Effect of rejuvenated accretors on the population of Thorne-Żytkow Objects

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Abstract

When a massive star with a neutron star (NS) or black hole (BH) companion enters a common envelope (CE) phase there are two possible outcomes: formation of a close binary, a potential double compact object (DCO) progenitor, or a merger. If the system has a NS companion it could form a Thorne-Żytkow Object (TŻO), which is comprised of a NS core surrounded by a stellar envelope. If the system has a BH companion, it can become a quasi-star, with a stellar-mass BH at the center. These systems could also have had a previous mass transfer event where the primary accreted onto the main sequence secondary, resulting in a rejuvenated secondary. Recent work shows that rejuvenated accretors have less bound envelopes, meaning that the envelope is more easily ejected than a star that has not experienced a previous mass transfer episode. This indicates that rejuvenation could result in lower TŻO and quasi-star rates, and therefore higher double compact object formation and merger rates. We use rapid population synthesis to study the effect of rejuvenation on the rates of TŻOs, quasi-stars, and DCOs. We find that the majority of TŻOs and quasi-stars would be formed from mergers in systems containing rejuvenated donor stars. Taking into account the changed structure of those rejuvenated stars would therefore result in higher formation rates for DCOs and lower formation rates for TŻOs and quasi-stars than has been previously predicted.

1 Introduction

A Thorne-Żytkow Object (TŻO) is a hypothetical type of star that contains a NS surrounded by the envelope of a red giant or red supergiant, created by a merger between the two, either via collision or inspiraling in a CE. We explore the CE channel in this study. They were first theorized in Thorne and Zytkow (1975), followed by the structural models of Cannon et al. (1992) and more recently revisited by Farmer et al. (2023). The luminosity is due to shell burning above the NS. An analogue with BH is known as a quasi-star (Hawking 1971; Begelman et al. 2008), which would be a BH surrounded by the envelope of a red giant or supergiant, with their luminosity due to material infalling into the BH.

Recently, Farmer et al. (2023) explored TŻO formation and properties using evolutionary models that assume TŻO formation and are calculated from TŻO birth. The zero-age mass spans $5\,\mathrm{M}_\odot$ to $20\,\mathrm{M}_\odot$ and they immediately begin to decrease in luminosity and temperature, despite the previously mentioned shell burning. They have a lifetime of 10^4 years to 10^5 years.

A TŻO forms from a binary system consisting of a NS and a star. When the star becomes a red giant (or supergiant), it expands to fill its Roche lobe and initiates a common envelope event. Once inside the common envelope, the NS and the star inspiral, which releases gravitational energy. If the energy released is greater than the binding energy, then the envelope is ejected and a stripped binary remains. If there is not enough energy to eject the envelope, it is possible that a merger occurs and a TŻO is born.

Recent work by Renzo et al. (2023) shows that rejuvenated accretors have less bound envelopes. Rejuvenation occurs when the primary star (the initially more massive star) in a binary system accretes mass onto the main sequence secondary (the initially less massive star). This process changes the internal structure of the secondary, most importantly at the core-envelope boundary, and could reduce the binding energy of the envelope. This means that the binding energy of a rejuvenated possible TŻO progenitor would be lower, increasing the likelihood that the envelope is simply ejected and a NS + star system is born instead.

Renzo et al. (2023) compares the binding energy of a rejuvenated accretor to that of a single star as a function of radial coordinate and the models show an initial sharp drop at the core-envelope boundary. The binding energy in the rejuvenated star is lower in the core up until the outer reaches of the envelope, but the difference is starkest at the core-envelope boundary. The models show that the binding energy in the envelope can be lowered by $42\,\%$ to $96\,\%$, which would have a large effect on the TŻO and quasi-star population.

In order to explore the effect of rejuvenated accretors we use rapid population synthesis to quantify and characterize the systems that enter a CE phase with a NS or BH companion and distinguish between those that merge (become TŻOs or quasi-stars) and those that do not. We analyze the output both qualitatively and quantitatively to determine the effect of rejuvenation on the population.

2 Methods

2.1 Data

We use the publicly available synthetic population of Grichener (2023), which studied NSs and BHs that merged with giant secondaries during CE evolution. The population consists of 10^7 COMPAS (Riley et al. 2022) systems at solar metallicity $Z = Z_\odot = 0.0142$ and has initial primary masses between $5\,\mathrm{M}_\odot$ to $100\,\mathrm{M}_\odot$ with a flat distribution in mass ratio from 0.1 to 1. The initial separations have a flat-in-log distribution from 0.1 AU to 1000 AU and all the orbits are assumed to be circular at ZAMS.

We cut the full population from 10^7 to 500 554 for initial exploration, which is what is shown in the figures of this report. Each binary system has a unique integer identifier known as a seed, which is generated sequentially by COMPAS. In order to preserve the distributions, we chose the 500 000th seed in the full population, then located the DCO with the nearest seed number. We then located this seed in all the COMPAS files (`System Parameters`, `RLOF`, `Common Envelopes`, `Double Compact Objects`, and `Supernovae`) and cut all systems with seeds greater than our chosen seed.

2.2 Identifying rejuvenated systems

To locate rejuvenated systems in the population we first found all the systems of interest (TŻOs, quasi-stars, and DCOs) and recorded their unique seeds. We then found the records of all their previous mass transfer events and looked for an event involving the primary stably transferring mass onto the main sequence secondary. If a system has such an event, we flagged it as rejuvenated.

2.3 Calculating binding energy and energy budget for CE ejection

In order to determine if a system is likely to eject its common envelope or merge we must compare the binding energy before the CE event to the orbital energy after the CE event. COMPAS calculates binding energy as

$$E_{\mathrm{bind}} \equiv -\frac{G M_{\mathrm{d}} M_{\mathrm{env}}}{\lambda R_{\mathrm{d}}}, \tag{1}$$

with G as the gravitational constant, M_{d} as the donor mass, M_{env} as the envelope mass, λ as the structure parameter, and R_{d} as the donor radius. The λ parameter is taken from the "Nanjing lambda" prescription in Xu and Li (2010b,a). In this study, the donor is the secondary in the binary system. For most systems, we can simply take the recorded value of the binding energy pre-CE, but main sequence stars are an exception. COMPAS does not differentiate between core and envelope for main sequence stars, meaning that main sequence stripped stars are documented as having zero binding energy. To counter this, we manually calculated the binding energy for these objects as

$$E_{\mathrm{bind,MS,i}} = \frac{GM_{\mathrm{d}}^2}{R_{\mathrm{d}}}. \tag{2}$$

COMPAS does not reliably record the orbital energy for mergers, so we manually calculated it as

$$|\Delta E_{\mathrm{orb}}| \sim \frac{GM_{\mathrm{core}}M_{\mathrm{X}}}{2a_{\mathrm{f}}}, \tag{3}$$

where M_{core} is the core mass of the donor, M_{X} is the mass of the compact object, and a_{f} is the final orbital separation post-CE. We wish to take the minimum separation possible in order to determine the maximum value of the orbital energy reservoir, so we calculate it as

$$a_{\mathrm{f}} = \frac{R}{r_{\mathrm{L}}}, \tag{4}$$

where R is the core radius and r_{L} is the Roche lobe factor, which Eggleton (1983) calculated a fit as

$$r_{\mathrm{L}} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \qquad 0 < q < \infty, \tag{5}$$

where $q = M_{\mathrm{d}}/M_{\mathrm{a}}$ is the mass ratio of the donor over the accretor.

We then compare the binding energy to the orbital energy, which we define as $\alpha = E_{\mathrm{bind,i}}/E_{\mathrm{orb,f}}$. If $\alpha < 1$ then the CE is ejected and we are left with a binary consisting of a stripped star and a compact object. If $\alpha \geq 1$ then there is not enough energy to eject the CE and we have a merger into a TŻO or quasi-star, under our extreme conditions.

3 Results and discussion

Here we present the population of TŻOs, quasi-stars, NS + star systems, and BH + star systems from COMPAS. The bottom left of Figure 1 shows progenitors of all four in a Hertzsprung-Russell diagram (HRD). Out of our population of 500 554 systems we found 5960 TŻOs, 556 quasi-stars, 2236 NS + star systems, and 726 BH + star systems. We estimate the event rates relative to core-collapse supernovae in the same synthetic population in the top and right panels.

We can see that TŻOs cover the main sequence and HG from $\sim 10^2\,\mathrm{L}_\odot$ to $\sim 10^6\,\mathrm{L}_\odot$, while the quasi-stars are only present from $\sim 10^4\,\mathrm{L}_\odot$ to $\sim 10^6\,\mathrm{L}_\odot$, with only a few in the main sequence and most in the HG. This makes sense because BHs form from higher mass stars and therefore generally have higher mass companions. NSs, however, can form from lower mass stars and therefore are more likely to have lower mass companions. The NS + star systems are mostly present past the HG, while the BH + star systems are in present in the HG with a small portion in the asymptotic giant branch. This shows that TŻOs and quasi-stars can form during any portion of a star's evolution, while a stripped binary has fewer channels to form.

The horizontal gap at $10^{4.5}\,\mathrm{L}_\odot$ marks the difference between stars that begin He core burning while in the Hertzsprung Gap (HG), vs stars that do not reach the required core temperature until after crossing the gap. The second gap at $\sim 10^3\,\mathrm{L}_\odot$ is covered by systems that have a WD companion, rather than a NS or BH.

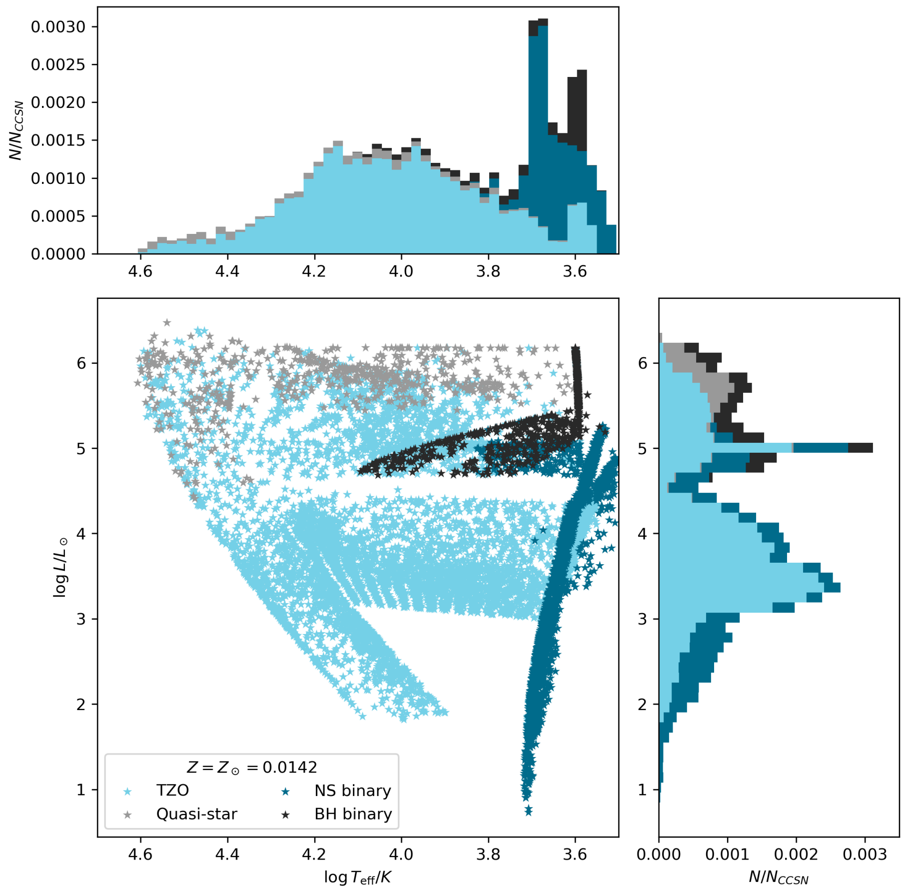

Figure 1: Progenitors of TŻOs (light blue), quasi-stars (gray), NS + star systems (dark blue), and BH + star systems (black) in the HRD. Above and to the right are stacked histograms showing the density in effective temperature and luminosity. The histograms' y-axis is scaled by the number of observable core-collapse supernovae in the dataset.

We then incorporated rejuvenation and the previously mentioned TŻO evolutionary models. The bottom left panel of Figure 2 shows just the TŻOs and quasi-stars from Figure 1, with all objects with masses outside the evolutionary model range ($5\,\mathrm{M}_\odot$ to $20\,\mathrm{M}_\odot$) faded out. The Farmer et al. (2023) tracks are overplotted in the HRD, along with the rejuvenated systems in the histograms on the top and right panels. As the TŻO progenitors form a common envelope and merge, they will all migrate to the small portion of the HRD where the evolutionary tracks are located.

We find that 91 % of the TŻO progenitors were rejuvenated and 92 % of the quasi-stars progenitors were rejuvenated. This indicates that any effect due to rejuvenation would have a major impact on not only the TŻO and quasi-star populations, but also the related populations of NS + star and BH + star systems.

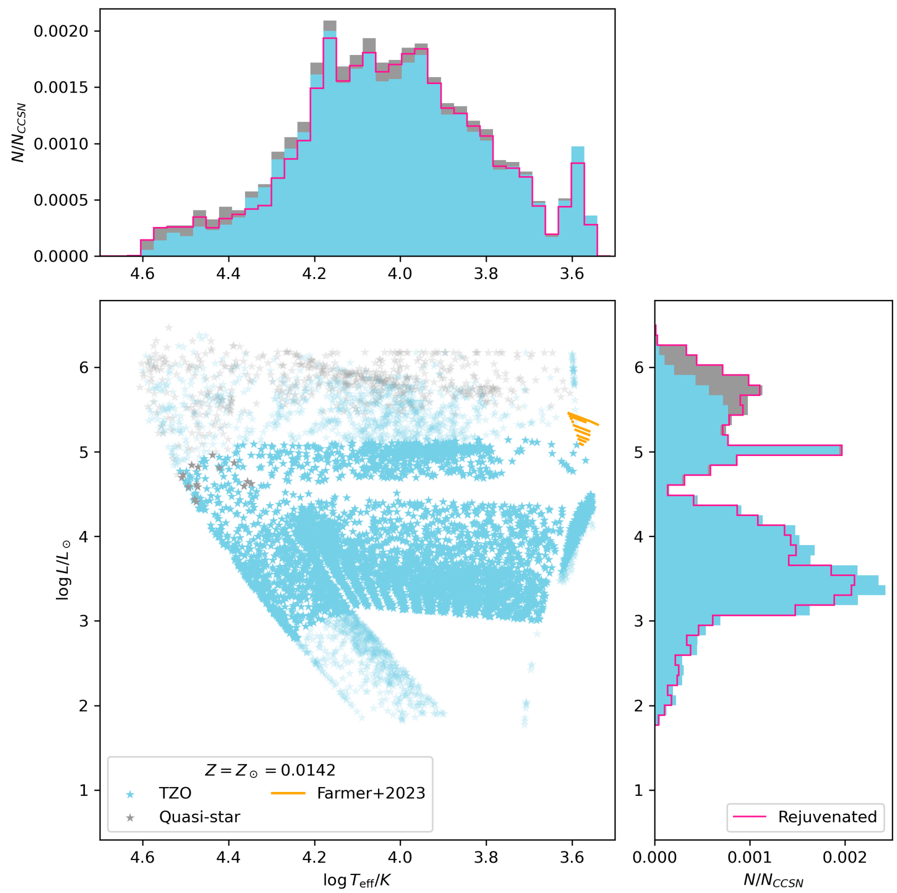

Figure 2: An HRD with the same progenitors of TŻOs (light blue) and quasi-stars (light gray) as in Figure 1. Objects with masses lesser than $5M_\odot$ or greater than $20M_\odot$ are faded out. The TŻO evolutionary models from Farmer et al. (2023) are overplotted in orange. The stacked histograms above and to the right are in the same format with the addition of a pink line for the number of rejuvenated systems.

Figure 3 shows the rates of events leading up to TŻO and quasi-star formation. We can see that the systems with a BH are consistently nearly fully rejuvenated, while there is a non-negligible portion of the NS systems that are not rejuvenated, especially those that eject their CE (the third bar). Overall, there are many more mergers than ejections, however this figure does not include the effect of rejuvenation.

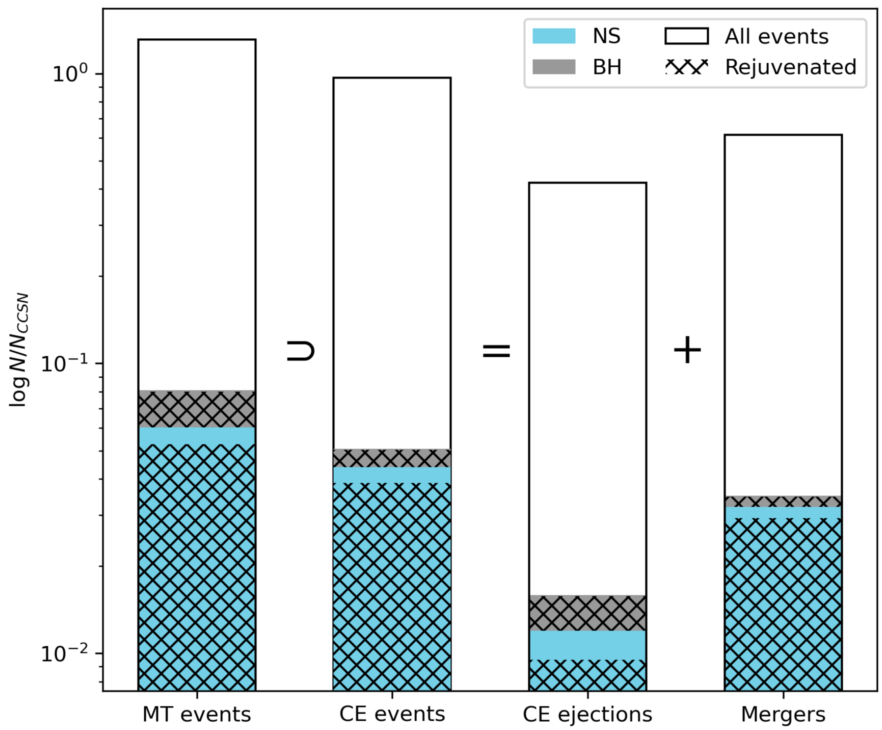

Figure 3: Event rates in the dataset. From left: the number of mass transfer events, the number of common envelope events (a subset of previous), the number of common envelope ejections, and the number of common envelope mergers. The y-axis is in logscale and scaled by the number of observable core-collapse supernovae in the dataset. The black line indicates all events in the dataset, light blue indicates events including a NS and the gray indicates events including a BH. The hatching indicates rejuvenated systems.

Figure 4 shows the rates of DCO formation for NS + NS, BH + BH, and NS + BH systems. We can see that slightly more NS + NS systems merge than not, but nearly all are rejuvenated either way. For BH + BH systems there are three times as many that do not merge as merge, and only about a quarter of the non-merging systems are rejuvenated, while nearly all the merging systems are rejuvenated. For the NS + BH systems we can see that the portion that merge versus stay a binary are equivalent, and the vast majority of both are rejuvenated.

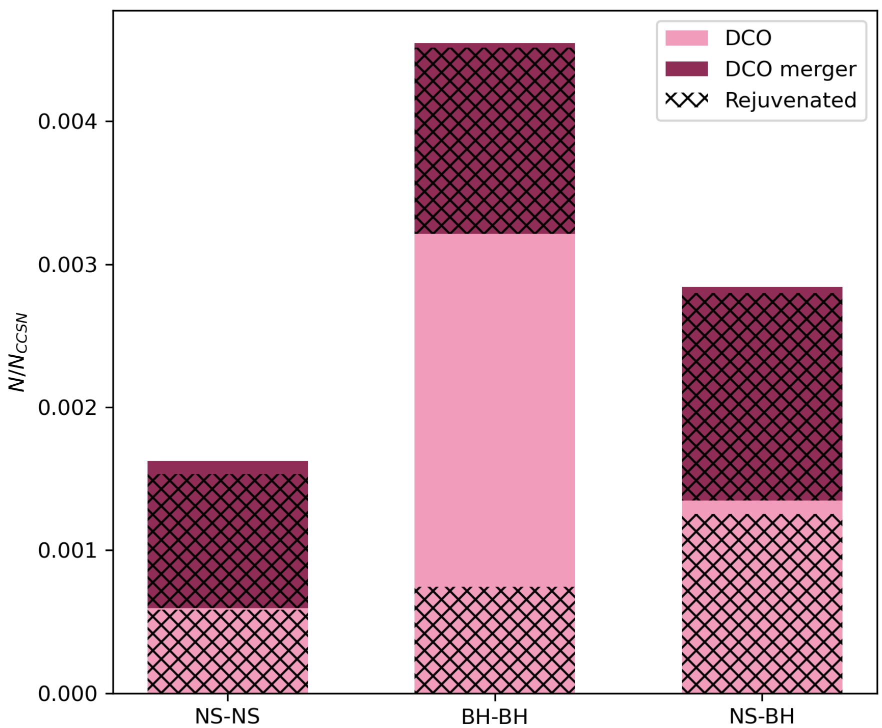

Figure 4: Event rates for DCOs. The light pink indicates systems that do not merge in a Hubble time, the dark pink indicates systems that do merge in a Hubble time. The hatching indicates rejuvenated systems, as in Figure 3. From left: double neutron star systems, double black hole systems, and neutron star black hole systems.

The final step of the project was to look at the energy budget for ejecting the CE, which is shown in Figure 5. We can see that there is a fraction of systems with $\alpha < 1$, which would result in an envelope ejection, despite the fact that COMPAS calculated these systems as mergers. Our calculations assume the extreme condition of a minimal final orbital separation, therefore a maximum orbital energy. The majority of the systems have $\alpha \geq 1$, resulting in a merger. This figure does not include the effect of rejuvenation, which could lower the binding energy and would result in many systems moving over to the $\alpha < 1$ region. The systems with a main sequence donor, however, are still assumed to result in a merger regardless of rejuvenation, because the structural changes in the core-envelope boundary are likely enhanced at later, cooler phases of evolution.

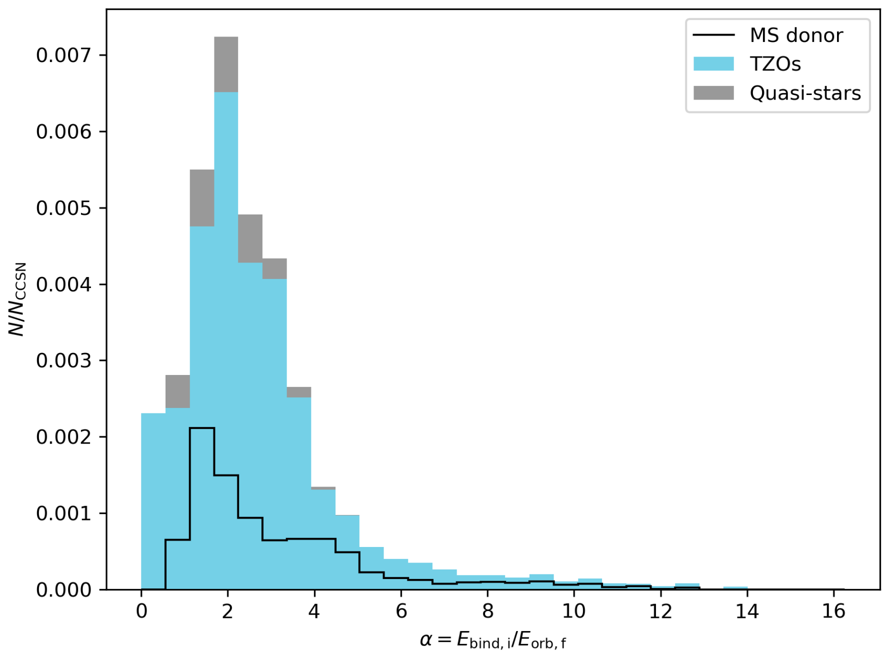

Figure 5: Histogram showing our estimates of the ratio of binding energy pre-CE event to orbital energy post-CE event for TŻOs (light blue) and quasi-stars (gray). The black line denotes the TŻOs and quasi-stars with main sequence donors. The y-axis is scaled with the number of observable core-collapse supernovae in the population.

4 Conclusions

We find that the majority (∼90 %) of TŻOs and quasi-stars would be formed with a rejuvenated donor star and that this rejuvenation would result in lower formation rates for TŻOs and quasi-stars and higher formation rates for stripped binaries and DCOs. The next steps for this project are as follows:

- Assess model uncertainty using the full population of 10^7 systems.
- Estimate the number of TŻOs and quasi-stars in the Galaxy.
- Estimate the number of red supergiant contaminants in the same area as the TŻO evolutionary models seen in Figure 2.
- Investigate peculiar properties such as systemic velocity.
- Explore the effect of rejuvenation on the DCO merger rate.

References

Begelman, Mitchell C. et al. (July 2008). "Quasi-Stars: Accreting Black Holes inside Massive Envelopes". In: *Monthly Notices of the Royal Astronomical Society* 387.4, pp. 1649–1659. DOI: 10.1111/j.1365-2966.2008.13344.x.

Cannon, R. C. et al. (Feb. 1992). "The Structure and Evolution of Thorne-Zytkow Objects". In: *The Astrophysical Journal* 386, p. 206. DOI: 10.1086/171006.

Eggleton, P. P. (May 1983). "Aproximations to the Radii of Roche Lobes." In: *The Astrophysical Journal* 268, pp. 368–369. DOI: 10.1086/160960.

Farmer, R et al. (Sept. 2023). "Observational Predictions for Thorne–Żytkow Objects". In: *Monthly Notices of the Royal Astronomical Society* 524.2, pp. 1692–1709. DOI: 10.1093/mnras/stad1977.

Grichener, Aldana (July 2023). "Mergers of Neutron Stars and Black Holes with Cores of Giant Stars: A Population Synthesis Study". In: *Monthly Notices of the Royal Astronomical Society* 523, pp. 221–232. DOI: 10.1093/mnras/stad1449.

Hawking, Stephen (Apr. 1971). "Gravitationally Collapsed Objects of Very Low Mass". In: *Monthly Notices of the Royal Astronomical Society* 152.1, pp. 75–78. DOI: 10.1093/mnras/152.1.75.

Renzo, M. et al. (Jan. 2023). "Rejuvenated Accretors Have Less Bound Envelopes: Impact of Roche Lobe Overflow on Subsequent Common Envelope Events". In: *The Astrophysical Journal* 942, p. L32. DOI: 10.3847/2041-8213/aca4d3.

Riley, Jeff et al. (Feb. 2022). "Rapid Stellar and Binary Population Synthesis with COMPAS". In: *The Astrophysical Journal Supplement Series* 258, p. 34. DOI: 10.3847/1538-4365/ac416c.

Thorne, K. S. and A. N. Zytkow (July 1975). "Red Giants and Supergiants with Degenerate Neutron Cores." In: *The Astrophysical Journal* 199, pp. L19–L24. DOI: 10.1086/181839.

Xu, Xiao-Jie and Xiang-Dong Li (Oct. 2010a). "Erratum: "On the Binding Energy Parameter λ of Common Envelope Evolution" (2010, ApJ, 716, 114)". In: *The Astrophysical Journal* 722.2, p. 1985. DOI: 10.1088/0004-637X/722/2/1985.

— (May 2010b). "On the Binding Energy Parameter λ of Common Envelope Evolution". In: *The Astrophysical Journal* 716.1, p. 114. DOI: 10.1088/0004-637X/716/1/114.