Summary

High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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High mass X-ray binaries: Beacons in a stormy universe

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Abstract. The discovery of gravity waves from the mergers of black hole binaries has focused the astronomical community on the high mass X-ray binaries (HMXBs) as the potential progenitors of close pairs of compact stars. This symposium gathered experts in observational and theoretical work for a very timely review of our understanding of the processes that drive the X-ray luminosity of the diverse kinds of binaries and what evolutionary stages are revealed in the observed cases. Here I offer a condensed summary of some of the results about massive star properties, the observational categories of HMXBs, their accretion processes, their numbers in the Milky Way and other galaxies, and how they may be related to the compact binaries that merge in a burst of gravity waves.

Keywords. stars: early-type, stars: emission-line Be, stars: evolution, X-rays: binaries

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1. HMXBs and Gravitational Waves from Merging Compact Objects

The LIGO detection in 2015 September of gravity waves from the merger of two black holes was a seminal moment in modern astrophysics that marked the first direct measurement of gravity waves and proved the existence of binary black holes. At the time of writing (2018 December), the number of detected black hole mergers has risen to ten, and some trends are already emerging (for example, pre-merger black hole masses do not exceed $45 M_\odot$ and both components tend to have similar mass; The LIGO Scientific Collaboration & The Virgo Collaboration 2018). The origins of compact merging objects are now a subject of intense study, and the logical starting point is assessing anew the evolutionary stages that lead to the known binaries with black hole components, the high mass X-ray binaries (HMXBs).

This IAU Symposium offered participants a critical appraisal of our understanding of the properties and processes that define the HMXBs and how they may be related to binary black hole mergers. In particular, the presence of a luminous component in HMXB systems means that observational studies across the electromagnetic can help us explore processes that are otherwise hidden from us, and thus HMXBs are beacons in our journey of discovering how black hole mergers may occur. This meeting brought together experts from many communities including observational optical and X-ray astronomy and binary star theory, and we enjoyed a diverse and vibrant exchange that included 50 talks and 109 poster presentations. What follows are my subjective impressions of the highlights from the work presented. In general, I will refer to results by the name of the presenter only (see index), while full citations are given for work presented elsewhere. This summary includes notes on massive star evolution (§2), the observed diversity of HMXBs (§3), accretion processes (§4), numbers of HMXBs (§5), evolutionary paths to black hole mergers (§6), and a few thoughts about future directions (§7). Readers interested in the origins of the field will enjoy reading a brief review by Trimble & Thorne (2018).

2. Massive Star Evolution and Donor Stars

The evolution of massive stars towards core collapse will inevitably create neutron star (NS) and black hole (BH) remnants depending on their intial mass, metallicity, and spin (Heger). However, the numerical modeling of processes leading to a supernova is extraordinarily complex due to the high neutrino flux, convection below the shock front, and gas fall-back, and small changes in the initial conditions can decide whether or not a supernova occurs and the kind of remnant created (Müller *et al.* 2016). There are several lines of evidence that suggest that stars more massive than $20 M_{\odot}$ may collapse without any supernova explosion (Smartt 2015; Adams *et al.* 2017) as predicted in some models (Heger *et al.* 2003). Theoretical models suggest that most massive stars $< 10 M_{\odot}$ will form NS remnants while those with masses $> 20 M_{\odot}$ will make BHs except in cases with high mass loss rates (particularly for high metallicity stars) or very high mass progenitors that are completely disrupted by pair instability supernovae. Thus, we expect that a large fraction of massive stars are destined to create neutron star and black hole remnants with the latter generally favored at higher initial mass and lower metallicity.

Investigations of the donor stars in HMXBs are particularly important because they are the source of gas that powers accretion-driven X-rays and their physical properties help us understand the evolutionary stage of the binary system. There are now computational tools available that model both the atmosphere and winds (such as the PoWR code: Sander, Hainich), and these create synthetic spectra that can be compared to observations to determine effective temperature $T_{\rm eff}$, gravity, abundances, projected rotational velocity, and mass loss rate. The dynamical state of the atmosphere will influence mass loss processes, for example through the action of sub-photospheric convective motions that create structure in the winds (Cantiello *et al.* 2009) and the constructive interference of nonradial pulsation modes that lifts gas out into the circumstellar disks of Be stars (Baade *et al.* 2018). The winds of luminous stars are very dynamic entities that are subject to both large scale (co-rotating interaction regions) and small scale (clumping) instabilities that control temporal variations in the accretion processes (§4). The wind mass loss rates are functions of luminosity, metallicity, rotation, and temperature (Vink), and the accretion properties reflect the diversity of the mass donor winds.

Massive stars such as the progenitors of the HMXBs are often born in dense, small number groups where gravitational encounters may occur and lead to the ejection of stars (Allen, Mapelli). HMXBs may attain a runaway velocity through the instantaneous mass loss of a supernova explosion, as first suggested by Blaauw (1961). However, kinematical studies indicate that most HMXBs have modest peculiar space velocities, and only those with lower mass progenitors have runaway speeds (Fragos, Gvaramadze, Mirabel). This may reinforce the idea that more massive stars collapse without exploding as a supernova (thus yielding a more massive BH). Identifying the specific progenitors of HMXBs is still speculative, but a clue is probably the presence of a He-star companion that was stripped of its hydrogen envelope through binary interaction. A number of massive WR+O binaries in the SMC are probably destined to make massive compact remnants (Shenar), and a growing number of Be stars are found with He-star companions that may be the progenitors of the Be X-ray binaries (Wang *et al.* 2018).

3. HMXB Zoo

The HMXBs form a diverse "zoo" (Reig 2011) that can be classified based upon kind of remnant, evolutionary stage, or observational properties. I will mainly focus on the categories related to the characteristics of the mass donor star, with the warning that

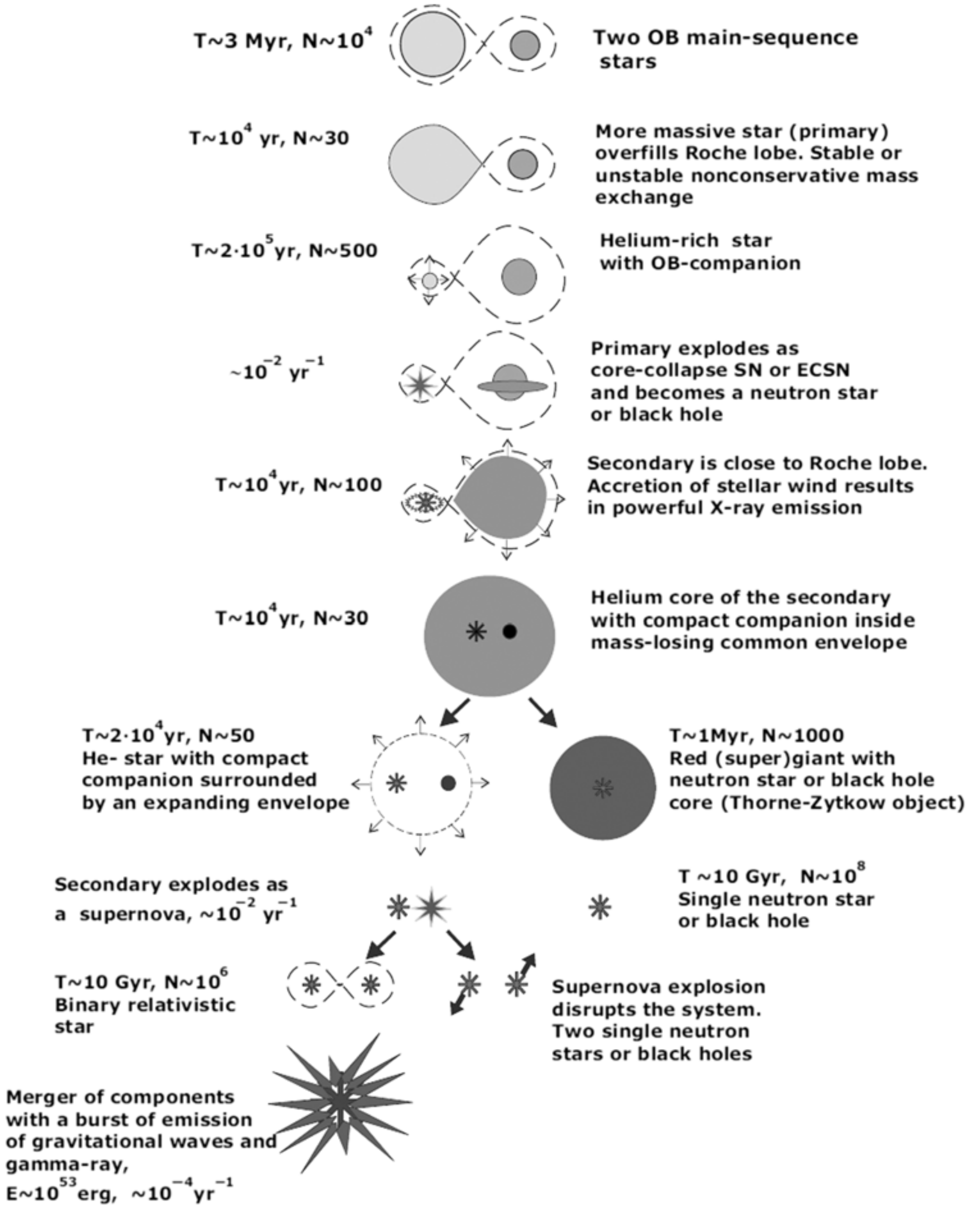

Figure 1. Evolutionary scenario for the formation of NSs or BHs in massive binaries (from Postnov & Yungelson 2014). T is the typical time scale and N is the estimated number of objects in a given evolutionary stage.

these groups are not entirely independent and that intermediate cases are known (Sidoli & Paizis 2018). The order below follows the evolutionary sequence shown in Figure 1†.

Be X-ray binaries – Be stars are rapid rotators that are shedding angular momentum to create transient disks (Rivinius), and a significant fraction of these were probably spun up through past mass transfer in a binary (Pols *et al.* 1991). If the companion is now a compact remnant, then mass transfer and accretion may power a BeXRB system

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(Fig. 1, stage 4). Most of the known BeXRBs host neutron star companions, but there is now one identified black hole system MWC 656 = HD 215227 (Ribo) and probably more exist (Brown). There are several cases of X-ray novae in the SMC that probably consist of a Be star plus a proto-white dwarf companion (Kawai). Be stars eject gas into a circumstellar and outflowing disk gas that acts as a reservoir for accretion onto the companion (Okazaki). However, the X-ray emission is generally episodic rather than continuous. In Type I sources, an outburst happens each orbit and is triggered by tidal forces that peak near periastron in an elliptical orbit. In Type II sources, there are giant, quasi-periodic outbursts that are related to precessional phases of a warped disk.

Supergiant X-ray binaries – Donor star mass loss increases as the stars become more luminous, so they tend to power X-rays by wind accretion during the supergiant phase (Fig. 1, stage 5). This category of sgXRB includes several recently recognized sub-groups that underscore the diversity of their environments and mass transfer processes. The first is a group of highly obscured sgXRBs in which the binary resides inside a cloud of gas and dust (Chaty). The best example is the *INTEGRAL* source IGR J16318–4848 that is surrounded by a disk-like cloud that has a heated inner rim (Chaty & Rahoui 2012). The second group is the supergiant fast X-ray transients (SFXTs), and these display bright and short flaring emission with a duty cycle of a few percent (Sidoli). The cause of these sudden X-ray flares is still mysterious, but there may be some gating mechanism that supresses accretion except at special times, for example, through an interaction between the magnetic fields of the wind and compact star (Hubrig). The SFXTs may represent the earliest stage of the sgXRBs when the donors are more compact and their winds more structured (Negueruela). Other objects that are related to the sgXRBs are sgB[e] stars like CI Cam (Bartlett), which host cool and dense equatorial zones, and symbiotic systems like IGR J17329-2731, which consist of a cool giant and NS (Bozzo).

Wolf-Rayet X-ray binaries – Evolution past the sgXRB stage will depend critically on the mass ratio (van den Heuvel). If the compact companion is low mass (NS), then the common envelope phase will lead to a spiral in and merger (Thorne-Zytkow object = TZO), unless the system has a wide separation, in which case a close NS+NS binary may result (Fig. 1, stage 7). On the other hand, if the companion is high mass (BH), then the spiral-in will end with a stripped He-star and companion in a short period orbit (van den Heuvel *et al.* 2017). Until recently, the only known example of such a He-star binary (or WR-XRB) was Cyg X-3, but now six others have been found in other galaxies, and one of these, CG X-1, is an Ultra-Luminous X-ray binary (Soria; Esposito *et al.* 2015). These WR-XRBs should create binary BHs in close orbits.

Ultra-Luminous X-ray sources – ULXs represent the brightest systems that often radiate at super-Eddington luminosities (Harrison; Kaaret *et al.* 2017). Some 400 ULXs have been discovered in nearby galaxies, and approximately 50 of these have optical counterparts (Anastasopoulou, Fabrika, Heida, Kovlakas, Maitra, Roberts, Soria). However, one relatively nearby ULX was found in outburst in our galaxy, Swift J0243.6+6124, and this is probably a Be star plus NS binary (Wilson-Hodge *et al.* 2018). This system joins five others that have known pulsar companions (Harrison). There is a wide diversity among ULXs in the kinds of donor stars (hot/cool) and compact components (both neutron stars and black holes; Fürst, Carpano, Soria, Heida). ULXs may be the outcome of stable mass transfer at an advanced mass-transfer stage, such as we find in SS 433 (Pavlovskii *et al.* 2017; van den Heuvel *et al.* 2017). One particularly striking environment is the Cartwheel Galaxy, a ring galaxy that experienced a burst in the star formation rate about 100 Myr ago and now hosts some 15 ULXs (Wolter).

Gamma-ray binaries – A number of HMXBs are also emit γ-rays with an orbital-phase modulated amplitude. The emission probably originates through up-scattering of the donor star's photons by relativistic particles or through the interaction of pulsar winds or jets with the winds of the donors (Mirabel 2012). There are perhaps about 100 γ-ray binaries in the Galaxy (Dubus *et al.* 2017). However, the *Fermi* LAT instrument has detected over a thousand additional γ-ray sources that include many more binaries. The known counterparts consist of a diverse assortment of binaries including HMXBs plus pulsars, microquasars (jet sources), novae, colliding wind systems, and Low Mass X-ray Binaries (LMXBs) with a pulsar (Wilson-Hodge, Zhang).

4. Accretion Processes

The processes that control the flow of gas from the donor to the region of X-ray formation near the gainer are complex, and developing a full picture requires modeling physical processes on vastly different spatial scales (Wilms; Negueruela 2010). On scales comparable to the binary separation, gas accretion occurs primarily through Roche lobe overflow (RLOF; dominant among the LMXBs), wind capture or Bondi-Hoyle-Lyttleton accretion (dominant among the the luminous sgXRBs with high mass loss rates), and episodic tidal gas capture (in eccentric orbit BeXRBs). These different accretion regimes are recognized in the Corbet (1986) diagram of ($P_{\rm orbit}, P_{\rm spin}$) relating the binary orbital and pulsar spin periods. Those systems with short orbital periods and small spin periods probably experience RLOF leading to a persistent disk around the neutron star. The BeXRBs form a near-linear sequence in the diagram that probably reflects the balance between magnetic spin-down and transient accretion spin-up of the pulsar. The sgXRBs tend to occupy the mid-range orbital period and long spin period part of the diagram in which wind accretion may create only a transient disk close to the neutron star and hence allow limited angular momentum transfer to spin up the pulsar.

All of the mass transfer processes are influenced by the characteristics of the X-ray source. The stellar winds of sgXRBs become ionized in the vicinity of X-ray source, and Doppler-shifted parts of the wind lines will disappear when the over-ionized region is seen in the foreground (the Hatchett-McCray effect). Furthermore, this X-ray ionization will remove the ion-specific absorbers of the stellar flux that drive the wind outwards, so that the wind acceleration ceases. Depending upon the detailed circumstances, the lower than expected wind flow near the compact object will often power increased X-ray luminosity (Krtička). The ionization boundaries may create large-scale photoionization wakes that trail the compact object. Furthermore, the stellar winds are dynamic entities that develop large scale co-rotation interaction regions between outflows of differing speed and that form wind clumps on smaller spatial scales (Martínez-Núñez *et al.* 2017). The clumping in particular will affect the intervening column density to the X-ray source and impart an intrinsic time-variability to the accretion process (Martínez-Núñez, El Mellah, Hainich, Chaty, Grinberg). Calculating the wind mass transfer rate requires both atmospheric and hydrodynamical models of wind flows and radiative transfer codes (El Mellah, Kurfurst, Sander), but sophisticated three-dimensional models now exist that deal with the flows on scales from the orbital, through the accretion zone, and into the vicinity of the compact component. El Mellah *et al.* (2019) show how such models predict that the wind-accreted gas in sgXRBs has sufficient angular momentum to create an accretion disk around the neutron star or black hole.

The net accretion rates onto the neutron star or black hole mass gainer depend critically on the gas flows in their immediate vicinity (Postnov; Shakura 2018). The magnetic fields of neutron stars tend to direct the gas onto the polar regions where they create accretion columns with an anisotropic X-ray flux that causes the observed variations with the spin period (Harrison, Wilms; Lai 2014; Revnivtsev & Mereghetti 2014). The interaction between the neutron star magnetosphere and the surrounding disk will set the accretion rate and X-ray flux that may range from super-Eddington in the case of ULXs (Walton *et al.* 2018) to shutting off accretion by the “magnetic propeller effect” when the magnetic field is very large and/or the accretion rate is low (Torrejón).

Black hole binaries experience X-ray state changes that make a loop in the (hardness, intensity) diagram as they vary between a hard state with emission from a hot corona (when jets appear) and a soft state with emission from an optically thick accretion disk (when the jets disappear; Fender 2016). These states probably correspond to low and high net accretion rates, respectively, into the central regions. Liska *et al.* (2018) present magnetohydrodynamic simulations of thick accretion disks around rapidly spinning black holes, and they show how magnetic dynamos in the disk can launch very energetic jets. They also find that the disk-jet systems undergo precession, and the precessional periods may be related to the observed super-orbital periods (Corbet, Townsend; Larwood 1998).

5. Census of HMXBs

Our position in the disk of the Galaxy imposes limits on our ability to make a complete census of HMXBs in the Milky Way, but there are about 200 known systems at present (Haberl; Liu *et al.* 2006; Walter *et al.* 2015) and most are found close to the star forming complexes in the spiral arms (Coleiro & Chaty 2013). The situation is somewhat better for nearby galaxies: for example, some 150 HMXBs are known in the SMC (Haberl, Zezas, Sell, Fornasini), which experienced several star formation bursts 25 to 60 Myr ago. An important census was recently completed for the nearby spiral galaxy M33 (Garofali). Garofali *et al.* (2018) used surveys from *HST* and Chandra to identify optical counterparts of 55 HMXBs in M33. They examined the colors and magnitudes of the stars in the immediate vicinity of each target to make a color − magnitude diagram and estimate the probable age of the system. They find a double-peaked distribution with peaks at ages < 5 Myr (sgXRBs) and ≈ 40 Myr (BeXRB). Other key surveys of HMXBs are now available for the spiral galaxies M31 (Zezas) and M51 (Lehmer).

These surveys of nearby galaxies are key to the calibration of the relationships between the net X-ray luminosity from LMXBs and HMXBs and a galaxy’s star formation rate and mass (Gilfanov). Large scale surveys of distant galaxies in the Chandra Deep Field South (Lehmer *et al.* 2016) and in the Chandra COSMOS-Legacy sample (Fornasini *et al.* 2018) show how these relations may have differed in the past (among high z galaxies). The ratio of X-ray heating by X-ray binaries to that from AGN appears to increase at high redshift, so that X-ray binaries may have played an important role in heating the intergalactic medium early in the history of the Universe (Lehmer, Mirabel).

6. Evolution and Gravitational Wave Sources

The great challenge is to understand what processes dominate in creating the kinds of BH+BH and NS+NS binaries that will lead to mergers like those discovered through gravitational waves. The time scale for orbital shrinkage by gravitational wave emission is proportional to separation to the fourth power, so in order for pairs to merge in a Hubble time, they must be brought into close proximity by other means. Thus, the fundamental problem is determining what processes lead to very close orbits of collapsed remnants (with periods less than 1 day). Three main scenarios offer promising explanations (Mandel): (1) common envelope or other shrinkage during the course of massive binary star evolution, (2) tidally forced rapid rotation in close binaries that leads to mixing and homogeneous evolution, and (3) dynamical encounters in dense stellar environments. All these channels were discussed vigorously at the meeting to explore the specific physical parameters and evolutionary stages that will lead to mergers.

There are many evolutionary paths that lead from an isolated massive binary system to a merger product (NS+NS, BH+NS, BH+BH; Belczynski; Dominik *et al.* 2012). There are two leading scenarios for creating close BH+BH systems. The first (Belczynski *et al.* 2016) begins with a very massive pair of stars in large orbit. The initially more massive star grows to fill its Roche lobe and commences RLOF with non-conservative mass loss from the binary and relatively little change in the orbital dimension. This star will subsequently collapse to form a BH without a supernova explosion or other significant mass loss. Later, the companion evolves to larger size and initiates a common envelope (CE) stage in which the black hole begins to spiral in through the envelope of the companion. In some circumstances, this will conclude with ejection of the envelope and a now much more close binary composed of a stripped He star and BH. Finally, the He star will collapse (again without a SN), yielding a close BH+BH pair. Lower mass stars follow a similar path to create a NS+NS pair, but each collapse is accompanied by a supernova explosion that has the potential to break up the binary through asymmetrical kicks (Chruslinska *et al.* 2018). A second potential scenario (Klencki, van den Heuvel; van den Heuvel *et al.* 2017) starts with a HMXB (BH+OB) with a period of order a week to several months. As long as the mass ratio is not too extreme and the donor star still has a radiative envelope, then RLOF occurs with most of the mass ejected by jets or other outflows (for example, as found in SS 433). This process will lead to a gentle spiral-in that avoids the CE stage, and it will result in a compact binary consisting of a stripped He star and BH (like Cyg X-3). Then, as in the first scenario, the He star collapses to form a BH+BH binary that is close enough to merge over a Hubble time.

The production rates associated with such binary star evolutionary channels depend upon many details of physical processes that are only partially understood. For example, the mass of the remnant depends critically upon mass loss suffered through wind loss (metallicity dependent), binary interactions (systemic mass loss), and supernova explosions (if they occur). The properties of the stars during mass transfer may change on relatively fast timescales, so stellar models using the MESA code (Paxton *et al.* 2015) are now being incorporated in binary evolutionary simulations (Klencki, Marchant). Finally, the energetic processes involved with the common envelope phase are poorly constrained (Fragos, Marchant, Ricker). These processes involve many temporal and spatial scales, and detailed hydrodynamical simulations are required to determine the extent of mass loss and the final outcome of the CE stage, i.e., a very close binary or a stellar merger. Some results indicate a low binary survival rate with a large production of merged Thorne-Zytkow objects (Bulik, Ricker). The CE episode will probably be marked by a short flux outburst (Bulik), and some of these might be observed as transient sources (Kochanek *et al.* 2014; Metzger & Pejcha 2017).

The second means of creating BH+BH binaries is through non-interacting pairs of very close binary stars (Mandel & de Mink 2016). Members of tight binaries will experience tidal interactions that can force rapid rotation that is synchronous with the binary period. Rapid rotation in turn promotes interior mixing that can lead to chemically homogeneous evolution. Instead of building up a He core, the He is mixed throughout until all the H is exhausted and a He star is formed. The star shrinks in the process and avoids binary mass transfer, so that the final BH remnants retain much of the original mass. This process assumes more importance at low metallicity (high z) because at larger metallicity massive stars have strong winds that will carry away angular momentum and cause the stars to spin down.

The third way to make close BH+BH binaries is through dynamical encounters in dense star clusters and other environments (Mapelli; Ziosi *et al.* 2014). Gravitational interactions between single and binary stars often act to eject the lowest mass component, so a close passage will often result in retention in the binary of the most massive component, which may be a BH in a cluster rich with massive stars. Subsequent interactions of a binary with cluster field stars tend to make the binary more compact (Heggie's

Law: gravitational encounters tend to make hard binaries harder and soft binaries softer, where hard and soft refer to the gravitational binding energy relative to the field star kinetic energy). We can see the results of these kinds of processes in the Galactic Center region where we find about a dozen quiescent BH binaries within 1 pc of Sgr A* (Hailey *et al.* 2018). These probably formed by tidal capture of companions (becoming orbitally bound by transforming kinetic energy into stellar oscillations) through encounters of field stars with a large pool of BHs (10^4) that have accumulated near Galactic Center (Generozov *et al.* 2018).

Presumably all these processes occur in the Universe, and in order to determine their relative significance we need to perform large scale population synthesis models that calculate the numbers of merger systems as a function of star formation rate and metallicity over the history of the cosmos (Belczynski, Chruslinska, Mapelli). These are ambitious and complex codes that must make numerous assumptions about the details of binary star properties and evolution, stellar dynamics, star formation, and galaxy evolution. They include simulations such as BPASS (Eldridge *et al.* 2017), COMBINE (Kruckow *et al.* 2018), COMPAS (Vigna-Gómez *et al.* 2018), MOBSE (Mapelli & Giacobbo 2018), and STARTRACK (Chruslinska *et al.* 2018), among others. The details of the simulations are important, because the vast majority of stellar systems never make it to become gravitational wave sources (Belczynski, Bulik), so we are studying the results of a restricted set of merger channels.

The predicted merger rate of neutron star pairs is especially interesting after the seminal discovery of gravity waves from the NS+NS merger of GW170817. This merger was also observed as a short γ-ray burster and a kilonova, verifying that such bursters are the result of NS mergers (Wilson-Hodge, Hakkila, Meszaros). With only a single NS+NS merger observation thus far, it is too early to compare predicted and observed merger rates, but the model predictions appear to be consistent with known population of radio-detected, double neutron stars (Tauris *et al.* 2017; Chruslinska *et al.* 2018; Vigna-Gómez *et al.* 2018).

There are many avenues available to create compact BH+BH binaries, and at present it is difficult gauge which processes dominate. Most models that rely on binary evolution and orbital shrinkage through a CE phase appear to produce BH+BH merger rates that are consistent with the initial LIGO estimates (Belczynski; Kruckow *et al.* 2018; Mapelli & Giacobbo 2018) even without contributions from the homogeneous evolution and dynamical capture processes. However, this is still a very young field with large uncertainties on both the observational and theoretical sides, so it is premature to assume which if any of these three processes is the prevalent one. However, future results from the gravity wave detectors on BH masses, spins, merger rates, and their metallicity and redshift dependence should provide the means to begin to discriminate between the relative contributions of the different processes (Belczynski, Fragos, Qin; Arca Sedda & Benacquista 2019).

7. Future promise

Since their discovery some 50 years ago, the study of HMXBs has grown in scope and depth in amazing ways as demonstrated by the work presented at this meeting. This growth will accelerate in the future through new opportunities in observational work and the expansion of computational facilities. The current gravitational wave experiments (LIGO, VIRGO) and those under construction (KAGRA, IndIGO, TianQin) will measure the mergers of several hundred compact objects, and this will provide the statistical basis to test theories of the origins of BH+BH, NS+NS, and also BH+NS systems (the latter may be observed as kilonovae; Gompertz *et al.* 2018). The legacy X-ray missions (XMM Newton, Integral, Chandra, Fermi, NICER, NuSTAR) and those ahead (Insight-HXMT

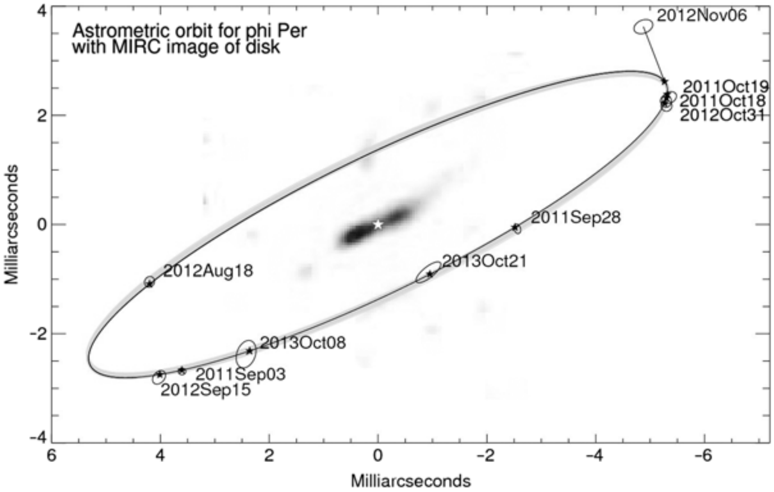

Figure 2. The Be star ϕ Per with the orbit of its He star companion.

[Zhang], eRosita, Athena, Lynx, XRISM) hold the promise of completing our picture of the populations of HMXBs in our galaxy and others. Likewise, the next generation of ground-based giant telescopes (ELT, GMT, TMT) and survey telescopes (LSST) will help characterize the mass donor stars of HMXBs.

Advances in high angular resolution work through optical and radio long baseline interferometry will be particularly striking in the near future to help us probe these binaries and their mass accretion and ejection processes. We learned at this meeting how optical long baseline interferometry with VLTI/Gravity has provided the means to explore the inner structure of the microquasars SS 433 and BP Cru (Waisberg), and the power of radio interferometry was demonstrated for a pulsar orbit measured with the Australian Long Baseline Array (Miller-Jones). One other remarkable example was the detection of the hot He star companion orbiting the Be star ϕ Persei (Fig. 2; made with the Georgia State University CHARA Array; Mourard *et al.* 2015). Objects like ϕ Per may be the precursors of BeXRBs and NS+NS mergers, so their study offers us an important opportunity to learn about this early stage of evolution. The gas disk of ϕ Per orbits in the same sense as the He star's orbit, consistent with the idea that the fast spin of the Be star was caused by a past mass transfer stage, and the age and luminosity of the He star support the idea that it has advanced into a bright, He-shell burning stage (Schootemeijer *et al.* 2018). Such work at the limits of high angular resolution will reveal the processes that forge the evolution of HMXBs.

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