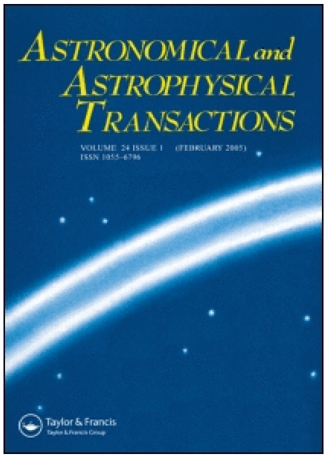

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Highly evolved close binary systems

A. M. Cherepashchuk [a]
[a] Sternberg Astronomical Institute, Moscow University, Moscow, Russia

Online Publication Date: 01 February 2007
To cite this Article: Cherepashchuk, A. M. (2007) 'Highly evolved close binary systems', Astronomical & Astrophysical Transactions, 26:1, 35 - 45
To link to this article: DOI: 10.1080/10556790701295175
URL: http://dx.doi.org/10.1080/10556790701295175

Astronomical and Astrophysical Transactions
Vol. 26, Nos. 1–3, February–June 2007, 35–45

Highly evolved close binary systems

A. M. CHEREPASHCHUK*

Sternberg Astronomical Institute, Moscow University, 13 Universitetskij Prospekt, Moscow 119992, Russia

(Received 26 January 2007)

The basic properties of highly evolved close binary systems are described. In these systems the first mass exchange between the components is completed and peculiar objects are formed: Wolf–Rayet stars, white dwarfs, neutron stars and black holes. The observational characteristics of these systems are in agreement with the modern theory of evolution of close binary systems. Investigation of these systems is very important for astrophysics and fundamental physics. In particular, 20 black-hole candidates of stellar masses have been discovered up to now in highly evolved close binaries. A catalogue of highly evolved close binary stars is described as well as its new electronic version, work on which is in progress at the Sternberg Astronomical Institute.

Keywords: Close binary stars; Evolution; Mass exchange; Neutron star; Black hole

1. Introduction

Highly evolved close binary systems (HECBSs) are systems in the evolutionary stage after the first mass exchange. A catalogue of HECBSs was published by Cherepashchuk *et al.* [1]. This catalogue contains about 650 HECBSs of different types. Work on an improved version of this catalogue, including its electronic version, is now in progress.

The first ideas about the evolution of close binary systems (CBSs) with mass exchange were put forward by Crawford [2], Morton [3], Paczynski [4, 5], Snezhko [6], and Kippenhann and Weigert [7]. Late stages of evolution of CBSs (after the first mass exchange) were investigated by Tutukov and Yungelson [8], van den Heuvel [9], and Kornilov and Lipunov [10]. Much earlier [11–13] the diagram of ‘spectral class versus orbital period’ for CBSs was discovered. According to this diagram [11], for each spectral class of CBS components there exists the shortest orbital period which suggests that both components are in contact. This observational fact may be considered as evidence for the possibility of mass exchange in CBSs [13]. Discovery of the Algol paradox [14–16] provided further observational evidence about the possibility of mass exchange in CBSs.

HECBSs are important tor astrophysics for several reasons as follows: the possibility of checking the theory of stellar evolution for the case of non-constant masses of stars, the possibility of discovering principally new objects (neutron stars and black holes) which may

*Email: cherepashchuk@gmail.com

Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790701295175

help to test the general relativity theory (binary pulsars, etc.), as well as bright observational appearances (accretion discs, X-ray radiation, streams, optical and X-ray flares, etc.).

A review of the observational properties of HECBSs has been published by Cherepashchuk [17].

Let us consider basic recent ideas on the evolution of HECBSs and their characteristics.

2. Evolution of a close binary system

First of all, consider a high-mass close binary system (HMCBS) ($m_1 + m_2 > 30M_\odot, m_1 > m_2$, $q = m_2/m_1$ is close to unity, and mass exchange is conservative). The time of nuclear evolution of a star in the core-hydrogen burning stage (see, for example, [18]) is

$$\log\left(\frac{t}{1\ \text{year}}\right) = 9.9 - 3.8\log\left(\frac{m}{M_\odot}\right) + \log^2\left(\frac{m}{M_\odot}\right). \tag{1}$$

For the star mass $m = 30M_\odot$, this time is about 3×10^6 years. A more massive OB_1 star in an HMCBS will evolve more rapidly and fill its Roche lobe. Let us suppose that this filling corresponds to 'case B' of the evolution [7]. When the first mass exchange is initiated in the system, the OB_1 star begins to transfer its mass through the inner Lagrangian point to the OB_2 star (we neglect the effects of wind–wind collision [19]). This matter is accreted by the OB_2 star because the times of thermal relaxation of both stars in the system are comparable. The process of the first mass exchange is very rapid (the corresponding timescale is thermal but not nuclear) because, in particular, the separation a between the components of the system with conservative mass exchange decreases in the case of mass transfer from the more massive component to the less massive component. Normally, this conclusion follows from the conservation of orbital angular momentum of the binary system:

$$J_{\text{orb}} = m_1 v_1 a_1 + m_2 v_2 a_2 = \frac{2\pi}{P}(m_1 a_1^2 + m_2 a_2^2), \tag{2}$$

where v_1 and v_2 are the orbital velocities and a_1 and a_2 are the radii of the absolute orbits of the stars (the orbit is suggested to be circular). Since $a = a_1 + a_2$, and

$$a_1 = \frac{m_2 a}{m_1 + m_2}, \quad a_2 = \frac{m_1 a}{m_1 + m_2},$$

we obtain

$$J_{\text{orb}} = \frac{2\pi}{P} a^2 \frac{m_1 m_2}{m_1 + m_2}. \tag{3}$$

Using the third Keplerian law

$$\frac{a^3}{P^2} = \frac{G}{4\pi^2}(m_1 + m_2),$$

we obtain

$$J_{\text{orb}} = G^{1/2} \frac{m_1 m_2}{(m_1 + m_2)^{1/2}} a^{1/2}. \tag{4}$$

From equation (4), we can obtain

$$a = \frac{J_{\text{orb}}^2 (m_1 + m_2)}{G m_1^2 m_2^2}. \tag{5}$$

In the case of conservative mass exchange, for $J_{\rm orb} = $ constant and $m_1 + m_2 = $ constant, we obtain

$$a = \frac{\text{constant}}{m_1^2 m_2^2}. \tag{6}$$

From equation (6) it is evident that the minimum separation a is reached when $m_1 = m_2$. Therefore, the separation a decreases when the more massive star, OB_1, transfers its mass to the less massive star, OB_2. Decreasing the separation stimulates the process of mass exchange in HMCBSs. The duration of the first mass exchange (in the case of the Ledoux criterion) is

$$t_k \approx \frac{10^{6.3}}{(m_1/M_\odot)^2} \text{ years.} \tag{7}$$

The primary component, OB_1, will lose up to 70–90% of its hydrogen envelope during a time of approximately 10^4 years. The matter of this envelope will be accreted by the OB_2 star, and an OB_2' companion will be formed in this system as a result of the primary mass exchange. All CBSs which contain, after the first mass exchange, white dwarfs, Wolf–Rayet (WR) stars, neutron stars and black holes, are usually called HECBSs.

Application of equation (6) to the CBS evolution theory is based on two suggestions.

(i) Mass exchange in CBSs is conservative. In reality, mass exchange may be non-conservative and equation (6) should be modified using the results of hydrodynamic calculations of mass exchange in CBSs (see, for example, [20]).
(ii) The total orbital angular momentum $J_{\rm orb}$ of CBSs is assumed to be constant. This suggestion is correct for the case of CBSs with constant masses of the components. In the case of non-constant masses, the motion of these components should be described by the Meshchersky equations [21]

$$m(t)\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = \boldsymbol{F} + \boldsymbol{u}\frac{\mathrm{d}m}{\mathrm{d}t} \tag{8}$$

rather than by the Keplerian equations, where $\boldsymbol{u}$ is the velocity vector of escaping matter with respect to the centre of mass of the star (the value $\boldsymbol{u}\,\mathrm{d}m/\mathrm{d}t$ is called the *reactive force*).

In the Meshchersky problem for two bodies there is no conservation law of the orbital angular momentum [22]. Therefore, even in the case of conservative mass transfer ($m_1 + m_2 = $ constant), equation (6) is not correct and should be modified.

It seems strange that such a fundamental law, the law of conservation of orbital angular momentum, is not fulfilled for the two-body problem with non-constant masses in the case when $m_1 + m_2 = $ constant. However, it is really the case because mass exchange in CBSs implies that the orbital angular momentum of a CBS is not the full angular momentum of the system. During mass transfer in CBSs, part of the orbital angular momentum of the CBS is inevitably accumulated in gaseous streams, in discs and in the axial rotation of the stars. The total angular momentum of CBSs (including the angular momenta of the gaseous streams and discs) is conserved but the orbital angular momentum of CBSs, which is only a part of its total angular momentum, is not conserved even in the case of mass transfer with constant total mass ($m_1 + m_2 = $ constant).

The Meshchersky problem for two bodies does not take into account the details of the mass transfer between components of the binary system. That is why the orbital angular momentum of the binary system in the case of the Meshchersky problem is not conserved. To treat this problem correctly, three-dimensional hydrodynamic CBS modelling should be carried out. We hope that such a calculation will provide the generalization of equation (6) and give the correct law of variability of the separation a between the components of the CBS during mass transfer.

It is evident from equation (5) that the effect of the gaseous streams on the orbital angular momentum during mass transfer in the CBS is most important in the case of mass exchange on a dynamic timescale when the matter density in gaseous streams is high. In this case the gaseous streams accumulate a significant part of the total angular momentum of the binary system and the total angular momentum $J_{\rm tot}$ of the system can be described by the formula

$$J_{\rm tot} = J_{\rm orb} + J_{\rm gas} \tag{9}$$

where $J_{\rm gas}$ is the angular momentum of gaseous streams, discs, etc. Recent hydrodynamic calculations of mass exchange in the CBS in the case of dynamic mass transfer [20] have shown that at the beginning of mass exchange the separation a varies with time in an oscillating way and decreases with time. The ratio $J_{\rm orb}/J_{\rm tot}$ decreases from 0.90 to 0.57 during 12 orbital periods. The basic part of the orbital angular momentum (up to 20%) is accumulated in the axial rotation of the components.

In the case of mass transfer in the CBS on a thermal or nuclear timescale, the ratio $J_{\rm orb}/J_{\rm tot}$ for a fixed time interval is close to unity because the density of matter in gaseous streams is relatively small. Since the characteristic time of CBS evolution in these cases is much longer than that on the dynamic timescale, an integrated value of the ratio $J_{\rm orb}/J_{\rm tot}$ may be significantly less than unity. Therefore, the correctness of equation (6) must be verified by further hydrodynamic calculations even for the cases of thermal and nuclear timescales of mass exchange.

Let us consider now the case of a low-mass close binary system (LMCBS). Calculations of the evolutionary scenario for LMCBSs is a much more complicated problem than that for HMCBSs because, in the former case, different mechanisms of angular momentum loss from the system and degeneration of stars should be taken into account. Good progress in understanding the evolution of LMCBS has been achieved up to now because of the application of two mechanisms for the angular momentum and energy loss from a binary system: gravitational radiation and magnetic braking by the stellar wind of a red dwarf. Let us consider both these mechanisms for the example of cataclysmic binaries. These LMCBSs consist of white dwarfs and low-mass ($m < 1M_\odot$) main-sequence stars (red dwarfs) filling their Roche lobes and transferring mass through inner Lagrangian points. In these systems the masses of red dwarfs are less than those of white dwarfs. In the conservative case of mass exchange during mass transfer from the less massive red dwarf to the accretion disc formed around the white dwarf the separation a between the components increases. The absolute dimensions of the red dwarf Roche lobe increase too. If the orbital period P of such a system is less than 10 h, then, according to Kraft *et al.* [23], the decreasing time of the separation a due to gravitational radiation loss may be shorter than the lifetime of the Galaxy as well as the time of nuclear evolution of the red dwarf. In this case the evolution of the LMCBS will be determined by angular momentum loss due to gravitational radiation. The Roche lobe filling by the red dwarf is due to the decrease in the separation a between the components caused by gravitational radiation rather than by the increase in the red dwarf's radius due to its nuclear evolution. After filling the Roche lobe, the red dwarf transfers its mass through the inner Lagrangian point. The rate of mass loss by the red dwarf is determined by two factors: the decrease in the absolute dimensions of its Roche lobe due to gravitational radiation loss, and the tendency for the dimension of this Roche lobe to increase owing to mass transfer from the less massive red dwarf to the more massive white dwarf. As a result, the change in the separation a between the components is described by the law (see, for example, [18])

$$\frac{{\rm d}a}{{\rm d}t} = \frac{2a}{m_1 m_2}(m_2 - m_1)\frac{{\rm d}m_2}{{\rm d}t} - \frac{64G^3}{5c^5a^3} m_1 m_2 (m_1 + m_2), \tag{10}$$

where the first term describes the mass transfer from the less massive red dwarf to the more massive white dwarf and the second term describes the role of gravitational radiation.

It is very important that for $m_2 \leq 0.8M_\odot$ the effects of nuclear evolution of the red dwarf are negligible. If the mass-losing star is a non-degenerate hydrogen–helium star, then the components of the binary system approach each other (the effect of decreasing separation due to gravitational radiation dominates). Mass exchange in the binary system may be strongly increased when the mass-losing star is degenerate (a white dwarf). Since the radius of a degenerate star is increasing while its mass decreases, the mass transfer in LMCBS will be self-supported. If the mass ratio of the components is sufficiently high, $q = m_2/m_1 \geq 0.83$, the mass transfer in such a system will occur on the dynamic timescale and the secondary component will be fully transferred on to the primary component during a very short (dynamic) time, of the order of several orbital periods. A massive disc around the primary component will be formed in this case. It has been shown also that magnetic braking by the stellar wind from the red dwarf having a deep convective zone may play an important role in the evolution of LMCBSs (see, for example, [24–26]).

3. High-mass close binary systems

3.1 *WR + OB binaries*

This is a well-known class of HMCBSs. Basic data on several dozens of WR + OB binaries have been presented in our catalogue [1] as well as in the catalogue of WR stars [27]. The orbital periods P range from about 1.6 days to about 4800 days. The values of eccentricity of the orbits are $e \approx 0$ for $P \leq 14$ days and $e = 0.3$–0.8 for $P > 70$ days [28]. The mass ratio $q = m_{\rm WR}/m_{\rm OB}$ is in the range 0.17–2.67. The masses of WN stars lie in the range $(4$–$80)M_\odot$; the masses of WC stars are $(5$–$30)M_\odot$. The mean mass of WN stars is approximately $21M_\odot$; that of WC stars is approximately $13M_\odot$. A model of a WR star as a helium remnant (bare core) of an initially massive O star in an O + O close binary formed as a result of mass exchange is confirmed by analysis of eclipses in WR + O binaries [29–33] and by the discovery of a WR star as a companion of the peculiarly short-period X-ray binary system Cyg X-3 [34, 35].

3.2 *Quiet X-ray binaries*

Discovery of four CBSs consisting of massive B and Be stars and radiopulsars has proved the real existence of such systems. In these systems, optical B or Be stars do not fill their Roche lobes and this fact implies, on average, a very low accretion rate on to neutron stars, X-ray luminosity in most cases being close to zero. For example, in the CBS consisting of the radiopulsar PSR 1259-63 and the massive Be star SS2993 [36] the orbital period is about 7.8 years and the eccentricity of the orbit is very high ($e = 0.97$) which suggests a supernova explosion in the HMCBS.

3.3 *High-mass Be-star X-ray transients*

Several dozens of such high-mass X-ray binaries have been presented in our catalogue. The orbital periods and eccentricities are high: $P \approx 10$–1000 days; $e = 0.2$–0.8. The optical stars are rapidly rotating Be stars ($v \sin i = 70$–$450\,{\rm km\,s^{-1}}$) with rotationally induced equatorial winds. The X-ray sources are neutron stars which are in most cases X-ray pulsars ($P_{\rm puls} \approx 0.07$–$6000\,{\rm s}$). X-ray flares have luminosities up to $L_{\rm X} \approx 10^{38}$–$10^{39}\,{\rm erg\,s^{-1}}$, and the duration of flares is $\Delta t \approx 30$ days. The X-ray flares occur basically during the periastron passage by the neutron star when the accretion rate from the equatorial Be-star wind is increased. The X-ray spectrum is relatively hard ($kT \approx 15$ keV). In the quiet stage the X-ray luminosity is approximately 10^{33}–10^{34} erg s^{-1}.

3.4 *Persistent high-mass X-ray binaries*

A dozen of such X-ray binaries have been presented in our catalogue. The optical components are massive O–B supergiants which are close to filling their Roche lobe. The orbital periods are relatively short: $P \approx 1.4$–9 days. The eccentricities of the orbits are close to zero: $e = 0$–0.1. Long-period (precessional?) variability is observed for several systems ($P_{\rm prec} \approx 30$–300 days). The X-ray sources are neutron stars and black holes. X-ray pulsars have spin periods $P_{\rm puls} \approx 0.7$–600 s. The mean X-ray luminosity is $L_{\rm X} \approx 10^{36}$–$10^{39}$ erg s^{-1}. Black-hole X-ray binaries are Cyg X-1, LMC X-3, LMC X-1, etc. None of these massive ($m_{\rm X} > 3M_\odot$) X-ray sources is a pulsar.

3.5 *$WR_2 + C$ binary systems*

After a secondary mass exchange in an HMCBS a $\rm WR_2 + C$ binary may be formed consisting of a WR star of 'second generation' and a relativistic object.

The SS433 binary system is a high-mass X-ray binary at an advanced evolutionary stage, in which the optical star overfills its Roche lobe [37, 38] and a supercritical accretion disc is formed around the relativistic object [39]. Therefore, intensive secondary mass exchange occurs in SS433 ($\dot{M} \approx 10^{-4} M_\odot$ year^{-1}) and this unique HMCBS may be considered as a precursor of a WR + C binary. It should be stressed that SS433 provides us with an example of the secondary mass exchange in an HMCBS when no common envelope is formed but the angular momentum loss from the binary system occurs via the formation of a supercritical accretion disc and strong stellar wind from it.

Discovery of a WR star in a peculiarly short-period X-ray binary Cyg X-3 [34] clearly shows that the Cyg X-3 system is a true $\rm WR_2 + C$ binary which has been formed as a result of secondary mass exchange in an HMCBS with common envelope evolution [35]. The observational characteristics of Cyg X-3 are $P \approx 4.8$ h, $L_{\rm X} = 10^{38}$ erg s^{-1} (1–60 keV) and $L_\gamma = 2 \times 10^{37}$ erg s^{-1}; it is a gamma, X-ray, infrared, optical and radio source. There are radio flares up to 20 J, and radiojets ($v \approx 0.35c$) as in SS433. There is no pulsar in the system. The visual magnitude is $V \approx 23$, the magnitude of the unique interstellar absorption is estimated to be $A_{\rm v} = 15$, and the distance to the system is $d \approx 11$ kpc. The infrared magnitude is $K \approx 12$. The spectral class of the optical WR star is WN 4-7.

4. Low-mass highly evolved close binary systems

4.1 *X-ray novae*

Several dozen such X-ray binaries have been discovered so far (see the review by Cherepashchuk [40], and references therein). The orbital periods are $P \approx 0.2$–33.5 days; the eccentricities of the orbits are $e = 0$. The optical stars are normally M, K, A and B dwarfs, subgiants and giants. X-ray flares have durations of several months. During the flares the X-ray luminosity increases by a factor of 10^2–10^6 and reaches the value of about 10^{37}–10^{38} erg s^{-1}. The duration of the quiet stage ($L_{\rm X} \le 10^{33}$ erg s^{-1}) may reach many years. The relativistic companions are neutron stars and black holes (see the review by Cherepashchuk [41], and references therein). Examples of black-hole X-ray novae are A0620-00, GS2023 + 338, GS1124-68 and GRS1915+105. None of the black holes in X-ray nova binaries is an X-ray pulsar. The X-ray spectra of X-ray novae are in general softer ($kT \approx 2$ keV) than those of Be–X-ray transients. For the X-ray novae GRO J1655-40, GRS1915 + 105, etc., radio flares and collimated relativistic jets after the X-ray flare were observed.

4.2 *Bright X-ray binaries of Galactic bulges*

Several dozen such low-mass X-ray binaries have been presented in our catalogue. The orbital periods are relatively short: $P \leq 1$–10 days. Also $e \approx 0$ and $L_X \approx 10^{36}$–10^{38} erg s^{-1}. The X-ray luminosity is persistent but irregular. X-ray variability up to 10^2 times is observed for several systems. The optical companions are G–M low-mass late stars: $m_v \leq 1.5 M_\odot$. The relativistic companions are neutron stars with relatively weak magnetic fields. Quasiperiodic oscillations of X-ray luminosity have been detected for many X-ray binaries of this type (Sco X-1, $\nu_c = 5.9$–6.4 Hz; Cyg X-2, $\nu_c = 5.2$–6 Hz; 4U1758-25, $\nu_c = 20$–24 Hz; etc.).

4.3 *X-ray bursters*

They are distributed in the Galactic bulge and globular clusters. Several dozen X-ray binaries of this type have been presented in our catalogue. These are LMCBSs exhibiting bursts of X-ray luminosity with duration $\Delta t = 1$–40 s. The X-ray luminosity reaches at maximum a value of approximately 10^{37} erg s^{-1}. Optical stars are low-mass late-type stars. The X-ray bursts are due to thermonuclear explosions of accreted matter on the surfaces of weakly magnetized neutron stars.

4.4 *Cataclysmic binaries*

This is a numerous class of LMCBSs containing a low-mass ($m < 1 M_\odot$; spectral type, G–M III–V) optical star filling its Roche lobe and an accreting white dwarf. About 200 such systems have been presented in our catalogue. In most cases the orbital periods are short: $P < 1$ day. Also $e = 0$. Cataclysmic binaries can be separated into three types depending on the magnetic field H of the white dwarf.

(i) For $H < 10^5$ G an accretion disc is formed around the white dwarf with its inner border reaching the surface of the white dwarf.
(ii) For $H \approx 10^5$–10^6 G the accretion disc is disrupted in its central parts by the magnetosphere of the rotating white dwarf (intermediate polar, such as DQ Her; optical and X-ray pulsations of the white dwarf are observed).
(iii) For $H \approx 10^7$–10^8 G the radius of the magnetosphere of the white dwarf exceeds the radius of the orbit of the binary system. No accretion disc is formed. The mass transfer from the non-degenerated G–M star and the accretion of matter occur while the matter flows along the magnetic field lines on to the magnetic poles of the white dwarf. It is a phenomenon of the polar. The optical and X-ray luminosity are on average modulated by the orbital period of the binary system.

Depending on the amplitude of the optical flares, cataclysmic binaries can be separated into three types: novae (orbital periods $P \approx 0.05$–230 days; magnitude of $\Delta V > 11$), recurrent novae (magnitude of $\Delta V \approx 7$–11; interval between flares $\Delta T \approx 20$–80 years) and dwarf novae (magnitude of $\Delta V \approx 2$–6; $\Delta T \approx 10$–100 days). The origin of the flares for novae and, probably, recurrent novae is connected with thermonuclear burning of the accreted matter on the surface of the degenerated white dwarf and, for dwarf novae, with gravitational energy release due to accretion of matter from the accretion disc onto the white dwarf, which is triggered by some instability in the accretion disc. Binary white dwarfs ($P \approx 0.02$–0.05 days) and precataclysmic binaries (in which the non-degenerated companion does not fill its Roche lobe) have also been presented in our catalogue.

4.5 *Symbiotic binary systems*

Several dozen such systems with known orbital periods have been included in our catalogue. They consist of a red giant (spectral type, G–M) and a white dwarf or a subdwarf ($R = (0.01$–$1)R_\odot$; $T \approx 30\,000$–$150\,000$ K) accreting matter of the red giant. Sometimes the second star is a main-sequence star or a neutron star. The orbital periods are long, from 70 days to several dozen years, and $e \approx 0$–0.3. Sometimes the red giant is a variable of Mira type. Depending on the amplitude of the optical flares, symbiotic binaries can be separated into three groups:

(i) classical symbiotic binaries, magnitude of $\Delta V = 2$–3 (CI Cyg and Z And);
(ii) recurrent novae, magnitude of $\Delta V = 5$–7 (T CrB and RS Oph);
(iii) symbiotic novae, magnitude of $\Delta V = 6$–10 (AG Peg, HM Sge and RR Tel).

Sometimes symbiotic novae are called slow novae; the flares from these are observed only once.

The origin of flares in most cases is thermonuclear burning of hydrogen matter accreting on the surface of the white dwarf. The duration of such flares reaches several dozen years. Shorter flares ($\Delta T < 1$–3 years) are due to accretion processes. Collimated jets from several symbiotic binaries were observed during the optical and radio flares ($v \approx 10^2\ \mathrm{km\,s^{-1}}$).

4.6 *Ultrasoft X-ray binaries*

Five such systems have been included in our catalogue (the total number of these systems has reached about ten at present). These systems consist of low-mass stars which fill their Roche lobe and accreting white dwarfs. The orbital periods are about 1 day. A basic peculiarity of these systems is their very soft X-ray spectrum ($kT \approx 20$–50 eV) and high X-ray luminosity ($L_X \approx 10^{37}$–$10^{38}\ \mathrm{erg\,s^{-1}}$). The X-ray luminosity is persistent and is due to stationary thermonuclear burning of accreted matter on the surface of the degenerated white dwarf. A typical example of such a system is CAL 83/4U0543-682.

5. Luminous blue variables

Luminous blue variables (LBVs) belong to the class of stars first defined by Conti [42]. Some LBVs are among the most luminous stationary stars ever known in the Universe. They are characterized by strong photometric variability (up to several magnitudes) on different timescales (from hundreds of years to months). Some of these are surrounded by a small nebula apparently formed by the matter ejected from a star, thus giving evidence of enrichment by nuclear-processed material. The corresponding value of the mass loss rate reaches about $10^{-2} M_\odot\ \mathrm{year}^{-1}$. A list of known LBVs was given by Lamers [43]. About ten LBVs have been presented in our catalogue. Three points of view concerning the nature of LBVs have been considered up to now: single very massive ($m > 100 M_\odot$) stars; HMCBSs in the common-envelope evolutionary stage just after the X-ray binary stage; Landau–Thorne–Zytkov [44, 45] objects, which are single massive stars with a relativistic object in the centre.

A recent discovery by the Hubble Space Telescope of collimated jets from the LBV object η Car [46], revealing the long-time X-ray periodicity of this object ($p = 5.54$ years), favours the binary nature of LBVs. The discovery of a WR star in the Cyg X-3 X-ray binary system [34] with a very short orbital period (about 4.8 h) implies a high probability of the existence of Landau–Thorne–Zytkov objects in the Galaxy [35].

6. Radiopulsars in binary systems

About 150 binary radiopulsars have been discovered to date; more than 30 of these have been presented in our catalogue. The orbital periods are $P_{\mathrm{orb}} = 0.07$–1300 days; the eccentricities of the orbits lie in the range $e = 0$–0.97; the companions are neutron stars, white dwarfs (magnitude of $V = 21$–23), Be stars or planets. The spin pulsar periods range between 0.0016 s and approximately 1 s. Most millisecond pulsars are binaries. They are recycled pulsars during the secondary mass exchange in binary systems, as was predicted by Bisnovatyi-Kogan and Komberg [47]. There exist radioeclipsing pulsars (*e.g.* PSR1057+20) in which evaporation of the white dwarf heated by the relativistic wind of the pulsar is observed.

Recent discovery of two pulsars in the binary system J0737-3039AB [48, 49] confirms the idea by Bisnovatyi-Kogan and Komberg [47] about recycled pulsars and allows us to check the general relativity theory (together with the Hulse–Taylor pulsar PSR1913 + 16). (See the recent review by Bisnovatyi-Kogan [50].)

According to theoretical considerations (see, for example, [24]), pulsars in binary systems with eccentric orbits and relatively high masses of the companions (neutron stars or high-mass white dwarfs) have been formed as a result of supernova explosions. Pulsars with circular orbits and relatively low-mass companions (white dwarfs) have been formed owing to the collapse of white dwarfs, which increased their masses up to the Chandrasekhar limit via accretion of matter transferred by the companion, a non-degenerated low-mass star. The strong increases in the orbital periods of such systems is due to the transfer of matter on the nuclear burning timescale from the low-mass normal star to the more massive white dwarf.

7. Conclusions

The basic observational properties of HECBSs have been briefly described in our review. In general, these properties are in agreement with the modern theory of evolution of close binaries. There are some new observational data which stimulate further development of the theory, *e.g.* the wind–wind collision effects in high-mass close binaries which implies a highly non-conservative mass exchange. Let us summarize some recent observational results which have high significance for astrophysics.

(1) The discovery of binary radiopulsars with Be and B stars as companions has proved the real existence of X-ray quiet binaries with relativistic companions.
(2) The discovery of two radiopulsars in the binary system J0737-3039AB strongly supports the earlier prediction of recycled pulsars made by Bisnovatyi-Kogan and Komberg [47].
(3) The discovery of binary white dwarfs is very important for evolutionary theory and for explaining Ia-type supernovae as a result of merging white dwarfs [51].
(4) The discovery of a WR star in a short-period X-ray binary Cyg X-3 has proved the real existence of $\mathrm{WR}_2 + \mathrm{C}$ binaries consisting of ‘second-generation’ WR stars and relativistic objects. The very short orbital period (approximately 4.8 h) implies common-envelope evolution for this system before the $\mathrm{WR}_2 + \mathrm{C}$ stage and suggests a high probability of the real existence of Landau–Thorne–Zytkov objects in the Galaxy.

(5) The object SS433 provides us with another type of secondary mass exchange in HMCBSs, namely without any common envelope but with a supercritical accretion disc around the relativistic object and strong stellar wind from this disc. In this connection, a recent selection of a special type of close binary with relativistic jets called microquasars should be mentioned.
(6) New results of the light curve solution for WR + O binaries V444 Cyg and BAT 99-129 [31, 32] have shown that the WR stars in these systems have small radii ($r < 4R_\odot$) and high effective temperatures ($T > 40\,000$–$50\,000$ K). These results strongly suggest the model of WR formation in binaries as a result of mass exchange in HMCBSs.
(7) The discovery of compact ultraluminous X-ray sources in the galaxies with X-ray luminosities up to 10^{42} erg s^{-1} (see, for example, [52]) suggests the existence of either intermediate-mass black holes or SS433-like objects in binary systems.
(8) Cosmic gamma-ray bursts were interpreted as being the result of the formation of rapidly rotating Kerr black holes in massive short-period close binary systems [53]. In this model the high rotational velocity of a massive star core is maintained by the orbital motion of a close binary companion.
(9) The masses of about 30 X-ray and radiopulsars in binary systems were determined with a high accuracy (see, for example, [54]). The masses of X-ray and radiopulsars as well as X-ray bursters of the first kind do not exceed $3M_\odot$ in accordance with Einstein's general relativity theory. Two very important results have been obtained from the investigations of HECBSs which contributed greatly to fundamental physics.
(10) Evidence for gravitational wave radiation by binary radiopulsars (PSR1913+16, J0737-3039AB, etc.) has been obtained.
(11) The masses for approximately 20 very reliable black-hole candidates in high- and low-mass X-ray binaries have been determined (see, for example, the review by Cherepashchuk [41], and references therein). It is very significant that none of these massive ($m_X > 3M_\odot$) X-ray sources is a pulsar in accordance with Einstein's general relativity theory.

References

[1] A.M. Cherepashchuk, N.A. Katysheva, T.S. Khruzina *et al.*, *Highly Evolved Close Binary Stars: Catalogue* (Gordon & Breach, New York, 1996).
[2] J.A. Crawford, Astrophys. J. **121** 71 (1955).
[3] D. Morton, Astrophys. J. **132** 146 (1960).
[4] B. Paczynski, Acta Astron. **16** 231 (1966).
[5] B. Paczynski, Acta Astron. **17** 287 (1967).
[6] L.I. Snezhko, Variable Stars **16** 253 (1967).
[7] R. Kippenhann and A. Weigert, Z. Astrophys. **65** 251 (1967).
[8] A.V. Tutukov and L.R. Yungelson, Nauchn. Inform. Astron. Sovet Akad. Sci. USSR **27** 58, 70 (1973).
[9] E.P.J. van den Heuvel, in *Structure and Evolution of Close Binary Systems*, edited by P. Eggleton, S. Mitton and J. Whelan (Reidel, Dordrecht, 1976), p. 35.
[10] V.G. Kornilov and V.M. Lipunov, Soviet Astron. **27** 163, 334 (1983).
[11] D.Ya. Martynov, Astron. Zh. **14** 306 (1937).
[12] O. Struve, Mon. Not. R. Astron. Soc. **86** 63 (1925).
[13] D.Ya. Martynov, in *Non-Stable Stars*, IAU Colloquium 3, edited by G.H. Herbig (Cambridge University Press, Cambridge, 1957), p. 138.
[14] O. Struve, Ann. Astrophys. **11** 117 (1948).
[15] P.P. Parenago and A.G. Massevich, Trudy Sternberg State Astron. Inst. **20** 81 (1950).
[16] O. Struve, in *Cinquième Colloque International d'Astrophysique* Liège, Belgium, Liège (1953), p. 236.
[17] A.M. Cherepashchuk, Space Sci. Rev. **74** 313 (1995).
[18] L.R. Yungelson and A.G. Massevich, Itogy Nauki Tekhniki, Ser. Astron. **21** 27 (1982).
[19] A.M. Cherepashchuk, Astrophys. Space Sci. **274** 159 (2000).
[20] M.C.R. D'Souza, P.M. Mote, J.E. Tholine *et al.*, Astrophys. J. **643** 381 (2006).
[21] Z. Kopal, *Dynamics of Close Binary Systems* (Reidel, Dordrecht, 1978), p. 265.
[22] L.G. Lukyanov, Astron. Zh., in press (2007).
[23] R.P. Kraft, J. Matews and J.L. Greenstein, Astrophys. J. **136** 312 (1962).

[24] S.N. Shore, M. Livio and E.P.J. van den Heuvel, *Interacting Binaries* (Springer, Berlin, 1994).
[25] A.G. Massevich and A.V. Tutukov, *Stellar Evolution: Theory and Observations* (Nauka, Moscow, 1988).
[26] G.S. Bisnovatyi-Kogan, Byull. Abastumanskaya Astrofiz. Obs., Akad. Nauk Gruz. SSR **58** 175 (1985).
[27] K.A. Van der Hucht, New Astron. Rev. **45** 135 (2001).
[28] A.M. Cherepashchuk and V.G. Karetnikov, Astron. Zh. **80** 42 (2003).
[29] A.M. Cherepashchuk, Soviet Astron. **19** 47 (1975).
[30] A.M. Cherepashchuk, J.A. Eaton and Kh.F. Khaliullin, Astrophys. J. **281** 774 (1984).
[31] I.I. Antokhin and A.M. Cherepashchuk, Astron. Zh. **78** 432 (2001).
[32] I.I. Antokhin and A.M. Cherepashchuk, Astron. Zh., **84** 6 (2007).
[33] N. St-Louis, A.F.J. Moffat, L. Lapointe *et al.*, Astrophys. J. **410** 342 (1993).
[34] M.N. Van Kerkwijk, P.A. Charles, T.R. Geballe *et al.*, Nature **355** 703 (1992).
[35] A.M. Cherepashchuk and A.F.J. Moffat, Astrophys. J. **424** L53 (1994).
[36] S. Johnston, R.N. Manchester, A.G. Lyne *et al.*, Astrophys. J. **387** L37 (1992).
[37] A.M. Cherepashchuk, Mon. Not. R. Astron. Soc. **194** 761 (1981).
[38] B. Margon, A. Rev. Astron. Astrophys. **22**, 507 (1984).
[39] N.I. Shakura and R.A. Sunyaev, Astron. Astrophys. **24** 337 (1973).
[40] A.M. Cherepashchuk, Space Sci. Rev. **93** 473 (2000).
[41] A.M. Cherepashchuk, Phys.—Usp. **46** 335 (2003).
[42] P.S. Conti, in *Observational Test of Stellar Evolution Theory*, IAU Colloquium 105, edited by A. Maeder and A. Rensini (Reidel, Dordrecht, 1984), p. 233.
[43] H.J.G.L.M. Lamers, *Instabilities in Luminous Early-type Stars* (Reidel, Dordrecht, 1987).
[44] L.D. Landau, Dokl. Akad. Nauk USSR **17** 301 (1937).
[45] K. Thorne and A.N. Zytkov, Astrophys. J. **212** 832 (1977).
[46] J.J. Hester, R.M. Light, J.A. Westpol *et al.*, Astron. J. **102** 654 (1991).
[47] G.S. Bisnovatyi-Kogan and B.V. Komberg, Pis'ma Astron. Zh. **2** 338 (1976).
[48] M. Burgay, N. D'Amico, A. Possenti *et al.*, Nature **426** 531 (2003).
[49] A.G. Lyne, M. Burgay, M. Kramer *et al.*, Science **303** 1153 (2004).
[50] G.S. Bisnovatyi-Kogan, Usp. Phys. Nauk **176** 59 (2006).
[51] I. Iben and A.V. Tutukov, Astrophys. J., Suppl. Ser. **54** 335 (1984).
[52] E.J.M. Colbert and R.F. Mushotzky, Astrophys. J. **519** 89 (1999).
[53] A.V. Tutukov and A.M. Cherepashchuk, Astron. Zh. **80** 419 (2003).
[54] M.K. Abubekerov, E.A. Antokhina and A.M. Cherepashchuk, Astron. Rep. **48** 89 (2004).

Director of Sternberg Astronomical Institute, A.M. Cherepashchuk