 111$ d. Normally, the X-ray pulsar is a strong X-ray emitter only during a small fraction of orbital period (one - two weeks) near the periastron passage. The typical X-ray luminosity in this state (the active phase) is $\sim$ 0.2-0.3 Crab. The typical time scale of spin-up observed during the active phase is $\sim$ 100 yr. During the remaining part ($> 90\%$) of the orbital motion the pulsar remains in quiescent (or low) state with X-ray luminosity on the level 5-10 mCrab or less. The observations indicate that during the quiescent phase the pulsar slows down its rotation on a time scale of 1000 yr. The spin-up during the active phase and spin-down during the quiescent phase roughly cancel each other and the pulse period remains approximately constant. However, in addition to typical X-ray outbursts (occuring near periastron), we observed, on three occasions (in 1975, 1980 and 1994) the so called superbursts. During these events the luminosity reached the level 1 - 6 Crab and on two (of three) occasions they occured while the neutron star was quite far from periastron. The superbursts were probably triggered by strong shell ejections from Be star. The effects of spin-up during the superbursts are much stronger than during the normal outbursts. The observations from the last superburst presented at this conference demonstrate an excellent, one to one correlation between the X-ray luminosity and the pulsar spin-up rate (Clark, Maisack - this conference). This is an impressive evidence that the very same matter which is producing X-rays in the process of accretion is also responsible for bringing angular momentum to the neutron star.

3. X-ray Bursters

This name is used for objects producing brief X-ray flashes on the top of the continuous X-ray emission. The bursts last $\sim$ 10 - 100 sec with recurrency time $\sim$ from few hours to few days. The peak luminocity exceeds the continuous emission by a factor of few to few tens. The basic properties of X-ray bursters: (1) relatively weak magnetic fields (B $\sim 10^8 - 10^{10}$ Gs); (2) soft X-ray spectra (kT $\sim$ few keV; due to weaker magnetic field accretion proceeds on most of surface of neutron star and as a result the spectrum is much softer than for X-ray pulsar); (3) probable rotation at equilibrium periods which in this case (low magnetic fields) must be of the order of 1 - 10 msec (not confirmed observationally so far); (4) presence of an accretion disc around neutron star; (5) optical companion is a low mass red dwarf or a white dwarf star.

Some X-ray bursters are observed as atoll or Z sources. However, no burster might be seen as an X-ray pulsar (too weak magnetic fields!).

X-ray bursts may be, in a satisfactory way, explained as a result of an unstable nuclear burning of hydrogen and helium in the matter accumulating on the surface of a neutron star in the process of accretion. In this respect the mechanism of X-ray bursts is identical with the mechanism of classical novae eruptions (but with proper scaling of all process from the surface of a white dwarf to the surface of a neutron star).

4. Atoll sources and Z sources

The names of these objects come from the shapes of the tracks performed by them on the X-ray color-color diagram. The shifts along the tracks are caused by the varying accretion rate. The characteristic Z-shaped track performed by Z sources consists of three sections: horizontal branch, normal branch and flaring branch. The accretion rate is smallest at the upper left end of the track (beginning of the horizontal branch) and grows along the Z-track to reach the highest value at lower right (the end of flaring branch). The track of atoll sources consists of two elements: a banana (a bow-shaped track) and an island (a small cloud of scattered points). The accretion rate is smallest at the left end of the track (an island), grows to the right (lower banana) and is largest at the right end (upper banana). Both, atoll and Z sources, are low mass binaries containing an accreting neutron star with a relatively low magnetic field (that explains why many of them show X-ray bursts). The differences between them are probably due to different magnetic field strengths (higher for Z sources) and different typical accretion rates (also higher for Z sources). Both atoll and Z sources display many types of X-ray variability (apart from X-ray bursts). Their power spectra show frequently QPOs (at 13-55 Hz for horizontal branch, 6-20 Hz for normal/flaring branch and 0.5-2 Hz for atoll sources). They show also low and high frequency noise. Van der Klis (1994, 1995) proposed a unified picture of different types of variability. His picture includes also other types of X-ray binaries: black hole candidates (QPOs at 3-10 Hz, low and high frequency noise) and X-ray pulsars (QPOs at 0.04-0.2 Hz, pulsar noise). He suggested that pulsar QPOs and horizontal branch QPOs are beat frequency phenomena (between spin of neutron star and Keplerian orbit at the inner disc), while black hole candidate, atoll and normal/flaring branch QPOs are accretion instabilities due to luminosity approaching the Eddington limit. High frequency noise of Z sources and pulsar noise are magnetospheric phenomena (cut-off frequency is correlated with spin frequency of neutron star). Black hole candidates noise, atoll noise and low frequency noise of Z sources are due to inner disc instabilities (cut-off frequency is correlated with accretion rate). Van der Klis' picture looks very promising although it is not firmly confirmed yet.

5. Black Hole Candidates

Hunting for black holes in X-ray binaries has been a favorite sport for over 20 years. The job is exciting but difficult and full of traps. Many strong candidates were later found to be "normal" neutron star systems. All characteristic properties suggested as X-ray signatures of black holes were sooner or later supplied with some counterexamples. At present, it seems that, while there exist usefull circumstantial indicators, the decisive argument still relies on dynamical mass estimate of the accreting component.

Let us list below the main characteristics suggested as X-ray signatures of accreting black hole. (1) X-ray flickering; counterexamples: Cir X-1 (X-ray burster), X 0331+53 (X-ray pulsar), (2) Bimodal X-ray behaviour - alternating between high states (high X-ray luminosity with soft spectrum) and low states (low X-ray luminosity with hard spectrum); counterexamples: Cir X-1 (X-ray burster), (3) X-ray spectrum composed of ultrasoft component and power law tail; counterexamples: some bursters, (4) Single power law X-ray spectrum; counterexamples: some LMXB.

As one can see, none of the above properties is unique for a black hole system. On the other hand, one has to state,that all respectable black hole candidates (except SS 433) show either property (3) or (4) or both. This is hardly a surprise. In fact, one might expect that X-ray radiation from a black hole vicinity should consist of an ultrasoft component (from inner accretion disc) and possibly of a hard power law tail (from upcomptonization i.e. changing of some soft photons into hard photons in the process of reverse Compton scattering in a hot plasma). Prominently missing is (as it should be) a black body component (at kT $\sim 1-2$ keV) originating on the surface of a neutron star and therefore characteristic for neutron star sources. For example, let us compare the spectra of two X-ray systems: GX 349+2 (a neutron star Z type source) and GX 339-4 (a black hole candidate). The former spectrum is easily decomposed into an ultrasoft component (inner accretion disc) and a black body component of kT $\sim$ 2 keV (surface of the neutron star). The latter spectrum contains only an ultrasoft component (no hard surface is present).

We can conclude that the presence of an ultrasoft component in the X-ray spectrum, while not a sufficient evidence, might be a useful tool in a search for black hole candidates. Another useful tool might be the shape of a light curve in the case of so called X-ray novae (or soft X-ray transients). The reader is refered to Tanaka and Lewin (1995) for comparison of strikingly similar light curves of four X-ray novae: A 620-00, GS 1124-68 and GS 2023+33 (confirmed black hole systems) and GS 2000+25 (a suspected black hole system).

At present, about 30 black hole candidates are known. Among them 7 (or perhaps 8) are confirmed candidates. Confirmation is based on mass estimates of X-ray components derived from binary orbits (the obtained masses are $\geq 3M_{\odot}$, and therefore too large for neutron stars). The list of all candidates is given in Table 3.

5.1. Black hole candidates with dynamical mass estimates

This section contains brief information about mass functions of X-ray component and dynamical mass estimates of this component for those systems for which such information is available.

(1) Cyg X-1

$f(M_x) = 0.25 \pm 0.01 M_{\odot}$
$M_x \geq 7M_{\odot}$, most probably $M_x \sim 16 \pm 5M_{\odot}$

(2) LMC X-3

$f(M_x) = 2.3 \pm 0.3M_{\odot}$
$M_x \sim 6 - 10M_{\odot}$

(3) LMC X-1

$f(M_x) = 0.14 \pm 0.05M_{\odot}$
$M_x \sim 2.5 - 6M_{\odot}$

(4) A 0620-00

$f(M_x) = 2.91 \pm 0.08M_{\odot}$
$q = M_{opt}/M_x \approx 0.07 - 0.10$
$M_x \approx 4.0 \pm 0.1M_{\odot}$ (if optical light curve is used, this leads to $i \approx 70^o$.)
$M_x \sim 7 - 20M_{\odot}$ (if IR light curve is used, this leads to $i \approx 37^o$)

(5) Nova Mus 91

$f(M_x) = 3.1 \pm 0.4M_{\odot}$
$M_x \geq 5 - 10M_{\odot}$ (i $\sim 26^o - 68^o$)

(6) V404 Cyg

$f(M_x) = 6.08 \pm 0.06M_{\odot}$

Table 3

Black Hole Candidates

Name	P_{orb}	Opt. Sp	Other Names	X-ray var
LMC X-3	1^d70	B3 V		
LMC X-1	4^d22	O7-9 III		
Cyg X-1	5^d6	O9.7 Iab		
A 0620-00	7^h75	K5 V	V616 Mon, Nova Mon 1975	RT
1124-684	10^h4	K0-4 V	Nova Mus 1991	T
2023+338	6^d47	K0 IV	V404 Cyg, Nova Cyg 1989	RT
GX 339-4	14^h8	+	V821 Ara	RT
1755-338	4^h4?	+		
1957+115	9^h3	+	V1408 Aql	
2000+251	8^h3	K V	QZ Vul, Nova Vul 1988	T
1543-475		A1-2 V		RT
1354-645		+		T
1524-617		+	TrA X-1	RT
1705-250		+	Nova Oph 1977	T
1630-472				RT
1740.7-2942				
1741-322				T
1758-258				
1826-238		+		T
1846-031				T
GRO J0422+32	5^h1	M0 V	Nova Per 1992	T
GRS 1009-45		+	Nova Vel 1993	T
GRO 1719-24		+	Nova Oph 1993	T
GRO J1655-40	2^d6	F V	Nova Sco 1994	T
1E 0035-72	4^h1			T
KS 1730-31				T
GRS 1915+105				RT
2S 2318+62		+		
1E 1740-29				
SS 433	13^d1	+	V1343 Aql	

NOTE: Opt. Sp = optical spectrum, + = optical counterpart was identified but the spectrum was not obtained, X-ray var. = X-ray variability, T = transient, RT = recurrent transient.

$q = M_{opt}/M_x \approx 0.050 \pm 0.005$
$M_x \sim 7 - 29 M_\odot$

(7) Nova Sco 94

$f(M_x) = 3.16 \pm 0.15 M_\odot$
$M_x \sim 3.5 - 5.5 M_\odot$

(8*) SS 433

We decided to add here this celebrated system, even if it has less direct mass estimate than the seven systems listed above. We know the mass function of the optical component: $f(M_{opt} \sim 10 M_\odot$. From modelling of complicated multiperiodic optical light curve, Leibowitz (1984) got $q = M_{opt}/M_x \leq 1.2$. Even accounting for large inaccuracy of $f(M_{opt})$, one gets $M_x \geq 4 M_\odot$.

6. Recycled Pulsars

Recycled pulsars are not, at present, members of X-ray binary systems. Some of them are even not members of any binary system. However, they are so closely related to X-ray binaries (they are descendants of LMXRB) that we should mention them briefly. The term recycled pulsar is used for an old radio pulsar that became dead long time ago but later got resurrected while accreting matter in a LMXRB system. It is generally believed that young pulsars are born as fast rotating strongly magnetized objects. They evolve on time scale $\sim 10^7 - 10^8$ yr, slowing down their rotation and decreasing their magnetic field. At certain moment, the combined effect of this evolution causes the radio emission mechanism to switch off and the pulsar becomes dead. However, if it happens to be a member of a close binary which enters LMXRB phase of evolution, the old pulsar might get alive again. It happens due to accretion induced spin-up of a former pulsar during X-ray phase of binary evolution. Old pulsars have weak magnetic fields and, as a consequence, short equilibrium periods P_{eq} (see eq. (6)). Therefore, they might get spun up to very short periods ($\sim$ few msec). For this reason, the majority of recycled pulsars belong to the class of milisecond pulsars. Some of them are single objects at present (probably due to disruption of the former binary).

About 50 recycled pulsars are known at present. Their parameters are given in Table 4. Inspection of the table indicates that more than half of them have periods below 10 msec and about 80% have periods below 60 msec.

7. Microquasars in X-Ray Binaries

The excitement about jet production in X-ray binaries erupted less than one year ago after discovery of the first superluminal radio source in a galactic X-ray binary. However, jet phenomena in X-ray binaries are already observed for about 20 years. Below, is a brief description of galactic microquasars associated with X-ray binaries.

(1) GRS 1915+105

The first galactic radio source with superluminal jets, whose discovery, announced

Table 4

Recycled Pulsars

Name	P_{pulse} [msec]	P_{orb} [d]	Name	P_{pulse} [msec]	P_{orb} [d]
1957+20	1.6	0.38	1953+29	6.1	117
1937+21	1.6	-	1257+12	6.2	26, 66.6, 98.2
0021-72J	2.1	0.12	2127+11H	6.7	-
0021-72F	2.6	-	1516+02B	7.9	6.9
1821-24	3.1	-	1639+36A	10.4	-
0021-72N	3.1	-	1620-26	11.1	191
0021-72H	3.2	$\sim$ days	1744-24A	11.6	0.075
0021-72I	3.5	$\sim$ days	1802-07	23.1	2.6
1639+36B	3.5	1.26	2127+11C	30.5	0.33
0021-72E	3.5	2.2	1310+18	33.2	255
1908+00	3.6	-	2127+11G	37.7	-
0021-72M	3.7	?	1534+12	37.9	0.42
2127+11F	4.0	-	2127+11B	56.1	-
0021-72G	4.0	-	1913+16	59	0.32
0021-72L	4.3	?	2127+11A	110.7	-
0021-72A	4.5	0.023	0655+64	196	1.03
2127+11D	4.6	-	1820-11	280	358
2127+11E	4.8	-	1745-20	288.6	-
0021-72D	5.4	-	1820-30B	378.6	-
1855+09	5.4	12.3	1744-24B	442.8	-
1820-30A	5.4	-	1831-00	521	1.81
1516+02A	5.6	-	0820+02	865	1232
0021-72C	5.8	-	1718-19	1004	0.25
0021-72B	6.1	7÷95	2303+46	1066	12.3

NOTE: sign "-" in the column P_{orb} indicates that pulsar is not a member of a binary system.
Values of P_{orb} for the pulsar 1257+12 describe the orbits of Wolszczan's planets.

in September 94, created big excitement. The analysis of radio observations by Mirabel and Rodriguez (1994) yielded the value of 0.92c for the true jet velocity. This transient X-ray binary is also listed in our Table 3 among the black hole candidates.

(2) GRO J1655-40

The second galactic radio source with superluminal jets. At the same time an X-ray nova (Nova Sco 1994) and also an eclipsing X-ray binary with late type dwarf (F V) as an optical component. The analysis of radio observations leads again to the value of 0.92c for the jet velocity (Hjellming and Rupen, 1995). The determination of radial velocities of the F dwarf (Bailyn et al., 1995) permitted to find the mass function: $f(M_x) = 3.16 \pm 0.15 M_{\odot}$. This value indicates that X-ray component must be a black hole (see also Table 3 and Section 5.1 pos. (7)).

(3) 1E 1740.7-2942

This double radio jet hard X-ray source is also called the Great Annihilator because of its strong emission in 511 keV annihilation line. Another black hole candidate (see Table 3).

(4) GT 2318+620

Another double radio jet source coincident with a SAS 3 (and Uhuru) X-ray source and a faint ($\sim 20^m$) star. Most probably a LMXRB, perhaps harboring a black hole (see Table 3).

(5) SS 433

This celebrated system exhibits the precessing (with 163^d period) jets moving at 0.26c velocity. The jets are well seen in radio, optical and X-ray band. The compact component is probably a black hole (see Table 3 and Section 5.1 pos. (8*)).

(6) Cyg X-3

A short period ($P_{orb} = 4^h8$) X-ray binary containing a W-R star and a compact X-ray component. On several occasions radio jets moving at velocity $\sim$ 0.3c were observed. The nature of the compact component is unknown. The suggestion that it is a fast spinning (P_{pulse} = 12.6 msec, periodicity found at TeV energy range) neutron star was not confirmed so far.

8. VHE - UHE emission of X-ray binaries

Only four years ago, five X-ray binaries (Cyg X-3, Her X-1, Cen X-3, Vela X-1 and 4U 0115+63) were listed as confirmed sources of VHE (TeV range) emission. Six other sources (SMC X-1, 1E 2259+59, 4U 1626-67, LMC X-4, 4U 1145-61 and X 0021.8-72) were listed as probable sources (Turver 1991). In addition, two systems (Cyg X-3 and Her X-1) were listed as confirmed sources of UHE (PeV range) emission (Hillas 1991). None of these sources could be seen during last few years, in spite of extensive monitoring with the use of more sensitive detectors. Either all earlier detections were wrong (!), or nature has conspired, exploiting the fact that VHE-UHE emission has very transient nature. Future observations will, undoubtely, answer this question.

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DISCUSSION

R. TERLEVICH's comment: The first evidence for superluminal motions in a galactic object was observed in Nova Persei (1910 or 1903?) and was published by P. Couderc in 1930's (Ann. d'Ap).

J. ZIOLKOWSKI: I did not know about that. Thank you for this comment.