Astro2020 Science White Paper

X-ray binaries: laboratories for understanding the evolution of compact objects from their birth to their mergers

Thematic Areas:

☒Formation and Evolution of Compact Objects

☒ Multi-Messenger Astronomy and Astrophysics

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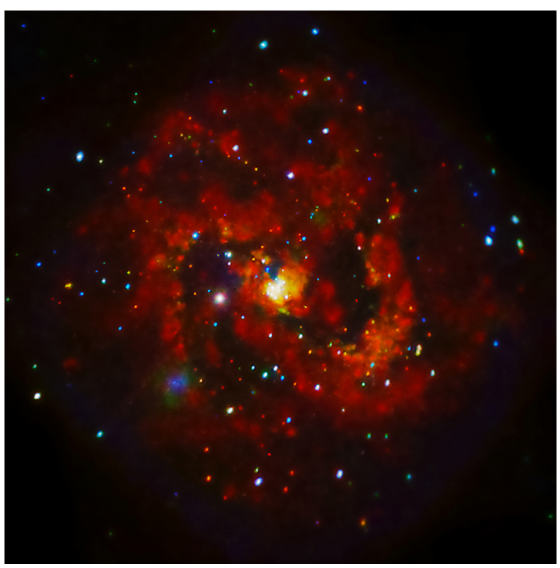

A deep (739 ksec) Chandra image of the nearby galaxy M83 (Long et al. 2014), showing numerous X-ray sources associated with accreting binaries. A next generation X-ray observatory with larger effective area and similar resolution will provide similar data for a fraction the exposure time currently required.

I. Introduction

Binary stellar systems are key tools for several areas of Astrophysics: star-formation processes, the late stages of stellar evolution, compact object formation, and compact object mergers. Aside from the direct observation of photometric or spectroscopic binary stars in our Galaxy, the most efficient probe of binary stellar systems is the observation of the X-ray emitting phase of interacting binaries. This X-ray binary phase is critical for the evolution of close binaries which may eventually become compact-object mergers and hence sources of gravitational waves and/or short γ-ray bursts. In addition studies of X-ray binaries provide critical information on the behavior of matter at extreme gravitational and/or magnetic fields. Understanding these processes is fundamental to modern astrophysics and has been the driver of multiple theoretical and observational studies.

Even if we could obtain a complete census of the accreting binaries in our Galaxy, its limited coverage of the (age, metallicity) parameter space gives us a partial view of the populations of compact objects and their evolution. Observations of external galaxies are essential to achieve the complete picture necessary for understanding compact object formation, and the evolutionary channels of binary stellar systems, especially given their strong dependence on the parameters of their parent stellar populations (e.g. Dray 2006; Fragos et al. 2013; Wikrorowich 2018). These questions are of fundamental importance for many areas of traditional astrophysics including evolution of galaxies (e.g. X-ray binary feedback in the early Universe; Cantalupo 2010; Mirabel et al. 2011), stellar evolution, populations of γ-ray bursts, and gravitational wave source progenitors (Fig. 1). Two major pieces of this puzzle are the demographics of stellar compact objects (neutron stars and "stellar mass" black holes).

The current generation of X-ray observatories (Chandra and to some extent XMM-Newton) has revolutionized our understanding of accreting binaries (e.g. Fabbiano 2006, Kaaret et al. 2017, and references therein). These observations showed conclusively the link between the total number of X-ray binaries, star-formation rate, and galaxy mass (e.g. Mineo et al. 2014; Lehmer et al. 2010; Boroson et al. 2011). They also provided the first measurements of the formation rate of X-ray binaries as function of their age (e.g. Antoniou et al. 2016; 2019) and their dependence on metallicity (e.g. Brorby et al. 2016). These observational constraints are critical for addressing the cosmological evolution of X-ray binaries (e.g. Basu Zych et al. 2013; Lehmer et al. 2016) and constraining X-ray binary evolution models (e.g. Fragos et al. 2013).

These advances required very long (~0.5Msec) Chandra observations reaching luminosities of $\sim10^{37}$erg/s at ~20Mpc. This is the limit of what can be achieved today with Chandra. Observations of lower-luminosity populations are possible only for the nearest objects (e.g. 200ksec on M81 reach $\sim10^{35}$erg/s), but our local volume (<5Mpc) contains only a handful of galaxies. Doing "resolved binary population work" in the X-ray band has just barely become possible with Chandra. Increased collecting area and high spatial resolution will extend these studies to a larger volume of galaxies and to currently inaccessible, fainter populations (Fig. 2).

With a sensitive, next generation X-ray observatory, we will address basic questions such as:

1. What is the mass spectrum and formation rate of stellar compact objects and on what parameters do they depend?
2. What are the evolutionary paths of binary stellar systems and how are they related to gravitational-wave sources and γ-ray bursts?

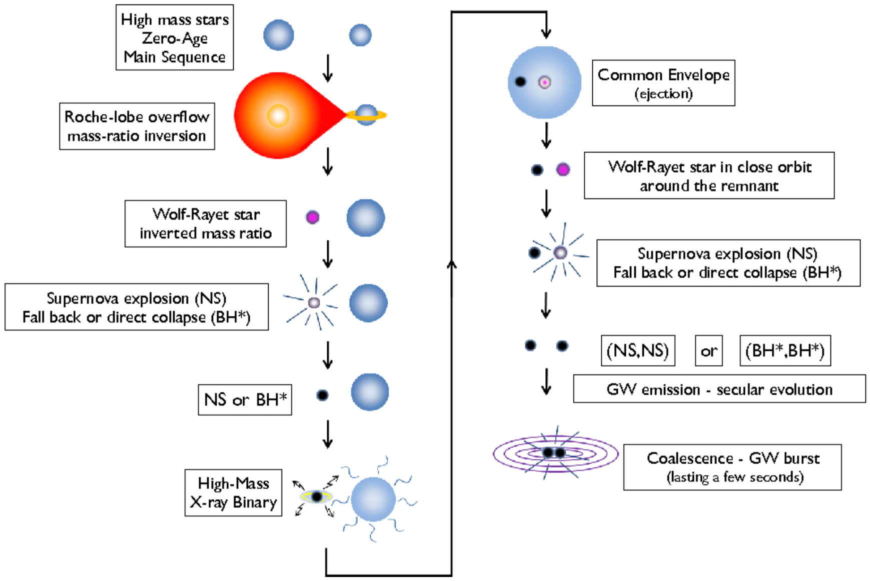

Fig. 1: Indicative evolution of a binary stellar system through the X-ray phase to the final compact object merger (Marchant et al. 2016). Each of the shown phases are key for the outcome of the evolution. The only phases that can provide observational constraints on the physical parameters of the system are the initial binary star phase and the X-ray binary phase.

II. Compact object populations and their relation to gravitational-wave sources and γ-ray bursts

a. <u>The formation rate of compact objects</u>

Measuring the formation rate of X-ray binaries requires: (a) a deep census of their populations, including those at lower luminosities, and (b) the characterization their donor stars. The former is important for avoiding biases against lower-luminosity sources (e.g. persistent wind-fed High-Mass X-ray Binaries –HMXBs– have typical luminosities of 10^{36}-10^{37} erg/s compared to the higher luminosities reached by objects accreting through Roche-lobe overflow). The latter is important for disentangling the different X-ray binary sub-populations and associating them with their parent stellar populations, especially the complex star-formation history and metallicity evolution of galaxies, both of which affect the populations of compact objects.

Pilot studies combining the high resolution of Chandra and HST show the power of this method for measuring the formation rate and X-ray luminosity functions of different X-ray binary sub-populations. Such studies are currently performed in the Local Group (e.g. Antoniou et al. 2019; Garofali et al. 2018), and a handful of nearby galaxies (e.g. Binder et al. 2015). However, the limiting factor in these studies is the sensitivity of the X-ray observatories which currently can only probe the higher-luminosity end of the active accreting binaries of nearby galaxies. The same holds for larger-scale statistical studies of the association of X-ray binary populations with stellar populations of different ages (e.g. Lehmer et al. 2017), which are also limited by the incomplete census of the X-ray binary populations.

The only way to make the next leap forward in our understanding of the formation rate of X-ray binaries and compact objects is with a sensitive X-ray observatory that can efficiently observe the bulk of the active X-ray binary populations in a representative sample of nearby galaxies with a spatial resolution of 0.5” or better allowing the identification of their multi-wavelength counterparts. In fact, the availability of large-area ground and space telescopes in the future (e.g. JWST, 30m class telescopes) open new possibilities through the identification of the spectral types of the optical counterparts of the accreting sources detected in X-ray observations of nearby galaxies, and the precise determination of their star-formation histories.

b. The mass spectrum of compact objects

The association of X-ray binaries with individual optical counterparts allow us to measure their mass functions based on optical spectroscopic monitoring. This has been particularly important for revealing some of the most massive black holes known in X-ray binaries (e.g. Orosz etal, 2007; Silverman & Fillipenko 2008). The optical telescopes planned for the next decade will be able to routinely obtain spectra of early-type stars in nearby galaxies allowing us to measure mass functions for most HMXBs in the Local Group. Measurements of compact object masses in accreting binaries will supplement those obtained from merging compact objects through their gravitational-wave emission, to provide a more complete picture of the compact object mass spectrum.

Furthermore, NuSTAR observations have demonstrated the ability to characterize the nature of the compact objects in X-ray binaries on the basis of their hard X-ray colours (e.g. Vulic et al. 2018). This way we can measure the demographics of black-hole and neutron-star binaries as a function of the age and metallicity of their parent stellar populations. Information on the compact object populations combined with characterization of their donor stars will give us a complete picture of the nature of the accreting binaries, which will allow us to set strong constraints on their evolutionary paths. This can be achieved with an X-ray observatory with an energy band extending up to 12 or even 25 keV (e.g. Fig 4 in Vulic et al. 2018).

Obviously, combining the demographics of the compact object populations in accreting binaries with those determined from gravitational wave emission from merging systems will give us a more complete picture of the compact object populations and hence better constraints of the compact object formation mechanisms and their evolution. In fact, the compact object mass spectrum (or even the fraction of neutron stars and black holes) is a sensitive test of the late stages of stellar evolution, one of the key factors that determine the mass spectrum of compact objects (e.g. Woosley et al. 2002; Belczynski et al. 2012)

Moreover when high quality X-ray spectral and timing information is available we can obtain independent insights in the nature of their compact objects based on the detection of spectral-state transitions, detection of quasi-periodic oscillations, or the shape of their X-ray power-density spectrum (e.g. McClintock & Remillard 2007). Spectroscopic information can also provide constraints on the spin of the accreting binaries in nearby galaxies (c.f. McClintock et al. 2014). We expect great advances in this area with the large collecting area, and high spectral and timing resolution of the Athena observatory (circa 2030). However, an X-ray observatory with similar collecting area (~ 2 m^2) but higher spatial resolution will enable combination of the spectroscopic/timing constraints with mass function determinations and the characterization of their donor stars.

c. Evolutionary channels of X-ray binaries: synergy with gravitational-wave astrophysics

The evolutionary channels of accreting X-ray sources are a key component for our understanding of the demographics of compact objects and particularly their mass and spin

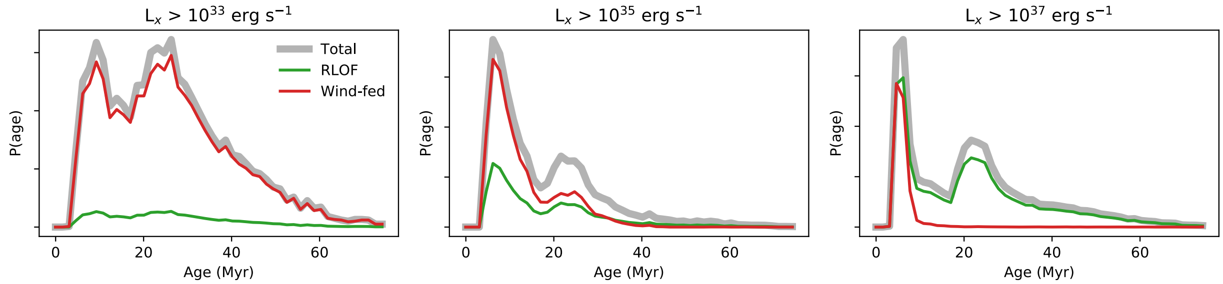

Fig. 2: A census of X-ray binaries down to low luminosities gives us an unbiased picture of their populations. This figure shows the age dependence of the different X-ray binary sub-populations at different luminosity limits. Roche-lobe overflow systems dominate at high luminosities, while at lower luminosities the dominant population are wind-fed systems (based on the `dart-board` population synthesis code; Andrews et al 2018).

distributions (e.g. Fragos & McClintock 2015; Qin et al. 2018, 2019). In addition, the populations of compact objects and their evolutionary paths are critical for modeling the populations of gravitational wave progenitors, short γ-ray bursts, and the role of X-ray binaries in preheating the intergalactic medium in the early Universe (e.g. Justham & Schawinski 2012; Fialkov et al. 2014; Madau & Fragos 2018).

Detailed modeling of individual sources in our Galaxy has already given a basic framework for the different phases in the evolution of binary stellar systems (e.g. Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2006). However, the small number of objects in combination with the limited parameter space covered by the stellar populations in our Galaxy does not represent the conditions in other galaxies where the majority of the gravitational wave and γ-ray burst progenitors are expected to originate. In fact several types of exotic X-ray binaries which challenge our models have been discovered in other galaxies, and have led to the identification of new evolutionary channels (e.g. neutron-star ULXs, Wolf-Rayett binaries etc; Valsecchi et al. 2010; Fragos et al. 2015 Wiktorowicz et al. 2017; Sorensen et al. 2017).

More general constraints on binary evolution channels can be obtained by combining X-ray binary population studies with population synthesis models (e.g. Belczynski et al. 2004; Fragos et al. 2008). For example, the application of state-of-the-art accreting binary population synthesis models with the deepest Chandra observations of nearby galaxies has led to broad constraints on binary evolution parameters (e.g. common envelope ejection efficiency, stellar wind mass loss rate; Tzanavaris et al. 2013).

However, since these studies are based on summary statistics (e.g. X-ray luminosity functions, variability patterns) they are limited by the fact that they include the contribution of several different populations not allowing us to disentangle the evolutionary parameters pertinent to each sub-population. Therefore, characterization of the X-ray binaries on the basis of their donor stars and/or compact objects allows us to: (a) model the different sub-populations individually focusing on the parameters that drive their formation, and (b) model the observational pathways of individual systems of interest (e.g. Sorensen et al. 2017; Andrews et al. 2018).

Constraints on the mass spectrum and formation rate of extragalactic compact objects in concert with characterization of their local stellar populations will test our current theories of compact object formation and the evolution of binary systems. In fact there are several parameters in binary evolution that are poorly known (e.g. stellar wind mass-loss rate, supernova kick velocity distribution, common envelope evolution). These parameters are decisive for the evolution and survival of binary systems, and of course the formation of compact object mergers.

III. Conclusion: the need for a high resolution, large area X-ray telescope

Chandra (which is our workhorse for studies of the extragalactic X-ray source populations) has demonstrated that high spatial resolution is critical for studies of the X-ray source populations. However, it is near to the limit of its capabilities in this field due to its relatively low effective area allowing us to study in detail only the small number of galaxies in our very local volume. Any major advances require a high spatial resolution, high sensitivity X-ray telescope in order to: (a) detect the bulk of active X-ray binary systems and minimize source confusion problems; (b) increase our sample of galaxies and better cover the (stellar age, metallicity) parameter space by increasing the accessible volume at those detection limits; (c) classify the X-ray sources based on their optical counterparts and spectroscopic and timing X-ray properties. With a more complete and representative census of the X-ray binary populations enabled by such an observatory, we will be able to make the next leap in our understanding of the formation and evolution channels of binary stellar systems and compact object populations.

These science requirements translate to a next generation X-ray observatory with spatial resolution similar to Chandra's (0.5″) and high effective area. Fig. 3 presents the different types of sources that we will be able to study in the local Universe in a 100ksec exposure with a 2m^2 (red line) and a 0.5 m^2 (green line) observatory.

It is clear that these observations will extend our reach to populations currently inaccessible outside our Galaxy (e.g. normal stars, CVs), or outside our immediate neighborhood (e.g. quiescent accreting binaries). In addition they will extend to the distance of M81 and even the Antennae important X-ray timing and spectroscopic diagnostics that are currently available only for Galactic or Magellanic Cloud sources (e.g. detection of pulsations and spectral state transitions, measurement of power density spectra). This way a high-resolution, high-throughput X-ray observatory will address diverse and fundamental questions such as compact object demographics, accreting binary evolution, the nature of γ-ray burst and gravitational wave progenitors, the cosmological evolution of galaxies.

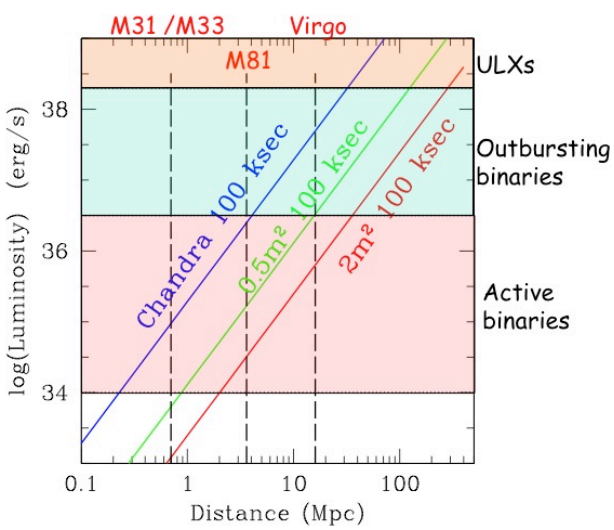

Fig. 3: Discovery space enabled by a high-resolution, high-throughput X-ray mission. The black curves show the limiting luminosity (3σ level) as a function of distance for a 100ksec observation with an X-ray observatory with effective area of 0.5m^2 (green) and 2 m^2 (red) and 0.5″ resolution. For comparison Chandra's liming luminosity is also shown. For reference are indicated the distances of nearby objects and the types of sources that are probed at various luminosities (active and quiescent X-ray binaries, ULXs).

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