Binary Evolution Constraints from Luminosity Functions of LMXBs

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ABSTRACT

The formation and evolution of low-mass X-ray binaries (LMXBs) is not well understood. The properties of a population of LMXBs depend on a number of uncertain aspects of binary evolution, and population studies offers a relatively new way of probing binary interactions. We have studied the shape of the faint end of the X-ray luminosity function (LF) of LMXBs in nearby galaxies with Chandra and in the Milky Way using the Swift all-sky monitor. We find a clear difference between the LF of LMXBs in globular clusters (GCs) and those outside, with a relative lack of faint GC sources. This indicates a difference in the composition of the two populations.

1. Introduction

The LF of bright X-ray sources (L_x > 10^{35} erg s^{-1}) in old stellar populations is dominated by LMXBs. Single galaxies can contain hundreds of these, and with Chandra it has become possible to study the properties of the population statistically. The average LF has been shown to be steep at high luminosities (> few times 10^{37} erg s^{-1}) with a (differential) power-law slope of 1.8-2.5 (Gilfanov 2004; Kim and Fabbiano 2004). At lower luminosities the average LF flattens to a slope of ~1 (Gilfanov 2004).

The LMXBs can be divided into two different categories, based on their location. Field LMXBs are found in low-density regions of galaxies, with a spatial distribution following the density of stars in each galaxy. In such a low-density environment binaries evolve without “noticing” other stars, and it is therefore believed that the LMXBs have evolved from primordial binaries. The other category, GC LMXBs are found in GCs or similar dense stellar systems, where the rate of stellar interactions is high. These systems are believed to be created through encounters between two or more stars, explaining the much higher specific density of LMXBs per unit stellar mass in this environment.

2. The Milky Way

The population of LMXBs in the Milky Way was studied by Grimm et al. 2002 using the RXTE All Sky Monitor (ASM). They emphasized the properties that an outside observer would see, which makes their study ideal for comparison with Chandra observations of other galaxies. However, the RXTE ASM only observes photons in the 2-10 keV band, and Chandra and XMM-Newton are also limited to observing photons below ~10 keV. Many LMXBs emit a significant fraction of their X-ray luminosity in more energetic X-rays, and it is important to understand this contribution when modelling the properties of the population of LMXBs.

We used the Swift BAT instrument to survey the population of LMXBs in the Galactic plane Voss and Ajello 2010. The Swift BAT instrument represents a major improvement in sensitivity for imaging of the hard X-ray sky. BAT is a coded mask, wide field of view telescope sensitive in the 15-200 keV energy range. BAT’s main purpose is to locate Gamma-Ray Bursts (GRBs). While chasing new GRBs, BAT surveys the hard X-ray sky with an unprecedented sensitivity. Thanks to its wide FOV and its pointing strategy, BAT monitors continuously up to 80% of the sky every day. Therefore the light curves
of all sources are sampled regularly in a manner similar to the RXTE ASM. Many X-ray sources are highly variable on a variety of timescales, and therefore regular sampling is important for deriving the average properties of objects, as opposed to pointed observations that are useful for deriving the physical properties of objects at specific times.

We used published identifications of the individual sources to distinguish source types and estimate their distances. The resulting map of sources is shown in figure 1. The LMXBs are seen to concentrate on the bulge region, as expected for a population following the density of stars. The sensitivity of the survey varies with the direction and the luminosity of the X-ray sources. Following (Grimm et al. 2002) we account for this by setting up a model for the Galaxy, and for the range of luminosities investigated we estimate the fraction of the Galaxy that is visible. For all directions we used the local background to estimate the limiting flux detectable by our survey, and used this to create a sensitivity map. For a given X-ray luminosity and direction, this enabled us to calculate the maximum distance, for which an X-ray binary is observable. However, to identify an X-ray source as an X-ray binary, and to determine the distance, it is necessary to have an optically identified counterpart. Grimm et al. (2002) estimated that above a distance of 10 kpc from the sun, the optical identification of X-ray binaries becomes incomplete. We adopted this result and limited our survey to this distance, irrespective of the X-ray brightness of the X-ray binaries. However towards the galactic bulge, source confusion and extinction are serious and optical/IR identifications might be incomplete beyond ∼ 2 − 3 kpc.

By combining the X-ray and optical limits with the model of the Galaxy, we estimated the fraction of the Galaxy observable as a function of source luminosity. The total Galactic luminosity function of LMXBs was then found by correcting the observed luminosity functions for the fraction of the Galaxy probed by our survey. The outcome is shown in figure 2. Also shown in these figures are the LFs of LMXBs obtained if the inner 10 deg of the bulge are excluded from our analysis, to assess the effects of source confusion. The LF is somewhat different with a lower normalization around $10^{36}$ erg s$^{-1}$. At both lower and higher luminosities the results are in agreement with the

Fig. 1.— Identifications in the Swift BAT Galactic plane survey.

Fig. 2.— The luminosity function of Galactic LMXBs in the 15-55 keV band. Squares indicate the entire survey, whereas the inner 10 deg of the bulge were excluded for the circles.
sample including the inner bulge. This is somewhat surprising as incompleteness due to a lack of optical IDs is expected to lead to the opposite effect, and could indicate a higher normalization of LMXBs per unit stellar mass in the bulge than in the disk. However, the statistical uncertainties, together with the uncertainties of distance determination and the mass distribution of the Galaxy (both of which are difficult to quantify), are too large for such a conclusion to be significant. We note that recent results (Kim and Fabbiano 2010) indicate that the LMXB luminosity functions are age dependent at bright end ($>10^{38}$ erg s$^{-1}$). As the bulge and the disk have different star formation histories some variation in the observed LFs is not unexpected.

The LF function displays roughly the same shape as the one found by (Grimm et al. 2002) in the 2-10 keV band. However, at luminosities above $\sim10^{37}$ erg s$^{-1}$ the 15-55 keV LF becomes much steeper, as the more luminous states of LMXBs are soft.

3. Andromeda and Centaurus A

Andromeda and Centaurus A are the best available external environments for studying the populations of LMXBs. Both are sufficiently nearby for LMXBs to be observed at faint luminosities ($<10^{36}$ erg s$^{-1}$) and massive enough to host significant populations. Importantly, a large part of their mass is situated in regions with little or no recent star formation, and the observations are therefore not contaminated by high-mass X-ray binaries or supernova remnants. We studied the LF of the LMXBs in the two galaxies (Voss and Gilfanov 2006, 2007a; Voss et al. 2009). The samples were contaminated by background AGNs. We used the fact that the distribution of these sources is flat on the scale of a single galaxy, and that their log $N$ – log $S$ distribution is known from deep-field surveys to subtract their contribution statistically from our samples. We estimated the sensitivity of the observations over the observed fields, based on the behaviour of the varying Chandra point-spread function and exposure, and used this to correct our results for incompleteness. The resulting LFs are shown in figure 3. In this figure, the LFs are shown separately for the field and the GC sources. A clear difference can be seen, with a relative dearth of faint sources in the GCs. The results are significant above the 3 $\sigma$ level. Investigations of more distant elliptical galaxies have confirmed this difference between the LFs of the GC and the field LMXBs (Kim et al. 2009).

4. The spatial distribution of LMXBs in the bulge of M31

The spatial distribution of LMXBs approximately follows the density of the old stellar component in galaxies (Gilfanov 2004). In Cen A we found good agreement with the radial profile of the LMXBs and the stellar mass traced by the K-band light. However, in the inner part of the M31 bulge the radial profile of the X-ray sources clearly deviate from the stellar density distribution (Voss and Gilfanov 2007b). In the central 1 arcmin there are 29 sources, whereas only 8.4 sources would be expected from an extrapolation of the radial profile at larger distances from the centre. The relative excess becomes larger at smaller radii. The profile of the sources is shown in figure 4. Also shown is the distribution of field sources (dashed line) extrapolated inwards from an annulus with 1-12 arcmin distance from the centre, and the distribution of GC sources.

We proposed that the surplus LMXBs are formed by dynamical interactions (similar to the formation in GCs) in the dense inner bulge of M31. The encounter rate is approximately proportional to the integral of $\rho^2/\sigma_v$ over a stellar system, where $\rho$ is the stellar density and $\sigma_v$ is the velocity dispersion. The bulge is less dense than the typical GCs hosting LMXBs and has a higher velocity dispersion (by a factor of $\sim10$), both of which decreases the encounter rate per unit mass. However, the bulge mass is very large and the rate of encounters is therefore still high enough to potentially produce LMXBs. The expected spatial distribution of these LMXBs is indicated by the line marked “Dyn” in figure 4, which provides a very good fit to the missing component. We studied the different encounter types which can possible lead to the formation of LMXBs to understand if they can successfully create LMXBs in a high velocity dispersion environment like the M31 bulge. The study confirmed the possibility that the sources indeed are formed through dynamical
interactions. It was furthermore found that the LF of the surplus sources follows the same behaviour as the LF of GC LMXBs, with a deficit of faint sources.

5. Discussion and conclusions

We investigated the LF and spatial distribution of LMXBs in the Milky Way, M31 and Cen A. These galaxies are the only massive galaxies in which the LF of LMXBs can be studied at the faint end ($< 10^{36}$ erg s$^{-1}$). We have shown that the LF flattens significantly at luminosities below few times $10^{37}$ erg s$^{-1}$. We have also found that the LF of field sources is different from the LF of the LMXBs found in GCs. This indicates that the two populations are formed differently, and is a strong argument against the idea that all LMXBs are formed in GCs (White et al. 2002). Furthermore the difference provides an additional constraint that can be important for modelling the formation and evolution of the LMXBs, and indicates that the bright and faint systems are not simply different evolutionary states of the same type of LMXBs.

We have also found a new population of LMXBs, formed dynamically in the central bulge of M31. This population shows up as a surplus of X-ray sources in the central 1 arcmin of M31, and the spatial distribution is in agreement with our theoretical model. The LF displays the same dearth of faint sources as the LF of dynamically formed LMXBs in GCs.

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