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Effects of variability of X-ray binaries on the X-ray luminosity functions of Milky Way

Nazma Islam[a,b,*], Biswajit Paul[a]

[a] Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bangalore 560012, India
[b] Joint Astronomy Programme, Indian Institute of Science, Bangalore 560012, India

HIGHLIGHTS

- We have constructed snapshot galactic XLFs using 2–10 keV RXTE-ASM light-curves.
- HMXB XLFs is described by a power-law model of index −0.48 and σ of 0.19.
- LMXB XLFs is described by a cut-off power-law of index −0.31 and σ of 0.07.
- Variability of XRBs have an important contribution in spread of XLFs.

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ABSTRACT

The X-ray luminosity functions of galaxies have become a useful tool for population studies of X-ray binaries in them. The availability of long term light-curves of X-ray binaries with the All Sky X-ray Monitors opens up the possibility of constructing X-ray luminosity functions, by also including the intensity variation effects of the galactic X-ray binaries. We have constructed multiple realizations of the X-ray luminosity functions (XLFs) of Milky Way, using the long term light-curves of sources obtained in the 2–10 keV energy band with the *RXTE*–ASM. The observed spread seen in the value of slope of both HMXB and LMXB XLFs are due to inclusion of variable luminosities of X-ray binaries in construction of these XLFs as well as finite sample effects. XLFs constructed for galactic HMXBs in the luminosity range 10^{36}–10^{39} erg/sec is described by a power-law model with a mean power-law index of −0.48 and a spread due to variability of HMXBs as 0.19. XLFs constructed for galactic LMXBs in the luminosity range 10^{36}–10^{39} erg/sec has a shape of cut-off power-law with mean power-law index of −0.31 and a spread due to variability of LMXBs as 0.07.

X-ray emission from a normal galaxy i.e. in absence of an AGN or X-ray emitting hot gas, is dominated by collective emission from its X-ray emitting point sources (Fabbiano, 2006). With the advent of *Chandra* and *XMM*–Newton X-ray telescopes era, detailed study of X-ray emission from nearby galaxies is now possible, and has further led to the identification of X-ray binaries in them. This in turn, has helped in construction of X-ray luminosity functions (XLFs) of such galaxies. These XLFs can also act as the indicators of star formation rate, stellar mass and evolution of these galaxies (Grimm et al., 2003; Ranalli et al., 2003; Gilfanov, 2004; Mineo et al., 2012; Kim and Fabbiano, 2010). In spite of the high angular resolution and sensitivity of these X-ray telescopes, the large distances to these galaxies limits us to probe higher luminosity end of their X-ray binary population. On the contrary, X-ray luminosity functions over a wide luminosities range can be constructed with the galactic X-ray binaries, the main hurdle of such an attempt being the distance uncertainty to these galactic sources. Initial attempts in constructing Log N–Log S relation for galactic X-ray binaries were made using X-ray sources from *Uhuru* catalog (Matilsky et al., 1973) and *ASCA* survey (Ogasaka et al., 1998; Sugizaki et al., 2001). Grimm et al. (2002) had constructed XLFs for X-ray binaries in Milky Way by averaging over their count-rates with the first five years of data of the *RXTE* All Sky Monitor. Galactic X-ray luminosity functions are also constructed using 15–50 keV *Swift*–BAT (Voss and Ajello, 2010) and 17–60 keV *INTEGRAL* surveys (Revnivtsev et al., 2008; Lutovinov et al., 2013).

However, the X-ray binaries are highly variable and are often unpredictable. The X-ray binaries show intensity variations by a large factor of a few to several orders of magnitude at all timescales above milliseconds. The galactic HMXB population is dominated by Be–HMXBs, in which the accretion onto the compact object occurs via formation of equatorial disc by stellar wind

* Corresponding author. Tel.: +91 9483709863; fax: +91 8023610492.
E-mail address: nazma@rri.res.in (N. Islam).

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(Reig, 2011). These Be–HMXBs are usually quiescent and occasionally undergo outburst, during which their X-ray luminosity increases by several orders of magnitude. Supergiant HMXBs are another class of HMXB population, where the accretion onto the compact object occurs via a stellar wind or Roche-lobe overflow of the companion star. The galactic low mass X-ray binaries population are dominated by neutron star LMXBs, where the accretion onto the neutron star occurs via Roche Lobe overflow. These systems undergo thermonuclear X-ray bursts lasting few tens to hundreds of seconds (Galloway et al., 2008a), super-bursts lasting up to few hours and outbursts lasting few weeks to few months (Campana et al., 1998). The galactic low mass X-ray binaries population also consists of an appreciable number of Black hole LMXBs, most of which are transient in nature. During quiescence, they occupy very low luminosity states and occasionally they go into outbursts (novae), during which their luminosities increase by several orders of magnitude and they occupy very high luminosity states for a considerable period of time (Remillard and McClintock, 2006).

Multiple *Chandra* and *XMM*–Newton observations show that a large fraction of sources in external galaxies are also variable and includes many transient sources (Voss and Gilfanov, 2007; Williams et al., 2006). The X-ray luminosity functions for external galaxies are constructed out of tens of kilosec exposure of *Chandra* and *XMM*–Newton X-ray telescopes, which are essentially snapshot observations of extragalactic X-ray binaries. However, the galactic XLFs constructed by averaging luminosities of galactic X-ray binaries over 5 years of *RXTE*–ASM observations (Grimm et al., 2002), do not represent the true positions of X-ray binaries luminosities. It is now possible to construct XLFs of Milky Way, taking into account the variability of X-ray binaries because of the availability of long term light-curves of X-ray binaries in our Galaxy with *RXTE*–ASM.

The aim of the present work is to construct X-ray luminosity functions of Milky Way taking into account the variable nature of the galactic X-ray binaries. We have used 16 years of *RXTE*–ASM data to construct differential and integral probability distributions of count-rates for X-ray binaries. Using this, we have constructed multiple realizations of X-ray luminosity functions of Milky Way. The X-ray luminosity functions, including completeness corrections for flux limited nature of ASM, are constructed separately for HMXBs and LMXBs and are fitted with power-law and power-law with cut-off respectively for each realization. These parameter values for multiple realizations are analyzed to estimate the effect of variability of X-ray binaries on the XLFs of Milky Way.

1. Data and analysis

1.1. RXTE All Sky Monitor light curves

In order to construct X-ray luminosity functions of Milky Way including the effects of variability of X-ray binaries, long term light-curves of these sources are required. The long term light-curves obtained with the *RXTE* All Sky Monitor are useful due to all sky nature of its operation and long operational time of 16 years. It had three coded mask telescopes, was sensitive in 2–10 keV energy band and had a sky coverage of 80% in every 90 min (Levine et al., 1996). The sources in the ASM catalogue satisfy the criterion that they have reached an intensity of at least 5 m Crab in the operational time of *RXTE*–ASM and this catalogue excludes some sources like the highly absorbed, hard X-ray sources found in other catalogues like *Swift*–BAT, *INTEGRAL*–IBIS etc. The light-curves of the sources are obtained from *RXTE*–ASM archival data.[1]

[1] (ftp://heasarc.gsfc.nasa.gov/xte/data/archive/ASMProducts/definitive_1dwell/lightcurves/).

1.2. Luminosity functions and variability effects

1.2.1. Construction of differential and integral probability distributions of count-rates

The cumulative X-ray luminosity function (XLF) for the X-ray binary population in a galaxy is defined as the number distribution N($>L$) of X-ray binaries in a galaxy with luminosity greater than L, which is used throughout this paper. The X-ray luminosity functions for the Milky Way are constructed separately for 84 High Mass X ray Binaries and 116 Low Mass X ray Binaries whose distances are found in literature with reasonable accuracy (given in **Appendix** along with references). The light-curves of these sources are extracted from the dwell light-curves and are binned with 1 day bin time.

We quantify the variability in luminosities of each sources in the following way. We first determine the frequency of occurrence of each count rate, taking into account the errors in the count-rate given in the one day binned light-curve of each source. The errors on the count-rate in *RXTE*–ASM data consists of counting statistics along with systematic errors. For the same value of count-rate of a source, we see different values of errors in the ASM light-curves, which makes it difficult to implement Maximum Likelihood method for determination of distribution of sources in presence of systematic errors, in the form suggested by Murdoch et al. (1973). Though it is not clear if the errors in the ASM light curve are gaussian, in the absence of any obvious alternative and for the sake of simplicity, the errors are assumed to be normally distributed for each count-rate. The true count-rate of the source corresponding to each data point in the light-curve, is then assumed to be normally distributed with the observed count rate as the mean of the distribution and the error associated with the count-rate as σ of the gaussian distribution.

To find the probability distribution corresponding to true count-rate, the gaussian distribution of each data point are integrated and summed up for all events as given by Eq. (1).

$$y(a) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{\sqrt{2\pi}\sigma_i}\int_{a-0.05}^{a+0.05} exp\left[\frac{-(x-c_i)^2}{2\sigma_i^2}\right]dx \qquad (1)$$

where N is the total number of data points in one day binned light-curve, c_i is the *i*th count rate, σ_i is the error associated with each c_i and a is the true count-rate bin along x-axis. The bin step for integration is taken to be 0.1 ASM count-rate and the integration for every true count-rate is carried out from half of the bin step preceding the count-rate (a−0.05) to half of the bin step after the count-rate (a+0.05).

The probability distribution of count-rates extending below zero obtained by this method are summed up for all data-points and is taken to be zero. The events which are registered as NULL in the ASM count rate, are neglected in the analysis. These events indicate the absence of any measurement for example, if the source is close to the Sun.

The probability distribution of count-rates constructed by this procedure is called differential probability distribution. From differential probability distribution, integral probability distribution is constructed which denotes the probability distribution of a source having count-rate greater than the c_x (count-rate bin along X axis).

The differential and integral probability distributions are constructed for 84 High Mass X ray Binaries and 116 Low Mass X ray Binaries (including field LMXBs as well as Globular clusters LMXBs). The distributions along with their light curves are shown for Cyg X–1 and Cyg X–3 in Fig. 1. In Fig. 1, the middle panel shows the comparison between differential probability distribution for the Cyg X–1 and Cyg X–3 and binned differential histogram of count-rates without accounting for errors on the count-rates.