Astron. Astrophys. 349, 505–510 (1999)

ASTRONOMY AND ASTROPHYSICS

The evolutionary evidence for Be/black hole binaries

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Received 27 January 1999 / Accepted 9 June 1999

Abstract. Using Monte Carlo simulation of the modern scenario of the evolution of binary systems (the "Scenario Machine"), we calculate the number of binary black holes with Be stars and their expected observational properties. So far, only two possible candidates for Be/BH binaries have been proposed among the observable sources, the superluminal source GRS 1915+105 in the Galaxy and RX J0117.6-7330 in SMC. Using the "Scenario Machine" we obtained an evolutionary track that can lead to the formation of such systems. The modern evolutionary scenario predicts the existence of binary black holes on eccentric orbits around Be stars and such systems may be discovered in the near future.

Key words: stars: binaries: close – black hole physics – stars: emission-line, Be – stars: evolution

1. Introduction

Discovery of binary black holes with massive Be stars would be of great importance for the modern theory of stellar evolution. Only a handful of *reliable* candidates for binary black holes with optical companions are known at present (see van Paradijs & McClintock 1995 for a review). They must all be products of the evolution of binary systems with massive companions. Only a few of the optical companions in these binaries are early-type. Among the massive X-ray binaries (MXRBs) with early-type companions, only three objects, Cyg X-1, LMC X-3 and LMC X-1 are considered black hole candidates because of their very soft X-ray spectra and high mass estimates ($\geq 4M_\odot$) for the X-ray star. The other black hole candidates are all low mass X-ray binaries (LMXBs): the companion stars, which are filling their Roche-lobes, are main-sequence G- or K-dwarf stars. Seven of these are known to contain black holes on the basis of a dynamical mass determination. Another 18 systems are suspected to be black hole X-ray binaries (BHXBs) on the basis of their X-ray spectra. Thus, there are far more LMXBs which contain black holes than MXRBs.

So far, two "currently active" *possible* candidates for Be/BH binaries have been proposed among the observable sources, the superluminal source GRS 1915+105 in the Galaxy (Mirabel et al. 1994; Mirabel et al. 1997) and RX J0117.6-7330 in SMC (Clark et al. 1997; Soria 1998). GRS 1915+105 is one of the most luminous X-ray sources in the Galaxy. Since this source has a fairly hard spectrum with emission up to 220 keV, and a variable spectral index between -2 and -2.8, observed by BATSE on the Compton Gamma-Ray Observatory (GRO), GRS 1915+105 is likely to be a collapsed object, perhaps a black hole in a binary system (Harmon et al. 1994). Mirabel et al. (1997) have found that the absolute K magnitude of GRS 1915+105 is consistent with that of massive X-ray binaries with late Oe and early Be companions. There is infrared photometric similarity between GRS 1915+105 and one of the best studied Be/X-ray transients, A0538-66 in the Large Magellanic Cloud. Both radio and hard X-ray light curves of GRS 1915+105 show transient behaviour. For 4 years, GRS 1915+105 had an erratic bursting history with recurrent peaks of similar intensity. These recurrent outbursts are characteristic of high-mass X-ray binaries with eccentric orbits of long period. The time and duration of the outbursts are sometimes well correlated with the orbital period of the binary. Mirabel & Rodrigues (1996) point out that in the course of 1994 recurrent ejections were observed in GRS 1915+105 every 20-30 days. Thus, the galactic superluminal source GRS 1915+105 is the first candidate binary black hole with a Be star in the Galaxy.

Another possible candidate Be/BH binary is RX J0117.6-7330 discovered recently in the Small Magellanic Cloud. Its soft X-ray spectrum, its long decay time after the 1992 X-ray outburst and the absence of pulsations make this system a possible black hole candidate (Clark et al. 1997). A common way to determine whether the compact object in an X-ray binary can be a neutron star is to deduce its mass function from the radial velocity of the primary, but such measurements are more difficult in high-mass X-ray binaries owing to the low velocity expected for the primary and to the long binary period. Soria (1998) has conducted spectroscopic and photometric observations of the optical companion of this X-ray transient and identified the primary star as a B0.5 IIIe. But the binary period and the mass function of the compact object is not yet determined.

In this paper we calculate the expected distributions of Be/BH systems over orbital periods and eccentricities for different scenario parameters using Monte Carlo simulation of the bi-

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nary evolution and discuss possible ways in which such systems can be formed. A similar method has been successfully applied for studies of the number and physical properties of binary pulsars with massive optical companions, which proved to be consistent with the observed properties of the binary PSR B1259-63 (Johnston et al. 1992; Lipunov et al. 1994). In the case of black holes which are free of complicated and ill-understood spin evolution connected with magnetic fields etc., these estimations seem to be more reliable and parameter-independent. We have found that our results depend sensitively only on two parameters: the lower limit to the initial BH progenitor mass, M_{cr} and the value of the mean kick velocity caused by the collapse anisotropy, w_m. Assuming that in our Galaxy one possible candidate Be/BH system is observed (GRS 1915+105), we can place some restrictions on these parameters. Calculation of evolutionary tracks and all statistical computations have been made using the "Scenario Machine" (a numerical code that models the evolution of large ensembles of binary systems; Lipunov et al. 1996a) developed at the Relativistic Astrophysics Department of the Sternberg Astronomical Institute. The demonstration version of the "Scenario Machine" is available at our WWW site http://xray.sai.msu.ru/sciwork/scenario.html

2. Be+BH versus Be+NS"A" in our Galaxy

The program "Scenario Machine" was described for the first time in a paper by Kornilov & Lipunov (1983). Recently a very detailed description of this program was given in a review by Lipunov et al. (1996a). Here we will only describe parameters which are needed for our calculations. Also, some common principles of single track calculations are described at the beginning of Sect. 4.

Each run of our calculations consisted of tracking the evolution of 1,000,000 ZAMS binaries with initial masses within a range from 10 to $120M_{\odot}$. The initial binary separations, a, were taken to be distributed as $f(loga) = \mathrm{constant}$. When calculating we made the zeroth order assumption that the mass ratio distribution has a flat shape ($\alpha_q \sim 0$), i.e. binaries with a high mass ratio occur as frequently as those with equal masses. Also we assume the primary mass to obey Salpeter's power law:

$$f(M_1) \propto M^{\alpha}(\alpha = 2.35)\ , \quad 0.1M_{\odot} < M_1 < 120M_{\odot}\ ,$$
$$f(q) \propto q^{\alpha_q}(\alpha_q \sim 0)\ , \quad q = M_2/M_1 < 1$$

The flat initial mass ratio spectrum was chosen because it is currently the most popular among researchers (e.g. Tutukov & Yungelson (1993); Pols & Marinus (1994)) and to which many physically reasonable assumptions about the initial mass ratio leads (say, both masses obeying a Salpeter-like power law, or the total binary mass and mass of the primary obeying Salpeter's law, etc.). Salpeter's power law is currently universally accepted. As a rule, other possible initial mass functions have failed to agree with observations. An example is initial mass function with $\alpha = 1.01$ proposed by Contini et al. (1995) for galaxy Mrk 712. Later Schaerer (1996) demonstrated that the observational properties of this galaxy can also be explained with Salpeter's power law. As shown by Popov et al. (1998) the change to an initial mass function with $\alpha = 1.01$ leads to a substantial increase in the number of binary X-ray systems. It leads to a substantial change of the hard X-ray luminosity of the Galaxy. Because of this, the existence of bursts of star formation with an initial mass function with $\alpha = 1.01$ would imply an increase in the hard X-ray fluxes. The absence of such a high X-ray luminosity is evidence for the absence of an $\alpha = 1.01$ initial mass spectrum in the present burst of star formation.

For the case of collapse into a BH ($M_* > M_{cr}$) we considered both isotropic and anisotropic collapse. The important point is that the collapse of a massive star into a BH can be asymmetrical, so that the newborn BH can acquire an additional, presumably randomly oriented in space, kick velocity w. In view of the importance of this parameter, we study the influence of this asymmetry on the evolutionary calculations for the Maxwellian and Lyne & Lorimer (1994) kick distributions. It seems natural to assume that the kick velocity is arbitrarily directed in space. The value of the kick velocity w can be quite different and may well depend on a number of parameters, such as magnetic field strength, angular velocity and so on. Let us consider the extreme assumption of a maxwellian-like distribution,

$$f_m(w) \propto w^2 \exp(-w^2/w_0^2)\ , \qquad (1)$$

which is natural to expect if several independent approximately equally powerful anisotropy mechanisms operate randomly. Here w_0 is a parameter which is connected with the mean kick velocity w_m by the relation $w_m = \frac{2}{\sqrt{\pi}} w_0$.

In the case of calculations for the kick velocity distribution taken so as to fit the observed transverse pulsars' velocity obtained by Lyne & Lorimer (1994) we use:

$$f_{\mathrm{LL}}(x) \propto \frac{x^{0.19}}{(1+x^{6.72})^{1/2}}\ , \qquad (2)$$

where $x = w/w_m$.

The observed number of Be/NS"A" systems in the Galaxy is equal to about 25 (we include transient Be/X-ray binaries such as A0535+26, X Per, 4U1145-619 etc.). Thus, the expected "observed number" of Be+BH transients in the Galaxy is equal to unity only for certain parameters of black hole formation. It is to be noted that we have made calculations only for our Galaxy. In other galaxies the observed number of Be/NS"A" systems would be different. Thus, in the Small Magellanic Cloud the observed number of such systems is equal to 14, and in the Large Magellanic Cloud it is 9.

Black hole formation during the collapse of massive stars is still not well understood. From core-collapse simulations it has become clear that the nature and mass of the remnant, the amount of fallback, and the amount of mass ejection depend sensitively on the details of the collapse mechanism, the energy involved, and the structure of the collapsing star. Mass ejection can be significant both in cases where black hole formation occurs promptly and when it is preceded by the formation of a neutron star, which then collapses to a black hole because of heavy fallback (Woosley & Weaver 1995). Given our limited current understanding of these processes, we allow the fraction of the presupernova mass (M_*) collapsing to the BH,

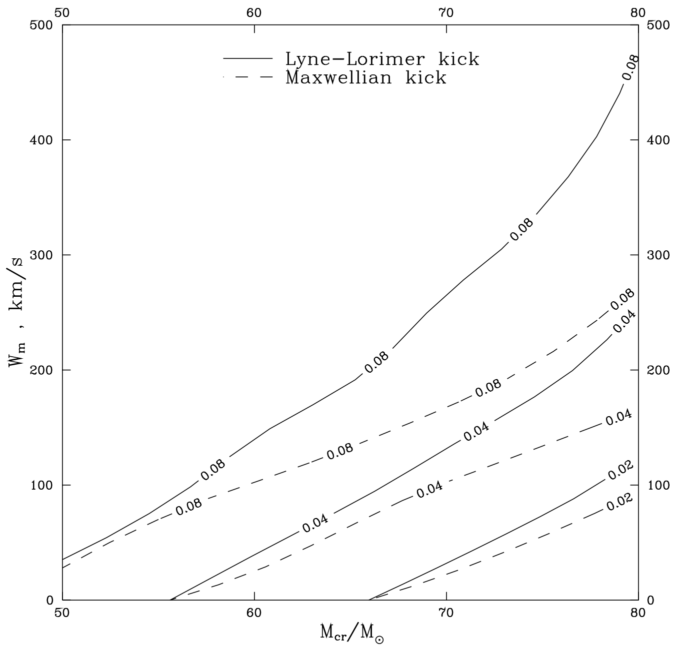


Fig. 1. The "curves of best correspondence" for scenario parameters (see description in text)

$k_{BH} = M_{BH}/M_* = 0.5$. Too small values of $k_{BH} \sim 0.1$–0.2 would give too "light" black holes with masses in the range 3–$5M_\odot$, and the large mass loss during the collapse would make binaries with high mass ratios unbound, so it would be difficult to understand how LMXB black hole candidates with high mass ratios (and observed now as X-ray novae) had been formed. Higher values of initial primary masses M_{cr} require higher values for k_{BH}, giving more massive black holes. Higher values for $k_{BH} \sim 0.7$–0.9 are less favorable given the most probable estimation of the black hole mass in Cyg X-1 of $\sim 10M_\odot$. As a separate independent criterion we included the calculated Galactic number of black hole candidates with evolved OB-companions. The observational estimation ~ 10 per Galaxy is given by a fraction ($\sim 1/4$) of black hole candidates among the observed number of bright massive X-ray binaries (MXRBs) scaled to the total Galactic number of MXRBs (~ 40, see van Paradijs & McClintock 1995). The observed lower mass limit for black hole formation in a binary, $M_{cr} \geq 50M_\odot$, was proposed by Kaper et al. (1995), based on the new measurement of a lower limit to the mass of the supergiant Wray 977 in the binary X-ray pulsar GX 301-2. From the above reasoning we adopt the constant value $k_{BH} = 0.5$ and a lower limit to the initial mass of the star collapsing to a black hole, M_{cr}, to vary in the range from 50 to $80M_\odot$.

The mass limit for a NS (the Oppenheimer-Volkoff limit) is taken to be $M_{OV} = 2.5M_\odot$, which corresponds to a hard equation of state of NS matter.

In our calculations we do not perform the simulation with the "enhanced" mass loss rate developed in some papers (Schaerer 1996; Schaller et al. 1992) because the calculated Galactic number of black hole candidates with evolved OB-companions ("Cyg X-1"-like objects) is equal to zero for such scenarios.

The results of our calculations in the form of the "curves of best correspondence" are presented in Fig. 1. These represent the set of possible values of scenario parameters of binary systems. For these parameters the calculated ratio of the number of Be/BH to Be/NS"A" systems agrees with the accepted observational value of 1/25. Taking into account that this value is only known to within a factor of 2, we also plot in Fig. 1 the curves corresponding to the ratios Be/BH and Be/NS "A" of 2/25 and 1/50, respectively.

3. The expected distributions of Be/BH binaries over orbital parameters

Based on the restrictions to the scenario parameters shown in Fig. 1 we have calculated the expected distributions of the number of Be/BH systems over eccentricities and orbital periods for the following cases: 1) no kick, lower limit of initial mass of BH progenitor star $M_{cr} = 55M_\odot$; 2) maxwellian kick velocity distribution for $w_m = 50\,\mathrm{km\ s^{-1}}$ and $M_{cr} = 65M_\odot$; for $w_m = 140\,\mathrm{km\ s^{-1}}$ and $M_{cr} = 75M_\odot$; 3) with the Lyne & Lorimer kick velocity distribution for $w_m = 80\,\mathrm{km\ s^{-1}}$ and $M_{cr} = 65M_\odot$; for $w_m = 180\,\mathrm{km\ s^{-1}}$ and $75M_\odot$.

These parameters have been chosen as corresponding with the "curves of best correspondence", that is, we accept the observed number of Be/BH binaries in our Galaxy is unity. The distributions we obtain are shown in Fig. 2. Note that similar calculations of the binary radiopulsar population with different companions based on more general observational data (Lipunov et al. 1996b) also give similar values of kicks. In Fig. 2 we can see that the expected orbital periods of Be/BH binaries lie in the range from several days to several years with a maximum at several tens of days. The expected eccentricities of such systems fall in a broad range of values and depend strongly on the value of kick velocity. With increasing additional kick velocity the number of binaries with high values of eccentricity increases and the maximum of the distribution shifts to large eccentricities.

4. Evolutionary scenario for high-eccentricity Be/BH binaries

Here we present an example of the "Scenario Machine" (Lipunov et al. 1996a) computations for the formation of a Be star paired with a black hole. The continuous evolution of a binary component is treated as a sequence of a finite number of basic evolutionary states (for example, main sequence, Wolf-Rayet star, etc), in which the stellar parameters significantly differ from each other. The evolutionary state of the entire binary can thus be determined as a combination of the states of each component, and changes once the faster evolving component goes into the next state. At each such stage we assume that the star does not change its physical parameters (mass, radius, luminosity, etc.) which affect the evolution of its companion (especially for the case of compact magnetized stars). Every time the faster evolving component goes over into the next stage we recalculate its parameters. Depending on the evolutionary stage,

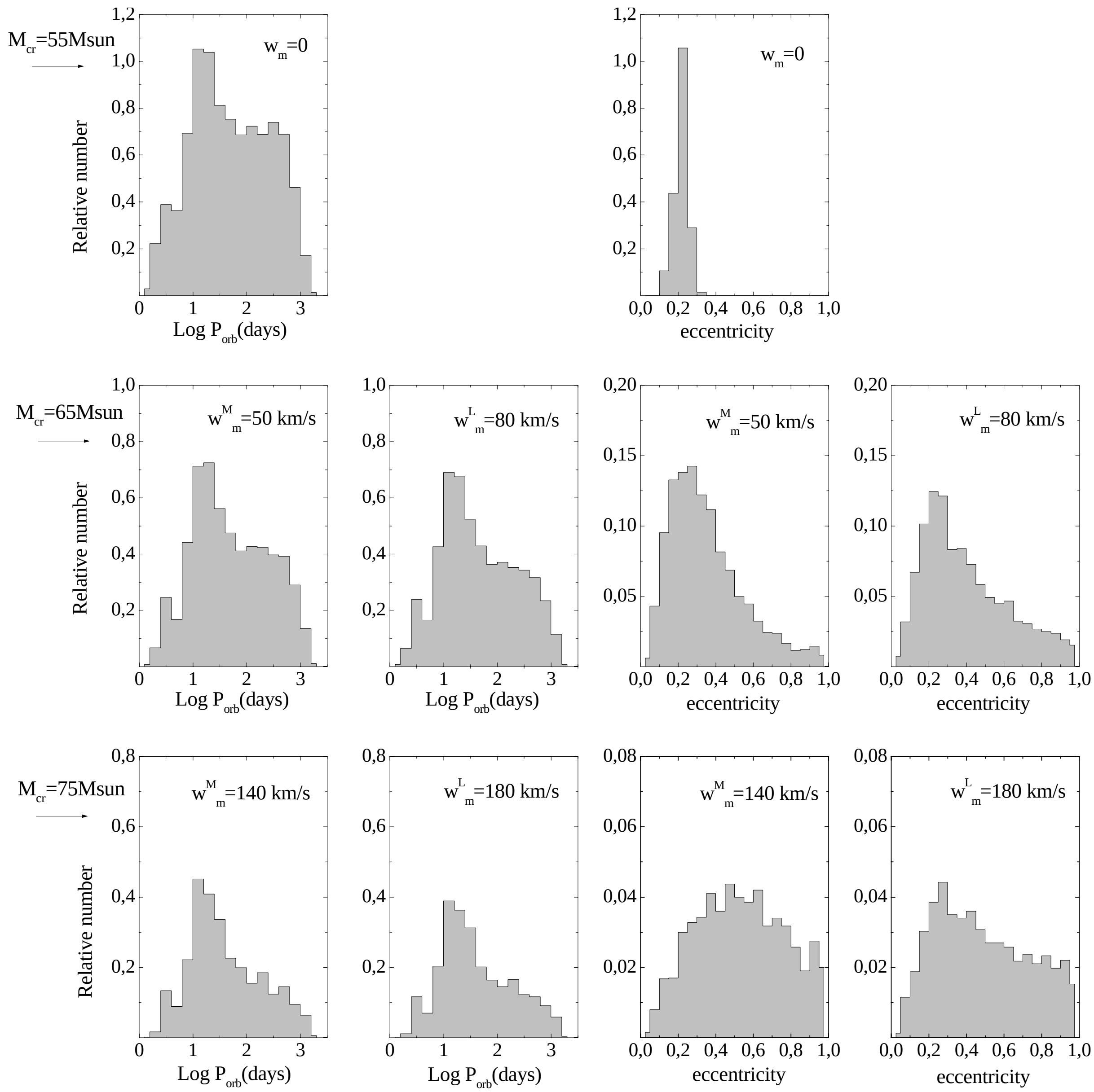
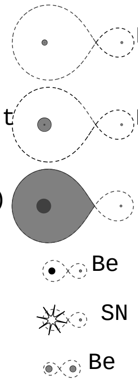


Fig. 2. Expected distribution of number of Be/BH binaries over orbital parameters

the state of the slower evolving star is changed accordingly or may remain the same. With some exceptions (such as the supernova explosion), no simultaneous change of state for both components can occur.

The evolutionary track that can lead to the formation of a Be+BH binary is presented in Fig. 3. Here we use the following notation for particular evolutionary stages of the components: MS = a main sequence star inside its Roche lobe (RL); a MS-star that accretes matter during the first mass transfer is considered to be a rapidly rotating Be-star if its mass is more than $10M_\odot$; Giant = evolved giant not filling its Roche lobe; RLO = a MS or post-MS star filling its Roche lobe — and transferring matter onto the companion; WR = a helium (Wolf-Rayet) star remaining after the mass transfer; RLO(f) = Roche lobe overflow on a thermal timescale; BH = black hole; SN Ib = core collapse of a star with initial mass $M > 10M_\odot$ in a binary with $a < 200AU$ (in such binaries, the hydrogen shell of the more massive primary star is in most cases removed due to tidal interaction between the components). We assume that Be stars are formed in binary systems where mass transfer spins up the accretor to high rotational velocity so that it starts showing the Be-effect. This scenario was proposed for the first time by Kriz & Harmanec (1975) and by Rappaport & Van den Heuvel (1982). Packet (1981) has shown that the accretor need gain only a few percent of its original mass ($\sim 0.1M_\odot$) in order to become a Be star.

Immediately before the supernova explosion the orbit is circular. This is due to strong tidal interaction in the mass-transfer phase. An asymmetric supernova explosion gives a kick to the collapsing star. In this way very large eccentricities can be obtained. When calculating evolutionary tracks we assumed



M1 Solar masses			M2 Solar masses	a Solar radii	T Million years	e	P_{orb} days
60.20	MS	MS	19.00	700.00	0.00	0.00	242.2
57.94	Giant	MS	18.53	725.00	3.42	0.00	259.8
55.25	RLO(f)	Be	18.49	751.90	3.77	0.00	279.4
31.01	WR	Be	20.09	278.70	3.80	0.00	75.7
		SN Ib kick = 25 km/s					
13.95	BH	Be	20.07	234.20	3.86	0.63	71.5

Fig. 3. Possible evolutionary track leading to Be/BH binary formation

anisotropic collapse with $w_m = 25\ \mathrm{km\,s^{-1}}$ in order to obtain the high eccentricity values. The critical initial mass of the supernova star that collapses to a BH is accepted to be equal to $60M_{\odot}$, and the fraction of the presupernova mass (M_*) collapsing to the BH, $k_{BH} = M_{BH}/M_* = 0.5$. The age of the system according to our evolutionary scenario is 4×10^6 yr.

5. Discussion

How can we identify a BH orbiting a Be star? If a black hole remains bound to the Be star companion of its progenitor after the supernova explosion, it might be detected in several ways. Sufficiently tight systems could be distinguished by spectroscopic variations due to the orbital motion of the Be star. Several authors have surveyed runaways for evidence of orbital Doppler shifts from unseen companions (Gies & Bolton 1986; Stone 1982). However, this method has practical difficulties, as Be star atmospheres exhibit intrinsic variability and line broadening, limiting spectral velocity measurements to a resolution of order 10 km $\mathrm{s^{-1}}$. Further, highly eccentric systems (our calculations show that binary black holes with Be stars must have eccentricities in the range $0.2 < e < 0.8$) are particularly difficult to detect as most of their spectroscopic variation occurs in a relatively small portion of the orbit, and could easily be missed if the systems are observed at widely separated epochs.

X-ray spectra played an important role in the development of the view that there are different groups of compact X-ray sources. Ostriker (1977) found that X-ray colour-colour diagrams provide an efficient way to separate different groups of X-ray sources. He suggested that accreting black holes could be distinguished this way. The importance of these diagrams was shown by White & Marshall (1984) who used them as an efficient tool to distinguish accreting neutron stars with strong and weak magnetic fields, and accreting black hole candidates. The spectra of the latter showed a strong low-energy excess whose strength appears to be related to the mass accretion rate.

The common way to determine whether the compact object in an X-ray binary can be a black hole is to deduce its mass function from the radial velocity amplitude of the primary star. But such measurements are more difficult in high-mass X-ray binaries owing to the low velocity expected for the primary and to the long binary period. The variability of the circumstellar envelope of Be stars and the line broadening due to rapid rotation also make it difficult to determine the mass function of the compact object.

6. Conclusion

In a framework of different assumptions about the parameters of binary evolution scenario we have estimated the relative number of binary black holes with Be star companions, which is not subject to observational selection effects. For probable parameters of black hole formation ($M_{cr} = 55$–$75M\odot$, $k_{BH} = 0.5$, $w_m = 0$–$200\ \mathrm{km\ s^{-1}}$) we obtained the expected number of BH+Be binaries to be of order of unity per 20–30 Be/NS"A" systems. The values of kicks obtained satisfy previous calculations of the binary radiopulsar population based on more general observational data (Lipunov et al. 1996b). This means that such binary black holes may be discovered in the near future. All such systems must be highly eccentric, with orbital periods lying in a range of 10 days to several years.

Acknowledgements. The authors would like to most gratefully thank S.N. Nazin for his help in preparing the manuscript and for useful discussions and comments. We thank the referee for his extremely useful comments and suggestions. This work is partially supported by the RFBR grant 98-02-16801, by the NTP program "Astronomija" (project 1.4.2.3) of Ministry of Science and High Technology, by grant of the Cariplo Foundation for Scientific Research and by the "Universitety Rossii" grant 5559.

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