BLACK HOLE X-RAY BINARIES

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ABSTRACT. Masses of black holes in 13 X-ray binary systems determined by different authors are summarized and compared with those of WR stars in close binary systems, which can be considered as progenitors of relativistic objects.

Average mass of CO cores of WR stars is $\sim (8-12)\ M_\odot$ which is close to that of black holes $\sim (8-10)\ M_\odot$. Distribution of masses of WR stars $M_{WR} = 5-55\ M_\odot$ is continuous but not bimodal in contrast with distribution of masses of neutron stars ($M_{NS} = 1.35 \pm 0.15\ M_\odot$) and black holes ($M_{BH} \approx 8 \div 10\ M_\odot$).

Key words: Black hole, neutron star, Wolf-Rayet star, binary system, X-ray, accretion.

1. Introduction

Black holes were predicted by Einstein's general relativity theory. Strong energy release from accreting black holes was predicted by Zeldovich (1964) and Salpeter (1964). The theory of disk accretion onto black holes was developped by Shakura (1972), Shakura and Sunyaev (1973), Pringle and Rees (1972) and Novikov and Thorne (1973). Binary systems as tracers of relativistic objects were 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 close binary systems (e.g. Tananbaum et al., 1972) confirmed all these theoretical predictions. Recent 3D gas-dynamic calculations of gaseous flows in close binary systems confirm basic suggestions about mass transfer (e.g. Bisikalo et al., 1998, Matsuada et al., 1999). Advectional solutions in the theory of disk accretion have been considered (e.g. Paczynski and Bisnovatyi-Kogan, 1981, Narayan et al., 1996). The influence of ohmic heating on advection dominated accretion flows calculated recently (Bisnovatyi-Kogan and Lovelace, 1997, Bisnovatyi-Kogan, 1999) suggests a much higher efficiency of conversion of the accretion energy to radiation than in the theory of advection-dominated disks. Thousands of compact X-ray sources in our Galaxy and in nearby galaxies have been discovered. Most of them are X-ray binary systems containing an optical star - the donor of matter and accreting relativistic object. Accretion of matter onto a relativistic object implies strong X-ray luminosities of about $10^{36} \div 10^{39}$ erg/s.

The first optical identification of X-ray binary systems allowed us to understand the basic origins of their optical variability: the X-ray heating effect (Cherepashchuk et al., 1972, Bahcall and Bahcall, 1972) and ellipticity effect of optical star (Lyuty et al., 1973, 1974). It is now widely known that the X-ray heating effect ("reflection effect") and ellipticity effect are typical for X-ray binary systems. Observations of optical variability caused by these effects enable reliable optical identification of X-ray binaries: coincidence of periods and phases of X-ray and optical variability as well as coincidence of X-ray and optical flashes, prove the correctness of identification. A method for estimating the orbital plane inclination i from the optical light curve of X-ray binary Cyg X-1, due mainly to ellipticity effect, was proposed by Lyuty et al. (1973). Now this method is widely used to estimate the masses of black holes in X-ray novae during quuiescence from their optical and infrared light curves (see reviews of Cherepashchuk, 1996a, 1997, 2000, Charles, 1999, Chakrabarti, 1999, and references therein).

In our review we summarize recent results about mass determination of 13 black holes in X-ray binaries and compare the distribution of the masses of relativistic objects with that of Wolf-Rayet stars.

2. Masses of black holes in X-ray binaries.

The investigation of motion, deformation and heating of the normal star in an X-ray binary system, as well as of eclipsing effects and the rotational broadening of absorption lines in the spectrum of optical star, allow to estimate mass function of the optical star

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

inclination of orbit plane i, mass ratio $q = m_x/m_v$ and other parameters of the X-ray binary (m_x and m_v are the masses of black hole and optical star respectively). Mass function $f_v(m)$ is absolute lower limit for the mass of black hole m_x. Value of m_x is determined by the formula:

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

Results of investigation of influence of non-zero dimensions of optical star as well as ellipticity and X-ray heating effects on the shape of absorption lines and corresponding radial velocity curve are published by Cherepashchuk (1996a), Antokhina and Cherepashchuk (1997) and Shahbaz (1998). For more details about methods of determination of the masses of black holes in X-ray binaries see Cherepashchuk (1996a), Charles (1999). Recently new method of determination of the values of q, i and masses of black holes from orbital variability of the profiles of absorption lines in the spectra of optical stars in X-ray binaries has been developped (Antokhina and Cherepashchuk, 1997, Shahbaz, 1998).

Up to now, the masses of 13 black holes have been estimated in the X-ray binary systems containing hot massive O–B or WR stars (Cyg X-1, LMC X-3, LMC X-1, Cyg X-3) as well as low mass M $\div$ A stars (V616 Mon, V404 Cyg, XN Mus 1991, QZ Vul, V518 Per, XN Sco 1994, XN Oph 1977, XN Vel 1993, HL Lup). The basic parameters of 13 black hole X-ray binary systems are summarized in table 1 (see recent reviews of Charles (1999) and Cherepashchuk (2000) and references therein).

At present we have 13 black holes in X-ray binary systems with known values of the masses m_x (see fig.1). Therefore, the problem of black hole investigation is now becoming not only a theoretical, but an observational one, too. Taking into account recent direct dynamical determinations of the masses of nuclei of the set of galaxies: M87 ($2.4 \cdot 10^9 M_\odot$),NGC4258($3.6 \cdot 10^7 M_\odot$), NGC7052($3 \cdot 10^8 M_\odot$), NGC4261($4.9 \cdot 10^8 M_\odot$) (Ford et al., 1994, Miyoshi et al., 1995, Ferrarese et al., 1996, van den Marel and van den Bosch, 1998), and the Galactic Center Sgr A (Eckart and Genzel, 1996)($2.4 \cdot 10^6 M_\odot$), the same conclusion may be drawn about supermassive black holes (Ho, 1999).

The masses of black holes as well as masses of X-ray and radiopulsars are presented in fig.1. There is no correlation between the masses of the relativistic objects and their companions in close binary systems. Black holes in binary systems can have both high-mass and low-mass companions. The same situation is for the neutron stars in binary systems. Evolutionary considerrations of the origin of the black holes in binary systems were published by (Tutukov and Cherepashchuk,1985, 1993, 1997, Brandt et al., 1995, Wijers, 1996). A very important result has been obtained up to now: in all the cases when the mass of an X-ray or radiopulsar (i.e. rapidly rotating magnetizied neutron star) has been determined (17 objects) it does not exceed $3M_\odot$, the theoretical upper limit for the mass of a neutron star predicted by the Einstein General Relativity theory. On the other hand, none of the 13 known massive compact X-ray souces with $m_x > 3M_\odot$ (black holes) has regular X-ray pulsation or X-ray bursts of the first type. Therefore, the X-ray souces in binary systems are distinguished from each other not only by masses but also by observational appearences in full agreement with Einstein General Ralativity theory. Due to high number of mass determinations (17 neutron stars and 13 black holes) the statistical significance of this conclusions is high. The X-ray spectra of accreting neutron stars and black holes on average are also different from each other (e.g. Tanaka, 1989, 1999, Greiner et. al., 1991, Sunyaev et al., 1992, 1993, Asai et al., 1998). Highly collimated relativistic jets ($v \approx 0.92c$) have been discovered recently from three galactic black hole X-ray binary systems: 1E1747 - 2942, GRS1915-105 and GROJ1655-40 (Mirabel et al., 1992, Mirabel and Rodriguez, 1994, Hjellming and Rupen, 1995).

In all the cases where the optical star is a hot massive O–B or WR star the X-ray source is persistent. But in all the cases where the optical star is a cool low-mass M-A star, the X-ray source is transient (X-ray nova). The relatively low mass accretion rate as well as X-ray heating effects are important for generation of quiet and active state of accretion disks in X-ray novae (e.g. Narayan and Yi., 1995, Chen et al., 1997, Esin et al., 1997, King et al., 1997). In particular, King et al. (1997) pointed out that heating by irradiation of the accretion disk is much weaker if the accreting object is a black hole rather than a neutron star (see also Sunyaev and Shakura, 1973).

Two peculiarities of the transient X-ray binaries may be important for understanding of their nature: the activity of the cool low-mass star, caused by its deep convective envelope, which may be a trigger stimulating the formation of turbulent viscosity of plasma in the disk around black hole, and the high mass ratio of the components $q = m_x/m_v = 2 \div 20$, which implies a relatively high dimension of the accretion disk around the black hole. For such a high-dimension disk, the tidal interaction from the optical star is important (e.g. Sawada and Matsuda,, 1992). The theory of instability of accretion disks and related problems for X-ray novae were considered by Hameury et al. (1986, 1990), Goutikakis and Hameury (1993), Mineshige and Wheeler (1989), Narayan et al. (1996) (see also recent book by Kato et al. (1998) and references therein).

3. Distribution of masses of relativistic objects and Wolf-Rayet stars.

Wolf-Rayet (WR) stars are considered to be bare cores of massive stars which lost most of their hydrogen envelopes (Paczynski, 1973, Conti, 1976). Note that Gamov (1943) was the first who suggested that

Table 1. Parameters of black hole binary systems.

System	Spectrum of optical star	P_{orb} (days)	$f_v(m)$ $(M_\odot)$	m_x $(M_\odot)$	m_v $(M_\odot)$	V_{pec} (km/s)	Remaks
Cyg X-1 (V1357 Cyg)	O9.7 Iab	5.6	0.24 ± 0.01	16 ± 5	33 ± 9	2.4 ± 1.2	pers.
LMC X-3	B3 III-V	1.7	2.3 ± 0.3	9 ± 2	6 ± 2	–	pers.
LMC X-1	O (7–9) III	4.2	0.14 ± 0.05	7 ± 3	22 ± 4	–	pers.
Cyg X-3	WN 3–7	0.2	~ 2.3	7–40	5–20	–	pers.
A0 620-00 (V616 Mon)	K4 V	0.3	2.91 ± 0.08	10 ± 5	0.6 ± 0.1	-15 ± 5	trans.
GS 2023+338 (V404 Cyg)	K0 IV	6.5	6.08 ± 0.06	12 ± 2	0.7 ± 0.1	8.5 ± 2.2	trans.
GRS 1124-68 (GU Mus)	K2 V	0.4	3.01 ± 0.15	6 (+5,-2)	0.8 ± 0.1	26 ± 5	trans.
GS 2000+25 (QZ Vul)	K5 V	0.3	4.97 ± 0.10	10 ± 4	0.5 ± 0.1	–	trans.
GRO J0422+32 (V518 Per)	M2 V	0.2	1.13 ± 0.09	10 ± 5	0.4 ± 0.1	–	trans.
GRO J1655-40 (XN Sco1994)	F5 IV	2.6	2.73 ± 0.09	7 ± 1	2.5 ± 0.8	-114 ± 19	trans.
H 1705-250 (V2107 Oph)	K5 V	0.5	4.86 ± 0.13	6 ± 1	0.4 ± 1	38 ± 20	trans.
4U 1543-47 (HL Lup)	A2 V	1.1	0.22 ± 0.02	5 ± 2.5	~ 2.5	–	trans.
GRS 1009-45 (MM Vel)	(K6–M0) V	0.3	3.17 ± 0.12	$3.6 - 4.7$	$0.5 - 0.7$	–	trans.

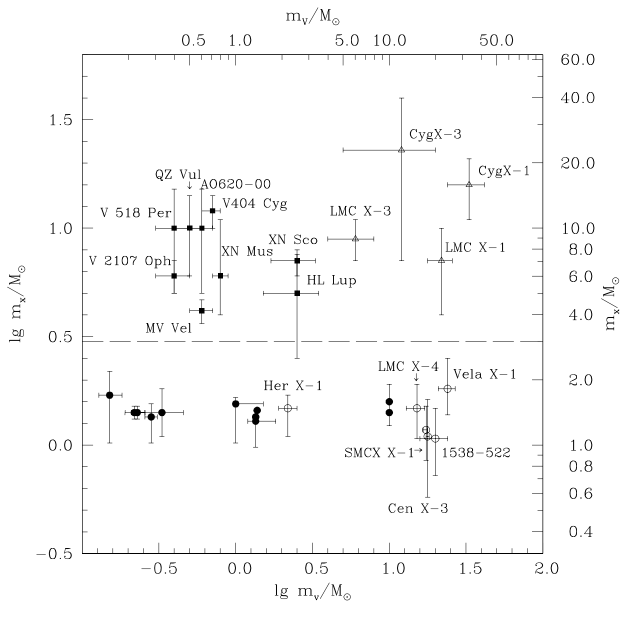

Figure 1: Dependence of the masses m_x of neutron stars (circles) and black holes (triangles and rectangles) on the masses of their companion starts m_v in close binary systems. Filled circles correspond to radio pulsars, filled rectangles correspond to black holes in X-ray novae. For the details see (Cherepashchuk, 2000).

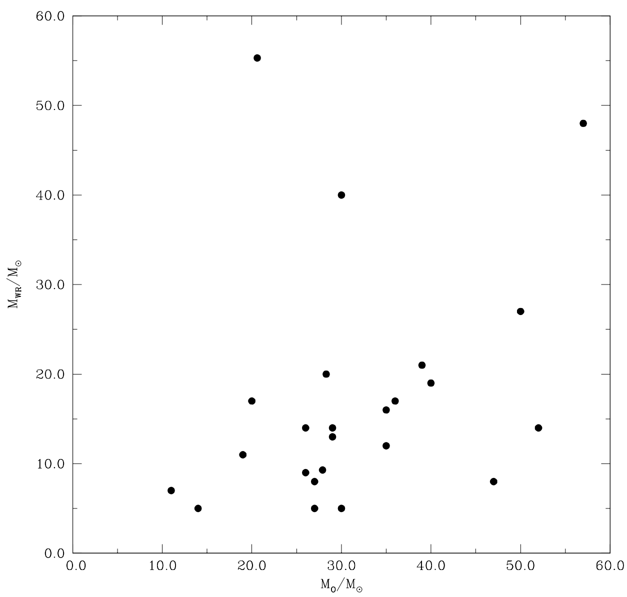

Figure 2: Dependence of the masses of WR stars in WR+O binary systems on the masses of the O-companion stars. This figure should be compared with the fig.1

WN and WC stars display at their surfaces products of different phases of thermonuclear processing. Recent determinations of radii and effective temperatures of some WR stars in binary systems (e.g. Cherepashchuk, 1996b, Cherepashchuk and Moffat, 1994, St.-Louis et al., 1993, Moffat and Marchenko, 1996) are in agreement with the model of WR stars as helium remnants which are formed from hot massive stars. Due to clumping of WR winds (Cherepashchuk et al., 1984, Moffat et al., 1988) values of mass loss rate $\dot{M}$ for WR stars determined from IR and radio observations seems to be overestimated at least by factor 2–4 (Antokhin et al., 1988, 1992, Hillier, 1991, Cherepashchuk,1992, Nugis et al., 1998). Therefore, we can neglect effect of decreasing of mass of WR stars by stellar wind mass loss during their evolution. Because WR stars are supposed to be progenitors of relativistic objects let us compare the distribution of masses of WR stars with that of neutron stars and black holes in close binary systems (Cherepashchuk, 1998, 2000) - see fig.1,2.

Distribution of the masses of relativistic objects may be suggested as bimodal (Baylin et al., 1998, Cherepashchuk, 1998). Average mass of neutron stars is $(1.35 \pm 0.15)\ M_\odot$ and average mass of black holes is $\sim (8-10) M_\odot$ (the ranges of the masses of neutron stars and black holes are $(1 \div 2)\ M_\odot$ and $(5 \div 15)\ M_\odot$ respectively). The gap in the distribution of the masses of relativistic objects between 2 $M_\odot$ and 5 $M_\odot$ can not be explained by observational selection effects (Bailyn et al., 1998). In contrast with relativistic objects (fig.1), the distribution of the masses of WR stars is continuous but not bimodal (fig.2).

Average mass of WR stars (23 stars) in WR+O binaries is 17.8 $M_\odot$ (Cherepashchuk, 1998, 2000). Masses of individual WR stars lie in wide range: from 5 $M_\odot$ to 48 $M_\odot$ and even 55.3 $M_\odot$ (HD 92740). The average mass of WN stars is 21.1 $M_\odot$ (12 stars), that of WC stars is 13.4 $M_\odot$ (9 stars). Average mass of CO cores of WC and WN stars is $(8 \div 12)\ M_\odot$ which is close to average mass of black holes $\sim (8 \div 10)\ M_\odot$. For more details about WR stars in binary systems see Catalog of Hifgly Evolved Close Binary Stars (Cherepashchuk et al., 1996a,b), and review of Cherepashchuk (1995).

Observed difference in the distribution of the masses of WR stars and relativistic objects allow us to suggest that origin and nature of newly formed relativistic object is determined not only by the mass of presupernova but also by some other stellar core parameters: its rotation, magnetic field and so on (Tutukov and Cherepashchuk, 1985, Ergma and van den Heuvel, 1998).

One WR SB1 binary and eleven suspected WR+c binaries are selected (Cherepashchuk, 1998, 2000) which could be considered as progenitors of black hole or neutron star low-mass X-ray binary systems containing low-mass M–A optical companions.

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