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The ultra-luminous X-ray phase as a progenitor channel for LIGO–Virgo–KAGRA sources

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The gravitational-wave signals detected by the LIGO, Virgo, and KAGRA (LVK) gravitational-wave network provide valuable insights into the masses, distances, and sky locations of compact binary systems. However, the evolutionary origins of these systems remain uncertain. In this study, we investigate ultra-luminous X-ray sources (ULXs) as potential progenitors of the double compact objects (DCOs) detected by the LVK collaboration. Using a population of ULXs generated in our previous work, we model the formation of DCOs with ULX priors and compare their properties with those inferred from LVK observations. Our results indicate that DCOs formed through the ULX channel can account primarily for the low-mass end of the LVK-detected population.

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1. Introduction

The groundbreaking detection of gravitational waves (GWs) by the Laser Interferometer Gravitational Wave Observatory (LIGO) in 2015, originating from the collision of two black holes (BHs), marked a new era in the study of double compact objects (DCOs) [1]. Subsequent detections by LIGO and Virgo have provided valuable insights into the masses and distances of these compact objects. To date, the LIGO, Virgo, and KAGRA (LVK) gravitational-wave network has 219 GW events in their gravitational wave transient catalogue version 4.0 (GWTC-4.0) [1] [2]. Figure 1 shows the primary and secondary masses of 173 binary compact objects from the GWTC-4.0 with reported masses. The 173 events comprise two double neutron stars (DNSs), three black hole-neutron star (BHNS), 163 double black hole (stellar-mass DBH, $2.7\,M_\odot \leq M \leq 100\,\mathrm{M}_\odot$), and four events where at least one object is an intermediate mass black hole (IMBH, $M > 100\,\mathrm{M}_\odot$).

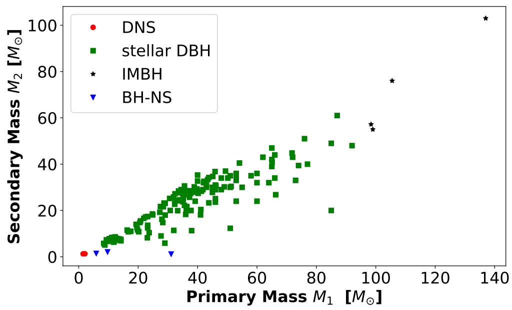

Figure 1: Primary and secondary masses of the GW event from GWTC-4.0[1].

The GW signals detected from the first observing run (O1) through the early fourth run (O4a) have provided valuable insights into the distribution of BH masses [3]. However, little is known about the evolutionary pathways that produced these systems. As shown in Figure 1, the observed GW sample is dominated by stellar-mass BH binaries.

The ultra-luminous X-ray (ULX) phase has been proposed as one of the potential formation channels of merging double compact objects (mDCOs) detected by the LVK network [4]. This project aims to study the connection between mDCOs and their progenitor stellar populations. While multiple channels (e.g., isolated binary evolution, dynamical interactions) contribute to DCO populations, this work tests the hypothesis that a significant fraction of mDCOs undergo a ULX phase before coalescence.

2. Simulation

In [5], we generated a population of X-ray binaries using COSMIC code [6] and selected our ULX population based on the X-ray luminosity of the system. In this work, we follow the evolution of the same population generated in our previous work [5] up to the Universe's current age and select all merging DCO systems. When the donor star in a ULX system exhausts its nuclear fuel, it evolves into a compact object, forming a DCO. If the binary remains bound during the formation of the

[1] https://gwosc.org/eventapi/html/GWTC/

second compact object, the two compact remnants continue to orbit their common centre of mass. Over time, the emission of GWs leads to orbital decay, causing the system to merge eventually. Our populations are simulated over a range of metallicities from 0.5% $Z_\odot$ to 1.5 $Z_\odot$ ($Z_\odot$ = 0.02).

3. Results and discussion

We present the results of our simulations exploring the ULX phase as a formation channel for merging DCO systems. We examine the relationship between ULXs and mDCO systems. We provide an analysis of the properties of mDCO systems from ULX phase and comparisons to observational data from LIGO, KAGRA, and Virgo (GWTC-4.0).

3.1 Number of double compact objects

In our simulations, we find that only about 10% of the DCO systems pass through the ULX phase, indicating that the ULX phase is not a dominant channel for DCO formation in general. The fraction of ULXs forming DCOs ranges between 20 and 50%, decreasing with increasing metallicity. The percentage of DCOs formed from the ULX phase is dominated by DBH systems, and less than 1% of DNSs are from the ULX phase. However, a high fraction of the merging DCOs come from the ULX phase (see Figure 3 and the discussion). In Figure 2, we show the total number of mDCO systems as a function of metallicity from the simulations. At low metallicities, the total number of mDCO is relatively unaffected by metallicity. However, there is a big drop in the number of mDCOs around $Z = 0.1Z_\odot$, for all types of DCOs. The sharp decrease at $Z = 0.1Z_\odot$ marks a critical transition where the efficiency of forming merging compact objects, particularly massive black holes, diminishes, leading to a significant reduction in the overall mDCO population. This drop highlights the importance of metallicity in determining the evolutionary pathways of massive stars and their remnants, which ultimately impacts the rates of compact object mergers. The drop around $Z = 0.1Z_\odot$ is also observed in previous studies [7].

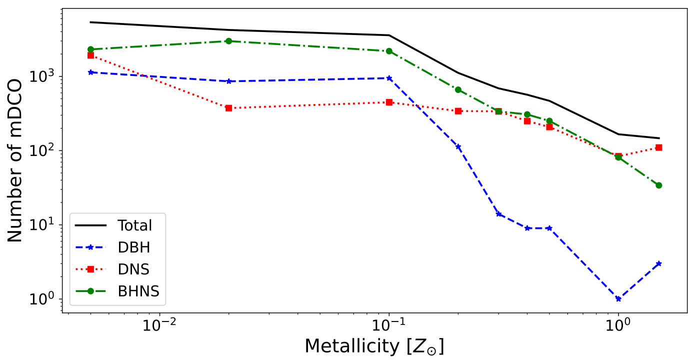

Figure 2: The number of mDCO systems as a function of metallicity in our simulations: solid line for total mDCOs, dashed for DBH, dotted for DNS, and dash-dot for BHNS.

However, when we look at merging DCOs, at least 70% of mDCOs have undergone a ULX phase during their evolution (see Figure 3). This result shows the importance of metallicity and the ULX phase, with low-metallicity environments being more favourable for mDCO formation.

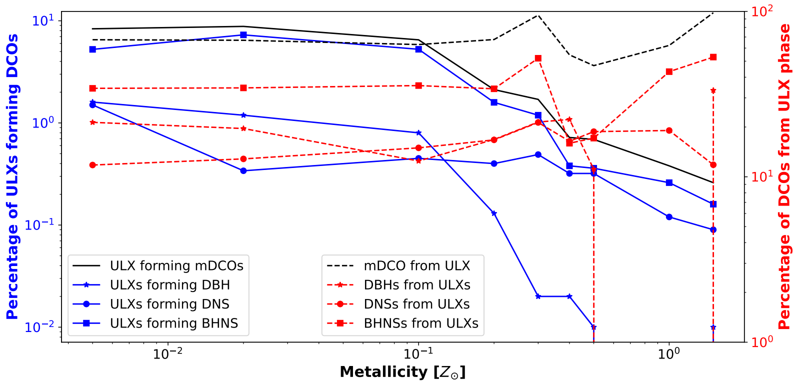

Figure 3: Fraction of ULXs forming mDCOs and mDCOs from ULX phase as a function of metallicity. The black solid and dotted lines indicate the sum of ULXs forming merging DCOs and merging DCOs formed from the ULX phase, respectively.

Earlier works [8, 9] have shown that lower metallicities allow for higher-mass black hole formation due to reduced stellar wind mass loss, which facilitates the retention of binaries through natal kicks and leads to higher mDCO formation rates. Similarly, [7] reported a significant contribution of wind-fed ULXs to the formation of mDCOs at low metallicities. While our study shows a higher percentage of mDCOs passing through a ULX phase, [7] provides additional insight into the differing roles of wind-fed versus RLOF-fed ULXs in the formation of mDCOs. Specifically, [7] found that wind-fed ULXs contribute more significantly to forming DBH and BHNS systems, while RLOF-fed ULXs are more likely to form at lower metallicities. Our study did not investigate the specific contribution of these different accretion mechanisms, leaving this as an area for future research. Furthermore, the sharp drop observed in both studies around $Z = 0.1Z_\odot$ marks a critical transition in the efficiency of mDCO formation, which needs further investigation.

3.2 Mass distribution

Previous studies [e.g., 3, 10] using GWTC-2 and GWTC-3 have shown that the primary mass distribution of DBHs can be described by a power law with a Gaussian peak, where the Gaussian is centred around 33 $M_\odot$ and the power law component dominating near 9 $M_\odot$. A recent study using GWTC-4.0 found evidence of a third feature around 20 $M_\odot$ [11]. In Figure 4, we show the primary mass distribution of all the mDBHs that evolved through the ULX phase across all metallicities from our simulations. We fit this distribution using three different models: a simple power-law (PL), a power-law plus a single Gaussian peak (PL+Peak), and a power-law plus a mixture of three Gaussian peaks (MULTIPEAK) as described in [3]. The PL model captures the general decreasing trend of the mass distribution with increasing mass. However, it fails to reproduce finer features, such as the apparent excess around $M_1 \sim 8{-}10\,M_\odot$. As a result, the PL model systematically underpredicts the number of systems near this preferred mass scale and overpredicts the number of high-mass systems.

Introducing a Gaussian peak (PL+Peak) significantly improves the fit by accounting for the enhancement around $8{-}10\,M_\odot$. This model successfully reproduces both the overall slope of the distribution. However, it fails to produce the features at high mass ($> 15\,M_\odot$), we note this is the

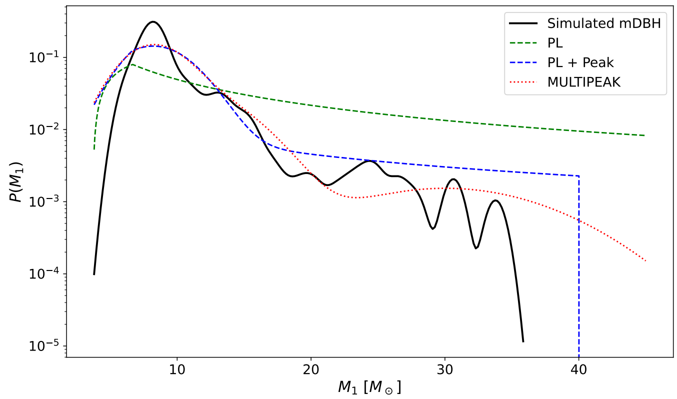

Figure 4: Primary mass distribution of the mDCO systems that evolved from the ULX, across all metallicities.

preferred model in [3]. The MULTIPEAK model, which extends PL+Peak by including three distinct Gaussian components, best matches our simulated mDBH data. It captures not only the primary peak near 8–10 $M_\odot$ but also additional features at higher masses. The MULTIPEAK fit indicates that the mDBH mass distribution comprises several subpopulations, possibly corresponding to different metallicity regimes.

In Figure 5, we compare the mass ratio (q) distributions predicted by our simulated mDBHs that evolved through the ULX phase with those inferred from LIGO-Virgo-KAGRA detections (GWTC-4.0). The distribution of the mass ratio of the simulated mDBHs exhibits a strong preference for systems of almost equal mass, with a peak at $q \sim 0.9–1.0$. Our results are consistent with previous studies; using the *StarTrack* code, [9] found that DBHs formed through classical isolated binary evolution often yield nearly equal mass binaries, especially at low Z.

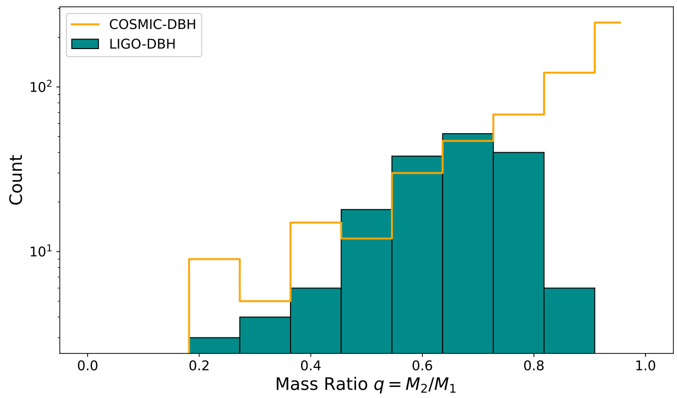

Figure 5: Mass ratio of the mDBH systems that evolved through the ULX phase, compared to DBH merger events reported in GWTC-3. Note that the COSMIC-DBH distribution does not take into account LIGO sensitivity.

While high mass ratio binaries are also in the GW data, the observed DBH population shows a broader distribution, with a noticeable population of systems having more moderate mass ratios around $q \sim 0.6 - 0.8$. We note that our mass ratio distribution is intrinsic and has not been weighted by the signal-to-noise ratio (SNR) or the detector sensitivity of the LIGO-Virgo-KAGRA network.

In Figure 6, we compare the chirp mass ($\mathcal{M}_c$) distributions predicted by our simulated mDBHs that evolved through the ULX phase with those inferred from LIGO-Virgo-KAGRA detections. The chirp mass, is a critical parameter in GW data analysis, as it primarily determines the phase evolution of the inspiral signal and is well constrained compared to the individual masses [12]. The chirp mass distribution of the simulated mDBHs peaks at lower values than the observed GW detection of the DBH population. In particular, our mDBH systems predominantly populate the range $\mathcal{M}_c \sim 5$–$15\,M_\odot$ with a peak at $7-8\ M_\odot$.

The LVK DBH sample shows significant events with higher chirp masses extending to $50\,M_\odot$, with a lower peak at $8-9\ M_\odot$ and a higher peak at $25-30\ M_\odot$. Our simulated mDBH population, by contrast, reproduces only the lower-mass peak observed in the GW data, with a peak located between 8–9 $M_\odot$, and do not produce a corresponding high-mass component. These results indicate that merging DBH systems with $\mathcal{M}_c \gtrsim 15\,M_\odot$ detected by LIGO-Virgo-KAGRA likely originate from a different evolutionary channel than the ULX-driven pathway captured by our simulations.

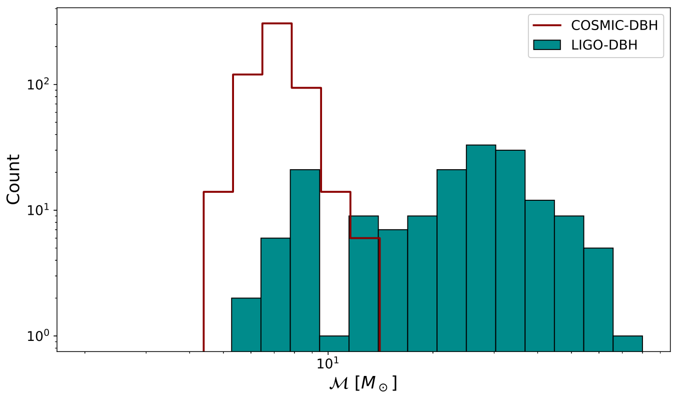

Figure 6: Chirp mass distribution of mDBH systems that evolved through the ULX phase, compared to DBH merger events reported in GWTC-3. Note that the COSMIC-DBH distribution plotted here does not take into account LIGO sensitivity.

While our results demonstrate that ULX systems could be important progenitors of the merging DBHs detected by LIGO-Virgo, they cannot account for the highest mass BHs observed by the LIGO-Virgo-KAGRA network.

4. Summary and concussion

This work examines the evolutionary relationship between ULX systems and the formation of DCOs, specifically mDBH, mDNS, and mBHNS systems. Using the ULX population generated in [5], we identify DCOs that evolved through a ULX phase and merged within a Hubble time, making them potential progenitors of GW sources. We compare the distribution properties (mass, mass ratio, and chirp mass) of our simulated population with ULX progenitors with previous studies and observational data. Our results show that metallicity plays a pivotal role: Lower metallicities enhance both the formation efficiency and merger likelihood of DCOs, particularly those involving black holes. At least 70 – 97% of mDCOs trace their evolutionary history through a ULX phase in our simulations. These mDCOs predominantly feature near-equal mass binaries.

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