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How abundant is the population of binary radio pulsars with black holes?

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ABSTRACT

Using a 'scenario machine' we have carried out a population synthesis of radio pulsars with black hole binaries (BH+Psr) in the context of the most widespread assumptions concerning star mass loss during evolution, the mass ratio distribution of binary stars, the kick velocity and the envelope mass loss during collapse. Our purpose is to show that under any plausible parameters for the evolution scenario, the BH+Psr population should be abundant in the Galaxy. It is shown that in all models (including those evolved by Heger et al. and Woosley, Heger & Weaver), the expected number of black holes paired with radio pulsars is sufficient for such systems to be discovered within the next few years.

Key words: black hole physics – stars: abundances – binaries: close – binaries: general – pulsars: general – X-rays: binaries.

1 INTRODUCTION

The discovery of binary radio pulsars with black holes (BH+Psr) would be of fundamental significance as evidence of the existence of black holes and for the precision of investigations into general relativistic effects (Narayan, Piran & Shemi 1991; Lipunov et al. 1994). In such systems parameters describing black holes (such as their mass and Kerr parameter) would be measured to a degree of precision that was orders of magnitudes better than indirect estimates from black hole candidates in X-ray/BH-candidate binaries (Blandford & Teukolsky 1975; Brumberg et al. 1975). Moreover, if mutual disposition is apt, it might allow the observation of propagation of radio emission arbitrarily near to an event horizon. First accounts of the possible number of BH+Psr binaries conducted 10 yr ago showed that the systems might be observable by modern radio-astronomy instruments (Lipunov et al. 1994).

However, the total number of radio pulsars observed has increased by a factor of 2 over the last 10 yr and has gone up to $N^{\mathrm{pul}}_{\mathrm{obs}} \approx 1500$, but none of them has been paired with a black hole (Manchester & Taylor 1972; Taylor & Manchester 1993; Manchester et al. 2001; Lewandowski et al. 2004; and the Australia National Telescope Facility (ATNF) pulsar catalogue 2005). Also during these 10 yr our conception of the evolution of stars that are able to produce black holes has changed appreciably. In particular, considerations in favour of greater mass loss for these stars were obtained and detailed numerical computations considering new factors have appeared (Heger et al. 2002, 2003; Woosley, Heger & Weaver 2002).

We have carried out a population synthesis of binary stars using a 'scenario machine'. A description of its working principles may be found in Lipunov, Postnov & Prokhorov (1996).

As binary radio pulsars with black holes have to be generated by massive binary stars, we relied on the observable statistics of the candidates for black holes paired with OB stars (BH+OB).

In the paper by Lipunov et al. (1994), it is assumed that any black hole paired with an OB supergiant must reveal itself as a system of Cyg X-1 type. However, as was shown by Karpov & Lipunov (2001), powerful X-ray radiation is able to originate only if an accretion disc has formed around the black hole. Accordingly, in this paper, we term Cyg X-1 type systems as a subclass of BH+OB binaries that have accretion discs.

Note that Cyg X-1 type systems are usually not progenitors of BH+Psr binaries. Over 90 per cent of them become BH+BH or single BHs after merging of components during our calculations. The Cyg X-1 system has an appreciable chance of merging in the next stage – the common-envelope (CE) stage (Bethe & Brown 1999). Ordinarily, BH+Psr binaries originate from wider systems which do not merge during the CE stage or come through it. During the BH+OB stage the accretion disc does not form and an observer would not be able to see a bright X-ray source.

An evolutionary scenario which results in BH+Psr formation may be roughly outlined as follows. We start with the calculation of a massive binary system. When the primary (more massive) star fills its Roche lobe, mass transfer takes place and a helium star remains instead of the primary star. As a rule a black hole forms first and its companion (OB star) is sufficiently separated from the BH. In wide systems, which can survive even after a second mass transfer, a disc does not form (the stellar wind velocity is too high near the black hole and the rotational momentum of the infalling matter is too small to form a disc). When the second component fills its Roche lobe, the CE stage begins and only wide systems (the number of which

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is greater than for close binaries) produce BH+Psr.[1] In scenarios with a high mass-loss rate, the CE stage might not begin, because the mass of the optical star is not sufficiently greater than that of the black hole. Another scenario for BH+Psr creation is possible: when a neutron star forms before a black hole. At that time the pulsar has a long and still purely explained history. Fortunately, this part of these evolutionary tracks is small (see below).

Note that the evolutionary scenario contains quite a number of key parameters that are poorly explained by theory (the stellar wind magnitude, the initial mass of a star which is able to form a black hole, the mass ratio distribution of the initial binary stars, the kick velocity during relativistic star formation, the efficiency of the common-envelope stage and part of the mass falling into the BH during collapse). Although it is possible to reduce them significantly (Lipunov et al. 1994; Lipunov, Postnov & Prokhorov 1997), in the present work we assume them to be independent parameters. The qualitative influences of these parameters on the stellar evolution scenario have been investigated more than once in previous works (de Jager 1980; Shore, Livio & van den Heuvel 1994; Lipunov, Postnov & Prokhorov 1996; Lipunov et al. 1997; Woosley et al. 2002) and it is possible to briefly delineate them in the following way.

The stellar wind magnitude essentially influences the scenario for two reasons. First, the spherically symmetric wind leads to an increase in component separation. Secondly, the total mass loss of a star by wind may cause a change in its remnant type (it may produce a neutron star instead of a black hole).

By increasing the initial mass $M_{\min}$ of a star which is able to form a black hole, one decreases the possible number of black holes due to the Salpeter power law (i).

The mass ratio distribution of the initial binary stars is important because BH+Psr binaries have massive progenitors, so in the case of a flatter ($\alpha_q \to 0$) distribution (ii) the probability of the birth of a BH+Psr system decreases.

The anisotropic kick during compact star formation has been investigated in detail by Lipunov, Postnov & Prokhorov (1997). An increase in the kick velocity leads to total decay of the binary stars including the relativistic companion. It was shown that an average kick velocity of $\langle v \rangle \approx 150$–$180$ km s^{-1} is in accord with the observable number of binary radio pulsars. Over the last few years a two-component kick velocity distribution with characteristic velocities of 90 and 500 km s^{-1} has been suggested (Arzoumanian 2000).

The effectiveness of the CE stage is described by the parameter $\alpha_{\mathrm{CE}} = \Delta E_{\mathrm{b}}/\Delta E_{\mathrm{orb}}$, where $\Delta E_{\mathrm{b}} = E_{\mathrm{grav}} - E_{\mathrm{thermal}}$ is the binding energy of the ejected envelope matter and ΔE_{orb} is the drop in the orbital energy of the system during spiral-in (Shore et al. 1994). Our population synthesis results shows a very weak dependence on the efficiency of the CE stage due to the flat initial distribution of the major semi-axis of the binaries (on a logarithmic scale). If one is decreasing α_{CE} close binary systems are originating from wider and wider binaries, the number of which is not changing on account of the flat initial distribution (Shore et al. 1994). We suggest $\alpha_{\mathrm{CE}} = 0.5$ (Lipunov et al. 1997), which is satisfactory for very close binary systems to form even in the case of a very high stellar wind. Henceforth we do not investigate any dependences on this parameter.

The part of the mass falling into the BH during collapse is denoted as $k_{\mathrm{bh}} = M_{\mathrm{bh}}/M_{\mathrm{preSN}}$, where M_{bh} is the black hole mass and M_{preSN} is the pre-supernova mass. It is an important value because the binary can experience possible decay depending on the quantity of mass ejected by a star during the supernova explosion, i.e. the smaller k_{bh} is, the smaller the chance a system has to survive the cataclysm.

We emphasize that the purpose of this work is not to find an optimal model(s) of stellar evolution (another work will concentrate on that point) but to show that the number of radio pulsar–black hole systems in the Galaxy has to be sufficient under any plausible evolution scenario parameters to observe them within the next few years. So we have obtained multiple models using various appropriate parameters.

As in Lipunov et al. (1994), we were calculating the ratio of the number of binary radio pulsars with black holes to the total number of pulsars (the latter being practically the number of single pulsars). This allows one to avoid many selection effects concerned with our lack of knowledge of the average polar pattern of pulsars, their lifetime, magnetic field decay time, the distribution of velocity of pulsars and their spatial distribution emerging in calculations of the absolute number as long as we assume that the physical parameters of radio pulsars paired with black holes have no differences relative to the average characteristics of the pulsars of the field. This natural suggestion is justified because all of them have the same progenitors, massive ($M > 10\,\mathrm{M}_\odot$) stars and, as was shown by our calculations, the part taken up by the non-typical evolutionary tracks[2] in BH+Psr binaries and any other radio pulsars (binary and, of course, single) is negligible (in most of models this quantity is smaller than 5 per cent and never higher than 35 per cent).

As BH+Psr systems have not been observed as yet, we suggest that the observational limit is $[(\mathrm{BH+Psr})/\mathrm{Psr}] \lesssim 1/1500$, where 1500 is a rounded number for the observed radio pulsars (binary and single; ATNF psr catalogue 2005).

2 DESCRIPTION OF MODELS

Common parameters for all of the models are (Lipunov et al. 1996): (i) the initial mass distribution (Salpeter function), where M_1 is the initial mass of the more massive star; (ii) the mass ratio function, where $q = M_2/M_1$ is the mass ratio of the initial component and α takes on the values 0 and 2; (iii) the semimajor axis distribution, where a is the semimajor axis within the limits of $10 < a < 10^6\,\mathrm{R}_\odot$ (Krajcheva et al. 1981):

$$f(M) = M_1^{-2.35}, \tag{1}$$

$$f(q) = q^{\alpha}, \tag{2}$$

$$f(a) = \frac{1}{a}. \tag{3}$$

The kick velocity along with the mass-loss rate is one of the crucial and poorly fixed parameters affecting the population synthesis results. A higher kick leads to a reduction in the number of binary systems containing relativistic companions (Lipunov et al. 1997). Although information concerning the kick for neutron stars may be found from the observable binary radio pulsars statistics (Lyne & Lorimer 1994; Hansen & Phinney 1997) and from the velocities of single pulsars, the kick for neutron stars is still under discussion (Willems, Kalogera & Henninger 2004; Murphy, Burrows & Heger 2004; Podsiadlowski et al. 2004).

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[1] Of course, the anisotropic kick plays an important role in this process, it leads not only to disruption of the system, but, if the kick velocity and direction are apt, it can bind a binary during the supernova explosion.

[2] When binary radio pulsars parameters might be dissimilar to the parameters of single radio pulsars, for instance, due to the effect of recycling.

In this work we have assumed a Maxwellian distribution for the kick velocity v during neutron star and black hole formation:

$$f(v) \sim \frac{v^2}{v_0^2} \exp\left(-\frac{v^2}{v_0^2}\right), \tag{4}$$

where v_0 is the characteristic kick velocity.

Even less it is known about the probable black hole kick, that is why we vary this quantity v_0^{bh} within the bounds of 0 and 1000 km s^{-1}, undoubtedly exceeding observable uncertainties. The absolute value of the characteristic kick velocity for black holes also depends on the proportion of mass lost during black hole formation:

$$v_0 = v_0^{\mathrm{bh}} \frac{M_{\mathrm{preSN}} - M_{\mathrm{bh}}}{M_{\mathrm{bh}}}, \tag{5}$$

where M_{preSN} is the star mass before collapse and M_{bh} is the black hole mass.

We have depicted the most important characteristic, the mass-loss rate of optical stars during evolution, by dint of five models: A, B, C, Wc and Wb.

Scenario A has a weak stellar wind. The mass-loss rate $\dot{M}$ during the main-sequence (MS) stage (de Jager 1980) is

$$\dot{M} \sim L/V_{\infty}, \tag{6}$$

where L is the luminosity of the star and V_{∞} is the wind velocity at infinity.

For giants we take a maximum between (6) and the result obtained by Lamers (1981):

$$\dot{M} \sim L^{1.42} R^{0.61} / M^{0.99}, \tag{7}$$

where R is the stellar radius and M is its mass.

For red supergiants we take a maximum between (6) and Reimers's formula (Kudritzki & Reimers 1978):

$$\dot{M} \sim LR/M. \tag{8}$$

The mass change ΔM in wind type A during one stage is no more than $0.1(M - M_{\mathrm{core}})$, where M is the mass of the star at the beginning of a stage and M_{core} is its core mass. Mass loss during the Wolf–Rayet (WR) star stage is parametrized as $0.1\,M_{\mathrm{WR}}$, where M_{WR} is the maximum star mass during this stage. For calculations of stellar wind type A we used the core masses obtained by Varshavskii & Tutukov (1975) and Iben & Tutukov (1985, 1987).

Scenario B uses calculations of single-star evolution by Schaller et al. (1992). According to these calculations, a massive star loses most of its mass because of the action of the stellar wind, down to $\approx$8–10 $\mathrm{M}_{\odot}$ before collapse, practically independent of its initial mass.

In scenario C the stellar evolution model is based on the results of Vanbeveren et al. (1998), which reproduce most accurately the observed galactic WR star distributions and stellar wind mass loss in massive stars. Calculations of mass loss by a star were conducted using the formula

$$\Delta M = (M - M_{\mathrm{core}}), \tag{9}$$

where M_{core} is the stellar core mass (equations 10α–10ϵ). If the maximum mass of the star (usually it is initial mass of a star, but mass transfer in binary systems is able to increase its mass over the initial value) $M_{\max} > 15\,\mathrm{M}_{\odot}$, the mass of the core in the main-sequence stage is determined using (10α), and in giant and in supergiant stages using (10β). In the Wolf–Rayet star stage, if $M_{\mathrm{WR}} < 2.5\,\mathrm{M}_{\odot}$ and $M_{\max} \leqslant 20\,\mathrm{M}_{\odot}$ it is described using (10γ), if $M_{\mathrm{WR}} \geqslant 2.5\,\mathrm{M}_{\odot}$ and $M_{\max} \leqslant 20\,\mathrm{M}_{\odot}$ as (10δ), if $M_{\max} > 20\,\mathrm{M}_{\odot}$ using (10ϵ):

$$M_{\mathrm{core}} = \begin{cases} 1.62 M_{\max}^{0.83}, & (\alpha) \\ 10^{-3.051+4.21 \log M_{\max} - 0.93 (\log M_{\max})^2}, & (\beta) \\ 0.83 M_{\mathrm{WR}}^{0.36}, & (\gamma) \\ 1.3 + 0.65(M_{\mathrm{WR}} - 2.4), & (\delta) \\ 3.03 M_{\max}^{0.342}, & (\epsilon). \end{cases} \tag{10}$$

Scenario C has high mass loss during the WR stage, it may reach 50 per cent of a star mass or more here. Mass loss in other stages (MS, giant, supergiant) for stars with masses higher than 15 $\mathrm{M}_{\odot}$ (for less massive stars this scenario is equivalent to a type A wind) may reach $\approx$30 per cent of the mass of a star. The total mass loss ΔM during all stages is always smaller than in scenario B and greater than in scenario A.

The W model consists of two types: with moderate (Wc) and with high (Wb) stellar wind. To calculate the parameter k_{bh}, pre-supernova, helium core and compact remnant masses according to the initial star mass were taken from Woosley et al. (2002, fig. 16) and Heger et al. (2002, fig. 2). We calculate k_{bh} as the ratio $M_{\mathrm{bh}}/M_{\mathrm{preSN}}$, where M_{preSN} is the mass of the pre-supernova star which produced the black hole with mass M_{bh}. We made our calculations under the assumption that model Wc has a type C wind and for model Wb we used a type B wind. This suggestion is correct because Schaller et al. (1992) made his calculations using the stellar wind obtained by Nieuwenhuijzen & de Jager (1990) [this type of wind was used by Woosley et al. (2002), Heger et al. (2002) as a high mass-loss type], Vanbeveren et al. (1998), including the mass-loss rate by Hamann & Koesterke (1998) [this type of wind was used by Woosley et al. (2002), Heger et al. (2002) as a reduced mass-loss type].

The parameter k_{bh} in models A–C is an adjusted constant value for all supernova explosions; in Wc and Wb models it is a variable quantity, dependent on the initial mass of a star which is able to produce the black hole.

Finally, it is necessary to introduce the minimal mass for the black hole $M_{\min}$ (i.e. the minimal pre-supernova star mass which is able to form a black hole multiplied by k_{bh}), which has been used for calculations in models A–C. We vary this parameter within very wide bounds: $2.5 \leqslant M_{\min} \leqslant 10\,\mathrm{M}_{\odot}$.

3 OBSERVATIONAL FOUNDATION

To estimate the probable number of binary pulsars with black holes we need to be guided by the observable quantity of black hole candidates in our galaxy. From this viewpoint the nearest relative to a black hole paired with a radio pulsar is the Cyg X-1 type system – a black hole paired with a blue supergiant. These binaries (BH+OB) are radio pulsars paired with black hole progenitors. As is well known we have observed only one such source in the Galaxy at the present time, Cyg X-1. Although it is not possible to speak about statistics, following van Paradijs & McClintock (1993) we suggest that this object is not a statistical anomaly and the total number of such systems in the Milky Way may reach a few. The existence of similar candidates in the Large Magellanic Cloud (LMC X-1 and X-3) convinces us of this.

As we have already noted that Cyg X-1 is not simply a binary consisting of a black hole and a blue supergiant; it is a very close binary system in which the regime of disc accretion on the black hole has been realized. This has not occurred by chance – a very low stellar wind velocity is necessary to form an accretion disc (Lipunov 1992):

$$V < V_{\mathrm{cr}} \approx 320 (4\eta)^{1/4} m^{3/8} T_{10}^{-1/4} R_8^{-1/8} (1 + \tan^2 \beta)^{-1/2}, \tag{11}$$

where η is averaged over the z-coordinate dynamic viscous coefficient, $m = M_x/\mathrm{M}_\odot$, M_x is the relativistic star mass, $T_{10} = T/10$, T is the orbital period in days, $R_8 = R_{\min}/10^8$ cm, $R_{\min}$ is the minimal distance from the compact object up to which free Keplerian motion is still possible and β is the accretion axis inclination angle with respect to the radial direction. For black holes $R_{\min} = 3R_{\mathrm{g}}$, where $R_{\mathrm{g}} = 2\,GM_{\mathrm{bh}}/c^2$.

The stellar wind velocity rises with increasing distance R from the normal star approximately as follows (de Jager 1980):

$$V = V_\infty(1 - R/a)^{1/2}, \tag{12}$$

where a is the characteristic radius of the star – an accretion disc does not form in most cases. Actually, the velocities of stellar winds are not precisely measured (de Jager 1980). However, equation (12) is quite a good approximation for this work. A spherically symmetric accretion could not give a bright source on the sky (Karpov & Lipunov 2001). Thus, in the present paper we assume throughout that a system of Cyg X-1 type is a very close binary including a blue supergiant with mass higher than 10 $\mathrm{M}_\odot$ in which the disc accretion regime has been realized by the data (11).

Let us estimate (11) and (12) for Cyg X-1. Davis & Hartmann (1983) obtained $V_\infty = 2300 \pm 400$ km s^{-1} for this system. It gives a lower limit for the wind velocity near the black hole of $V \approx 1240$ km s^{-1} (12). Parameters in (11) and (12) for Cyg X-1 have the values (Abubekerov, Antokhina & Cherepashchuk 2004): $R/a \approx 0.57$, $T_{10} = 0.56$, $m = 10$, $R_8 = 0.1$ and $\tan\beta \approx 0.1$; we also assume that $(4\eta)^{1/4} \approx 1$. So, the critical velocity $V_{\mathrm{crit}} \approx 1170$ km s^{-1}. Taking into account that the observational data have great uncertainties in V_∞ and (11) has an approximate character ($V < V_{\mathrm{cr}} \approx \cdots$), this coincidence can be considered quite good. Hence our theoretical estimates (11) and (12) are in approximate agreement with the observational data concerning accretion disc formation conditions in the Cyg X-1 system.

We especially note that Cyg X-1 is not a direct forerunner of a binary radio pulsar with a black hole, most likely this system will merge after Roche lobe infill and the common-envelope stage (Bethe & Brown 1999). However, it is clear that Cyg X-1 type systems are very similar to BH+Psr progenitors which becomes apparent in the correlation between their abundances during population synthesis (see below).

During population synthesis we were picking out only the pulsars with black holes having observable orbital periods (less than 10 yr; Lamb & Lamb 1976; Manchester & Taylor 1977; Johnston et al. 1992; ATNF psr catalogue 2005). It may be hard to find larger periods and most known binary radio pulsar orbital periods are less than 4 yr.

4 RESULTS

The dependence of the quantity of radio pulsars with black hole binaries on the Cyg X-1 number $N_{\mathrm{Cyg\,X-1}}$ numerical modelling results are presented in the two figures. Note that we calculate the number of BH+Psr systems as the ratio 1500 $[N_{\mathrm{BH+Psr}}/N_{\mathrm{Psr}}]$, where 1500 is the rounded number of known radio pulsars, $N_{\mathrm{BH+Psr}}$ is the number of BH+Psr binaries and N_{Psr} is the total number of radio pulsars appearing during population synthesis.

There were no Cyg X-1 type systems in all of the models with type B wind including the Wb model, so all of these scenarios must be discounted right away because we observe the object and do not regard it as a statistical anomaly.

In the models shown in Fig. 1 for mass-loss scenarios A and C, a very wide range is given for all of the unknown parameters. As we know only one Cyg X-1 type X-ray source (namely Cyg X-1) and the purpose of this work is to display that under any feasible parameters BH+Psr systems have to be observable, we have presented in Figs 1 and 2 only models in which the number of Cyg X-1 type systems is no more than four and the number of BH+Psr binaries is no more than three. The ‘forbidden zone’ in these figures is the highlighted area where there are no models with conceivable appropriate parameters.

Black squares (model 1, Fig. 1) denote the model calculated with $k_{\mathrm{bh}} = 0.45$, minimal black hole mass $M_{\min} = 7\,\mathrm{M}_\odot$, mass-loss type A and a uniform initial mass ratio distribution ($\alpha_q = 0$). The characteristic kick velocity v_0 for neutron stars and the parameter v_0^{bh} for black holes take on values of 0, 180, 360 and 720 km s^{-1}. We change these velocities for NS and BH both to give a demonstration of its influence on the dependence between BH+Psr and Cyg X-1 quantities. The number of BH+Psr systems is much more than three if $v_0 = 0$ and $v_0^{\mathrm{bh}} = 0$, so this point is not presented. Models in which the characteristic kick velocity for neutron stars and the parameter v_0^{bh} for black holes take on values of 720, 360 and 180 km s^{-1} are shown in order of increasing numbers of Cyg X-1 type systems (a higher kick reduces the number of binaries including a relativistic companion).

Grey circles (model 2, Fig. 1) depict models with a stellar wind of type A, a uniform initial mass ratio distribution ($\alpha_q = 0$), a characteristic kick velocity of $v_0 = 180$ km s^{-1} for neutron stars and a parameter $v_0^{\mathrm{bh}} = 180$ km s^{-1} for black holes. During calculations the quantity k_{bh} has been varied within the limits of 0.1 and 1 in steps of 0.1, the black hole minimal mass takes on values of 2.5, $3.0, 4.0, \ldots, 9.0, 10.0\,\mathrm{M}_\odot$. Circles in Fig. 1 evidently group in some vertical lines. Each line corresponds to one value of k_{bh}, minimal black hole masses change along lines. Cyg X-1 type systems are usually products of the evolution of very massive binaries, so the difference between their number in the case of $M_{\min} = 10\,\mathrm{M}_\odot$ and in the case of $M_{\min} = 2.5\,\mathrm{M}_\odot$ is negligible. Otherwise the number of binary radio pulsars with black holes has a strong dependence on the minimal black hole mass – the greater $M_{\min}$ is, the lower the number of BH+Psr systems. So the bottom–up sequence order of points in lines which depict models with various k_{bh} is: $M_{\min} = 10, 9, \ldots, 4, 3, 2.5\,\mathrm{M}_\odot$. The parameter k_{bh} influences both the number of Cyg X-1 and BH+Psr systems: the greater k_{bh} is, the larger the number of binaries including a relativistic companion. Note that in many cases the number of Cyg X-1 or BH+Psr systems is higher than the limits in Fig. 1. That is why in this figure we present only those models in which $k_{\mathrm{bh}} \leqslant 0.6$ and not all points in vertical lines. So for model 2 vertical lines correspond (in order of decreasing $N_{\mathrm{Cyg\,X-1}}$) to the following k_{bh} values: 0.6, 0.5, 0.4, 0.3. Models with $k_{\mathrm{bh}} = 0.1$, 0.2 have no Cyg X-1 type binaries and are merged with many other models without such systems in Fig. 1.

Open squares (model 3, Fig. 1) describe models with a type C stellar wind and a quadratic initial mass ratio distribution ($\alpha_q = 2$). The quantity k_{bh}, the minimal black hole mass $M_{\min}$, the characteristic kick velocity for neutron stars v_0 and the parameter v_0^{bh} for black holes take on the same values as in model 2. Also as in model 2 points group into some vertical lines corresponding to their k_{bh} values, with minimal BH mass change along the lines. The maximum k_{bh} value for the models presented is 0.7.

Black triangles (model 4, Fig. 1) mark models with a type A stellar wind and a quadratic initial mass ratio distribution ($\alpha_q = 2$). The quantity k_{bh}, the minimal black hole mass $M_{\min}$, the characteristic kick velocity for neutron stars v_0 and the parameter v_0^{bh} for black holes take on the same values as in model 2. Also as in model 2 points group into some vertical lines corresponding to their k_{bh} value, with

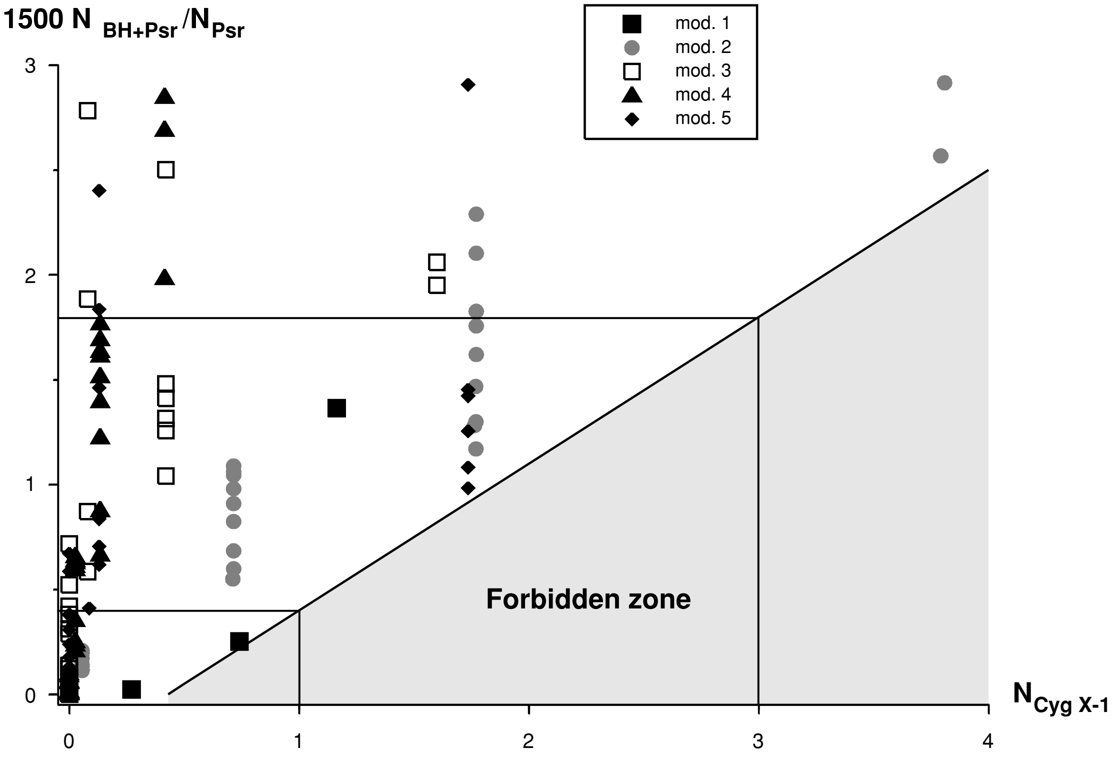

Figure 1. Dependence between the number of BH+Psr binaries and Cyg X-1 type systems. The ‘forbidden zone’ is the highlighted area where there are no models with conceivable appropriate parameters of stellar evolution. See text (Section 4, fourth paragraph) for more details.

minimal BH mass change along the lines. The maximum k_{bh} for the models presented is 0.6.

Black diamond formations (model 5, Fig. 1) designate models with stellar wind of type C and a uniform initial mass ratio distribution ($\alpha_q = 0$). The quantity k_{bh}, the minimal black hole mass M_{min}, the characteristic kick velocity for neutron stars v_0 and the parameter v_0^{bh} for black holes take on the same values as in model 2. Also as in model 2 points group into some vertical lines corresponding to their k_{bh} values, with minimal BH mass change along the lines. The maximum k_{bh} for the models presented is 0.6.

As one can see from Fig. 1, in the value area containing at least one black hole candidate of Cyg X-1 type, all of the models comply with the condition $1500\,[(N_{\mathrm{BH+Psr}})/N_{\mathrm{Psr}}] \gtrsim 0.4$. In the zone which has limits $1 \leqslant N_{\mathrm{Cyg\,X-1}} \leqslant 3$, the lower limit of the number of binary radio pulsars with black holes is between ≈0.4 and ≈1.75 in all models.

In Fig. 2 two kinds of Wc models are shown (the Wb model is discounted because it has no Cyg X-1 type systems).

Upright crosses (model 6, Fig. 2) describe a model with a uniform initial mass ratio distribution ($\alpha_q = 0$). During calculations the characteristic kick velocity v_0 for neutron stars and the parameter v_0^{bh} for black holes take on the values 0, 180, 360, 720 and 1000 km s^{-1}. If $v_0 = 0$ and $v_0^{\mathrm{bh}} = 0$, the quantity of Cyg X-1 systems and BH+Psr binaries is more than the limits of Fig. 2 and the appropriate point is not presented. So upright crosses depict model 6 and crossbucks depict model 7 in which the characteristic kick velocity for neutron stars and the parameter v_0^{bh} for black holes taking on values of 180, 360, 720 and 1000 km s^{-1} are shown respectively in order of decreasing numbers of Cyg X-1 type systems.

Crossbucks (model 7) denote models with a quadratic initial mass ratio distribution ($\alpha_q = 2$). During calculations the characteristic

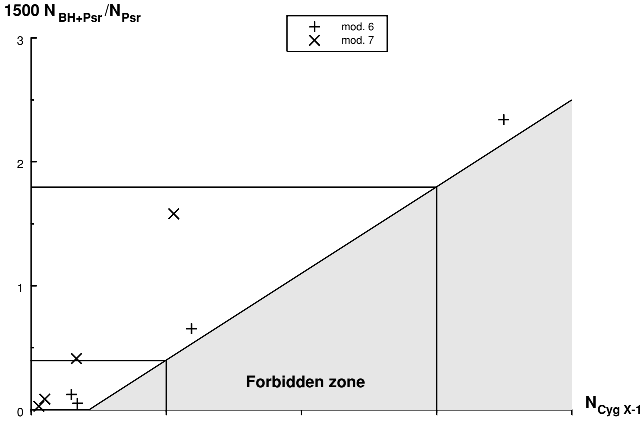

Figure 2. The dependence between the number of BH+Psr binaries and Cyg X-1 type systems (Wc model). Upright crosses (model 6) describe models with a uniform initial mass ratio distribution ($\alpha_q = 0$). Crossbucks (model 7) denote a model with a quadratic initial mass ratio distribution ($\alpha_q = 2$). During calculations the characteristic kick velocity v_0 for neutron stars and the parameter v_0^{bh} for black holes take on values of 0, 180, 360, 720 and 1000 km s^{-1} in both cases. If $v_0 = 0$ and $v_0^{\mathrm{bh}} = 0$ the quantity of Cyg X-1 systems and BH+Psr binaries is greater than the limits in the figure and the point is not presented. So upright crosses depict model 6 and crossbucks depict model 7 in which the characteristic kick velocity for neutron stars and the parameter v_0^{bh} for black holes take on values of 180, 360, 720 and 1000 km s^{-1} are shown correspondingly in order of decreasing numbers of Cyg X-1 type systems. The ‘forbidden zone’ is the highlighted area where there are no models with conceivable appropriate parameters of stellar evolution.

kick velocity v_0 for neutron stars and the parameter $v_0^{\rm bh}$ for black holes take on values of 0, 180, 360, 720 and 1000 km s^{-1}. If $v_0 = 0$ and $v_0^{\rm bh} = 0$ the quantity of Cyg X-1 systems and BH+Psr binaries is more than the limits of Fig. 2 and appropriate points are not presented. So upright crosses depict model 6 and crossbucks depict model 7, in which the characteristic kick velocity for neutron stars and the parameter $v_0^{\rm bh}$ for black holes take on values of 180, 360, 720 and 1000 km s^{-1} are shown respectively in order of decreasing numbers of Cyg X-1 type systems.

It is evident from Fig. 2 that in the value area containing at least one black hole candidate of Cyg X-1 type, all of the models comply with a condition 1500 $[(N_{\rm BH+Psr})/N_{\rm Psr}] \gtrsim 0.4$. In the zone which has limits $1 \leqslant N_{\rm Cyg\,X-1} \leqslant 3$ the lower limit on the number of binary radio pulsars with black holes is between ≈0.4 and ≈1.75 in all models.

5 CONCLUSIONS

Lipunov et al. (1994) drew the conclusion that BH+Psr binaries observable by modern techniques have to be present in the Galaxy. Despite new theories concerning the evolution of the appearance of massive stars, we confirm this conclusion concerning the possibility of discovering binary radio pulsars with black holes. We suggest that with the expected value of pulsars paired with black holes, a comparative abundance may be found within the limits $0.4 \lesssim [(N_{\rm BH+Psr})/N_{\rm Psr}]\ 1500 \lesssim 2$. We also confirm the conclusion made by Lipunov et al. (1994) concerning the high eccentricity of such systems (Fig. 3) and on there being a sufficient number of systems close enough to observe (Fig. 4). The distribution of eccentricities shows an evident peak at $e \approx 1$, which is the consequence of mass loss and the kick during the second supernova explosion (Kornilov & Lipunov 1984).

Our calculations are important for the estimation of merging of BH+BH and BH+NS systems. The results of Lipunov & Panchenko (2003) show that the merging rate can increase by ≈5–7 times with respect to previous computations made by Lipunov et al. (1997). New estimations of the merging rate of relativistic systems will be carried out in future work.

In closing we emphasize again that the results of this work do not depend on optimal evolutionary scenario parameters: radio pulsars paired with black holes have to be in the Galaxy and might be discovered within the next few years. We emphasize the fact that the relative number of BH+Psr systems to the total number of pulsars has been calculated in this work and most of the pulsars do not experience a recycling effect. The radio pulsars in BH+Psr binaries used in our calculations have no differences with respect to more than 90 per cent of the radio pulsars that have already been observed.

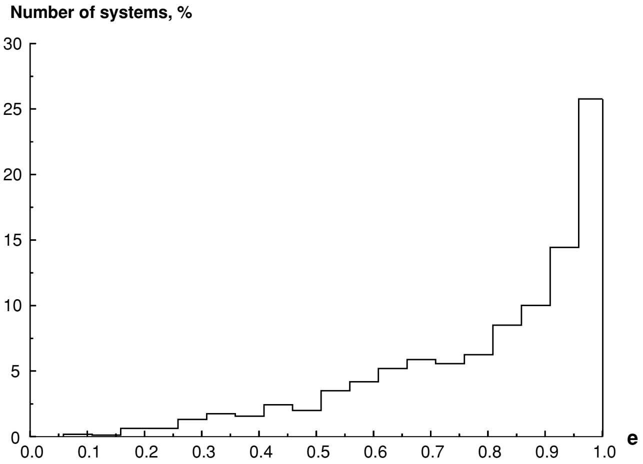

Figure 3. The eccentricity distribution of BH+Psr binaries in the Wc model with a quadratic initial mass ratio distribution ($\alpha_q = 2$), the characteristic kick velocity for neutron stars v_0 and the parameter $v_0^{\rm bh}$ for black holes take on a value of 180 km s^{-1}.

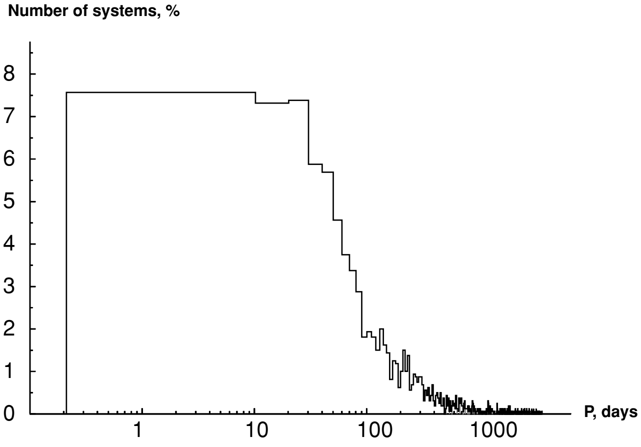

Figure 4. The orbital period distribution of BH+Psr binaries in the Wc model with a quadratic initial mass ratio distribution ($\alpha_q = 2$), the characteristic kick velocity for neutron stars v_0 and the parameter $v_0^{\rm bh}$ for black holes take on a value of 180 km s^{-1}.

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APPENDIX: POSSIBLE EVOLUTIONARY TRACKS WHICH PRODUCE BH+PSR BINARIES

We have presented possible evolutionary tracks that produce BH+Psr binaries in Table A1 and possible evolutionary tracks that produce Psr+BH systems in Table A2. Note that they do not depict all the possibilities and the evolution of a concrete binary depends strongly on the evolutionary scenario. In both cases we used stellar wind type A, with parameter $k_{\mathrm{bh}} = 0.43$.

Marks in Tables A1 and A2 depict the following stages: MS, main-sequence stage; SG, supergiant stage; Rov, Roche lobe overflow stage; WR, Wolf–Rayet star stage; BH, black hole; Psr, radio pulsar; Ej, ejecting neutron star which does not appear itself as a radio pulsar due to free–free absorption of radio emission in the stellar wind of the second component [a detailed nomenclature of neutron stars may be found in the book written by Lipunov (1992)]; and SN, a supernova explosion.

Table A1. Possible evolutionary track which produces BH+Psr.

Stage of primary star (1)	Stage of secondary star (2)	$M_1/\mathrm{M}_\odot$	$M_2/\mathrm{M}_\odot$	$a/\mathrm{R}_\odot$	Time (10^6 yr)	CE stage
MS	MS	69.5	5.1	700	0.0	–
SG	MS	66.4	5.0	730	3.3	–
Rov	MS	63.5	5.0	760	≈3.6	+
WR	Rov	37.9	5.1	13	≈3.6	–
SN						
BH	Rov	16.4	4.9	410	3.7	–
BH	WR	16.4	4.9	14	4.9	–
	SN					
BH	Psr	16.4	1.34	21	26.3	–

Table A2. Possible evolutionary track which produces Psr+BH.

Stage of primary star (1)	Stage of secondary star (2)	$M_1/\mathrm{M}_\odot$	$M_2/\mathrm{M}_\odot$	$a/\mathrm{R}_\odot$	Time (10^6 yr)	CE stage
MS	MS	23.9	11.5	450	0.0	–
SG	MS	22.4	11.4	480	6.3	–
Rov	MS	21.0	11.4	500	≈6.9	–
WR	MS	8.5	23.9	690	≈6.9	–
SN						
Psr	MS	1.34	23.9	790	7.1	–
Ej	SG	1.34	22.3	830	13.0	–
	SN					
Psr	BH	1.34	9.0	80	14.0	–

The first and second columns in each table contain information concerning the current stage of the primary (more massive) and secondary companion, respectively; the third and fourth columns gives their masses; the fifth column contains the value of the major semi-axis of the system; in the sixth column we have presented the time elapsed from the moment of birth of the binary system. The seventh column answers the question of whether or not the system is in the common-envelope stage.

Tracks which produce a neutron star before a black hole can lead to the formation of so-called ‘recycled’ radio pulsars. In general, we calculate the evolution of rotation of a neutron star and can include these pulsars within our considerations. Nevertheless, in this case the results of our work would be dependent on many extra assumptions: the distribution of neutron stars on their magnetic field, the magnetic field dissipation time, the influence of accretion on the magnetic field of the neutron star, etc. We prefer not to use any additional hypothesis since part of such tracks is negligible (see the introduction).

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