Astro2020 Science White Paper

Time Domain Studies of Neutron Star and Black Hole Populations: X-ray Identification of Compact Object Types

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Neven Vulic[1,2,3]
Institution: (1) NASA Goddard Space Flight Center (2) Center for Research in Space Sciences and Technology II (3) University of Maryland, College Park
Email: neven.vulic@nasa.gov
Phone: +1 (301) 286-8672

Co-authors: A. E. Hornschemeier (NASA GSFC/John Hopkins University), V. Antoniou (Texas Tech University/Harvard CfA), A. R. Basu-Zych (NASA GSFC/CRESSTII/University of Maryland Baltimore County), B. Binder (California State Polytechnic University), F. M. Fornasini (Harvard CfA), F. Furst (ESAC), F. Haberl (MPE), M. Heida (Caltech), B. D. Lehmer (University of Arkansas), T. J. Maccarone (Texas Tech University), A. F. Ptak (NASA GSFC/John Hopkins University), G. R. Sivakoff (University of Alberta), P. Tzanavaris (University of Maryland Baltimore County/NASA GSFC), D. R. Wik (University of Utah), B. F. Williams (University of Washington), J. Wilms (Universitat Erlangen-Nurnberg), M. Yukita (John Hopkins University), A. Zezas (University of Crete/Harvard CfA)

Abstract

What are the most important conditions and processes governing the growth of stellar-origin compact objects? The identification of compact object type as either black hole (BH) or neutron star (NS) is fundamental to understanding their formation and evolution. To date, time-domain determination of compact object type remains a relatively untapped tool. Measurement of orbital periods, pulsations, and bursts will lead to a revolution in the study of the demographics of NS and BH populations, linking source phenomena to accretion and galaxy parameters (e.g., star formation, metallicity). To perform these measurements over sufficient parameter space, a combination of a wide-field (> 5000 deg^2) transient X-ray monitor over a

dynamic energy range ($\sim 1-100$ keV) and an X-ray telescope for deep surveys with $\lesssim 5''$ PSF half-energy width (HEW) angular resolution are required. Synergy with multiwavelength data for characterizing the underlying stellar population will transform our understanding of the time domain properties of transient sources, helping to explain details of supernova explosions and gravitational wave event rates.

1 Introduction

The end result of the evolution of massive stars is the production of a population of NS and BH. These stellar-origin compact objects grow through two main channels: accretion and mergers. The accretion growth, which is likely the dominant mode, is affected by star formation, stellar evolution, and binary processes such as the strength of stellar winds, the common envelope phase, and the initial mass function. Merger growth (e.g., gravitational wave sources) gives us a unique snapshot view of the masses of stellar origin compact objects, which is also connected to stellar evolution and star formation processes in the Universe. It is critically important that we better understand NS/BH populations. As remnants of supernova explosions and the end states of massive stars, they allow us to probe key phases in stellar evolution and death. Also, in addition to understanding the progenitor paths for gravitational wave sources, the X-ray emission from this population likely plays an important role in the early heating of the primordial intergalactic medium (IGM) at $10 < z < 20$ (e.g. Fragos et al., 2013; Mesinger et al., 2014; Pacucci et al., 2014; Madau & Fragos, 2017; Sazonov & Khabibullin, 2017; Das et al., 2017).

We have had an explosion of information on the overall energy output (including refinement of key population properties) from accreting compact objects detected via X-ray emission over the age of the Universe, thanks to a suite of X-ray observatories (e.g. Lehmer et al., 2010; Stiele et al., 2011; Mineo et al., 2012; Fragos et al., 2013; Mineo et al., 2014; Lehmer et al., 2014; Basu-Zych et al., 2016; Haberl & Sturm, 2016; Peacock & Zepf, 2016; Vulic et al., 2018). Key breakthroughs have come via X-ray imaging by *Chandra*/*XMM-Newton* in the $0.3-10$ keV energy band and *NuSTAR* at $E > 10$ keV, combined with emerging multi-messenger constraints on mergers from gravitational wave observatories such as LIGO. Properties of NS and BH populations have been reliably connected to galaxy properties such as star formation rate (SFR), stellar mass ($M_\star$), stellar age, and metallicity, and has been studied over significant intervals of cosmic time. However, nearby galaxy surveys have long classified X-ray binaries (XRBs) by the mass category of their donor stars, high-mass (HMXB) and low-mass (LMXB). The identification of the compact-object type has been limited to XRBs in our Galaxy, the Magellanic Clouds, and a few of the brightest nearby extragalactic systems.

There are a number of methods that have been used to determine the compact object type in XRBs. The most reliable to date are in the X-ray time domain. The detection of coherent pulsations and/or a Type I X-ray burst provides confirmation that the object is a NS. Otherwise, Kepler's third law is required to determine the mass of the compact object in the XRB and classify it as a NS or BH. Quasiperiodic oscillations from the ultraluminous X-ray sources (ULX) M82 X-1 and NGC 1313 X-1 (Pasham et al., 2014, 2015) have also been used to obtain mass estimates for candidate BHs. These methods require high signal-to-noise data only available for a handful of the brightest extragalactic sources. Time domain studies of compact object *populations* have thus not yet been possible outside the Milky Way and Magellanic Clouds.

Compact object formation is important for a wide range of topics in astronomy and astrophysics. We can improve our understanding of hard-to-model supernova explosions if we more accurately map them to their resulting stellar remnants. The demographics of BH and NS populations are required to determine formation rates for gravitational wave events. Here we discuss some important, yet poorly understood populations (e.g., ULXs, pulsars, Wolf-Rayet XRBs, and some enigmatic ultraluminous burst sources) that would yield key insight into these topics via X-ray measurements of spin/orbital periods, bursts, and complementary multiwavelength constraints.

2 Ultraluminous X-ray Sources & Pulsar Populations

ULXs are off-nuclear X-ray sources having X-ray luminosities $L_X \gtrsim 10^{39}$ erg s^{-1} $(0.5-10$ keV) that exceed the Eddington luminosity for a $\approx 10\ M_\odot$ BH, assuming isotropy. ULXs were generally thought to be massive, possibly-beamed, stellar-mass BHs, or intermediate-mass BHs accreting at sub-Eddington rates. The detection of coherent pulsations from 4 ULXs in nearby galaxies[1] with *XMM-Newton*/*NuSTAR* and one source in the Milky Way (detected with *Swift* and *Fermi*) has demonstrated that NSs are capable of producing the high luminosities that previously were thought to be the domain of BH systems (Bachetti et al., 2014; Fürst et al., 2016, 2017; Israel et al., 2017a,b; Carpano et al., 2018; Kosec et al., 2018; Walton et al., 2018; Wilson-Hodge et al., 2018). Figure 1 shows the peak L_X of known ULX pulsars as a function of distance.

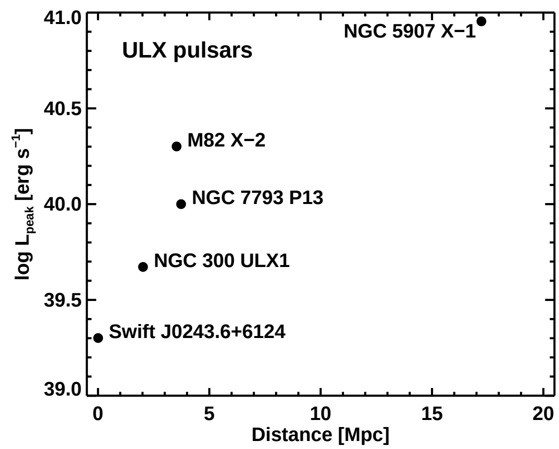

Figure 1: **Some NSs emit as much as 100 times above the Eddington limit and we do not yet understand how.** Peak L_X $(0.5-10.0$ keV) vs. host galaxy distance for currently known ULX pulsars. The sensitivity and collecting area of current X-ray telescopes limit the detection of ULX *pulsars* having $L_X \simeq 10^{39}$ erg s^{-1} to $d \approx 5$ Mpc.

Wiktorowicz et al. (2017) simulated isolated binaries using the STARTRACK population synthesis code, finding that NS were the dominant ULX accretors a few hundred Myr post-starburst. Current X-ray telescopes have the ability to detect pulsations from ULXs with $L_X \simeq 10^{39}$ erg s^{-1} out to $d \approx 5$ Mpc ($\sim 20\%$ pulsed fraction). We are therefore unable to search for pulsations within the known population of >400 ULXs (all with $L_X \gtrsim 10^{39}$ erg s^{-1}) that have been detected out to $d \approx 200$ Mpc, even though 80% are within 50 Mpc (Liu, 2011; Walton et al., 2011; Earnshaw et al., 2019). Detailed surveys of nearby ULXs are necessary for statistically-significant studies of their population characteristics (e.g., variability/pulsed fraction, age dependence, spin period distribution) in addition to compact object identification.

X-ray timing analysis can also be extended to the general (non-ULX) X-ray pulsar population in a range of formation environments in nearby galaxies. Currently, X-ray pulsar *populations* can only be studied in the Milky Way and Magellanic Clouds (e.g. Haberl & Sturm, 2016; Antoniou et al., 2010; Antoniou & Zezas, 2016). In a single year, the *Swift* SMC survey detected Type I X-ray bursts and orbital periods for 6 B*e*-XRBs (Kennea et al., 2018), systems that are useful for predicting gravitational wave event rates. To extend ULX pulsar detection from $d \approx 5$ to 25 Mpc and study non-ULX pulsars beyond the Magellanic Clouds, an X-ray telescope must have sufficient throughput to detect sources with flux $\sim 10^{-17}$ erg cm^{-2} s^{-1} within

[1] Also the candidate ULX pulsar M51 ULX8, inferred from the cyclotron resonance scattering feature (Brightman et al., 2018).

200 ks, as well as a large field of view (~ 0.5 deg^2) for efficient surveys of galaxies with large angular sizes (e.g., M31 and the Magellanic Clouds), and a $\lesssim 5''$ PSF HEW to avoid confusion in star-forming regions.

3 Wolf-Rayet XRBs & Massive Stellar-Mass BH Production

LIGO/Virgo have now discovered seven binary BH mergers with pre-merger (individual BH) masses $\gtrsim 30\ M_\odot$ (The LIGO Scientific Collaboration et al., 2018). These are comparable to the most massive known[2] stellar-mass BHs Cyg X-1 and M33 X-7 ($\sim 15\ M_\odot$, Orosz et al. 2007, 2011). When looking for gravitational wave progenitor populations, massive BH XRBs with orbital periods less than ~ 1.5 days are excellent candidates, as they will merge within a Hubble time (van den Heuvel et al., 2017). Likely candidates for this scenario include Wolf-Rayet (WR) XRBs, which constitute a subclass of HMXBs that have a WR star as their donor, for which, to date, there are only four confirmed examples, namely Galactic source Cyg X-3 (van Kerkwijk et al., 1996) and three additional extragalactic candidates (e.g. Esposito et al., 2015). Fig. 2 shows WR XRB orbital periods compared to host galaxy distance.

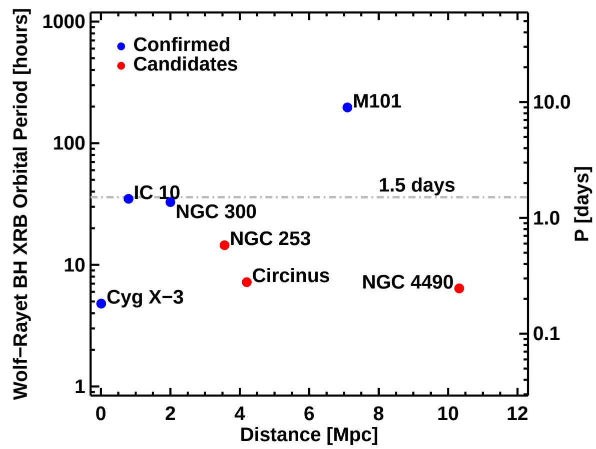

Figure 2: The confirmed (blue) and candidate (red) Wolf-Rayet BH-XRBs in the Universe. Shown is their orbital period vs. distance of the host galaxy. WR XRBs below the horizontal line at ~ 1.5 days are expected to form a BH-BH binary and merge within a Hubble time.

Since WR stars will likely end their lives as BHs, a census of BHs in WR XRB systems is critical to understanding how the Universe is able to produce massive BH mergers. This census can be accomplished by identifying and confirming more of these unique systems in the nearby Universe with next-generation X-ray observations/surveys. van den Heuvel et al. (2017) estimated that the Milky Way should have ~ 10 WR XRBs, about half of which should have luminosities at the Cyg X-3 level (survey completeness throughout the Galactic plane likely hampers detection for other WR XRBs). Due to comparable host environments (star-forming regions) and count rates necessary for detection of ULX pulsations and WR XRB orbital periods, an X-ray telescope with the specifications described in Section 2 is required. This would expand the available detection volume by a factor of 100 to $d \approx 20$ Mpc, sufficient to create a statistically significant sample of WR XRBs via orbital period measurements. Currently, obtaining BH masses is hampered by the difficulty of measuring optical absorption lines to determine the radial velocity amplitude. Future 30-m class telescopes will enable such measurements for many of these systems. Populating the BH mass distribution will put important constraints on supernova explosions by identifying the range of potential remnant masses and gravitational

[2] BH masses for IC 10 X-1 and NGC 300 X-1 were likely overestimated (Laycock et al., 2015a,b; Binder et al., 2015).

wave events via BH masses in XRBs.

4 Stochastic Ultraluminous Bursts

XRBs are known to be highly transient sources, where the phenomenology for state transitions (e.g., quiescence to outburst) in BH and NS systems has been well studied (e.g. Maccarone, 2003; McClintock & Remillard, 2006; Done et al., 2007; Church et al., 2014; Tetarenko et al., 2016). However, outliers have been identified among the extragalactic population that present new challenges to explaining their behavior.

Irwin et al. (2016) recently discovered ultraluminous X-ray bursts in two ultracompact companions of nearby elliptical galaxies in archival *Chandra*/*XMM-Newton* data. The flares had rise times of < 1 min and decay times of ~ 1 hr, with peak L_X of 10^{40-41} erg s^{-1}. Five other similar flaring sources have been detected by *Chandra* (Sivakoff et al., 2005; Sun et al., 2013; Jonker et al., 2013; Glennie et al., 2015; Bauer et al., 2017). These flares are reminiscent of the mysterious transient extragalactic fast *radio* bursts.

What leads to seemingly stochastic ultraluminous bursts from X-ray sources? Potential explanations include tidal stripping of a white dwarf onto an intermediate-mass BH, an X-ray afterglow from an off-axis short-duration gamma-ray burst, or a low-luminosity gamma-ray burst at high-redshift (Bauer et al., 2017; Shen, 2019). However, none of these scenarios can completely explain all the properties of these sources. Identifying the accreting compact object in these burst sources is the first step to understanding the physical mechanisms responsible for this behavior. Any X-ray time domain instrument capable of studying ULXs, pulsars, or WR XRBs will also be able to detect ultraluminous bursts in pointed observations and/or sensitive surveys of nearby galaxies.

5 Multiwavelength Connections

When combined with X-ray observations, multiwavelength data will enhance studies of the various XRB source classes discussed. For ULXs, optical and infrared photometric/spectroscopic observations have been used to confirm ULX distances, counterparts, and probe the surrounding environment (e.g. Moon et al., 2011; Heida et al., 2015, 2016; Binder et al., 2018). For instance, *JWST* will be able to study the obscured star-forming regions surrounding ULXs and Wolf-Rayet XRBs, drawing parallels between local dwarf starburst galaxies and reionization-era analogues[3]. In the optical, the Large Synoptic Survey Telescope (LSST; expected first light in 2021; start of 10-year all-sky survey in 2022) will detect $\sim 10^7$ transient sources per night in the $ugrizy$ filters. Johnson et al. (2019) predict that $\sim 18\%$ of Galactic LMXBs will have their orbital periods (in the range of 10 min to 50 days) determined from LSST variability data. Difference imaging using LSST data will also help to identify counterparts to transient X-ray sources (e.g., previous work in M31; Williams et al., 2004; Barnard et al., 2012, 2015), which can then be used to estimate orbital periods from the optical/X-ray flux ratio (Revnivtsev et al., 2012). High-cadence optical observations are thus a powerful tool that can be used to help determine compact object types. At radio wavelengths, next-generation radio telescopes having

[3] See white paper by Basu-Zych et al. regarding heating of the early intergalactic medium by HMXBs.

an order of magnitude increase in sensitivity will make nearby galaxy monitoring campaigns feasible, and at the very least offer precise astrometric follow-up for luminous XRBs/outbursts. However, all multiwavelength approaches require X-ray detection of sources to identify XRB candidates.

Lastly, future gravitational wave detections in well-studied nearby galaxies will advance our understanding of progenitor populations and environments conducive to these events. For example, the NS-NS merger GW170817 observed by LIGO/VIRGO was also detected as a short gamma-ray burst by *Fermi* (Abbott et al., 2017, 2019) and at X-ray wavelengths by *Chandra* 9 days after merger (Haggard et al., 2017; Troja et al., 2017), corresponding to a likely off-axis orientation.

6 Experimental Requirement Necessary to Answer Key Question

A combination of X-ray observatories with unique instrumental specifications are required to address the fundamental questions outlined here. For deep surveys of, e.g., nearby galaxies and the Galactic Center, a combination of ~ 1 ms time resolution to detect pulsations, a large field of view (~ 0.5 deg^2) and collecting area (> 1 m^2 at 1 keV) for efficient surveys, and moderate to exquisite angular resolution ($\lesssim 5''$ PSF HEW to resolve nearby point sources in crowded fields) will be required to transform our understanding of XRB populations at $\sim 0.1 - 10$ keV energies.

Finally, we should also point out that sub-luminous outbursts from BH and NS populations, such as very fast X-ray transients (VFXTs, e.g., Degenaar & Wijnands, 2009; Degenaar et al., 2015) and supergiant fast X-ray transients (SFXTs, e.g., Sguera et al., 2005, 2006) are important in addressing our science goals. This motivates the need for a transient X-ray monitor having a large field of view (> 5000 deg^2), rapid response time (< 1 hr) for follow-up, sensitivity of $\sim 10^{-8}$ erg cm^{-2} s^{-1} in 1 s to detect bursts in the Milky Way and nearby galaxies, angular resolution of $\sim 1'$ to aid with localization, optimized time resolution and collecting area for timing studies and to mitigate pile-up for bright Galactic source populations, and hard X-ray capability in the $\sim 1 - 100$ keV energy range to probe obscured sources. These specifications will be especially useful for time domain studies of transients given the wealth of all-sky multiwavelength data in the coming decade.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, ApJ, 848, L12
—. 2019, Physical Review X, 9, 011001
Antoniou, V., & Zezas, A. 2016, MNRAS, 459, 528
Antoniou, V., Zezas, A., Hatzidimitriou, D., & Kalogera, V. 2010, ApJ, 716, L140
Bachetti, M., Harrison, F. A., Walton, D. J., et al. 2014, Nature, 514, 202
Barnard, R., Galache, J. L., Garcia, M. R., et al. 2012, ApJ, 756, 32
Barnard, R., Garcia, M. R., & Murray, S. S. 2015, MNRAS, 449, 3426
Basu-Zych, A. R., Lehmer, B., Fragos, T., et al. 2016, ApJ, 818, 140
Bauer, F. E., Treister, E., Schawinski, K., et al. 2017, MNRAS, 467, 4841
Binder, B., Gross, J., Williams, B. F., & Simons, D. 2015, MNRAS, 451, 4471
Binder, B., Levesque, E. M., & Dorn-Wallenstein, T. 2018, ApJ, 863, 141
Brightman, M., Harrison, F. A., Fürst, F., et al. 2018, Nature Astronomy, 2, 312
Carpano, S., Haberl, F., Maitra, C., & Vasilopoulos, G. 2018, MNRAS, 476, L45
Church, M. J., Gibiec, A., & Bałucińska-Church, M. 2014, MNRAS, 438, 2784
Das, A., Mesinger, A., Pallottini, A., Ferrara, A., & Wise, J. H. 2017, MNRAS, 469, 1166
Degenaar, N., & Wijnands, R. 2009, A&A, 495, 547
Degenaar, N., Wijnands, R., Miller, J. M., et al. 2015, Journal of High Energy Astrophysics, 7, 137
Done, C., Gierliński, M., & Kubota, A. 2007, A&A Rev., 15, 1
Earnshaw, H. P., Roberts, T. P., Middleton, M. J., Walton, D. J., & Mateos, S. 2019, MNRAS, 483, 5554
Esposito, P., Israel, G. L., Milisavljevic, D., et al. 2015, MNRAS, 452, 1112
Fragos, T., Lehmer, B. D., Naoz, S., Zezas, A., & Basu-Zych, A. 2013, ApJ, 776, L31
Fürst, F., Walton, D. J., Stern, D., et al. 2017, ApJ, 834, 77
Fürst, F., Walton, D. J., Harrison, F. A., et al. 2016, ApJ, 831, L14
Glennie, A., Jonker, P. G., Fender, R. P., Nagayama, T., & Pretorius, M. L. 2015, MNRAS, 450, 3765
Haberl, F., & Sturm, R. 2016, A&A, 586, A81
Haggard, D., Nynka, M., Ruan, J. J., et al. 2017, ApJ, 848, L25
Heida, M., Jonker, P. G., Torres, M. A. P., et al. 2016, MNRAS, 459, 771
Heida, M., Torres, M. A. P., Jonker, P. G., et al. 2015, MNRAS, 453, 3510
Irwin, J. A., Maksym, W. P., Sivakoff, G. R., et al. 2016, Nature, 538, 356
Israel, G. L., Belfiore, A., Stella, L., et al. 2017a, Science, 355, 817
Israel, G. L., Papitto, A., Esposito, P., et al. 2017b, MNRAS, 466, L48
Johnson, M. A. C., Gandhi, P., Chapman, A. P., et al. 2019, MNRAS, 484, 19
Jonker, P. G., Glennie, A., Heida, M., et al. 2013, ApJ, 779, 14
Kennea, J. A., Coe, M. J., Evans, P. A., Waters, J., & Jasko, R. E. 2018, ApJ, 868, 47
Kosec, P., Pinto, C., Walton, D. J., et al. 2018, MNRAS, 479, 3978
Laycock, S. G. T., Cappallo, R. C., & Moro, M. J. 2015a, MNRAS, 446, 1399
Laycock, S. G. T., Maccarone, T. J., & Christodoulou, D. M. 2015b, MNRAS, 452, L31
Lehmer, B. D., Alexander, D. M., Bauer, F. E., et al. 2010, ApJ, 724, 559
Lehmer, B. D., Berkeley, M., Zezas, A., et al. 2014, ApJ, 789, 52
Liu, J. 2011, ApJS, 192, 10

Maccarone, T. J.; Coppi, P. S. 2003, MNRAS, 338, 189
Madau, P., & Fragos, T. 2017, ApJ, 840, 39
McClintock, J. E., & Remillard, R. A. 2006, Black hole binaries, ed. W. H. G. Lewin & M. van der Klis (Cambridge University Press), 157–213
Mesinger, A., Ewall-Wice, A., & Hewitt, J. 2014, MNRAS, 439, 3262
Mineo, S., Gilfanov, M., & Sunyaev, R. 2012, MNRAS, 419, 2095
Mineo, S., Fabbiano, G., D'Abrusco, R., et al. 2014, ApJ, 780, 132
Moon, D.-S., Harrison, F. A., Cenko, S. B., & Shariff, J. A. 2011, ApJ, 731, L32
Orosz, J. A., McClintock, J. E., Aufdenberg, J. P., et al. 2011, ApJ, 742, 84
Orosz, J. A., McClintock, J. E., Narayan, R., et al. 2007, Nature, 449, 872
Pacucci, F., Mesinger, A., Mineo, S., & Ferrara, A. 2014, MNRAS, 443, 678
Pasham, D. R., Cenko, S. B., Zoghbi, A., et al. 2015, ApJ, 811, L11
Pasham, D. R., Strohmayer, T. E., & Mushotzky, R. F. 2014, Nature, 513, 74
Peacock, M. B., & Zepf, S. E. 2016, ApJ, 818, 33
Revnivtsev, M. G., Zolotukhin, I. Y., & Meshcheryakov, A. V. 2012, MNRAS, 421, 2846
Sazonov, S., & Khabibullin, I. 2017, MNRAS, 468, 2249
Sguera, V., Barlow, E. J., Bird, A. J., et al. 2005, A&A, 444, 221
Sguera, V., Bazzano, A., Bird, A. J., et al. 2006, ApJ, 646, 452
Shen, g.-F. 2019, ApJ, 871, L17
Sivakoff, G. R., Sarazin, C. L., & Jordán, A. 2005, ApJ, 624, L17
Stiele, H., Pietsch, W., Haberl, F., et al. 2011, A&A, 534, A55
Sun, L., Shu, X., & Wang, T. 2013, ApJ, 768, 167
Tetarenko, B. E., Sivakoff, G. R., Heinke, C. O., & Gladstone, J. C. 2016, ApJS, 222, 15
The LIGO Scientific Collaboration, the Virgo Collaboration, Abbott, B. P., et al. 2018, arXiv e-prints, arXiv:1811.12940
Troja, E., Piro, L., van Eerten, H., et al. 2017, Nature, 551, 71
van den Heuvel, E. P. J., Portegies Zwart, S. F., & de Mink, S. E. 2017, MNRAS, 471, 4256
van Kerkwijk, M. H., Geballe, T. R., King, D. L., van der Klis, M., & van Paradijs, J. 1996, A&A, 314, 521
Vulic, N., Hornschemeier, A. E., Wik, D. R., et al. 2018, ApJ, 864, 150
Walton, D. J., Roberts, T. P., Mateos, S., & Heard, V. 2011, MNRAS, 416, 1844
Walton, D. J., Bachetti, M., Fürst, F., et al. 2018, ApJ, 857, L3
Wiktorowicz, G., Sobolewska, M., Lasota, J.-P., & Belczynski, K. 2017, ApJ, 846, 17
Williams, B. F., Garcia, M. R., Kong, A. K. H., et al. 2004, ApJ, 609, 735
Wilson-Hodge, C. A., Malacaria, C., Jenke, P. A., et al. 2018, ApJ, 863, 9