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ON THE NATURE OF THE BINARY RADIO PULSAR PSR B0042−73 IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

The modern scenario of evolution of massive binary systems predicts the existence of a subclass of binary radio pulsars (PSRs) with black holes (BHs). Their Galactic number was evaluated as ~1 per 1000 single pulsars (Lipunov et al. 1994b). Distinctive properties of such binaries would be (1) mass of the unseen companion $M_c > 3\text{–}4\ M_\odot$ and (2) absence of eclipses of the pulsar radiation with no distinctive variance of the dispersion measure along the pulsar orbit. The pulsars themselves must be similar to standard isolated ones. The recently discovered binary 1 s pulsar PSR B0042−73 = PSR J0045−7319 in the Small Magellanic Cloud (SMC) with a massive companion in a highly elongated (eccentricity $e = 0.8$) 51 day orbit (Kaspi et al. 1994) may be the first such pulsar with a BH. The paradoxical fact that the first pulsar discovered in the SMC proved to be in a binary system can be naturally understood if its companion actually is a 10–30 $M_\odot$ black hole. We illustrate this fact by the numerical calculation of evolution of radio pulsars after a star formation burst.

Subject headings: binaries: close — black hole physics — pulsars: individual (PSR B0042−73)

1. INTRODUCTION

Soon after the discovery of neutron stars, it was recognized that a rotating magnetized star should appear differently depending on the physical conditions of the surrounding plasma (density, velocity, temperature, etc.) (Shwartsman 1970; Illarionov & Sunyaev 1975; see detailed review in Lipunov 1992), so the neutron star in a binary system would be a genuine plasma probe (Lipunov & Prokhorov 1984). Until recently, neutron stars in massive binaries have been observed only as X-ray pulsars accreting matter from the Roche lobe–filling component or from the stellar wind of a massive Be star. PSR B1259−63 (Johnston et al. 1992) was the first detected binary consisting of a Be star and a radio pulsar, which was in accordance with theoretical expectations of the number of such binaries in the Galaxy (~1 per 500 single radio pulsars; Kornilov & Lipunov 1983). Evolutionary considerations based on the current understanding of massive binary systems (see Bhattacharia & van den Heuvel 1991 and references therein for a review of evolutionary scenarios) have led to the conclusion that black hole + radio pulsar (BH + PSR) binaries constitute a subclass equally numerous (~1 per 1000 isolated pulsars; Lipunov et al. 1994b). This means that the massive radio pulsar binary in the SMC discovered by Kaspi et al. (1994) can be either a PSR + Be or a PSR + BH binary with roughly equal probability.

A 16th mag B1 star detected inside the radio error box of this pulsar was suggested as the optical companion of a possible pulsar. This identification, however, must be proved by optical detection of variations of the B star radial velocity with the 51 day period.

In the present paper we focus on the second possibility, that the PSR B0042−73 is a binary pulsar with a massive black hole companion.

2. PSR B0042−73: A CANDIDATE PSR+BH BINARY

The interpretation of the reported 16th mag B star as a companion to the PSR B0042−73 encounters some difficulties (Kaspi et al. 1994), which, to our mind, are principal. The basic arguments against this star as the optical companion to the PSR B0042−73 are as follows:

1. Observations show no eclipse or distortion of the pulsar radiation as it passes close to the orbital periastron (Kaspi et al. 1994). Taking the observed parameters of the PSR B0042−73 binary, a condition for the optical depth against free-free absorption of the 430 MHz radio emission by a fully ionized spherically symmetrical stellar wind with a constant velocity v, $\tau < 1$ close to the periastron, requires $\dot{M}_{-8} < 10^{-3} \times v_8$, where $\dot{M}_{-8} \equiv \dot{M}/(10^{-8}\ M_\odot\ \text{yr}^{-1})$ is the rate of the wind, $v_8 \equiv v/10^8$ cm s^{-1} (see Lipunov et al. 1994a for a more detailed study of pulsars with massive optical companions). A similar restriction on the value of $\dot{M}$ is imposed by the 3 σ upper limit of the observed dispersion measure variance 3.2 pc cm^{-3} (Kaspi et al. 1994). The standard radiation-driven stellar wind rate for a B1 star with bolometric luminosity $\sim 3 \times 10^{37}$ ergs s^{-1} is of the order of $10^{-7.5}$ to $10^{-8.5}\ M_\odot$ yr^{-1} (de Jager 1980), which would completely absorb radio emission, unless one assumes an unusually weak stellar wind for a normal B1 star. In principle, weaker stellar mass loss rates in the Magellanic Clouds could be connected with the observed deficit of metals ($z_{\text{MC}} \sim 1/6 z_\odot$), and absorption of radiation by the lines of metals can be the main mechanism of stellar winds in massive stars (de Jager 1980). However, analysis shows that $\dot{M} \propto z^{1/2}$ (Kudritzki, Pauldrach, & Puls 1987); this reduces the maximum value of $\dot{M}$ 2–3 times, and the observed lack of absorption of the pulsar's radiation and dispersion measure constancy cannot be fully explained by the stellar wind chemical composition.

In addition, the low rates of stellar wind can hardly be a general property of all B stars in the SMC, because this would contradict the observational fact of a high X-ray luminosity of massive wind-fed X-ray binary sources in the Magellanic Clouds. We also note that the weak stellar winds from B stars that are transparent for the pulsar radiation in binary systems with a separation between components of 20 $R_\odot$ would lead to

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an unobservably high fraction of visible radio pulsars with massive normal stars among single pulsars in the Galaxy (~ 50 per 500 isolated pulsars).

2. The observed radial velocity of the B star is surprisingly close to the mean velocity of a field star in the SMC ≈ 165 km $\mathrm{s^{-1}}$, whereas the high orbital eccentricity $e \approx 0.8$, that must have been acquired during the last supernova explosion in this system, implies a high space velocity of the barycenter after the supernova explosion (e.g., Boersma 1961):

$$V_b \approx (100\ \mathrm{km\ s^{-1}}) m_c (m_p + m_c)^{-2/3} ,$$

where m_p and m_c are masses of the pulsar and its companion in solar units. With $m_p = 1.4$ and $m_p + m_c = 10$, we obtain $V_b \approx 200$ km $\mathrm{s^{-1}}$ much higher than the peculiar velocity dispersion in the SMC.

3. The apside-like motion rate is observed to be $\dot{\omega} = 0^\circ\!.010 \pm 0^\circ\!.003\ \mathrm{yr^{-1}}$. If this is interpreted as a sum of tidal quadrupole and relativistic effects for a BV star, even the 3 σ upper limit yields the upper mass limit of the pulsar's companion $M(B) < 8\ M_\odot$, which is too low for a reported 16th mag candidate (Kaspi et al. 1994). Minimal mass of the companion $\approx 4\ M_\odot$, evaluated from the companion mass function $f_c = 2.17\ M_\odot$ (Kaspi et al. 1994), corresponds to at least a B3 spectral class, implying we would observe it as a $m_v = 18.8$ star.

Instead, assuming a pure relativistic periastron advance that high, we get the total mass of the binary PSR B0042−73 $M_p + M_c = 43\ M_\odot(\omega/0^\circ\!.01/\mathrm{yr})^{3/2}$. This does not contradict the existence of a massive BH in this system.

The evolutionary track that can lead to a formation of a PSR + BH binary with the parameters similar to those of the PSR B0042−73 is presented in Table 1. Here we use the notations of evolutionary stages of the components introduced by Kornilov & Lipunov's (1983) statistical modeling of binary star evolution: roman numerals denote states of normal (nondegenerate) stars (I = main sequence; II = evolved giant not filling its Roche lobe; III = Roche lobe–filling star); WR stands for helium remnant after mass transfer (seen as a Wolf-Rayet star); E, P, A correspond to ejecting, propelling, and accreting stages of a compact magnetized star (white dwarf or neutron star) (see Lipunov 1992; Lipunov et al. 1994a, b for more details. No anisotropy during collapse onto a neutron star or black hole was assumed during the calculation. As we showed in a previous *Letter* (Lipunov et al. 1994b), from 30% to 70% of all PSR + BH binaries are formed via similar tracks ("Cyg X-1–connected tracks").

3. WHY IS THE ONLY KNOWN PULSAR IN THE SMC IN A BINARY SYSTEM?

The pulsar itself is a very efficient one; that is, it has the highest ratio of radio luminosity ($\sim 10^{30}$ ergs $\mathrm{s^{-1}}$) to the total rotational energy loss of neutron star ($\sim 10^{32}$ ergs $\mathrm{s^{-1}}$) (Kaspi et al. 1994). The number of such pulsars in the SMC can be estimated by scaling the Galactic pulsar number ($\sim 10^5$) by the ratio of the amount of the massive X-ray sources in the SMC to that in our Galaxy, $\sim 1/10$. Further, this figure must be multiplied by a factor of $\sim 1/100$ (the fraction of the efficient Galactic isolated pulsars; Taylor, Manchester, & Lyne 1993) times $\sim 1/20$ (the fraction of Galactic pulsars with the highest radio luminosity; Taylor et al. 1993). Possible selection effects, such as pulsar beaming, allow only several pulsars to be detected at the current sensitivity of 1 mJy.

The fact of the binarity of the first pulsar discovered in the SMC seems to be very strange, because in our Galaxy the fraction of binary pulsars with massive companions is $\sim 1/500$. Independently of the nature of the secondary companion, this fact can be explained only by a noticeable deficit of single stars and wide binaries at least among massive stars in the SMC. This deficit may be pointed to by the observed lack of Type II supernovae in the Magellanic Clouds, as was suggested by Shklovskii (1983).

The second independent factor that can increase the fraction of binary PSRs with massive companions is a possible burst-

TABLE 1

POSSIBLE EVOLUTIONARY TRACK LEADING TO PSR B0042−73 FORMATION

Stage	Observational Appearance	Δt (10^6 yr)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	A ($R_\odot$)	e
I + I	Two ZAMS stars	2	75.00	21.00	650	0
			71.72	20.35	680	
II + I	Giant + ZAMS	0.2	71.72	20.35	680	
			68.76	20.29	700	
III + I	Fast Roche lobe overflow and common envelope stage	0.01	68.76	20.29	700	
			42.18	32.10	120	
WR + I	OB + WR binary	0.073	42.18	32.10	120	
			37.96	32.10	120	
	"Silent Collapse" WR → BH					
bh + I	BH + MS star	2	11.39	32.10	320	0.61
			11.39	30.74	330	
bh + II	BH + OB giant; Cyg X-1–like binary	0.28	11.39	30.74	330	
			11.39	28.95	350	
sh + IIIS	Strongly supercritical accretion onto BH; SS 433–like object	6×10^{-4}	11.39	28.95	350	
			11.39	26.34	222	0.38
sh + III	Fast mass transfer; common envelope stage	0.01	11.39	26.34	220	
			11.39	12.86	21	0
bh ≈ WR	Massive close BH + WR; gravitational wave emission controls binary evolution	0.17	11.39	12.86	21	
			11.39	11.57	21	
	Explosion of the WR Star and Birth of Young Pulsar					
bh + E	Ejecting NS + BH; PSR B0042−73	12	11.39	1.40	100	0.8
			11.39	1.40	100	

like behavior of star formation in the Magellanic Clouds. Indeed, if one assumes a star formation burst to have occurred some 10^6 yr ago, one can expect a substantially larger fraction of massive binary pulsars among the whole pulsar population, because the majority of single pulsars are formed from ~ 10 $M_\odot$ stars, which have not evolved to this point at the present time. These massive binaries with pulsars will preferentially have black holes formed from the most massive short-lived stars (> 50 $M_\odot$). To illustrate this idea, we calculated the evolution of different types of radio pulsars (single and entering into binary systems) after a star formation burst by using the "Scenario Machine," a numerical code that models evolution of large ensembles of binary systems (Lipunov et al. 1994b). The results are presented in Figure 1. The relative numbers of different types of radio pulsars depend extremely on time elapsed after the burst, especially during first 10^6 yr. This shows that in a galaxy with a nonstationary star formation, one can expect quite different ratios between different types of radio pulsars. This can explain a surprisingly large fraction of PSR + BH binaries in the SMC.

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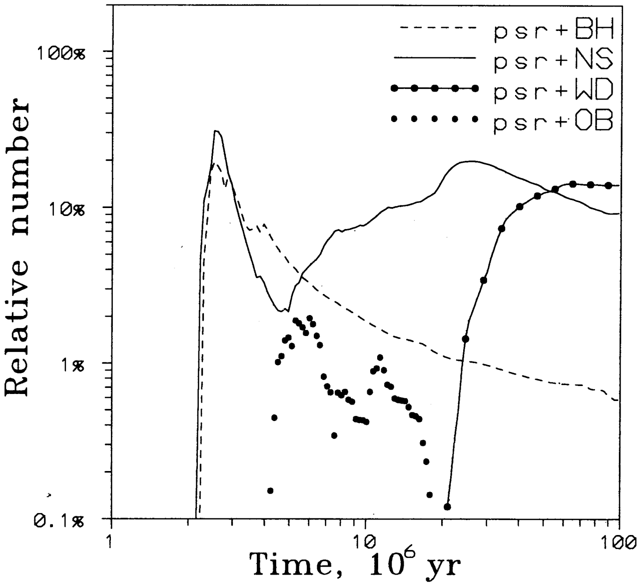

FIG. 1.—Relative number of visible binary radio pulsars with different secondary companions among single radio pulsars as a function of time (10^6 yr) after a model star formation burst. Evolution of 10^6 binary systems was tracked. Initial binary distributions and evolutionary parameters were the same as in Lipunov et al. (1994b), but the fraction of mass that collapses to form BHs was $k_{\rm BH} = 0.7$.

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