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ON THE EXISTENCE OF MASSIVE NEUTRON STARS

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Methods for estimating the masses of neutron stars in the Vela X-1, 4U 1700-37, and J0751+1807 are analyzed. The possible existence of massive neutron stars, the fraction of such stars among the overall total of neutron stars, and possible channels for their formation are discussed.

Keywords: *stars: neutron*

1. Introduction

At present the masses of about 30 neutron stars have been estimated. Only the mass estimates for radio pulsars in the binary Hulse-Taylor [1] and the recently observed binary radio pulsar J0737+3039 [3] have been done with precision. These estimates show that the mass of neutron stars lies within a fairly small interval, 1.25 - 1.44 $M_\odot$. Based on this, the standard mass of a neutron star is taken to be ~1.4 $M_\odot$ in many astrophysical calculations and standard formulas.

Theoretical calculations, however, show that the expected mass of neutron stars formed during the collapse of the nuclei of massive stars can lie in the range 1 - 1.8 $M_\odot$ [3-5]. The existence of neutron stars with masses greater than ~1.8 $M_\odot$ is not inconsistent with modern astrophysical ideas. There are a series of rigid equations of state for neutronic matter in which the Oppenheimer-Volkoff mass exceeds 1.8 $M_\odot$ [6]. Special attention should be paid to a recent series of papers on so-called skyrmion stars. IN 1999 Ouyed and Butler [7] examined an equation of state based on the Skyrme model [8]. A characteristic feature of neutron star models based on the Skyrme equation is a large limiting mass 2.95 $M_\odot$ for nonrotating configurations and 3.45 $M_\odot$ for rotating systems [9,10]. Another feature of neutron stars based on the Skyrme model is their large radius (up to 232 km).

Recent calculations of the evolution of the mass of neutron stars in binary systems on the "scenario machine" [11] show that channels for the evolution of binary systems are realized during the course of which a neutron star can increase its mass by more than ~1 $M_\odot$ owing to accretion [12,13].

An ever increasing number of observational indications of the possible existence of massive neutron stars have

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appeared recently. Three binary systems are already known in which the central values for the mass of the compact objects exceed $1.8\,M_{\odot}$. According to existing estimates, the mass of the neutron star in the Vela X-1 system is close to $\sim 2\,M_{\odot}$, while the masses of the compact objects in the binaries 4U 1700-37 and J0751+1807 exceed $2\,M_{\odot}$. Since observational confirmation of the hypothesis that massive neutron stars exist is extremely important from the standpoint of the fundamental properties of neutronic matter, it is once again necessary to focus attention on the methods for and results from estimates of the masses of neutron stars in the binary systems Vela X-1, 4U 1700-37, and J0751+1807.

2. Estimates of the mass of neutron stars in the systems Vela X-1, 4U 1700-37, and J0751+1807

The binary system Vela X-1. The x-ray binary Vela X-1 was discovered in 1967 [14]. This system consists of an x-ray pulsar and a supergiant of spectral class B0.5 Ibeq (HD 77581) with a mass of 24-25 $M_{\odot}$.The optical component is close to filling its Roche cavity. The orbital period of this system is 8.96 days. The orbit of the binary system has a significant eccentricity ($e \simeq 0.09$ compared to the orbital eccentricity of other x-ray pulsars).

The x-ray binary Vela X-1 is of close interest because of the high mass of the x-ray pulsar. Figure 1 is a plot of the mass of the x-ray pulsar as estimated by various authors.

Zuiderwijk et al. [15] were the first to estimate the mass of the x-ray pulsar at $m_{NS} > 1.9\,M_{\odot}$. Van Paradijs et al. [16] obtained an estimate of $m_{NS} = 1.6 \pm 0.3\,M_{\odot}$ with a confidence level of 1s. According to Rappaport and Joss [17] the mass of the x-ray pulsar lies within the range $m_{NS}(2\sigma) = 1.85^{+0.35}_{-0.30}\,M_{\odot}$. Later estimates of the mass of the compact object in Vela X-1 include $m_{NS}(1.64\sigma) = 1.77^{+0.27}_{-0.21}\,M_{\odot}$ (Nagase, 1989) [18], $m_{NS}(2\sigma) = 1.9^{+0.7}_{-0.5}\,M_{\odot}$ (van Kerkwijk et al.,

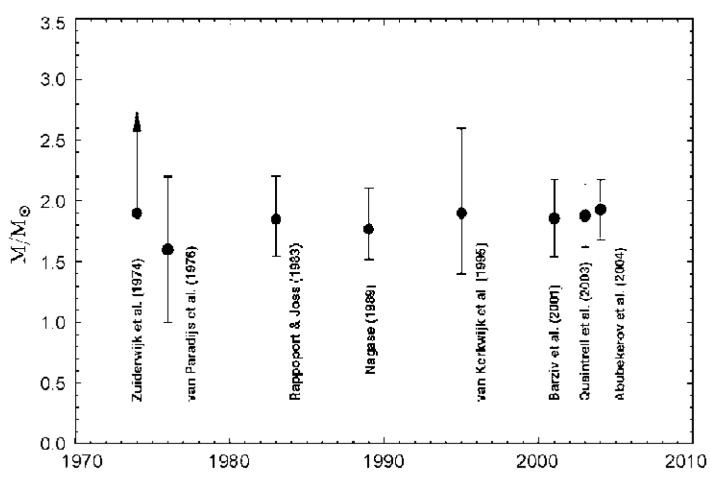

Fig. 1. Estimates of the mass of the x-ray pulsar in the Vela X-1 binary system obtained through 2004. The error bar indicates the 2σ level.

1995) [19], and $m_{NS}(2\sigma) = 1.86 \pm 0.32 M_\odot$ (Barziv et al., 2001) [20]. Assuming that the optical star fills the Roche cavity $\mu = 1$ and that the orbit is inclined at $i = 70^\circ.1 \pm 2^\circ.6$, Quantrell et al. [21] find a mass of $m_{NS}(1\sigma) = 2.27 \pm 0.17 M_\odot$ for the x-ray pulsar. For an orbital inclination $i = 90^\circ$ and an incomplete filling of the Roche cavity with $\mu = 0.89 \pm 0.03$, the mass of the neutron star is $m_{NS}(1\sigma) = 1.88 \pm 0.13 M_\odot$ [21].

The estimates of the mass in Refs. 15 and 16 were based on observations of the radial velocity curve and a point mass model. In Refs. 17-21 the mass of the x-ray star was estimated using a Monte Carlo solution of a system of equations (see Ref. 20, for example). In this method the observable parameter is just the half-amplitude of the radial velocity curve of the optical star, K_v. Its shape is not taken into account. This is a fundamental shortcoming of this method.

It should be noted that part of the equations upon which this method of calculating the parameters of the binary is based have been derived for a point mass model. At the same time, the point mass formalism is not at all applicable to the Vela X-1 binary system. The radius of the optical star in this binary is close to ~$30 R_\odot$ while the distance between the centers of mass of the components is ~$55 R_\odot$. In this case, a correct interpretation of the radial velocity curve must take the interaction of the components into account. In a first approximation a model of a binary system must take into account: the location of the center of mass of the binary in the body of the optical satellite, the tidally deformed shape of the optical star, and the effect of x-ray heating and gravitational darkening of its surface

Abubekerov, Antokhina, and Cherepashchuk [22] have estimated the mass of the x-ray pulsar using a first-approximation Roche model that takes into account the above mentioned effects owing to the interaction of the components [23]. In addition, they [22] verified the consistency of the calculated parameters of the binary system with the observed data. The dynamic estimate of the mass in Ref. 22 was based on a set of observational data obtained in 1967-2003. We briefly describe the method for estimating the mass of the compact object in Ref. 22.

In order to reduce the effect of random errors owing to oscillations of the surface and additional absorption in the gaseous structures of the binary, some effort was made [22] to interpret the average observed radial velocity curve. The interpretation relied on all the average values of the observed radial velocity except those for orbital phases of 0.4-0.6 which were the most distorted by the anisotropy of the stellar wind.

When the interpretation was based on all the data on the radial velocity, the mass of the compact object turned out to be $m_{NS} = 2.02 M_\odot$ (since the model is rejected by the Fisher criterion, the error in m_{NS} was not determined). When the anisotropy of the stellar wind was taken into account indirectly, the mass of the x-ray pulsar turned out to be $m_{NS} = 1.93 M_\odot$ (since the model is rejected by the Fisher criterion, the error in m_{NS} was not determined). In both cases the model was rejected with a significance level $\alpha = 5\%$. Only an artificial increase in the error of the average observed radial velocity by a factor of 2 made it possible to accept the model with a confidence level $\gamma = 95\%$ while interpreting the average observed radial velocity curve with indirect accounting for the anisotropy of the stellar wind. The mass of the x-ray pulsar was then $m_{NS}(2\sigma) = 1.93^{+0.25}_{-0.21} M_\odot$. Note that when the entire averaged radial velocity curve is interpreted with even the error in the average observed velocity increased by a factor of two, the model is, as before, rejected with a level of significance $\alpha = 5\%$.

Thus, all the models currently in use for the Vela X-1 binary system fail to interpret the available experimental data correctly. There is, therefore, still some doubt regarding the high value for the mass of the x-ray pulsar in the Vela X-1 system.

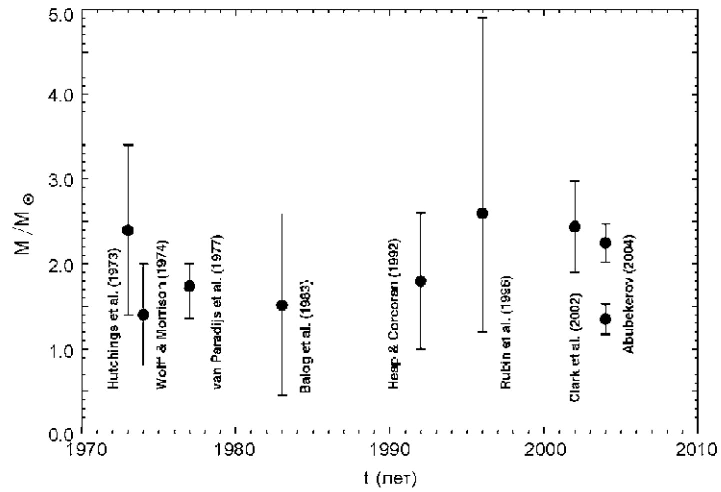

Fig. 2. Estimates of the mass of the compact object in the 4U 1700-37 binary system obtained through 2004. The error bar indicates the 2σ level. The results of Balog et al. [35] are indicated in the figure as "Balog et al. (1983)."

The binary system 4U 1700-37. The x-ray binary system 4U 1700-38 was discovered by the Uhuru satellite in December 1970 [24]. This binary consists of a supergiant of spectral class O6.5Iaf (HD 153919) [25,26] and a compact object.

The x rays from 4U 1700-37 have a hard spectrum [27,28] similar to that of accretion neutron stars. In addition, the regular pulses associated with the lighthouse effect that occur during accretion of mass to a neutron star are not observed from the compact object. This makes it impossible to plot a radial velocity curve for the compact object and, therefore, to determine the mass of the optical satellite. The mass of the optical satellite is calculated from its spectral class or from the mass-luminosity relation. These estimates, however, are not reliable enough. Because of this the estimates of the mass of the compact object are not sufficiently accurate. Figure 2 shows estimates for the mass of the compact object in the 4U 1700-37 system made by various authors.

In 1973 Hutchings et al. [29] solved the observed radial velocity curve by least squares for a model of two point masses. Assuming that the mass of the optical component is $35M_\odot$ and the inclination of the orbit is 90°, the mass of the compact object ended up being $m_{NS}(1\sigma)=2.4\pm0.5M_\odot$. in 1974 Wolff and Morrison [30] found that the mass of the compact object lies within the range $m_{NS}(1\sigma)=1.4\pm0.3M_\odot$ for a mass $m_v=25M_\odot$ of the optical satellite. For a mass $m_v(1\sigma)=40M_\odot$ of the optical star, the mass of the compact object exceeds $2M_\odot$. According to the 1977 paper by Van Paradijs et al [31] the mass of the relativistic component is $m_{NS}(1\sigma)=1.74^{+0.13}_{-0.19}M_\odot$ for a mass $m_v(\sigma)=21.3^{+1.1}_{-1.8}M_\odot$ of the optical star. Heat and Corcoran [32] estimate the mass of the compact object to be $m_{NS}(1\sigma)=1.8\pm0.4M_\odot$, while the optical satellite has a mass of $m_v=52\pm2M_\odot$. Rubin et al. [33] find a mass $m_{NS}(1\sigma)=2.6^{+2.3}_{-1.4}M_\odot$ for the compact component with a mass for the optical star of $30^{+11}_{-7}M_\odot$. Clark et al [34] obtained a mass $m_{NS}(1\sigma)=2.44\pm0.27M_\odot$

for the compact object with a mass $m_v(1\sigma) = 58 \pm 11 M_{\odot}$ for the optical satellite. A estimate of the mass of the compact object in terms of a "purely" ellipsoidal optical light curve yielded m_{NS} within the range 0.95-2.08 $M_{\odot}$ with a confidence level γ = 50% [35].

The mass of the compact object has been estimated using a point mass model [29]. In Refs. 31-34 the mass of the compact object has been estimated by solving a system of equations (see, Ref. 34, for example) by the Monte Carlo method. First of all, as noted above, some of these equations are derived in a point mass formalism. Second, only the half amplitude of the radial velocity curve, K_v, has been used as an observed parameter, while its shape has been neglected. On the other hand, it has been shown [22] that the shape of the radial velocity curve is significantly different for systems with $q = m_x / m_v < 1$ in a point mass model and in a Roche model.

The binary system 4U 1700-37, like Vela X-1, consists of a compact object and an OB supergiant that nearly fills its Roche cavity. Thus, as in the case of the Vela X-1 binary system, a point mass model cannot be used to interpret the observational data. In the case of 4U 1700-37, the uncertainty in the mass is implicit both in the insufficiently correct model employed for interpreting the observed radial velocity curve and in the uncertainty in the estimated mass of the optical satellite.

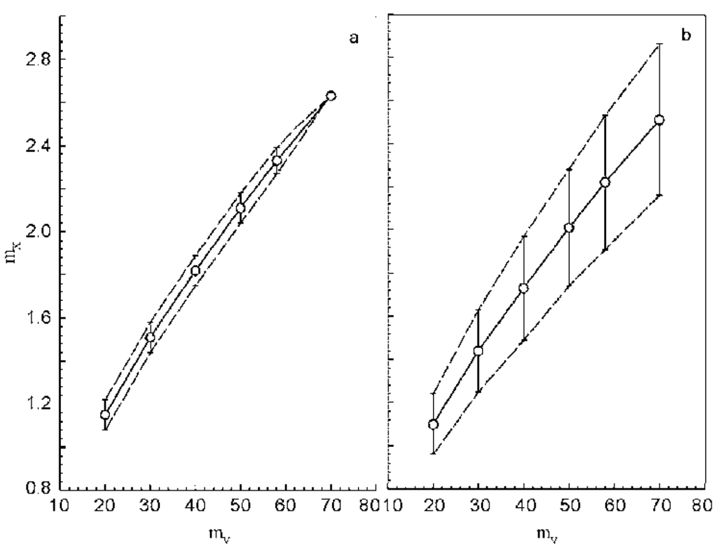

Fig. 3. (a) The mass of the compact object in the close x-ray binary system 4U 1700-37 as a function of the mass of the optical star for an orbital inclination of 67°. The interpretation was based on a Roche model using the radial velocities determined from hydrogen absorption lines in Ref. 36 neglecting those values of the average observed radial velocity within the phase interval 0.4-0.6. (b) The mass of the compact object in the close x-ray binary system 4U 1700-37 as a function of the mass of the optical star for an orbital inclination of 67°. The interpretation was based on a Roche model using spectral data from IUE [37] neglecting those values of the average observed radial velocity within the phase interval 0.4-0.6.

Thus, Abubekerov [38] has interpreted the radial velocity curve in terms of a Roche model for a discrete set of masses of the optical star, $20\,M_\odot$, $30\,M_\odot$, $40\,M_\odot$, $50\,M_\odot$, $58\,M_\odot$, and $70\,M_\odot$. The results of this interpretation revealed a relationship between the masses of the compact object and the optical star (see Fig. 3). In this paper the adequacy of the models of the observational data was tested based on the Fisher criterion. The mass of the compact object was estimated in several ways. The mass of the optical star based on the acceleration of gravity is $m_\upsilon - 55^{+7}_{-6}\,M_\odot$. This mass for the optical star corresponds to a mass of $m_{NS}(2\sigma) = 2.25^{+0.23}_{-0.24}\,M_\odot$ for the compact object. Given the mass of the optical star obtained from the mass-luminosity relation for close binary systems [38], $m_\upsilon \simeq 27\,M_\odot$, the mass of the compact object is $m_{NS}(2\sigma) - 1.35^{+0.18}_{-0.18}\,M_\odot$.

Thus, observational data at a confidence level γ = 95% are adequate for the close binary model, both with a high mass for the compact object, $m_\upsilon = 2.25^{+0.23}_{-0.24}\,M_\odot$, and with the standard value for the mass of the neutron star, $m_\upsilon(2\sigma) = 1.35^{+0.18}_{-0.18}\,M_\odot$. Thus, at present the high estimate $m_{NS} \simeq 2.2\,M_\odot$ for the mass of the compact object in the system 4U 1700-37 is not sufficiently reliable.

The binary system J0751_1807. The binary system J0751_1807 was discovered in 1993 [39]. This system consists of a millisecond radio pulsar and a white dwarf. In such systems the mass of the components is measured using the timing of the pulses from the radio pulsar. Four relativistic parameters of the binary system have been determined from the observations: the rate of change $\dot{\omega}$ of the periastron of the orbit, the parameter γ which describes the delay in the radio pulsar pulses owing to effects of general relativity, the Shapiro delay time, and the rate $\dot{P}_{orb}$ at which the orbital period is decreasing owing to emission of gravitational waves. In order to determine the mass of the components of the binary system, it is necessary to know two of the four parameters (the others are used to check the result).

The orbit in J0751+1807 is almost circular, with $e = 0.000003$ [41]. This value of the eccentricity is too small for determining the rate $\dot{\omega}$ of change in the periastron of the orbit or the parameter γ. Thus, the mass of the radio pulsar is estimated using only two parameters: the Shapiro time delay and $\dot{P}_{orb}$.

The value of $\dot{P}_{orb}$ obtained from an analysis of the observational data for 1993-1994 and 1999-2003 is (-6.2±1.1)·10^{-14} s/s and the corresponding radio pulsar mass lies in the range $m_{PSR}(2\sigma) - 1.6 - 2.8\,M_\odot$ [40]. Later the same authors obtained an improved value of $\dot{P}_{orb}$, (-6.2±0.8)·10^{-14} s/s. The new value for the mass of the radio pulsar is $m_{PSR}(2\sigma) = 2.1^{+0.4}_{-0.5}\,M_\odot$. No other estimates of this mass have been made up to now. The accuracy of the estimated mass of the radio pulsar in the binary J0751+1807 is still not accurate enough to serve as proof of the presence of a massive neutron star.

3. Results of a population synthesis

The mass of the neutron star in a close binary system may change owing to accretion of matter from the satellite. In order to estimate the amount of accreted mass ΔM, a population synthesis has been carried out [12,13] on the Scenario Machine [11].

A population synthesis of 19.5 million binary systems is made in Ref. 12. The initial masses of the components were varied over $5\,M_\odot$ to $120\,M_\odot$. The distribution of the initial mass ratios of the components of the binary was assumed uniform. The initial value for the major semiaxis of the binary could take any value in the range $10-10^6\,R_\odot$. The initial mass of the neutron star drawn from the range 1.25-1.44 $M_\odot$. The synthesis was carried out for different dissipation times t_d of the radio pulsar's magnetic field: 10^7, $5\cdot10^7$, and 10^8 years. It was assumed that the velocity of the anisotropic impulse of the neutron star obeys a maxwellian distribution with a characteristic velocity $v_0 = 180$ km/s and the Oppenheimer-Volkoff limit is taken to be $2.5\,M_\odot$.

The population synthesis of 19.5 million binary systems led to formation of $\sim7\cdot10^4$ radio pulsar systems with a neutron star (PSR+NS) and $\sim16\cdot10^4$ radio pulsar systems with a white dwarf (PSR+WD). The synthesis was done both including hyperaccretion and without it. When hyperaccretion was included the maximum mass attainable by the pulsar was $\sim1.75\,M_\odot$. The radio pulsar formation channel was quite narrow. Radio pulsars were formed during the evolution of binary systems with initial masses $M_1 \simeq 15-22\,M_\odot$, and $M_2 \simeq 15-22\,M_\odot$ with an initial major semiaxis $a \simeq 10-10^3\,R_\odot$. The radio pulsars gained mass in two stages: superaccretion ($\Delta M \simeq 0.1-0.2\,M_\odot$) and hyperaccretion ($\Delta M \simeq 0.2-0.3\,M_\odot$). Here the accumulation of matter occurs fairly rapidly with $t < t_d$. When the hyperaccretion stage is left out the maximum mass of the radio pulsars in PSR+NS systems was $\sim1.6\,M_\odot$.

The mass of the radio pulsars in PSR+WD systems obtained in the population synthesis was as high as $2.5\,M_\odot$. The channels for formation of massive radio pulsars depended on the magnetic field dissipation time. (For more detail, see Ref. 12.) However, aside from a dependence on the time t_d, radio pulsars with masses $\sim2.5\,M_\odot$ appeared in each of the scenarios. These radio pulsars were a product of the evolution of a binary system with component masses $M_1 \geq 10\,M_\odot$ and $M_2 \simeq 1.5-3.0\,M_\odot$ and a major semiaxis $a = (6-7)\cdot10^2\,R_\odot$. Radio pulsars in this evolution channel acquire mass only in the accretion state. In them the matter flows from the low-mass donor star through an interior Lagrange point. Since the low-mass satellite fills its Roche cavity on a nuclear time scale ($t\sim10^7$-10^8 years), the field of the radio pulsar is damped out and does not keep matter from falling out.

The population synthesis of Ref. 12 was done taking account of the mass accumulation ΔM during the hyperaccretion stage and neglecting mass accumulation by the radio pulsar during the hyperaccretion phase. When the accumulation of mass during the hyperaccretion phase was included, the number of radio pulsars with $m_{PSR} > 1.8\,M_\odot$ was ~12% of the total number of radio pulsars in PSR+WD systems for a magnetic field dissipation time $t_d = 10^7$ years, ~30% for $t_d = 5\cdot10^7$ years, and ~30% for $t_d = 10^8$ years. When the accumulation of mass by the radio pulsar during the hyperaccretion phase was not taken into account, the number of radio pulsars with $m_{PSR} > 1.8\,M_\odot$ was ~4% of the overall number of radio pulsars in PSR+WD systems for a magnetic field dissipation time $t_d = 10^7$ years, ~3% for $t_d = 5\cdot10^7$ years, and ~3% for $t_d = 10^8$ years. It should be noted that when the Oppenheimer-Volkoff limit is artificially increased, a radio pulsar can increase its mass to $\sim5\,M_\odot$ owing to accretion [12].

Popov and Prokhorov have estimated [13] the rate of creation of massive neutron stars to be $6.7\cdot10^{-7}$ year^{-1}, which corresponds to $\sim10^4$ massive pulsars in the galaxy. According to their distribution in terms of the type of their evolutionary state, most of the massive neutron stars are in an accretor stage (53% of the total), 39% of the massive neutron stars are in the ejector stage, and 8% are in a propeller and georotator state. About 25% of the accretion neutron stars are in pairs with normal stars that fill their Roche cavities and 75%, with white dwarfs that fill their Roche cavities [13].

The population synthesis shows that the most likely observational manifestations for massive neutron stars are the same as for ordinary ones: radio pulsars and x-ray sources. Massive neutron stars should show up as millisecond radio and x-ray pulsars. The probability of encountering a massive radio pulsar in PSR+WD systems is higher than with binary PSR+NS systems. Pulsars with masses $m_{PSR} > 1.8 M_{\odot}$ should be encountered only in PSR+WD binary systems. According to the population synthesis of Ref. 12, such massive radio pulsars should be absent in PSR+NS binary systems.

4. Conclusion

The main conclusion from the population synthesis is that evolutionary channels may exist in which a neutron star can substantially increase its mass. In the case of a rigid equation of state for the matter in the neutron star, its mass can be as high as $\sim 3.5 M_{\odot}$. That is, the theoretical calculations support the existence of massive neutron stars.

Nevertheless, definitively convincing proofs of their existence have not been found. The models for the binaries Vela X-1 and 4U 1700-37 are not accurate enough to permit correct interpretation of the observational data. In the J0751+1807 binary system the mass of the radio pulsar is known with a rather large error, which will have to be reduced using a longer time series of observations.

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