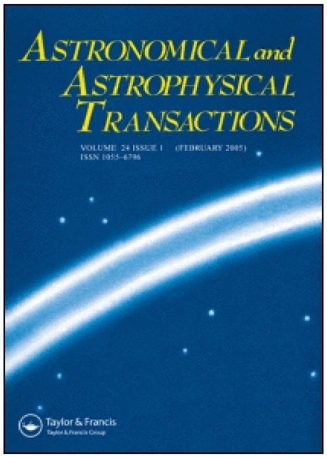

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 January 1994
To cite this Article: Cherepashchuk, A. M. (1994) 'The masses of black hole candidates in binary systems', Astronomical & Astrophysical Transactions, 5:1, 155 - 162
To link to this article: DOI: 10.1080/10556799408245870
URL: http://dx.doi.org/10.1080/10556799408245870

Astronomical and Astrophysical Transactions, 1994,
Vol. 5, pp. 155–162
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THE MASSES OF BLACK HOLE CANDIDATES IN BINARY SYSTEMS

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(31 March 1993)

Recent results concerning the determination of the masses of five black hole candidates are described. It is very significant that there are no pulsars among five massive ($M_x > 3M_{\odot}$) X-ray sources in binary systems.

KEY WORDS X-ray, mass, black hole.

1. INTRODUDCTION

The possibility to detect an accreting black hole due to its X-ray emission has been predicted by Zeldovich (1964) and Salpeter (1964). Theory of the disk accretion of matter on black holes in close binary systems has been developed by Shakura (1972), Shakura and Sunyaev (1973), Pringle and Rees (1972) and Novikov and Thorne (1973).

Binary systems as tracers of neutron stars and black holes have been proposed by Novikov and Zeldovich (1966) and Guseinov and Zeldovich (1966), see also Trimble and Thorne (1969). The discovery of compact X-ray sources in binary systems (e.g. Tananbaum *et al.*, 1972) confirmed all these theoretical predictions.

Optical appearances of X-ray binaries (the ellipticity effect of the optical star, X-ray heating, eclipses of the accretion disk by the optical star and of the star by the disk) have been discovered by Bahcall and Bahcall (1972), Cherepashchuk *et al.* (1972), Lyutyi *et al.* (1973, 1974).

All these results allow to estimate basic physical characteristics of X-ray binaries, in particular the values of the masses of neutron star and black hole candidates.

2. DETERMINATION OF THE MASSES OF RELATIVISTIC OBJECTS IN X-RAY BINARY SYSTEMS

Up to now, many thousands of compact X-ray sources in our Galaxy and other galaxies have been discovered (e.g., Forman *et al.*, 1978, Giacconi, 1981). Most of them are binary systems consisting of a normal optical star and an accreting relativistic object. The normal star is the donor of matter. The investigation of the motion, deformation and heating of the normal star in an X-ray binary system, as well as the eclipsing effects, allows to estimate the mass function $f(m)$, the inclination of the orbital plane i, the value of the mass ratio $q = m_x/m_v$ and other parameters of the X-ray binary system.

In the case when an X-ray pulsar is observed in an X-ray binary system, two mass functions are known:

$$f_x(m) = \frac{m_v^3 \sin^3 i}{(m_v + m_x)^2} = 1.038 \cdot 10^{-7} K_x^3 p (1 - e^2)^{3/2}, \tag{1}$$

$$f_v(m) = \frac{m_x^3 \sin^3 i}{(m_v + m_x)^2} = 1.038 \cdot 10^{-7} K_v^3 p (1 - e^2)^{3/2}, \tag{2}$$

where m_x, m_v are the masses of the relativistic object and the normal star, respectively, K_x, K_v are the semiamplitudes of the radial velocity curves of the X-ray pulsar and the optical star, p is the orbital period and e is the eccentricity of the orbit. Also, the mass ratio $q = K_v/K_x$ and the values of $m_v \sin^3 i$ and $m_x \sin^3 i$ are known in this case. Note that the mass function of the normal star $f_v(m)$ may be distorted by the proximity effects in binary systems (X-ray heating and the ellipticity effect). That is why the value of q must be checked by independent determination of this quantity from the analysis of the optical light curve.

If X-ray eclipses are observed in a binary system, the duration D_1 of an X-ray eclipse allows us to write additional equation for the determination of the parameters of the system:

$$D_1 = D_1(q, \mu, i), \tag{3}$$

where μ is the parameter of the Roche lobe filling by the normal star. Tables of D_1 are calculated for the Roche model of a binary system for circular and elliptic orbits (e.g. Khruzina, 1985).

If the distance d is known for an X-ray binary as well as the value of interstellar reddening, an independent equation can be written for the determination of the parameters q, μ, i:

$$\sin i = \frac{0.38\mu}{R_v} \sqrt[3]{\frac{Gp^2 f_v(m)}{4\pi^2}} \cdot \frac{1+q}{q^{1.208}}, \tag{4}$$

where R_v is the mean radius of the normal star, determined from the information about d and A_v and G is the gravitational constant.

From equations (3), (4) and from $q = \frac{m_x}{m_v} = \frac{K_v}{K_x}$ we can conclude that if an X-ray pulsar is observed in an X-ray binary, the X-ray eclipses are observed too and the distance for this X-ray binary is known, than the basic parameters of this system (q, μ, i) and the masses of the components m_x, m_v (from known $m_x \sin^3 i$ and $m_v \sin^3 i$) can be determined independently of the optical light curve (e.g. Rappaport and Joss, 1984). The optical light curve can be used in this case for checking the value of q and for the determination of the parameters of the accretion disk.

In the case when the information about the X-ray pulsar, the X-ray eclipse and distance d is not complete, the optical light curve should be used for the determination of parameters of the X-ray binary system. Therefore, in the case of black hole candidates we should use the optical light curve for the mass determination. Note that Lyutyi *et al.* (1973, 1974) were the first to suggest the analysis of the optical light curve for the determination of the parameters of the X-ray binary system Cyg X–1.

The idea to use the information about distance d for the determination of the parameters of an X-ray binary system (Cyg X-1) was put forward by Paczynski (1974).

Methods of the light curve analysis of X-ray binaries have been developed recently by many investigators (e.g., Avni and Bahcall, 1975; Bochkarev *et al.*, 1975; Antokhina and Cherepashchuk, 1987; Goncharsky *et al.*, 1991). These methods allow to estimate basic parameters of accreting neutron stars and black holes in X-ray binary systems.

3. RESULTS OF THE MASS DETERMINATIONS

Up to now, the masses of five black hole candidates have been estimated: Cyg-1, LMC X-3, AO620-00, GS2023 + 338 (V 404 Cyg) and XN Mus 1991.

The binary systems SS 433, LMC X-1 and binary Wolf–Rayet star HD 197406 also were suspected as black hole candidates (e.g. Leibowitz, 1984; Antokhina and Cherepaschuk, 1987; Hutchings *et al.*, 1987; Drissen *et al.*, 1986). But the reliability of the determination of the masses of SS 433, and LMC X-1 is not yet sufficient (e.g. D'Odorico *et al.*, 1991); the nature of the unseen companion in the HD 197406 binary system is not yet clear due to the lack of a strong X-ray emission (e.g. Pollock, 1987).

In the cases of Cyg X-1, LMC X-3, AO620-00, GS 2023 + 338 and XN Mus 1991, we have reliable mass estimates. The values of the mass functions $f_v(m)$ which are absolute lower limits for the mass of the relativistic object m_x are the following: $0.2M_\odot$ for Cyg X-1 (Webster and Murdin, 1972; Bolton, 1975), $2.3M_\odot$ for LMC X-3 (Cowley *et al.* 1983), $3.1M_\odot$ for AO620-00 (McClintock and Remillard, 1986), $6.26M_\odot$ for GS2023 + 338 (Casares *et al.*, 1992) and $3.1M_\odot$ for XN Mus 1991 (Remillard *et al.*, 1993).

The value of the mass m_x of the relativistic object can be determined from the mass function $f_v(m)$ as follows:

$$m_x = f_v(m)\left(1 + \frac{m_v}{m_x}\right)^2 \cdot \frac{1}{\sin^3 i}.$$

The values of $\frac{1}{q} = \frac{m_v}{m_x}$ and i are determined from the independent information about the binary system: the optical light curve, the duration of the X-ray eclipse, distance d to the system.

Basic parameters of all the five X-ray binaries containing black hole candidates are summarized in Table 1. Let us discuss the reliability of the mass determinations for these systems.

First of all, consider the problem of the optical identification of these X-ray binaries. Despite the lack of X-ray eclipses, we have a reliable optical identification in all the five X-ray binaries. For the systems Cyg-1 and LMC X-3, a long term (precession ?) variability in optical and X-ray range with the periods of 294 days (Cyg X-1) and 198 days (LMC X-3) has been recently discovered (Priedhorsky *et al.*, 1983; Kemp *et al.*, 1983, 1987; Cowley *et al.*, 1991). The

Table 1. Characteristics of X-ray binary systems containing black hole candidates

Object	*Spectrum of optical star*	*Orbital period (days)*	*Precess. period (days)*	$f_v(m)$ $M_\odot$	m_x $M_\odot$	m_v $M_\odot$	L_x *erg/s*	*Ref.*
Cyg X-1	09.5Iab	5.6	294	0.2	7–18	20–30	$\sim 8 \cdot 10^{37}$	(1)
LMC X-3	B3-6II-III	1.7	198	2.3	7–11	3–6	$\sim 4 \cdot 10^{38}$	(2)
A 0620 -00	K5-7V	0.3	—	3.1	5–7	~0.7	$\leq 10^{38}$	(3)
GS2023 + 338 (V404 Cyg)	G-K	6.5	—	6.3	10–15	~1	$\leq 6 \cdot 10^{38}$	(4)
XN Mus 1991	KO-K4V	0.4	—	3.1	8–12	~0.8	$\leq 10^{38}$	(5)

(1) Webster and Murdin, 1972.
(2) Cowley *et al.*, 1983.
(3) McClintock and Remillard, 1986.
(4) Casares *et al.*, 1992.
(5) Remillard *et al.*, 1992.

coincidence of the periods of the long-term variability in optical and X-ray ranges proves the identification. The systems AO620-00, GS2023 + 338 and XN Mus 1991 are transient X-ray sources. During X-ray flares, the corresponding optical flares caused by the X-ray heating of the normal star and the accretion disk were observed. This proves the reliability of the optical identification.

The first black hole candidate was discovered in the X-ray binary system Cyg X-1 (Webster and Murdin, 1972; Lyutyi *et al.*, 1973; Paczynski, 1974; Bolton, 1975). Here $f_v(m) \approx 0.2 M_\odot$ but the analysis of the optical light curve (Lyutyi *et al.*, 1973, 1974) together with the information about the distance, $d > 2$ Kpc (Margon *et al.*, 1973; Paczynski, 1974), lead to the value of the mass of black hole candidate as $m_x > 7 M_\odot$ (Balog *et al.*, 1981a,b).

The second black hole candidate was discovered in the X-ray binary system LMC X-3 (Cowley *et al.*, 1983). Here $f_v(m) = 2.3 M_\odot$. The analysis of the optical light curve (Van der Klis *et al.*, 1985), with taking into account the distance for the LMC, allows to estimate the mass of black hole candidate: $m_x > 7 M_\odot$ (e.g., Khruzina and Cherepaschuk, 1984; Bochkarev *et al.*, 1988).

The third black hole candidate was discovered by McClintock and Remillard (1986) in the transient X-ray binary system AO620-00 (X-ray Nova) containing a low mass optical K-companion. The value of the mass function of the optical star for this system is $f_v(m) = 3.1 M_\odot$ and exceeds the theoretical upper limit for a neutron star, $3 M_\odot$, as predicted by Einstein's general relativity. So the X-ray source in the system AO620-00 is one of the most reliable black hole candidates, despite some difficulties with the interpretation of its optical light curve (e.g., McClintock and Remillard, 1986; Khruzina *et al.*, 1988).

The fourth black hole candidate was discovered by Casares, Charles and Naylor (1992) in the transient X-ray binary GS2023 + 338 (V 404 Cyg). It was a sensational publication because the value of mass function of the optical G-K star for this system is $f_v(m) = 6.26 M_\odot$ (!). This object may be considered up to now as the best black hole candidate (Casares *et al.*, 1992). A preliminary optical light curve of V404 Cyg and its analysis confirm this conclusion (Antokhina *et al.*, 1992).

The fifth black hole candidate was recently discovered by Remillard, McClintock and Bailyn (1992) in the X-ray binary Nova Muscae 1991. The value of the mass function of the optical K-star in this system is $f_v(m) = 3.1M_\odot$, so it is one of the best black hole candidates. The X-ray Nova Muscae 1991 was discovered independently by the WATCH/Granat instrument and the Ginga All-sky X-ray Monitor (Lund and Brandt, 1991; Makino *et al.*, 1991; Sunyaev *et al.*, 1992). The associated optical nova $V \simeq 13^m$ was soon discovered at the position normally occupied by a faint star $R = 19\overset{m}{.}4$, $B = 20\overset{m}{.}9$ (Della Valle, Jarvis and West, 1991). The analysis of the infrared I-light curve of XN Mus 1991, obtained by Remillard *et al.* (1992) yields the mass estimate for the black hole candidate in this system as $m_x > 7M_\odot$ (Antokhina and Cherepashchuk, 1993), but the optical B + V light curve of this system (Remillard *et al.*, 1992) is inconsistent with the standard model of X-ray binary systems.

A model of triple systems has been proposed for the system Cyg X-1 (Bahcall *et al.*, 1974; Fabian *et al.*, 1974). In this model the X-ray source may be a neutron star but the high value of the mass function $f_v(m)$ is due to the third massive star in the system. Also a model of a massive laminar disk-accumulator rotating around the neutron star has been proposed for the system Cyg X-1 (Kundt, 1979). In the case of the X-ray novae AO620-00, GS2023 + 338 and XN Mus 1991 both these models should be rejected. Indeed, if the massive bright third star exists in these systems, it would be impossible to see the faint low-mass G-K optical stars. Also, if the laminar disks-accumulators exist in these systems, optical stars here must be the helium remnants of originally massive stars but not G-K stars with normal chemical composition. It should be noted also that the search for the third body in the systems Cyg X-I and LMC X-3 was not successful (e.g. Aslanov and Cherepashchuk; Cowley *et al.*, 1983).

So, at present we have five black hole candidates with reliable mass estimates: Cyg X-1, LMC X-3, AO620-00, GS2023 + 338 and XN Mus 1991. Also up to now masses of 10 pulsars (6 X-ray and 4 radiopulsars) were measured in binary systems. Masses of X-ray and radiopulsars as well as the black hole candidates are presented also in Fig. 1. As we can see from Fig. 1, there is no correlation between the masses of relativistic objects and their companions in binary systems. Black hole candidates in binary systems can have both high-mass and low-mass companions. The same situation is for neutron stars in binary systems. Evolutionary considerations of the origin of black holes in binary systems have been published by Tutokov and Cherepashchuk (1985, 1993).

A very important result was obtained up to now: in all cases when the mass of an X-ray or radiopulsar (i.e. a rapidly rotating magnetized neutron star) has been determined (there are 10 determinations—see Fig. 1), it does not exceed $3M_\odot$, the theoretical upper limit for the mass of a neutron star predicted by Einstein's general relativity. On the other hand, none of the five known massive X-ray sources with $m_x > 3M_\odot$ (black hole candidates) has regular X-ray pulsations. Therefore, X-ray sources in binary systems are distinguished from each other not only by masses but also by an observational appearances. The X-ray spectra of accreting neutron stars and black hole candidates are also different from each other (e.g. Tanaka, 1989; Greiner *et al.*, 1991; Sunyaev *et al.*, 1992). In particular, the variable, narrow emission line near 500 Kev, possibly related to

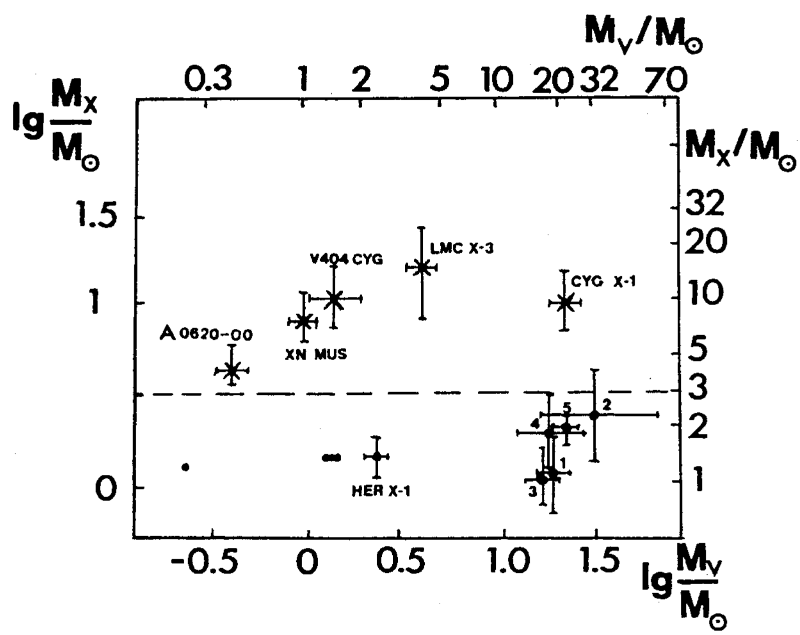

Figure 1 The dependence of the masses M_x of the neutron stars (points) and black hole candidates (crosses) on the masses of the companion stars M_v in close binary systems. 1 – Cen X-3, 2 – LMC X-4, 3 – SMC X-1, 4 – 4U 1538-52, 5 – 4U 0900–40. The errors of the mass determinations from the observations are indicated. All the pulsars have the masses which do not exceed $3M_\odot$. On the other hand, there are no pulsars among massive X-ray sources ($M_x > 3M_\odot$).

the production of electron-positron pairs as well as a "hard tail" in the X-ray spectrum have been discovered recently in many black hole candidates (Sunyaev *et al.*, 1988, 1991, 1992; Tanaka, 1989).

These results are very significant and have a great importance for testing Einstein's general relativity in the strong gravitation. Therefore, further investigations of X-ray binary systems seem to be very promising.

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