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Neutron Star Mass and Radius Constraint from X-ray Burst in LMXBs

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Abstract. X-ray bursts have been observed in low-mass X-ray binaries (LMXBs) in which neutron stares are believed to exist. Type-I X-ray bursts showing photospheric radius expansion (PRE) are main sources which can provide possibilities of determining the neutron star masses and radii in the binary systems. Only 20% of total X-ray bursts show the evidence of PRE explosion. Masses and radii of neutron stars in LMXBs are constrained by using the Monte-Carlo analysis based on the touchdown flux and the normalized angular surface area that can be extracted from the observed lightcurve data. In this paper, we investigate the change of mass and radius probability distribution for a fixed hydrogen mass fraction (X) which depends on neutron star's atmosphere condition since the fraction is not observed directly. Not only the masses but also radii of neutron star depend on the composition of accreted matter.

1 Introduction

Low-mass X-ray binaries (LMXBs) are the major sources of the X-ray bursts and have been found in globular clusters or galactic bulges where old star population is high. X-ray in the binary systems are produced by the matter falling from the companion star to the compact object, such as a neutron star or black hole. Since the first observation of X-ray burst in 1975 [1], more than 50 X-ray burst sources have been observed. X-ray bursts are classified into two types according to the shape of the lightcurves [2]. Lightcurves of type-I X-ray bursts show sharp rising and slow decline while those of type-II X-ray bursts exhibit sharp pulse shape. From the observation, only two sources have been confirmed as type-II source. Type-I X-ray bursts can be explained by the explosive thermonuclear burning of falling matter into a weakly magnetized neutron star. Accreted hydrogen and/or helium are accumulated and compressed hydrostatically near the envelope of a neutron star. After the temperature reaches up to a critical temperature (about 10^7 K) which is enough to burn the unstable hydrogen and/or helium [3, 4], thermonuclear burning starts and a X-ray burst occurs [5].

Photospheric radius expansion (PRE) is a unique phenomenon caused by the strong radiation pressure which is associated with the powerful explosion in an X-ray burst. When the radiation pressure is greater than the gravitational force, photospheric layer is lifted off from the surface of

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the neutron star. During the PRE burst, the luminosity of the X-ray reaches the Eddington luminosity. About 20% of total X-ray bursts show the evidence of PRE [6]. Using the burst observations with PRE evidence and the spectral analyses, the first attempt to constrain the physical quantities was made by Özel [7] with EXO 0748-676, a binary system with repeated thermonuclear bursts.

From the PRE X-ray burst observation, we can obtain flux and temperature as a function of time. Distance to the X-ray burst is another observable quantity that can be determined by estimating the distance to the globular cluster where the binary system is located. Estimation of mass and radius of the neutron star depends on these three observable quantities and two model-dependent parameters. In this article, we focus mainly on the hydrogen mass fraction (X) which is model-dependent. The analytical methods which we use in this work are introduced in Sec. 2. In Sec. 3, the estimated masses and radii for two objects are summarized. Our broad conclusions of this research are discussed in Sec 4.

2 Methods

Estimating the mass and radius of a neutron star in the low-mass X-ray binary (LMXB) starts with two basic equations. If we assume that neutron star luminosity equals the local Eddington limit, the touchdown flux is

$$F_{\mathrm{TD},\infty} = \frac{1}{4\pi D^2}\frac{4\pi GMc}{\kappa}\left(1-\frac{2GM}{Rc^2}\right)^{1/2}, \tag{1}$$

where the ∞ subscript stands for the measured quantities at earth, and c and G are the speed of light and the gravitational constant, respectively. In a later stage of the burst, the ratio of the flux to the temperature is maintained roughly constant. One can define a normalized angular surface area of the neutron star using the flux;

$$A \equiv \frac{F_\infty}{\sigma T^4_{\mathrm{bb},\infty}} = f_c^{-4}\frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}. \tag{2}$$

These two quantities are obtained from the X-ray burst observation, both lightcurve and spectrum. Distance, D, is another quantity that can be estimated separately from X-ray observations. There are two model-dependent parameters in Eq. (1) and (2). The first one is opacity κ which is closly related to the stellar atmosphere. In Thomson scattering in a H-He plasma, $\kappa = 0.2(1+X)\ \mathrm{cm^2 g^{-1}}$, where X is hydrogen mass fraction [8]. The other one is a color-correction factor f_c. With two given equations, Eq. (1) and (2), one can constrain two unknown physical quantities, M and R, if all the other quantities are given, either from the observations ($F_{\mathrm{TD},\infty}$, A, and D) or from the models (f_c and κ). In the previous researches, uniform distribution of model-dependent parameters were used to estimate the neutron star mass and radius probability distributions adopting Monte-Carlo statistics [8]. The main reason for the uniform distribution is uncertainties in estimating the exact values of model-dependent parameters.

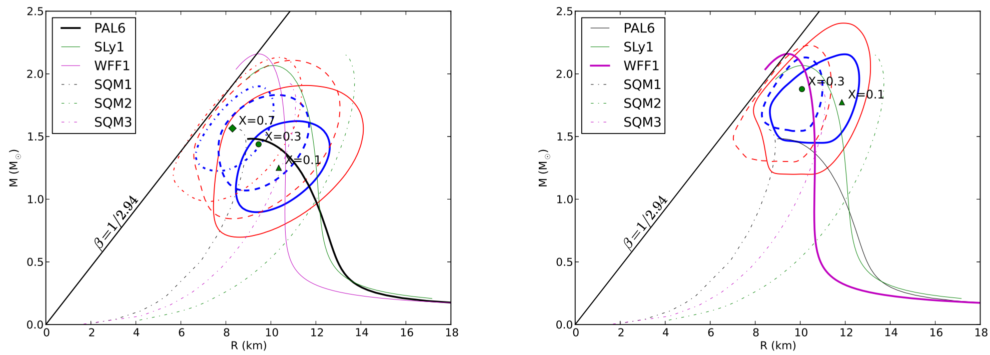
In this work, when the photospheric radius is larger than the neutron star radius ($r_{\mathrm{ph}} \gg R$), we simplified the touchdown flux term by neglecting the general relativity effect in Eq. (1). In this case, Eq. (1) is simplified as

$$F_{\mathrm{TD},\infty} = \frac{1}{4\pi D^2}\frac{4\pi GMc}{\kappa}, \tag{3}$$

where the touchdown flux is independent of the stellar radius. This assumption leads to the significant increase in the acceptance rate in the Monte-Carlo statistics. Since we are dealing with the statistical estimation on the physical quantities, higher acceptance rate produces more statistically meaningful results. This is because, we assume $r_{\mathrm{ph}} \gg R$ and adopt Eq. (3).

Object	D (kpc)	A (km^2 kpc^{-2})	$F_{\mathrm{TD},\infty}$ (erg cm^{-2} s^{-1})
EXO 1745–248	6.3 ± 0.6	1.17± 0.13	6.25± 0.2
4U 1820–30	8.2± 0.7	0.9198± 0.024	5.39± 0.12

Table 1. Observational data for two Type-I X-ray burst sources



(a) EXO 1745-248

(b) 4U 1820-30

Figure 1. Probability distribution of masses and radii of neutron stars estimated based on the PRE bursts for two LMXBs (EXO 1745-248 and 4U 1820-30). Left and right panel show numerical results with fixed hydrogen mass fractions. In both panels, blue and red lines indicate 1-σ (68%) and 2-σ (95%) probability contours, obtained from the Monte-Carlo simulation. Most probable masses and radii are marked by filled symbols with corresponding X values. The general relativity limit is drawn with black straight line, which corresponds to $\beta \equiv GM/Rc^2 = 1/2.94$.

3 Results

By appalying the Monte-Carlo methods with Eq. (2) and (3), we are able to estimate masses and radii of two neutron stars. Because there is no observational constraint on the hydrogen mass fraction for EXO 1745-248 [9], and the companion star of 4U 1820-30 is low-mass helium white dwarf [10], in this work, we consider three different values of hydrogen mass fraction, corresponding to three different types of the envelopes; a hydrogen-poor envelope, a hydrogen-rich envelope and an envelope with intermediate hydrogen abundance.

In Table 1, three observed quantities with uncertainties are given for two LMXBs. In previous studies, two model-dependent parameters are considered to be distributed uniformly; f_c values are given between 1.3 and 1,4 and X is between 0.0 and 0.7. However, in this work, we separated hydrogen mass fraction X for three cases in order to estimate the effects of X to the masses and radii distribution. Our results on the estimated mass and radius distributions for two objects are shown in Fig. 1 in which we used three X values, 0.1, 0.3 and 0.7. We found that the mass distribution shifts to higher values while the radius distributions shifts to lower values as we increase X. If we compare results with X = 0.1 and 0.7, the probability peak in the mass distribution of EXO 1745-248 shifts from 1.24 to 1.57 $M_{\odot}$ while the probability peak in the radius distribution shifts from 10.38 to 8.29 km. For 4U 1820-30, we considered only two values of X, 0.1 and 0.3, because its companion is a helium white dwarf. The probability peak in mass and radius distribution change from (1.80 $M_{\odot}$, 11.67 km) to (1.91 $M_{\odot}$, 10.16 km) as X increases from 0.1 to 0.3.

Estimated masses and radii, which are obtained using Monte-Carlo statistics, can be used to constrain the equations of state (EoS). In Fig. 1, six different EoS models are compared. Recently, neutron stars with masses around 2 solar masses were discovered [11, 12]. These observations allow only three models (SLy1, WFF1, and SQM2) among six models we compare. By comparing the distribution and the most probable point, our new estimates can be used to check the suitability of EoS. As an example, both SLy1 and WFF1 can describe the estimated mass and radius in 4U 1820-30.

4 Summary

In this article, using the Monte-Carlo statistics, we estimated the mass and radius distributions of neutron stars mainly by using three observations (touchdown flux, normalized angular surface area, and distance). Especially, we tested the dependence on the hydrogen mass fraction X by considering three different values of X which correspond to the hydrogen-poor, hydrogen-rich, and intermediate For the case study, we analyze EXO 1745-248 whose X is unknown and 4U 1820-30 whose companion star is known to be a helium-rich star. In both cases, we found that, as we increase X, the M-R distributions shifts to the upper-left side of figures. This indicates that the expected mass increases while the expected radius decreases as X increases. In near future, with more accurate observations on the hydrogen mass fractions of the companion stars of LMXBs, we will be able to provide estimates on the masses and radiii of the neutron star in LMXBs with higher accuracy.

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