

UC Santa Cruz

UC Santa Cruz Electronic Theses and Dissertations

Title

Gravitational Torques Across Scale: Galactic Bars and Common Envelopes

Permalink

<https://escholarship.org/uc/item/9mc6s9t9>

ISBN

9798184163024

Author

Hutchinson-Smith, Tenley

Publication Date

2026-07-01

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**GRAVITATIONAL TORQUES ACROSS SCALE: GALACTIC BARS
AND COMMON ENVELOPES**

A dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ASTRONOMY AND ASTROPHYSICS

by

Tenley Hutchinson-Smith

June 2026

The Dissertation of Tenley Hutchinson-
Smith is approved:

Enrico Ramirez-Ruiz, chair

Brooke Simmons

Myriam Telus

Jonathan Fortney

Dean Peter F. Biehl
Vice Provost and Dean of Graduate Studies

Copyright © by

Tenley Hutchinson-Smith

2026

Table of Contents

List of Figures	vi
Abstract	xviii
Dedication	xx
Acknowledgments	xxi
1 Roadmap of the Dissertation	1
 I The Evolutionary Path from High-Mass X-ray Binaries through Luminous Transients to Thorne–Żytkow-like Objects	 4
2 Introduction and Roadmap to Part I	5
2.1 Summary and Lessons Learned	7
3 Rethinking Thorne–Żytkow Object Formation: The Fate of X-ray Binary LMC X-4 and Implications for Ultra-long Gamma-ray Bursts	9
3.1 Introduction	10
3.2 The Fate of HMXBs and the evolution of LMC X-4	13
3.2.1 Stellar mergers involving neutron stars and the role of HMXBs as TŻO progenitors	13
3.2.2 Forward modeling the pre-merger evolution of LMC X-4	16
3.2.3 Properties of LMC X-4	16
3.2.4 Stellar Models	17
3.3 Studying the fate of X-ray binary LMC X-4 with hydrodynamical Simulations	19
3.3.1 FLASH Setup	19
3.3.2 Dynamical Inspiral	20
3.3.3 Mass Ejection during Merger	22

3.3.4	On the Accretion-fed Growth of the Neutron Star during the Merger Phase	26
3.3.5	Embedded Phase and Merger with the Stellar Core	30
3.4	Implications for Thorne–Żytkow Object Formation and Ultra-long Gamma-ray Bursts	31
3.4.1	A Rapidly Rotating Stellar Core Accreting onto a Central Neutron Star	31
3.4.2	Ultra-long GRBs and Recombination Transients	35
3.4.3	Previously discussed transients arising from TŻOs	40
3.4.4	Thin-envelope TŻOs	41
3.5	Summary	42
3.6	Supplementary details on the initial stellar model and global simulations	44
3.7	On the applicability of equilibrium TŻO solutions	46
4	Thin-Envelope Thorne–Żytkow Objects: A New Evolutionary Paradigm	51
4.1	Introduction	51
4.2	Common Envelope Merger Outcomes: Black Holes versus Neutron Stars	53
4.3	Testing the Merger Paradigm with Hydrodynamical Simulations	59
4.4	Thin-Envelope TŻOs as the Natural Outcome of Binary Interactions	63
4.5	Summary	67
5	Hydrodynamic Response of Mildly Evolved Common Envelope Donors in Luminous Red Novae	68
5.1	Introduction	69
5.2	Demographics of Mildly Evolved Common-Envelope Donors	73
5.3	Hydrodynamical Simulations	77
5.3.1	FLASH Setup	77
5.3.2	Dynamical Inspiral at Fixed Companion Mass Ratio	80
5.3.3	Dependence on Companion Mass Ratio	85
5.3.4	Hydrodynamic Mass Ejection Beyond the Alpha-Formalism	88
5.4	Discussion, Lessons Learned, and Observational Implications	90
5.4.1	Hydrodynamic Evolution in the Context of Common-Envelope Simulations	90
5.4.2	Hydrodynamic Evolution Regulated by Donor Central Concentration	92
5.4.3	Implications for Envelope Ejection and Luminous Red Novae	94
5.5	Comparison Simulations at Fixed Stellar Central Concentration	96
5.6	Donor Structures in Previous Common-Envelope Simulations	98

II The Evolution of Galactic Bar Structure 101

6	Galaxy Zoo Bar Lengths: A Catalogue of Measurements from <i>Hubble Space Telescope</i> Images and the Evolution of Galactic Bar Structure at $z < 1$	102
6.1	Introduction	103
6.2	Galaxy Zoo Bar Lengths	105
6.2.1	Correction for projection effects	114
6.2.2	Purity and completeness	116
6.3	COSMOS	120
6.3.1	A cleaner, more complete sample of disks	123
6.3.2	Additional useful quantities: relative bar sizes and delta log SFR	127
6.4	Star formation Properties of barred versus unbarred galaxies	128
6.5	Overall properties of bars in galaxies at $0.25 < z < 1$	136
6.5.1	Overall trends with galaxy properties	138
6.5.2	A closer look at bar properties with star formation	147
6.6	Summary	152

List of Figures

3.1	HMXBs in the context of Luminous Red Novae (LRNe) and binary population synthesis. The masses and radii of eclipsing HMXB systems are depicted as stars, and pre-CE transient observations for a sample of LRN progenitors are depicted as circles. Also shown are progenitor population demographics of CE events generated with the rapid binary population synthesis code COMPAS. The COMPAS populations include successful CE events, CE events with NS accretors that successfully eject the envelope, and CE events with NS accretors that merge. The gravitational binding energy of a polytrope of index $n = 3$ with mass M and radius R is shown for guidance.	15
3.2	The predicted radial evolution of the primary star as calculated by MESA using the mean LMC metallicity of $[\text{Fe}/\text{H}] = -0.42$. The initial mass of the model is $18 M_{\odot}$, with mass loss $2.4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Chernov, 2020). The selected model (black symbol) is consistent with the properties given by Falanga et al. (2015a) within 1σ . The model used for the hydrodynamical simulation performed with FLASH is marked with a turquoise symbol in the panel. At this stage, the donor has overfilled its Roche lobe and its radial scale matches the forward-evolved separation a (dashed line).	18
3.3	Two-dimensional slices across the orbital plane of FLASH simulated inspiral and merger of LMC X-4 at three stages: early in the evolution (2.3 hr), at an intermediate time when the NS enters the stellar core (4.5 hr), and at a late time (13.8 hr) after the NS has settled in the center of the stellar core. <i>Top panels:</i> Logarithm of gas density. <i>Bottom panels:</i> Sum of specific kinetic and potential energy, $\varepsilon = \varepsilon_{\text{kin}} + \varepsilon_{\text{grav}}$, in units of $10^{16} \text{ cm}^2/\text{s}^2$. The orange region corresponds to unbound material ($\varepsilon > 0$) and the green region corresponds to bound material ($\varepsilon < 0$). Animation available at: https://tinyurl.com/hydrosims	21

3.4	Relevant quantities required to estimate envelope unbinding during the merger, which are shown in mass coordinates. The binding energy of the primary's stellar material exterior to a given mass coordinate (E_{grav} , red line) and the change in orbital energy expected to be dissipated during the inspiral (ΔE_{orb} , purple line) are plotted against the mass coordinate for the model used as the initial condition for the hydrodynamical simulation, with mass $18 M_{\odot}$ and neutron star mass ratio $q \approx 0.09$. The mass coordinate at which the $\alpha = (E_{\text{grav}}/\Delta E_{\text{orb}}) = 1$ condition is satisfied is shown as a vertical dashed line.	23
3.5	The outward radial velocity histogram of the envelope debris expelled during the merger (with a total mass $\approx 1.4 M_{\odot}$). This is done by analysing the velocity vectors and masses of each grid cell in the envelope with $\varepsilon > 0$ at $t = 4.5\text{hr}$. Also plotted is the local escape velocity at the $\alpha = 1$ critical radius, which is computed based on the enclosed mass of the initial model (Figure 3.4). This velocity is $v_{\alpha=1} \approx 1140 \text{ km s}^{-1}$ and is shown as a vertical dashed line.	25
3.6	Mass accretion rate onto the inspiraling NS as a function of time during the simulation shown in Figure 3.3. In compact primaries, the NS is able to accrete above the limit at which neutrinos are able to provide the main cooling agent (red dashed line). In LMC X-4 the NS is able to gain about $0.14 M_{\odot}$, but remains well below the maximum NS mass until merging with the core (blue dashed line).	27
3.7	Two dimensional slices of the logarithm of gas density at two different times (7.3hr and 13.8hr) for material near the core of the primary. The <i>top</i> panels show slices in the orbital plane (y - x) while the <i>bottom</i> panels display slices in the meridional plane (y - z). The position of the core's center of mass is denoted by an X mark, while the position of the NS is denoted by a white circle. The evolution of the trajectory of the NS in the orbital plane from the time the NS reaches the core is shown in the respective inset panels with a characteristic height and width of $(4R_{\odot})^2$. Animations available at: https://tinyurl.com/hydrosims	28
3.8	The normalized specific angular momentum content j/j_{isco} of the stellar core at the end of the simulation is shown in mass coordinates (green curve). The profile is calculated by taking the spherical average about the center of mass in the FLASH simulation shown in Figure 3.7. Here j_{isco} is the specific angular momentum required for disk formation (dashed vertical line). We note that the simulated stellar model satisfies this condition for disk formation at all radii.	32

3.9	The accretion rate onto the newly formed BH as a function of time. The rotating in-falling core material is assumed to free fall without any pressure support and without mixing of radial layers. A disk is presumed to form from the collapse of every infalling shell and then subsequently accreted before the next shell collapses, as described in Bavera et al. (2020) . When feedback from the accretion disk is taken into account, we show that it can unbind the infalling material on timescales that are comparable to the peak accretion time. The two ejection timescales shown as vertical lines are introduced in Figure 3.10.	34
3.10	Relevant energy scales needed to estimate envelope unbinding during the accretion phase onto the newly formed BH. The binding energy of the rotating collapsing envelope, E_b , exterior to a given mass coordinate (pink) and the integrated wind accretion energy, E_w , expected to be shared with the infalling envelope (blue and dark green) are plotted against the mass coordinate of the post-merger model. The integrated energy required for ejection is uncertain. Here we assume two feedback efficiencies when calculating the fraction of energy that is shared with the collapsing stellar material. These are 1% (blue) and 0.2% (dark green), respectively. The formation of an accretion disk induces feedback, which in turn imposes a limit to the fraction of the star that can collapse and power an accretion event (dashed and dotted vertical lines). . . .	36
3.11	Diagram illustrating the post-merger evolution of the LMC X-4 system. After the primary fills its Roche lobe (represented by the blue sphere) and engulfs the NS (represented by the grey sphere), a merger event cannot be avoided (Figure 3.2). As the engulfment proceeds (Figure 3.7), the NS rapidly ($\approx 13.8\text{hr}$) sinks into the core (represented by the orange sphere). As a result, the core spins up due to shocks produced in the course of the inspiral. The further evolution of the rapidly rotating merger product can produce several interesting phenomena. The neutron star is expected to accrete a significant amount of mass to collapse to a BH. The rotating core, as it continues to collapse, will produce an accretion disk (Figure 3.8), which will likely also power and launch a relativistic jet.	37

3.12	Luminosity as a function of the duration of high-energy transients adapted from Levan et al. (2014) . For the GRB and ULGRB sources we plot t_{90} as the duration and the peak isotropic luminosity. The duration of the event assumes the ejection timescale determined by accretion feedback in Figure 3.9. The properties of the high-energy transient roughly coincide with those of the emerging class of ultra-long GRBs, such as GRB 101225A, GRB 111209A, and GRB 121027A.	38
3.13	Stellar structure profiles for the $18 M_{\odot}$ MESA model presented in Figure 3.2. Plotted are the specific nuclear energy generation rate (in units of $10^5 \text{ erg g}^{-1} \text{ s}^{-1}$), the convective velocity according to mixing length theory (in units of 10^5 cm s^{-1}), and the H and He mass-fraction profiles as a function of radial coordinate. The left and right panels show the interior properties of the companion as inferred “today” by Falanga et al. (2015a) and at the time of mapping into the FLASH simulation, respectively. The radial coordinate at which the $\alpha = 1$ condition is satisfied is shown as a green vertical dashed line in the right panel.	45
3.14	Two dimensional slices of the logarithm of gas density in the meridional plane (y - z) at three different times during the spiral-in phase (2.3hr, 4.5hr and 13.8hr). The upper panels in Figure 3.3 show the corresponding density slices in the orbital plane (y - x). Animations available at: https://tinyurl.com/hydrosims	45
3.15	ρ - T parameter space relevant to TŻO hydrostatic solutions and the spiral-in phase of a NS during CE. The grey line shows how temperature varies with density at the base of static TŻO solutions (Cannon, 1993). The spiral-in trajectory starts at comparatively low temperature and less dense material (lower corner) and becomes hotter and denser (upper corner) as the NS sinks into the core. The neutrino emission is dominated by electron-positron pair production process, which are computed for solar metallicity material according to the fit formulae of Itoh et al. (1996)	48

4.1	Reproduced from Everson et al. (2024a) . Stellar masses and radii for a population of CE interaction outcomes modeled with MESA are shown as dark brown dots. The left panel displays systems with a neutron star (NS) companion, where the white star represents the forward-evolved LMC X-4 model from Chapter ?? with the observed $1.57 M_{\odot}$ NS companion. The right panel displays systems with black hole (BH) companions, with the white star again representing the LMC X-4 stellar model but assuming a $6.6 M_{\odot}$ BH companion. Systems above the CE ejection boundary successfully eject their envelopes and survive the CE phase (beige region), while systems below the boundary undergo merger. Among the merger systems, brown denotes cases in which the stellar core is disrupted, whereas coral denotes systems in which the core remains intact following merger.	55
4.2	Reproduced from Everson et al. (2024a) . Density snapshots during inspiral for the BH case (top row) at 2.4 hr and 3.3 hr, and for the NS case (bottom row) at 4.6 hr and 5.5 hr. The black circle denotes the tidal disruption radius, the black X marks the center of mass of the primary, and the white circle outlined in black represents the secondary. In both simulations, the secondary inspirals toward and merges with the stellar core. The BH case exhibits significant tidal disruption of the core, whereas the NS case undergoes a non-disruptive merger in which the core remains comparatively intact.	60
4.3	Reproduced from Everson et al. (2024a) . Schematic illustration of the expected TETŻO structure. The central BH accretes through a disk with characteristic radius R_{in} , while a diffuse optically thick envelope extends outward to the photosphere at radius R_{r}	65
5.1	Binary interactions involving unstable mass transfer obtained from the binary population synthesis calculations of Twum et al. (2026) . Panel <i>a</i> : Distribution of mildly evolved (Zone I) donors in the mass-radius plane. Panel <i>b</i> : Distribution of the ratio of central to average density, $\rho_c/\bar{\rho}$, across the mass-radius plane for the mildly evolved donor population. In panels <i>a</i> and <i>c</i> . Symbols indicate the subset of donor models selected for the three-dimensional hydrodynamical simulations. Panel <i>c</i> : Joint distribution of binary mass ratio, q , and donor central concentration, $\rho_c/\bar{\rho}$, for mildly evolved common-envelope donors. The masses and radii of eclipsing high-mass X-ray binaries (HMXBs) studied by Falanga et al. (2015b) are shown as star symbols. The simulated models (orange and purple) span the characteristic range of structural and binary properties occupied by the majority of mildly evolved common-envelope donors.	74

5.2	Time evolution of the mid-plane density for the two representative $q = 0.1$ simulations. The moderately concentrated $18M_{\odot}$ donor (top panels) with $\rho_c/\bar{\rho} = 251$ undergoes rapid inspiral over only a few dynamical timescales, after which the orbital separation decreases more gradually as the embedded companion settles near the core radius of the donor. The more centrally concentrated $2.14M_{\odot}$ donor (bottom panels) with $\rho_c/\bar{\rho} = 962$ evolves over tens of dynamical timescales and settles into a quasi-stationary orbit while the donor envelope undergoes substantial expansion. Mass loss continues throughout this extended phase for hundreds of dynamical timescales, ultimately leading to the ejection of most of the donor envelope. Animations available at: https://tinyurl.com/hydrosims	79
5.3	Time evolution, in units of the dynamical timescale of the donor, representative $q = 0.1$ simulations for the moderately concentrated $18M_{\odot}$ donor with $\rho_c/\bar{\rho} = 251$ (left) and the high-central-concentration $2.14M_{\odot}$ donor with $\rho_c/\bar{\rho} = 962$ (right). The top panels show the cumulative ejected mass, normalized to the initial donor mass, together with the evolution of the enclosed-mass response parameter Ψ . Horizontal solid lines indicate the ejecta mass predicted by the standard α -formalism assuming $\alpha = 1$. Vertical dotted lines mark the times corresponding to the hydrodynamical snapshots shown in Figure ???. The bottom panels show the orbital separation of the embedded companion normalized to the donor radius, a/R_* . The horizontal dashed line indicates the characteristic radius at which the released orbital energy equals the binding energy of the overlying envelope in the $\alpha = 1$ formalism, while the purple dashed line marks the tidal disruption radius assuming a zero-age main-sequence companion (Twum et al., 2026). The shaded region denotes the donor's core region.	81
5.4	Time evolution of the moderately concentrated $18M_{\odot}$ donor with $\rho_c/\bar{\rho} = 251$ for companion mass ratios spanning $q = 0.1$ – 0.4 . The panels show the cumulative ejected mass, enclosed-mass response parameter Ψ , and orbital separation as functions of time in units of the donor dynamical timescale. All models exhibit qualitatively similar inspiral evolution, with the embedded companion rapidly inspiraling toward the donor core over only a few dynamical timescales. The total ejected mass increases systematically with companion mass ratio, although the ratio between the simulated ejecta mass and the $\alpha = 1$ prediction does not increase with q . Line styles and additional quantities are defined as in Figure 5.3.	83

5.5	Time evolution of the high-central-concentration $2.14M_{\odot}$ donor with $\rho_c/\bar{\rho} = 962$ for companion mass ratios spanning $q = 0.1\text{--}0.4$. The panels show the cumulative ejected mass, enclosed-mass response parameter Ψ , and orbital separation as functions of time in units of the donor dynamical timescale. In all models, the inspiral undergoes an initial dynamical contraction phase followed by a transition to prolonged envelope expansion once the companion settles into a quasi-stationary orbit. The subsequent evolution is dominated by sustained hydrodynamic expansion and continued mass loss over tens to hundreds of dynamical timescales, ultimately leading to the ejection of most of the donor envelope largely independent of companion mass ratio. Line styles and additional quantities are defined as in Figure 5.3.	86
5.6	Comparison between the total ejecta mass obtained from the hydrodynamical simulations and the predictions of the standard α -formalism assuming $\alpha = 1$. The left panel shows the moderately concentrated donor suite, while the right panel shows high-central-concentration donor suite. The moderately concentrated donors broadly follow the orbital-energy scaling expected from the inspiral, although the simulations consistently eject more mass than predicted by the simple energy formalism. By contrast, the high-central-concentration donor suite ejects most of the donor envelope largely independent of companion mass ratio due to prolonged hydrodynamic expansion following the inspiral phase.	88
5.7	Comparison of simulations involving donors with similar central density contrasts but substantially different masses and evolutionary states. Top panels show the orbital separation evolution normalized by the donor radius, while bottom panels show the cumulative unbound mass fraction normalized by the total donor mass as a function of time normalized by the donor dynamical timescale. Despite significant differences in stellar mass and detailed envelope structure, systems with similar values of $\rho_c/\bar{\rho}$ exhibit qualitatively similar inspiral morphologies and mass-ejection histories, supporting the interpretation that donor central concentration regulates the global hydrodynamic response during common-envelope evolution.	97

5.8	Initial donor masses and radii adopted in previous global common-envelope simulations compared to the donor models studied in this work (<i>blue circle</i> symbols). Literature simulations primarily probe evolved RGB, AGB, and red-supergiant donors with large radii, while the present models occupy a distinct regime of mildly evolved progenitors with intermediate central concentration. The masses and radii of eclipsing high-mass x-ray binaries studied by Falanga et al. (2015b) are shown as white star symbols. The background color indicates the central-to-average density ratio, $\rho_c/\bar{\rho}$, highlighting that the present study explores a region of donor structure that has been comparatively underrepresented in previous three-dimensional common-envelope calculations. The dotted and dashed lines delineate the three evolutionary regimes identified by Twum et al. (2026). Binary population demographics based on the Sana et al. (2012) initial binary distributions suggest that approximately 27.4%, 11.7%, and 58.2% of systems undergoing unstable mass transfer populate Zones I, II, and III, respectively. Observed LRN progenitors with pre-explosion imaging are plotted for comparison (Matsumoto and Metzger, 2022a). From left to right, in order of increasing inferred mass, these include V1309 Scorpii, M31LRN2015, V838 Monocerotis, M101-OT2015, SN Hunt248, and AT 2018bwo. These progenitors are either main-sequence progenitors (<i>black squares</i> ; Zone I) or extended progenitors (<i>white dots</i> ; Zones II and III).	99
-----	---	----

6.1	Demographics of the Galaxy Zoo Bar Lengths sample, based on (a) raw classification counts and (b) plurality classification for each galaxy. In each panel, the full classification tree (Table 1) is shown. Each node in each diagram (dark blue horizontal bars with white text inset) represents a task in the classification tree. The paths between tasks represent each possible answer to the task above it, and they flow to the next task shown to a classifier who gives that response. From the initial task, the classification ends if the classifier indicates the galaxy is unbarred; otherwise, they answer two further questions and complete a drawing task, with no further branches of the classification tree. In panel (a) on the left, the width of each path is proportional to the number of raw classifications received for each response, for any galaxy. In panel (b) on the right, we apply a label to each galaxy based on the plurality (highest vote fraction) answer to each task, with ties broken by entering the galaxy into the “Yes” category for that task. For example, in panel (b), a galaxy is considered barred if at least 50% of classifiers answered “Yes” to task T0. For a task with more than 2 answer choices, the plurality need not reach the 50% threshold. This visualization is a useful overview of the morphologies of the disk galaxies in this dataset.	106
6.2	Example images from the Galaxy Zoo Bar Lengths project (left column), with markings by individual classifiers shown as thin lines (middle column) and clustered markings of bar length and width shown in thick purple lines (right column). Marks in the middle column are color-grouped by final cluster membership. Light blue marks in the right column indicate low-confidence clusters (typically containing outlier marks). Agglomeration with median combination of line parameters is robust to outliers that <i>do</i> fall within a high-confidence cluster and often produces accurate measurements even at values of p_{bar} below our selection threshold (<i>e.g.</i> , top row).	107
6.3	Purity (blue circles) and completeness (red triangles) of samples as a function of the p_{bar} threshold used to select the barred sample from within the full set of disk galaxies examined in Galaxy Zoo Bar Lengths. As the threshold is raised, the sample becomes more pure (less contaminated by unbarred galaxies) but less complete. Considering these tradeoffs, we choose a threshold of $p_{\text{bar}} = 0.5$ to select a barred galaxy sample.	117

6.4	Bar width versus length for all bars in the Galaxy Zoo Bar Lengths project that meet the definition of barred described in Section 6.2.2. The dotted line at constant bar width shows the FWHM size of the <i>HST</i> ACS point-spread function, the minimum size we might expect to measure a bar width; the dashed line at constant length shows twice this value, the minimum size at which we would resolve a bar. Most bars are very well resolved. Bar length and width generally correlate, with a median length-width ratio of ~ 3 . From within the full sample of barred galaxies in GZBL we further analyze the subset that have well-measured additional properties from data sets in the COSMOS field (described further in Section 6.3).	118
6.5	Rest-frame galaxy stellar mass versus redshift. At left, the full COSMOS sample used here (Section 6.3; Leauthaud et al., 2007; Muzzin et al., 2013a,b; Weaver et al., 2022) is shown as a grayscale density plot. Solid blue contours show the subset of COSMOS galaxies examined in the GZH project (W17). From this GZH-COSMOS parent sample, disk galaxies falling within the MASS-COMPLETE sample (limits drawn by the dotted red lines) are shown as red circles. The figure at right is zoomed to show only the limits of the MASS-COMPLETE sample, with barred galaxies shown as filled blue squares and unbarred galaxies shown as open green triangles, and normalized mass and redshift distributions of the BAR-MASS and NO-BAR-MASS samples shown as blue solid and green dashed lines, respectively. The BAR-MASS-WT and NO-BAR-MASS-WT samples are then defined with weights such that the weighted (M_*, z) distributions are statistically indistinguishable (Section 6.3.1).	121

- 6.6 Rest-frame $U - V$ versus $V - J$. The gray density plot shows all galaxies (of all morphologies) COSMOS within the boundaries of the MASS-COMPLETE sample; the gray contour encloses 99% of COSMOS galaxies. Points show COSMOS disk galaxies analyzed by the Galaxy Zoo Bar Lengths project, split into BAR-MASS (blue circles) and NO-BAR-MASS (green triangles) sub-samples. For both sub-samples, the opacity of each point is scaled according to its weight, such that the weighted BAR-MASS-WT and NO-BAR-MASS-WT samples have statistically indistinguishable stellar mass and redshift distributions. For barred galaxies, the size of the point is proportional to the fractional bar length ℓ_{rel} . The dashed line separates passively-evolving (top-left region) and star-forming galaxies (from Williams et al., 2009, $z \geq 0.5$ coefficients). Histograms of $U - V$ and $V - J$ for the BAR-MASS-WT (blue solid lines) and NO-BAR-MASS-WT (green dashed lines) distributions are also shown: even controlling for stellar mass and redshift, barred and unbarred galaxies have different color distributions. 130
- 6.7 Left: star formation rate versus stellar mass for barred (blue circles) and unbarred (green triangles) disk galaxies, as well as for the overall COSMOS sample within the mass and redshift limits (gray 2D histogram and outer 99% dotted contour). The size of each barred-galaxy point is scaled to the relative bar length, as in Figure 6.6. Each point's opacity is scaled according to its weight, such that the points represent the weighted BAR-MASS-WT and NO-BAR-MASS-WT samples. Binned medians for the BAR-MASS-WT and NO-BAR-MASS-WT samples are shown as blue solid and green dashed lines, respectively. Axis histograms show weighted sample counts for barred (blue solid) and unbarred (green dashed) disks, and all galaxies (grey dotted) in the volume limit. Both samples occupy the full range of all galaxies, although there are relatively few disk galaxies with features such as spiral arms and bars that are both low-mass and off the star-forming sequence. Right: distribution of positions of BAR-MASS-WT and NO-BAR-MASS-WT galaxies relative to where they would be expected if they were in the middle of the star-forming sequence at their stellar mass and redshift, according to the method of Aird et al. (2019). The lowest-value bin includes galaxies with $\delta \log SFR$ lower than that value (highly quiescent galaxies). Generally, there is an excess of barred versus unbarred disk galaxies below the star-forming sequence. These categories will be used for analysis in sections below. 134

- 6.8 Properties of bars in the subset of the BAR-MASS sample with bar width $W_{\text{bar}} > 1.5$ kpc (blue circles) versus galaxy properties. From top to bottom, y -axes show bar length in kpc, relative bar length ℓ_{rel} , relative bar width ω_{rel} , and length-to-width ratio $L_{\text{bar}}/W_{\text{bar}}$ (a measure of bar strength). From left to right, x -axes show redshift z , stellar mass M_* , and offset from the star-forming sequence $\delta \log SFR$. Solid lines show binned median bar property values, with 95% confidence intervals on the median, estimated by varying binning and resampling 1,000 times within ± 0.1 in each x -axis value, shown as gray shaded regions. Dashed lines enclose the central 68% of galaxies in each bin. In the top left panel, the dotted line shows the evolution of $2 \times \text{PSF FWHM}$ (*i.e.*, the minimum resolvable bar length) with redshift. There are some statistically significant trends in the median values, although these differences are much smaller than the width of the overall population distributions. 137
- 6.9 Bar length L_{bar} (top), relative bar length ℓ_{rel} (upper middle), relative bar width ω_{rel} (lower middle), and bar strength (bottom) versus redshift z (left) and stellar mass M_* (right) within the subset of the BAR-MASS sample with $W_{\text{bar}} > 1.5$ kpc. The sample has been split by star-forming status, with each galaxy assigned to be starburst (cyan dotted), on the star-forming sequence (blue solid), sub-sequence (green dashed), or quiescent (red dot-dashed) based on its position on the $SFR-M_*$ diagram relative to the centre of the star-forming sequence at its stellar mass and redshift ($\delta \log SFR$). Many $\delta \log SFR$ -based differences with redshift disappear when comparing galaxies at the same stellar masses across the star-forming categories, but there are still some statistically significant median differences between galaxies in different star-formation categories at a given stellar mass and a given redshift. 143

Abstract

Gravitational Torques Across Scale: Galactic Bars and Common Envelopes

by

Tenley Hutchinson-Smith

Despite spanning more than ten orders of magnitude in physical scale, common-envelope interactions and galactic bars are governed by the same fundamental process: gravitational torques redistribute angular momentum, drive dissipation, and reshape self-gravitating systems far from equilibrium. In common envelopes, this transport proceeds through hydrodynamical drag and shock-driven dissipation in collisional gas, while in barred galaxies it emerges through largely collisionless stellar dynamics. This dissertation explores how these processes govern the evolution of astrophysical systems across vastly different environments.

This thesis is divided into two parts. The first and primary part investigates interacting binary evolution, focusing on common-envelope (CE) inspiral, stellar mergers, luminous red novae, and Thorne–Żytkow object (TŻO) formation. Using one-dimensional stellar evolution calculations together with three-dimensional hydrodynamical simulations, I examine how orbital energy and angular momentum are redistributed during compact-object inspiral inside massive stellar envelopes. These studies revisit the long-standing paradigm for classical TŻO formation and demonstrate that angular momentum deposited during inspiral naturally produces rotationally supported accretion flows and strong feedback, challenging the assumptions of long-term quasi-spherical accretion. Instead, the simulations favor the formation of thin-envelope TŻOs, in which disk accretion onto an embedded compact remnant powers the removal of most of the stellar envelope and may generate high-energy transients such as ultra-long gamma-ray bursts. I

further investigate the hydrodynamical response of mildly evolved CE donor stars relevant to luminous red novae, showing that their observational diversity depends not only on ejecta mass, but also on the temporal structure of the outflow and the transition between impulsive ejection and prolonged mass-loss evolution.

The second part of this dissertation examines the secular evolution of galactic bars using observations from the Hubble Space Telescope and Galaxy Zoo. By constructing and analyzing a catalog of galactic bar measurements across cosmic time, I investigate how angular momentum redistribution shapes bar structure and drives the long-term dynamical evolution of disk galaxies.

Together, these studies demonstrate how gravitational torques and dissipative processes govern the evolution of astrophysical systems across an enormous range of scales, from compact stellar mergers to galactic structure.

To Black people and our refusal to let the world limit us

Acknowledgments

I really don't know where to even begin, because I have been so grateful for the community I have fostered around me these past 7 years of grad school (and before!), and so many people have had such a tremendous impact on me and my own development not just as a researcher, but as a person.

Enrico, I barely have the words to express how grateful I am to have had you as my advisor and mentor. Outside of the more obvious ways you have taught me to be a scientist, you have also given me a much more meaningful gift of bravery, and you have helped me find my voice. Thank you for teaching me that there is room to stand up for what I believe in and to care deeply about people, even within the walls of academia. I am so grateful for all the ways you showed up for me beyond science, especially during some of the hardest times in my life. Those moments meant more to me than I think I'll ever be able to fully express. Also, thank you for looking up the meaning of my name "a clearing or meadow that has been burned" and giving me such a beautiful way to think about it. I now brag to everyone that that's what my name means! I'm excited for all the possibilities that exist in continuing to share community with you during this brand new chapter of my life. Also, I seemed to have picked up some of your perfectionist tendencies. Was I already like this, or did I get it from you? Unclear. Maybe both!

Alex and Arcy, I genuinely don't even know where to begin, so I'll just start by saying that I love you all so much. Spending such important formative years of my adult life with you has impacted me in ways that I know will stay with me forever, and has truly been the highlight of my adulthood. Us moving in together back in 2019 and creating a real home together has meant so much to me. And then when we moved into another house after that and continued to maintain

such a healthy, loving, and supportive relationship with one another, I remember just always being amazed that we had actually built something so special. Living with your friends is definitely not for the weak!! And we really made it work! Our very last day together, after getting our matching house tattoos, finishing most of the packing, then crying together in the parking lot, that was such a sad but also beautiful day. What a journey. Living with you all completely changed how I think about home and family. Something I appreciated a lot about our home was that it often felt like a bridge between us and our larger community. All the video game nights, watch parties, spontaneous hangouts, and all the friends we would invite over between the 3 of us made our home feel so alive. The presence of community in our home gave me a sense of safety and belonging that I miss so deeply. This journey together taught me that regular social interaction without needing to schedule it is so top tier for me. Because it leaves room for the joy and peace that comes from simply being around/sharing space with people you love and trust, and existing alongside one another through the ordinary parts of life. There is so much beauty in those seemingly mundane moments. Watching TV in the evenings, the conversations in passing. And the syncing of routines (like when you would brush your teeth in my doorway every morning Alex, which was what would get me to get out of bed lol). Those moments became some of the most meaningful parts of my life.

Rosa, thank you for being such an amazing mentor to me. I feel like you basically raised me (but in a research/academic way lol). You are such an amazing mentor, and I'm excited to continue being in each others lives and learning from you in the future! And Deana, thank you for being such an amazing presence in my life all these years, providing a safe landing space for me and many other students in your office, all the emotional support, and for all the milkshakes!! Angela, I

absolutely love how we've been friends since 2016 and at some point many years ago, we said to each other that we want to try to be co-authors together. And the way we finally made it happen!!! I absolutely love that for us and cherish our friendship so deeply. Thummim, thank you as well for being such an amazing friend to me all these years, as well as a co-working buddy now that we share offices. I have so many more people that have been so integral to my journey, my mom, dad, family, friends, UCSC grad students, my research group, and so many mentors, including Brooke Simmons, Luke Kelley, Nia Imara, and many many more. Thank you all so much for helping me grow into the person I am today.

And lastly, I gotta thank me?!?! saving the best for last! Future Tenley who is reading this (maybe 40 year old me, 60 year old me, 100 year old me!?!) i want you to know that i am so grateful for, proud of, and in love with the person I have grown into and am today. and i am so excited to get to know the many iterations that are to come.

Chapter 1

Roadmap of the Dissertation

Understanding the detailed physics and consequences of energy and angular momentum transport in astrophysical systems is essential for explaining how matter redistributes and evolves across the universe, ultimately shaping the observable properties and final outcomes of these systems. This dissertation is divided into two main parts, both centered on the transport and redistribution of energy and angular momentum as unifying physical processes operating across vastly different scales.

The first and primary part of this dissertation focuses on stellar interactions, particularly common-envelope (CE) evolution and CE-driven mergers. Through the study of CE interactions, I investigate how the deposition and redistribution of energy and angular momentum alter stellar structure, drive shocks and mass ejection, and produce outcomes ranging from high-energy transients and luminous red novae to newly re-envisioned systems such as Thorne-Żytkow-like objects, representing the classic “star within a star” picture. These studies explore how dynamically evolving stellar interactions and mergers reshape our understanding of the physical origins, diversity, and observable signatures of these phenomena

through collisional hydrodynamic processes, dissipation, and orbital energy release. This part of the dissertation is based on three papers, two of which were led by me as first author and one companion paper where I am second author. In the chapter based on the second-author publication (Chapter 4), the discussion is substantially expanded and rewritten to emphasize my individual scientific contributions and to provide an independent and unified presentation beyond the original published work. The remaining two chapters (Chapter 3 and 5) are closely based on papers for which I served as lead author.

- *Rethinking Thorne–Żytkow Object Formation: The Fate of X-Ray Binary LMC X-4 and Implications for Ultra-long Gamma-Ray Bursts*, Hutchinson-Smith, T., Everson, R. W., Twum, A. A., et al. 2024, *Astrophysical Journal*, 977, 2, 196.
- *Rethinking Thorne–Żytkow Object Formation: Assembly via Common Envelope in Field Binaries*, Everson, R. W., Hutchinson-Smith, T., Vigna-Gómez, A., et al. 2024, *Astrophysical Journal*, 971, 2, 132.
- *Hydrodynamic Response of Mildly Evolved Common Envelope Donors in Luminous Red Novae*, Hutchinson-Smith, T., Twum, A. A., Ramirez-Ruiz, E. 2026, submitted to *The Astrophysical Journal Letters*, arXiv:2605.27579.

The second part of this dissertation examines the secular evolution of barred galaxies (Chapter 6). In these systems, the redistribution of energy and angular momentum proceeds primarily through collisionless stellar dynamics and gravitational torques, driving the long-term evolution of galactic bars and influencing star formation, morphology, and the structural evolution of galaxies. This part of the dissertation is based on one paper for which I served as lead author.

- *Galaxy Zoo Bar Lengths: A Catalogue of Measurements from Hubble Space Telescope Images and the Evolution of Galactic Bar Structure at $z < 1$* , Hutchinson-Smith, T., Simmons, B. D., Masters, K. L., et al. 2026, submitted to the Astrophysical Journal, arXiv:2604.27100

Together, these studies demonstrate how the transport of energy and angular momentum through gravitational torques and dissipative processes serves as a common physical mechanism linking the evolution of systems that span many orders of magnitude in size, mass, density, and timescale. While the physical manifestation of these processes differs dramatically between collisional stellar fluids and collisionless galactic systems, the underlying dynamical principles reveal a remarkable universality in how gravity redistributes matter, energy, and angular momentum throughout the universe.

Part I

The Evolutionary Path from High-Mass X-ray Binaries through Luminous Transients to Thorne–Żytkow-like Objects

Chapter 2

Introduction and Roadmap to Part I

A substantial fraction of stars in the Universe, particularly massive stars, do not evolve in isolation but instead undergo their evolutionary journeys alongside one or more stellar companions. Population studies suggest that the majority of massive stars experience binary interactions during their lifetimes, making binary evolution a central ingredient in shaping stellar populations (e.g., Sana et al., 2012). Through the exchange of mass, energy, and angular momentum, these interactions can produce a diverse range of phenomena, including X-ray binaries, common-envelope (CE) evolution, stellar mergers, luminous transients, and exotic compact-object remnants.

Despite its importance, many stages of interacting binary evolution remain poorly understood. CE evolution, in particular, involves highly complex hydrodynamical processes in which the redistribution of orbital energy and angular momentum throughout the stellar envelope determines whether the envelope is successfully ejected, whether the binary survives as a compact system, or whether

the interaction culminates in a merger. These processes not only govern the immediate dynamical evolution of the system but also shape its long-term observational outcomes, including the production of luminous transients, compact binaries, and exotic merger remnants.

One proposed outcome of CE evolution is the formation of a TŻO, a hypothetical stellar configuration in which a compact object becomes embedded within the center of a massive star. Systems such as LMC X-4 have long been considered potential progenitors of these objects. However, realistic modeling of their formation and long-term evolution remains limited, particularly in the context of angular momentum transport and the multidimensional hydrodynamics of the merger process.

Binary interactions also produce observable transients that provide direct insight into the hydrodynamical evolution of these systems. Luminous red novae (LRNe), which are thought to arise from stellar mergers and CE interactions, offer a unique opportunity to connect internal processes such as energy deposition, shocks, and angular momentum redistribution with observable signatures including mass ejection, orbital evolution, and radiative output.

In Part I of this dissertation, several manifestations of interacting binary evolution are investigated using a combination of one-dimensional stellar evolution calculations and three-dimensional hydrodynamical simulations. The first two studies revisit the expected evolution of systems originally predicted to form TŻOs and reframe their evolution in favor of an alternative post-merger configuration shaped by rotational support and subsequent disk accretion. In these scenarios, the rapid rotation and accretion following merger can power high-energy transients, including ultra-long gamma-ray bursts, accompanied by a more standard red luminous transient associated with the ejection of the stellar envelope. The final

study presents an in-depth hydrodynamical investigation of how companion mass and stellar structure influence the internal response of the donor star and the resulting mass ejection associated with LRNe. Rather than depending solely on the total ejecta mass, the simulations suggest that the observable diversity of LRNe may also be strongly shaped by the temporal structure of the outflow, including the transition between impulsive envelope ejection and prolonged wind-like or multi-stage mass-loss evolution.

2.1 Summary and Lessons Learned

Together, these studies examine how mass transfer, energy deposition, and angular momentum redistribution during binary interactions shape the evolution and outcomes of CE systems. In particular, they demonstrate that CE evolution is not governed solely by the amount of orbital energy released during inspiral, but also by how that energy and angular momentum are redistributed throughout the stellar envelope and core. The resulting hydrodynamical response determines whether the envelope is ejected impulsively or through prolonged mass loss, whether the binary survives or merges, and whether the merger remnant evolves toward a compact binary, a luminous transient, or an exotic post-merger object such as a TŻO.

A recurring theme throughout these studies is that angular momentum transport fundamentally alters the post-merger structure of the system. Shocks, gravitational torques, and rotationally driven flows naturally spin up the merger remnant, modify accretion geometry, and promote the formation of rotationally supported disks. These effects challenge simplified pictures of spherical accretion and reveal that rotational support and feedback are central ingredients in determining the long-term evolution of compact object mergers inside stellar envelopes.

The studies further show that the observational diversity of CE-driven transients depends not only on the total amount of ejected material, but also on the temporal structure of the outflow and the coupling between orbital energy deposition and stellar structure. Differences in donor concentration, companion mass, and inspiral evolution can produce qualitatively different mass-loss histories, ranging from impulsive envelope ejection to multi-stage or wind-like outflows. These results provide a more physically motivated framework for interpreting luminous red novae and other merger-powered transients.

Collectively, Part I motivates a more dynamical and multidimensional picture of interacting binary evolution in which hydrodynamical dissipation, rotational support, and feedback processes play a defining role in shaping the fate of CE systems and their observable outcomes.

Chapter 3

Rethinking Thorne–Żytkow Object Formation: The Fate of X-ray Binary LMC X-4 and Implications for Ultra-long Gamma-ray Bursts

Abstract

We present a start-to-end simulation aimed at studying the long-term fate of high mass X-ray binaries and whether a Thorne–Żytkow object (TŻO) might ultimately be assembled. We analyze results from a 3D hydrodynamical simulation that models the eventual fate of LMC X-4, a compact high mass X-ray binary system, after the primary fills its Roche lobe and engulfs the neutron star companion. We discuss the outcome of this engulfment within the standard paradigm of TŻO

formation. The post-merger angular momentum content of the stellar core is a key ingredient, as even a small amount of rotation can break spherical symmetry and produce a centrifugally supported accretion disk. Our findings suggest the inspiraling neutron star, upon merging with the core, can accrete efficiently via a disk at high rates ($\approx 10^{-2} M_{\odot}/\text{s}$), subsequently collapsing into a black hole and triggering a bright transient with a luminosity and duration typical of an ultra-long gamma-ray burst. We propose that the canonical framework for TŻO formation via common envelope needs to be revised, as the significant post-merger accretion feedback will unavoidably unbind the vast majority of the surrounding envelope.

3.1 Introduction

High mass X-ray binaries (HMXBs) are X-ray emitting sources commonly featuring an early-type massive star and an accreting neutron star (see, e.g., Falanga et al., 2015a; Liu et al., 2006). A critical juncture in the life of a HMXB is the period just after the primary fills its Roche lobe and engulfs the neutron star companion (Paczynski, 1976a; van den Heuvel, 1976). Mass transfer is unstable and a catastrophic merger with the stellar core cannot be avoided (see, e.g., Belczynski et al., 2002; Gallegos-Garcia et al., 2022; Liotine et al., 2023; Qin et al., 2019). The further evolution of the merger product has been speculated to potentially give rise to a Thorne–Żytkow object (TŻO; Thorne and Żytkow, 1975, 1977).

A TŻO is a conjectured type of star containing a neutron star at its core, claimed to be formed by the engulfment of a neutron star by an evolving stellar companion (Thorne and Żytkow, 1975, 1977). TŻOs are speculated to be powered by thermonuclear reactions near the base of the central compact object or by gravitational energy released by mass accretion (Biehle, 1991, 1994; Cannon, 1993;

Cannon et al., 1992). In these objects, accretion or thermonuclear heating (and the accompanying radiation) is usually thought to be limited by the self-regulatory balance between gravity and radiation pressure (Cannon et al., 1992; Thorne and Żytkow, 1975, 1977). Biehle (1991) and Cannon (1993) distinctly showed how in TŻOs with massive stellar envelopes most of the energy is in fact not provided by accretion onto the NS but by thermonuclear reactions. The fact that TŻOs with massive envelopes generate their luminosities by exotic rp-process opens the possibility for stellar abundance measurements to be used to differentiate TŻOs from ordinary evolved stars.

Recently, a chemical anomaly in the red supergiant star HV 2112 in the Small Magellanic Cloud was speculated to be produced by an embedded accreting compact object (Levesque et al., 2014). The claim that HV 2112 might be a TŻO candidate arises from the anomalously high ratios of calcium, lithium, ruthenium, and molybdenum, which have been predicted to exist inside the exotic accretion-powered stellar interiors of TŻOs. While this claim has incurred numerous rebuttals (Beasor et al., 2018; Maccarone and de Mink, 2016; O’Grady et al., 2020; Tout et al., 2014), it has reinvigorated the construction of numerical models of TŻOs (e.g., Farmer et al., 2023), particularly in the context of common envelope (CE) evolution.

While most TŻO calculations suppose a non-rotating, spherically symmetric structure (Biehle, 1991; Cannon et al., 1992; Farmer et al., 2023; Thorne and Żytkow, 1977), formation via CE will invariably lead to the inspiraling NS accreting material at rates that are in excess of the Eddington photon limit (Chevalier, 1993, 1996; MacLeod and Ramirez-Ruiz, 2015b). The accretion rate is expected to dramatically increase as the NS sinks dynamically into the center of the star. Chevalier (1993, 1996) argued that TŻOs may not be able to form during CE since

accretion onto the NS might occur in the neutrino-dominated regime. Yet, we note that no fully realistic global simulation of the spiral-in phase had been performed.

At the final stage of the stellar merger, the NS ends up being surrounded by dense core material with significant rotational support, whose properties are reminiscent of gamma-ray burst (GRB) progenitors (Fryer et al., 1999b; Popham et al., 1999). Understanding the angular momentum content of the surrounding gas is thus critical when thinking about the post-formation evolution of TŻOs. This is because the angular momentum content of the post-merger material determines if a disk will form: if there is no rotation, only Bondi-like accretion will ensue (Cannon et al., 1992), which, in turn, has important implications for how accretion will advance (Halevi et al., 2023; Lee and Ramirez-Ruiz, 2006; Murguia-Berthier et al., 2020).

Motivated by this, we present here and in a companion paper by Everson et al. (2024a) a study of the long-term fate of HMXBs and whether a near steady-state TŻO might ultimately be produced. In this work, we use the binary system LMC X-4 in the neighboring Large Magellanic Cloud (LMC) satellite galaxy to guide our understanding of such outcomes: LMC X-4 is a highly compact, two-star system consisting of a pulsar and a massive stellar companion and currently has one of the most accurate determinations of the orbital parameters of HMXBs available to date (Falanga et al., 2015a). LMC X-4 thus appears to be an ideal progenitor candidate for a merged stellar remnant with an embedded neutron star in its core, offering clear constraints for the formation of TŻOs. In a companion paper, Everson et al. (2024a) expands this analysis by exploring the potential formation pathways of TŻOs across a broad parameter space of field binaries comprised of an evolved star and stellar-mass compact object, as well as the expected outcomes for such systems.

This paper is structured as follows. In §3.2, we discuss the role of HMXBs in the context of TŻO candidates arising from stellar mergers involving neutron stars and show using stellar evolution calculations that, as expected, the LMC X-4 binary system will merge via common envelope. Added to that, in §3.2.1 we talk about the fate of accreting LMC X-4 binary system, which results in the previously accreting neutron star merging with a stellar companion holding to one of the most gravitationally bound envelopes known within the HMXB galactic population. Our stellar evolution models after the primary fills its Roche Lobe are used as initial conditions for three-dimensional (3D) hydrodynamical calculations, which are described in §5.3. Our results are then discussed in §3.4, with a summary of this work in §6.6. For completeness, in Appendix 3.7 we make use of the results of our global hydrodynamical simulations to show that during the NS spiral-in phase, neutrino losses become the dominant energy-loss mechanism, as originally envisioned by Chevalier (1993, 1996), and the known hydrostatic solutions are not applicable in this regime (Cannon, 1993; Thorne and Żytkow, 1975).

3.2 The Fate of HMXBs and the evolution of LMC X-4

3.2.1 Stellar mergers involving neutron stars and the role of HMXBs as TŻO progenitors

The extensively discussed formation scenario for classical TŻOs is that they are the descendants of HMXBs (Cannon, 1993; Podsiadlowski et al., 1995; Taam et al., 1978b). When in these binary systems the massive primary fills its Roche lobe, unstable mass transfer ensues and the system will likely evolve into a CE phase,

where the NS is completely engulfed by the envelope of the evolving companion (Everson et al., 2024a). Due to gas drag (MacLeod and Ramirez-Ruiz, 2015b), the NS will then naturally spiral towards the primary’s core. If the orbital energy released in the sinking is enough to eject the envelope, the end product will likely give rise to a merging compact binary (Fragos et al., 2019). If, on the other hand, the orbital energy released is not sufficient to eject the envelope, the NS will sink into the core of the primary star and could become a TŽO (Taam et al., 1978b).

The formation of classical TŽOs, as argued by Everson et al. (2024a) in a companion paper, is likely to be aided by the engulfing primary being lighter and early on its evolution. The reasons for this are two-fold. First, the stellar envelope is more highly bound and thus less likely to be ejected during CE. Second, the core is less dense, which naturally gives rise to lower mass accretion rates once the NS has settled into the primary’s core. Because of this, here we study the long-term fate of HMXBs and scrutinize whether a near steady-state TŽO might ultimately be produced.

Figure 5.3 shows the population demographics of binary systems at the onset of CE, constructed using the library generated using the rapid binary population synthesis code COMPAS version 02.27.05 (Riley et al., 2022a) at $Z = 0.142$ and with CE efficiency parameter set to unity. As expected, HMXBs are included in the population of CE events with NS companions that are expected to merge (i.e., unable to eject the entire envelope).

Only in a handful of sources among the more than one hundred HMXBs is the inclination of the binary along our line of sight high enough for the NS to be periodically obscured by the orbiting companion. This naturally gives rise to X-ray eclipses, which can be used to constrain a wide range of properties of the binary system. Figure 5.3 shows the properties of the stellar companions

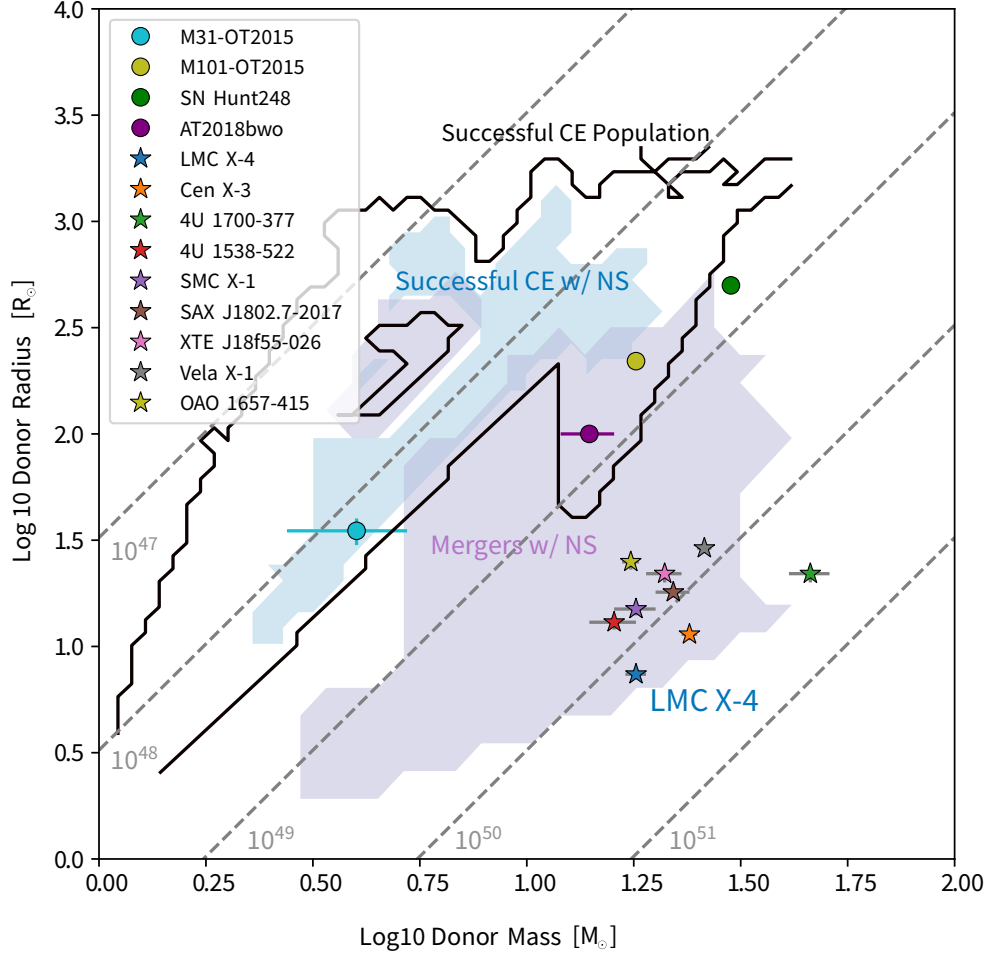


Figure 3.1: HMXBs in the context of Luminous Red Novae (LRNe) and binary population synthesis. The masses and radii of eclipsing HMXB systems are depicted as stars, and pre-CE transient observations for a sample of LRN progenitors are depicted as circles. Also shown are progenitor population demographics of CE events generated with the rapid binary population synthesis code **COMPAS**. The **COMPAS** populations include successful CE events, CE events with NS accretors that successfully eject the envelope, and CE events with NS accretors that merge. The gravitational binding energy of a polytrope of index $n = 3$ with mass M and radius R is shown for guidance.

in the eclipsing HMXB systems studied by [Falanga et al. \(2015a\)](#). LMC X-4 is particularly noteworthy. It has a relatively moderate mass and a highly bound envelope as well as currently having one of the most accurate determined orbital properties. As such, LMC X-4 appears to be an ideal TŻO progenitor candidate.

3.2.2 Forward modeling the pre-merger evolution of LMC X-4

In order to explore the potential for TŻO formation during the expected merger of the LMC X-4 system, we develop initial conditions based on the best current mass, size, and kinematic constraints available ([Falanga et al., 2015a](#)), forward-evolve them with MESA to common envelope onset, then map the resulting future system into three dimensional hydrodynamics and evolve it through CE and merger.

3.2.3 Properties of LMC X-4

Over a decade of monitoring with multiple instruments ([Falanga et al., 2015a](#); [Liu et al., 2006](#)) has provided strong constraints on the properties of LMC X-4. According to [Falanga et al. \(2015a\)](#), this HMXB system is comprised of a $1.57 \pm 0.11 M_{\odot}$ neutron star (NS) that is accreting from its $18 \pm 1 M_{\odot}$ stellar companion. The companion, hereafter referred to as the primary, somewhat underfills its Roche lobe with a stellar radius of $7.4 \pm 0.4 R_{\odot}$. The system has a separation of $14.2 \pm 0.2 R_{\odot}$ and an observed orbital period of 1.408 days. [Falanga et al. \(2015a\)](#) estimates the orbital period change $\dot{P}/P$ as $-1.0 \times 10^{-6} \text{ yr}^{-1}$, suggesting a gradual tightening of the orbit. The estimated mass loss rate of the primary due to winds is $2.4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ ([Chernov, 2020](#)), which alone cannot account for the estimated $\dot{P}/P$ value.

3.2.4 Stellar Models

We begin with modeling the evolution of the primary from the present time to the onset of CE using the MESA Isochrones and Stellar Tracks (MIST) package (Choi et al., 2016; Dotter, 2016) with MESA v7503 (Paxton et al., 2011b, 2013b, 2015b). The MIST framework is chosen due to its calibration to observations, including in the LMC. We evolve the primary as a single star using the mean LMC metallicity of $[\text{Fe}/\text{H}]=-0.42$ (Choudhury et al., 2021). We choose our initial mass range $[16, 20] M_{\odot}$ to be consistent with the 2σ mass estimates from Falanga et al. (2015a). This allows us to create a grid of potential models that will be narrowed down based on the properties of the primary star.

Because the evolution of the orbital period is not totally independent of the evolution of the primary, we consider both. Prior work has attempted to explain the $\dot{P}/P$ value of LMC X-4 with conservative mass transfer (Safi-Harb and Ögelman, 1996) and changes in the primary’s moment of inertia (Levine et al., 2000). Upon revisiting these works, in the former case the mass transfer rate required is much higher than the observationally derived mass loss values for the primary, and in the latter case, the formalism cannot match the measured $\dot{P}/P$ when applied to up-to-date stellar models in the appropriate stage of evolution (Chernov, 2020). For this system, wind mass loss serves only to make orbital tightening more difficult.

Recent work by Chernov (2020), however, demonstrates that tides alone are sufficient to explain LMC X-4’s orbital tightening. Though the rate of orbital tightening does include effects from winds, mass transfer, and the primary’s change in moment of inertia, it’s not possible to completely distinguish these effects with those of the degree of corotation on dynamical tides. This leaves LMC X-4’s separation as a function of time $a(t)$ as our last additional constraint on the

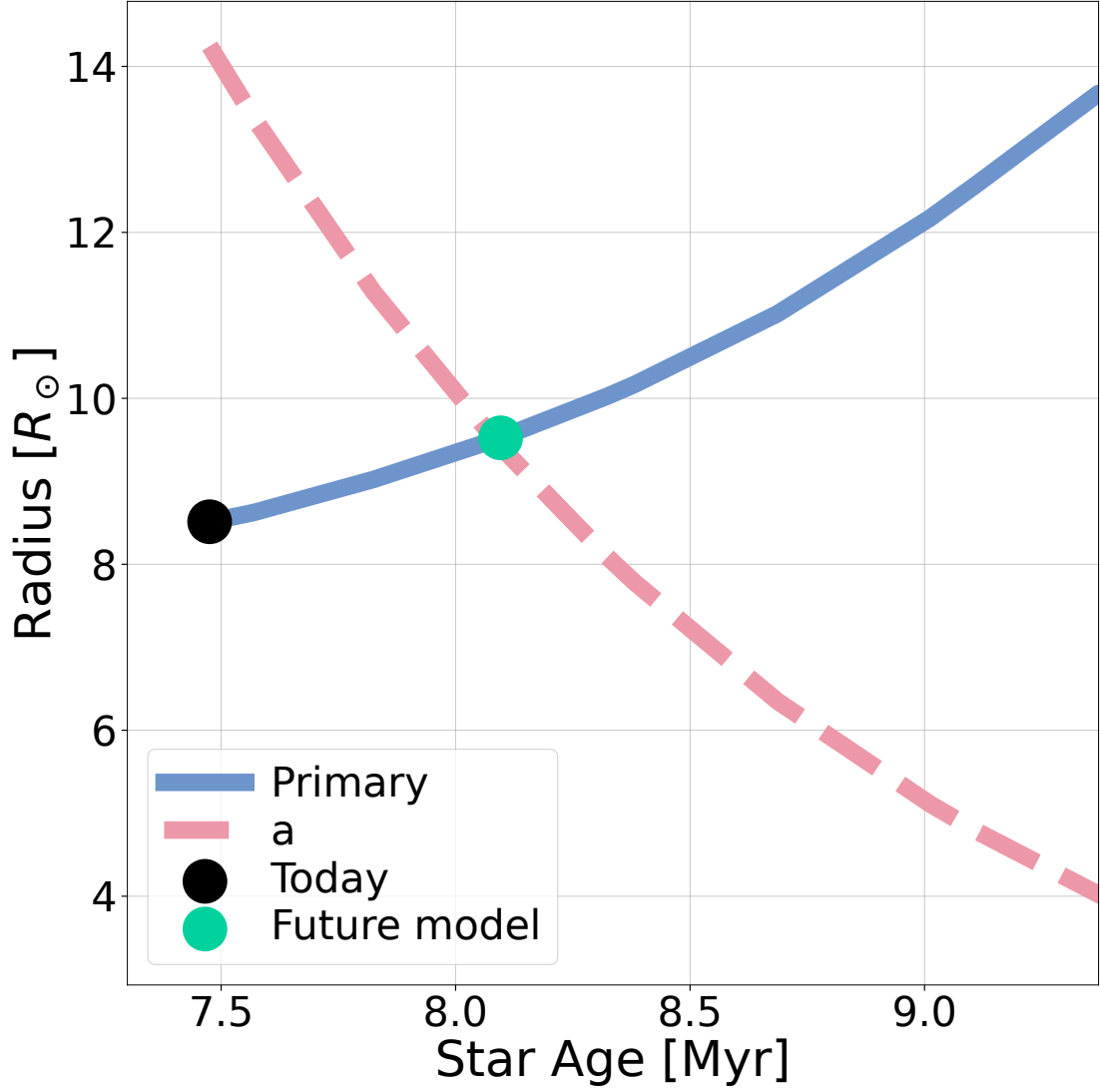


Figure 3.2: The predicted radial evolution of the primary star as calculated by MESA using the mean LMC metallicity of $[\text{Fe}/\text{H}] = -0.42$. The initial mass of the model is $18 M_{\odot}$, with mass loss $2.4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Chernov, 2020). The selected model (black symbol) is consistent with the properties given by Falanga et al. (2015a) within 1σ . The model used for the hydrodynamical simulation performed with FLASH is marked with a turquoise symbol in the panel. At this stage, the donor has overfilled its Roche lobe and its radial scale matches the forward-evolved separation a (dashed line).

primary, as the Roche lobe acts as a size constraint and trigger of mass loss for our models. The models with initial masses of $18 M_{\odot}$ and $19 M_{\odot}$, with mass loss as prescribed by [Chernov \(2020\)](#), are consistent with the properties given by [Falanga et al. \(2015a\)](#) within 1σ , and as the three dimensional hydrodynamical results for both are qualitatively similar, we present those from the $18 M_{\odot}$ model below.

Using the size of the primary’s Roche lobe, we allow the models to lose mass as they approach the end of the main sequence via winds and a radius-limited prescription for Roche lobe overflow. When the model reaches the observed mass and radius constraints (black symbol in Figure 3.2), we mark that model as “today,” then allow the star to continue its evolution while evolving the separation a using the observed $\dot{P}/P$. We then map the resulting “future” model, in which the donor has overfilled its Roche lobe and its radius equals the forward-evolved separation a (turquoise symbol in Figure 3.2), into 3D for the simulation of CE and merger. The reader is referred to Appendix 3.6 for additional details on the interior properties of the stellar companion MESA model.

3.3 Studying the fate of X-ray binary LMC X-4 with hydrodynamical Simulations

3.3.1 FLASH Setup

We map the properties of the MESA profile (density, pressure, temperature, and composition) onto a three dimensional grid using FLASH version 4.32 ([Fryxell et al., 2000a](#)). Our numerical scheme is adapted from [Wu et al. \(2020\)](#), which was originally developed by [Guillochon et al. \(2009\)](#) and [Guillochon and Ramirez-Ruiz \(2013\)](#), and subsequently upgraded by [Law-Smith et al. \(2019\)](#) and [Law-Smith](#)

et al. (2020a,b). The upgraded version uses an extended Helmholtz equation of state (Timmes and Swesty, 2000) to track individual elements as described in Law-Smith et al. (2019) and Wu et al. (2020). The reader is referred to these works for further numerical details. A brief summary including key aspects and alterations to the setup is given below.

To set up the initial model, we first relax the MESA profile in FLASH for a few dynamical timescales. The computational domain is cubic with volume $(60R_{\odot})^3$ and is comprised of an 8^3 block grid with a minimum cell size of $0.02 R_{\odot}$. During the relaxation process, a point mass, representing the NS with $M_{\text{ns}} = 1.57M_{\odot}$, is introduced at $9R_{\odot}$. The primary star has a radial scale $\approx 9.4R_{\odot}$ when it overfills its Roche lobe (Figure 3.2). The NS is initially at rest but its velocity is slowly augmented as the relaxation process ensues until reaching a circular Keplerian velocity. At the time the relaxation finishes, the model of the primary star is in hydrostatic equilibrium and the inspiral trajectory of the NS is calculated self-consistently (Wu et al., 2020). The properties of the merger remnant are found to be rather indifferent to the exact initial conditions of the NS’s velocity, as long as it is close to Keplerian. We stop the simulation after the NS sinks into the center of the primary’s core ($t = 13.8$ hr).

3.3.2 Dynamical Inspiral

Now we turn our attention to LMC X-4 at the onset of CE and beyond. As the engulfment proceeds (from left to right in the top three panels of Figure 3.3), the NS plunges dynamically into the stellar core of the mildly evolved primary star. This steep plunge-in is driven by strong drag forces, which are significantly higher than those predicted by Bondi–Hoyle–Lyttleton accretion theory (Hoyle

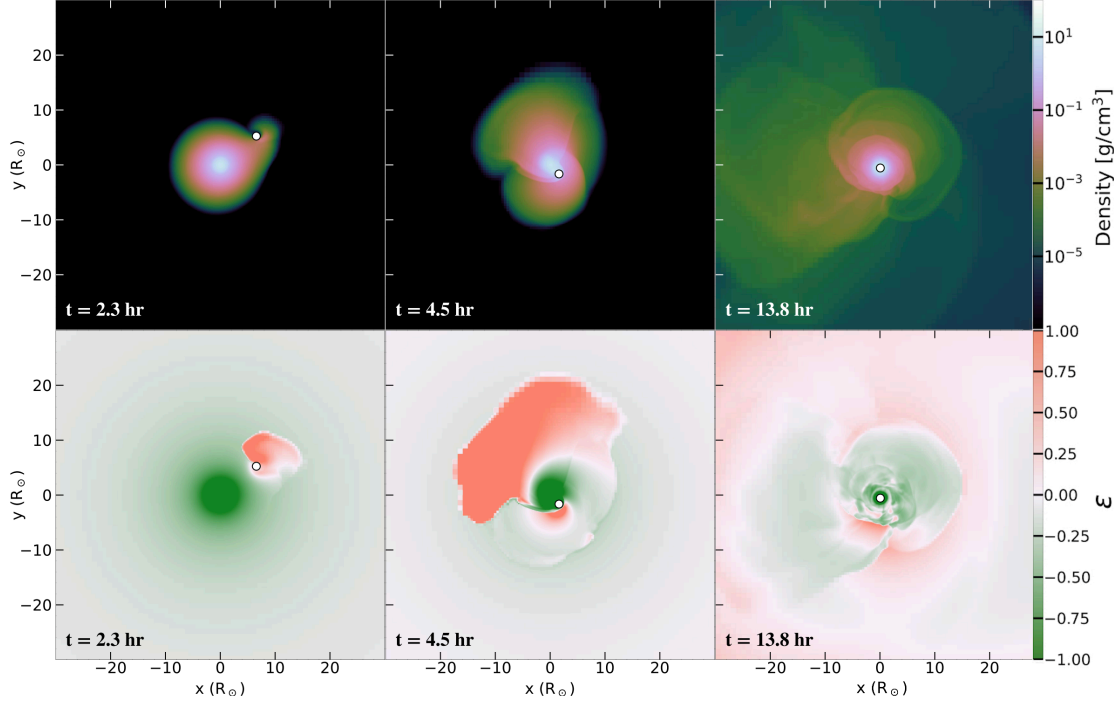


Figure 3.3: Two-dimensional slices across the orbital plane of FLASH simulated inspiral and merger of LMC X-4 at three stages: early in the evolution (2.3 hr), at an intermediate time when the NS enters the stellar core (4.5 hr), and at a late time (13.8 hr) after the NS has settled in the center of the stellar core. *Top panels:* Logarithm of gas density. *Bottom panels:* Sum of specific kinetic and potential energy, $\varepsilon = \varepsilon_{\text{kin}} + \varepsilon_{\text{grav}}$, in units of $10^{16} \text{ cm}^2/\text{s}^2$. The orange region corresponds to unbound material ($\varepsilon > 0$) and the green region corresponds to bound material ($\varepsilon < 0$). Animation available at: <https://tinyurl.com/hydrosims>

and Lyttleton, 1939) when the stellar density gradients are included, as shown by MacLeod and Ramirez-Ruiz (2015a,b), MacLeod et al. (2017a) and Everson et al. (2020). We compare the numerical trajectories with the modified drag predictions presented in MacLeod and Ramirez-Ruiz (2015b) and find rough agreement with the dynamical plunge seen in Figure 3.3.

As can be seen from Figure 3.3, the NS disturbs a non-negligible fraction of the outer stellar envelope during inspiral. It then crosses the core without disrupting it and settles inside the stellar core after about 13.8 hr. As a result of the merger, the NS injects energy and angular momentum (via spiral waves) into the primary and unbinds a small fraction of the envelope material. The bottom panels in Figure 3.3 show specific energy, $\varepsilon = \varepsilon_{\text{kin}} + \varepsilon_{\text{grav}}$ (the sum of specific kinetic and potential energy while the internal energy is not included). The orange region corresponds to unbound material ($\varepsilon > 0$) while the green region corresponds to bound material ($\varepsilon < 0$). At early times, $\varepsilon < 0$ for most cells in the box. At the final time depicted in Figure 3.3, a non-negligible fraction (see Section 5.3.4 for details) of the material in the box (except for the surviving core) has $\varepsilon > 0$. The reader is referred to Figure 3.14 in Appendix 3.6 for a meridional view of the dynamical plunge seen in Figure 3.3. In what follows we engage in a more comprehensive evaluation of the ejection of material during the merger.

3.3.3 Mass Ejection during Merger

Figure 3.4 shows, as a function of the mass coordinate, the binding energy of the envelope and the change in the orbital energy from the start of the inspiral, using the properties of the stellar model that we have selected as the initial condition for the hydrodynamical simulation. This shows the necessary conditions for effective

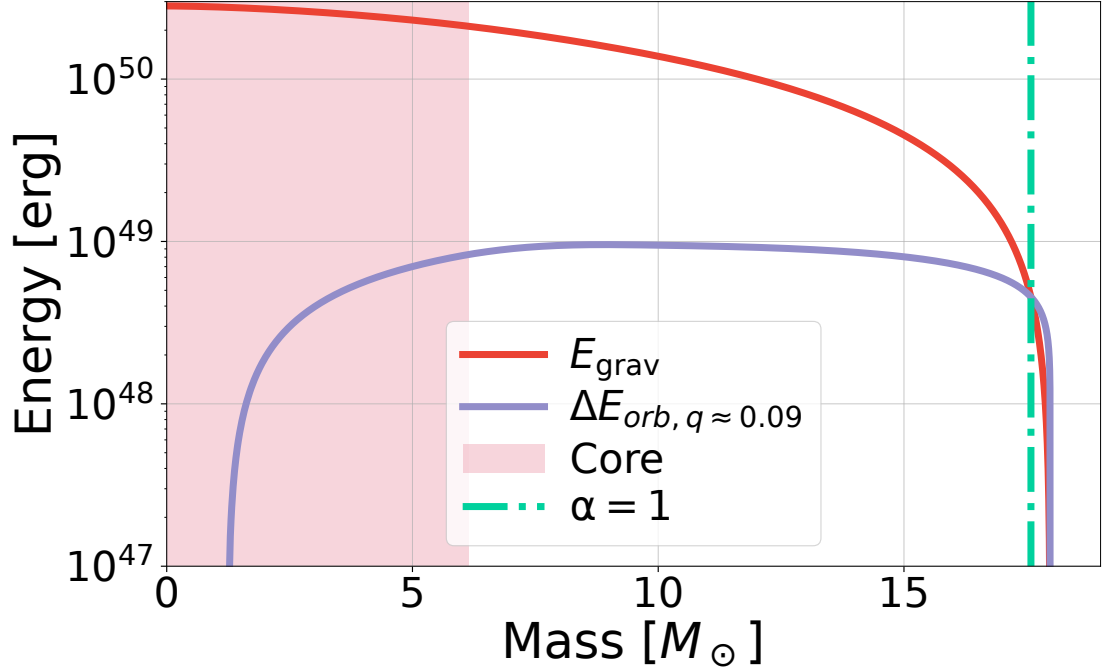


Figure 3.4: Relevant quantities required to estimate envelope unbinding during the merger, which are shown in mass coordinates. The binding energy of the primary’s stellar material exterior to a given mass coordinate (E_{grav} , red line) and the change in orbital energy expected to be dissipated during the inspiral (ΔE_{orb} , purple line) are plotted against the mass coordinate for the model used as the initial condition for the hydrodynamical simulation, with mass $18 M_{\odot}$ and neutron star mass ratio $q \approx 0.09$. The mass coordinate at which the $\alpha = (E_{\text{grav}}/\Delta E_{\text{orb}}) = 1$ condition is satisfied is shown as a vertical dashed line.

envelope ejection, which are expected to be satisfied when the change in orbital energy of the NS, lost through drag during inspiral, is similar to the envelope’s binding energy at a particular mass coordinate, known as the $\alpha = (E_{\text{grav}}/\Delta E_{\text{orb}}) = 1$ condition. The calculations presented in Figure 3.4 predict that the NS would unbind $\approx 0.4 M_{\odot}$ of envelope material. Note that although this calculation is only approximate it allows us to better understand the results of a detailed simulation able to capture the energy sharing during the inspiral process.

Since the orbital energy deposited by the NS through inspiral is less than the gravitational binding energy of the stellar envelope, a merger is an inevitable outcome for LMC X-4. As the NS inspirals, the structure of the envelope internal to the position of the NS will remain fairly unaltered and the orbit of the NS will shrink until it merges with the stellar core.

We first note that the change in orbital energy continues to slightly increase although it remains well below the envelope’s binding energy for the region between the core and the $\alpha = 1$ crossing point. As seen in Figure 3.3, the envelope is shocked and swept preferentially outwards as the NS moves through the envelope of the primary. Basically, the NS acts as a local diffusive energy source term, giving surrounding material roughly outward radial velocities. By the time the engulfed NS reaches the outer edge of the stellar core we find $\approx 1.4 M_{\odot}$ of mass to be unbound in our simulation (Figure 3.5) by summing the mass of the cells with $\varepsilon > 0$ at the $t = 4.5$ hr snapshot of our hydrodynamic simulation. This time is chosen as the moment when the NS reaches the core, and no envelope material has yet been ejected from the computational domain. The velocity vectors of each grid cell that meets this criterion at $t = 4.5$ hr are nearly all pointed radially outwards. The outward radial velocity distribution of the envelope material expelled during the merger episode is shown in Figure 3.5. The distribution shown

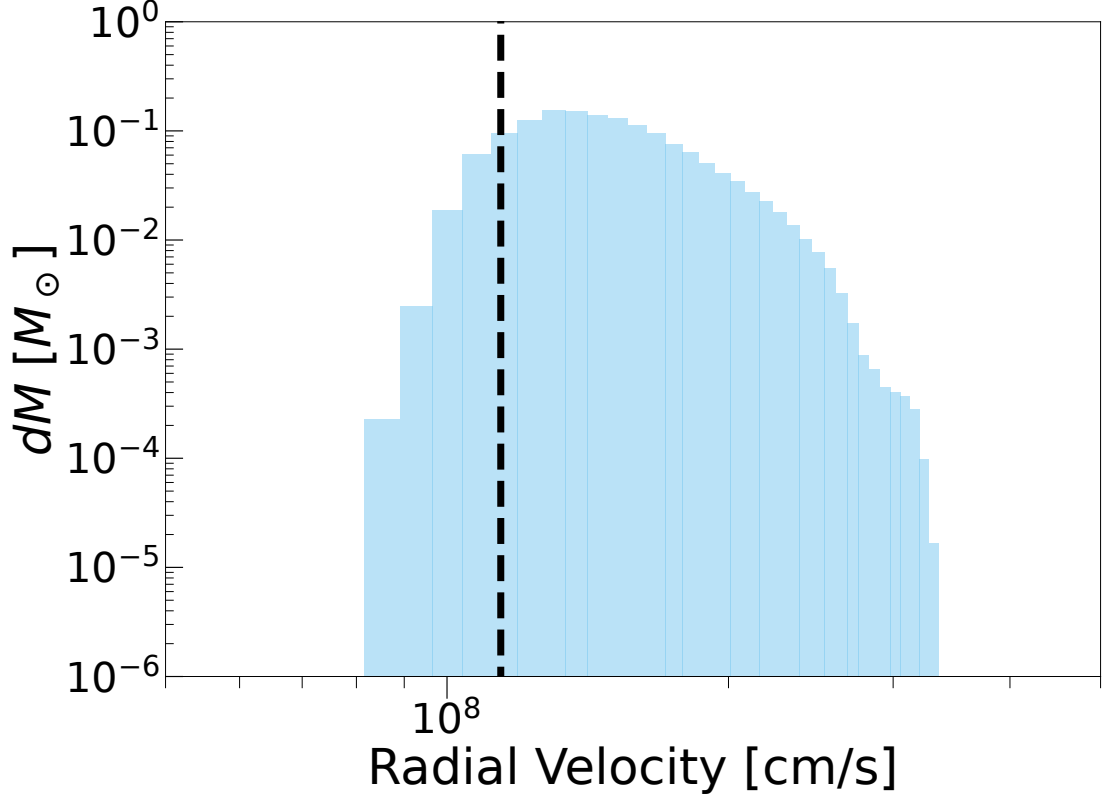


Figure 3.5: The outward radial velocity histogram of the envelope debris expelled during the merger (with a total mass $\approx 1.4M_{\odot}$). This is done by analysing the velocity vectors and masses of each grid cell in the envelope with $\varepsilon > 0$ at $t = 4.5\text{hr}$. Also plotted is the local escape velocity at the $\alpha = 1$ critical radius, which is computed based on the enclosed mass of the initial model (Figure 3.4). This velocity is $v_{\alpha=1} \approx 1140 \text{ km s}^{-1}$ and is shown as a vertical dashed line.

in Figure 3.5 is compared to the the local escape velocity at the $\alpha = 1$ critical radius, $v_{\alpha=1} \approx 1140$ km/s, which is computed based on the enclosed mass of the initial model (Figure 3.4). The deposited energy is not shared efficiently throughout the envelope (MacLeod et al., 2022) as the orbit of the NS shrinks and, as a result, shocks accelerate a non-negligible fraction of the envelope mass to well above the escape velocity.

We conclude that the $\alpha = 1$ condition provides a lower limit to the amount of energy injected into the stellar envelope. Some of the excess energy resides in the thermal energy content stored in the primary star (Fragos et al., 2019), which as the envelope expands, does work. In addition, as the NS continues to sink below the $\alpha = 1$ critical radius, a larger fraction of orbital energy can be injected into the envelope (Wu et al., 2020). As such, we must consider the internal energy (e.g., Fragos et al., 2019), the remaining orbital energy as the NS continues to sink (e.g., Law-Smith et al., 2020b; Wu et al., 2020) and the anisotropic sharing of this energy in the envelope (e.g., MacLeod et al., 2018a) in order to better estimate the properties of the outflow. The outcomes of this study have direct consequences for the efficiency of envelope ejection, which is directly relevant to astronomical transients powered by recombination (e.g., MacLeod et al., 2017b; Schröder et al., 2020).

3.3.4 On the Accretion-fed Growth of the Neutron Star during the Merger Phase

The accretion-fed growth of NSs during CE events has been discussed extensively in the context of successful CE ejection. In these cases, possible outcomes include close binaries comprised of a He-star and a NS, which might leave behind a double

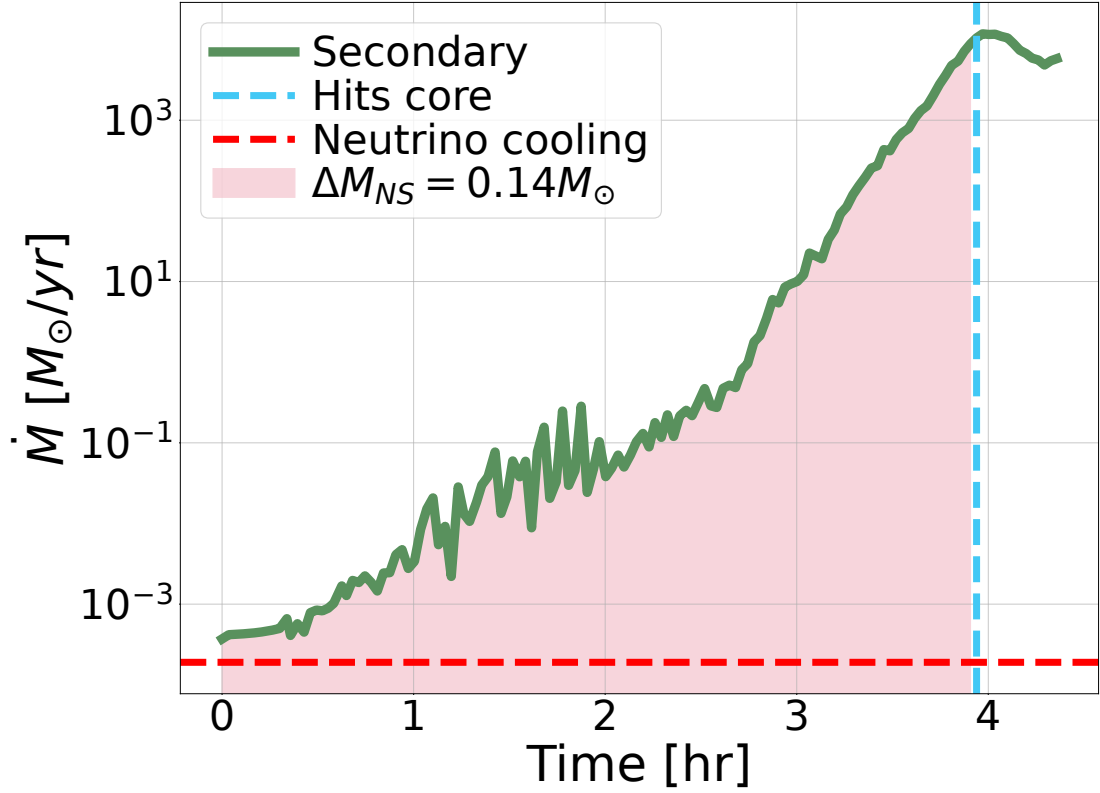


Figure 3.6: Mass accretion rate onto the inspiraling NS as a function of time during the simulation shown in Figure 3.3. In compact primaries, the NS is able to accrete above the limit at which neutrinos are able to provide the main cooling agent (red dashed line). In LMC X-4 the NS is able to gain about $0.14M_\odot$, but remains well below the maximum NS mass until merging with the core (blue dashed line).

NS or NS–BH binary (Postnov and Yungelson, 2014). Accretion onto the NS during this phase was thought to be effectual as neutrinos provide a cooling mechanism (Chevalier, 1993; Fryer et al., 1996; Houck and Chevalier, 1991), suggesting that a NS might undergo accretion-induced collapse to a BH in some, but not all, cases (Bethe and Brown, 1998; Brown, 1995; Chevalier, 1993).

The idea that a NS might be able to grow via accretion during CE is hard to reconcile with the observed distribution of NS masses (e.g., Özel et al., 2012) and, most notably, with those inferred in double NS binaries. These systems show a narrow range of inferred masses centered at $1.33M_\odot$ with dispersion of

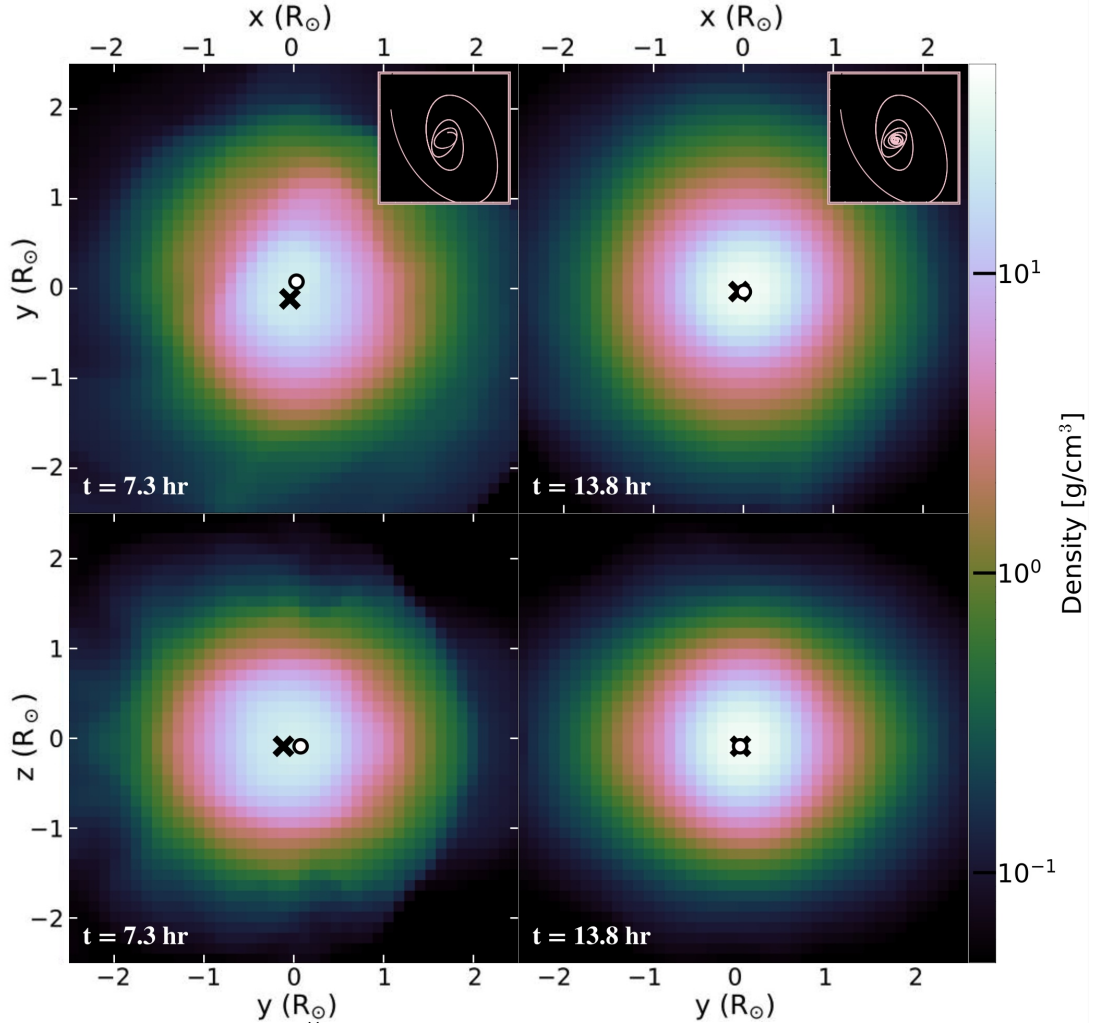


Figure 3.7: Two dimensional slices of the logarithm of gas density at two different times (7.3hr and 13.8hr) for material near the core of the primary. The *top* panels show slices in the orbital plane (y - x) while the *bottom* panels display slices in the meridional plane (y - z). The position of the core's center of mass is denoted by an X mark, while the position of the NS is denoted by a white circle. The evolution of the trajectory of the NS in the orbital plane from the time the NS reaches the core is shown in the respective inset panels with a characteristic height and width of $(4R_\odot)^2$. Animations available at: <https://tinyurl.com/hydrosims>

$0.05M_{\odot}$ (Özel et al., 2012). MacLeod and Ramirez-Ruiz (2015b) demonstrated that the presence of a density gradient in stellar envelopes significantly restricts accretion by imposing a net angular momentum to the flow around the NS, and that embedded NSs should accrete only modest amounts of envelope material. This study presented a clear hydrodynamical solution that successfully explains the narrow mass distribution seen in double NS binaries. This was later confirmed by Law-Smith et al. (2020b) with the use of global hydrodynamical simulations. These studies have been, however, restricted to survival of NSs in successful CE events. Further work is needed to probe the efficiency of accretion in NSs that are unable to eject the envelope and, as a result, merge with the dense core.

We now extend these calculations to consider the accretion history of the NS in LMC X-4. In Figure 3.6 we plot the mass accretion rate onto the inspiraling NS before reaching the core (dashed vertical line). We find that the NS is able to gain about $0.14M_{\odot}$ and the inferred accretion rate across the point mass remains above the neutrino-cooling rate of $\dot{M}_{\nu} \approx 10^4 \dot{M}_{\text{Edd}} \approx 10^{-4} M_{\odot}/\text{yr}$ (Houck and Chevalier, 1991) at which accretion growth can proceed effectively. The results presented in Figure 3.6 are in agreement with the mass accretion rates derived using the formalism of MacLeod and Ramirez-Ruiz (2015b) for this specific progenitor. A limitation of most numerical models is that the accretion rate depends sensitively on the size of the central absorbing sink (e.g., De et al., 2020; Murguía-Berthier et al., 2017a), which implies that the results presented in Figure 3.6 are upper limits. This mass gain, nonetheless, represents a small fractional amount and won't drastically affect the structure of the NS, which will remain well under the maximum mass limit.

3.3.5 Embedded Phase and Merger with the Stellar Core

Here, we take a closer look at the final plunge of the NS and its impact on core structure and final merger. Figure 3.7 provides a zoomed-in view of the stellar core near the end of the inspiral. The relevant quantity fixing the strength of the interaction is $q_c^{1/3} = (M_{\text{NS}}/M_{\text{core}})^{1/3}$ (Everson et al., 2024a) and, as such, we expect the NS to only mildly impact the stellar core. This is because $q_c < 1$, making the extent of the core larger than the tidal radius with respect to the NS (Everson et al., 2024a). Shown in Figure 3.7 are illustrations of the gas density of the primary’s core at two different times, where the *top* panels show slices in the orbital plane (y - x), and the *bottom* panels display slices in the vertical plane (y - z). The two inset panels in Figure 3.7 show the trajectory of the NS in the orbital plane from the moment it reaches the core until the end of the simulation.

The core of the primary spins up due to shocks generated during inspiral, absorbing orbital angular momentum deposited by the NS. If the spin of the core material is lower than that required to form a disk, we can assume quasi-spherical accretion, which is necessary to power a classical TŻO (Everson et al., 2024a). If, on the other hand, the spin of the core is higher than that required to form a disk, significant post-merger accretion feedback is expected to unbind the vast majority of the remaining envelope (Bavera et al., 2020; Murguia-Berthier et al., 2020). The post-merger angular momentum content of the stellar core is thus essential to defining the type of merger product that will result. Motivated by this, our aim in the next section is to discuss the post-merger flow pattern around the NS, involving accretion, rotation, and directional outflow.

3.4 Implications for Thorne–Żytkow Object Formation and Ultra-long Gamma-ray Bursts

We now explore the final outcome of LMC X-4 as informed by our simulations. As a result of the merger, the NS injects energy, mass, and angular momentum into the core of the primary star (Figure 3.3) and unbinds a small amount of envelope material in the process (Figure 3.5). Shocks in the course of the inspiral spin up the core before the NS ultimately settles into the core’s interior (Figure 3.7). LMC X-4 thus naturally evolves into a collapsar-like progenitor system (Fryer and Woosley, 1998). That is, a hyper-accreting NS surrounded by a rotating stellar core.

3.4.1 A Rapidly Rotating Stellar Core Accreting onto a Central Neutron Star

The first task in attempting to construct a general scheme that is able to successfully describe the fates of X-ray binaries such as LMC X-4 is to decide which parameters exert a controlling influence upon their final properties. The mass of the central object is a key parameter, as it dictates a characteristic luminosity scale for the ensuing accretion activity (e.g., Fryer and Woosley, 1998) as well as determining the post-merger properties of the stellar core (Everson et al., 2024a). The total angular momentum of the core may be, however, more important in this regard as it determines whether or not an accretion disk will be formed immediately upon merger.

Figure 3.8 displays the specific angular momentum content in the stellar core, calculated by taking the spherical average about the center of mass of the FLASH

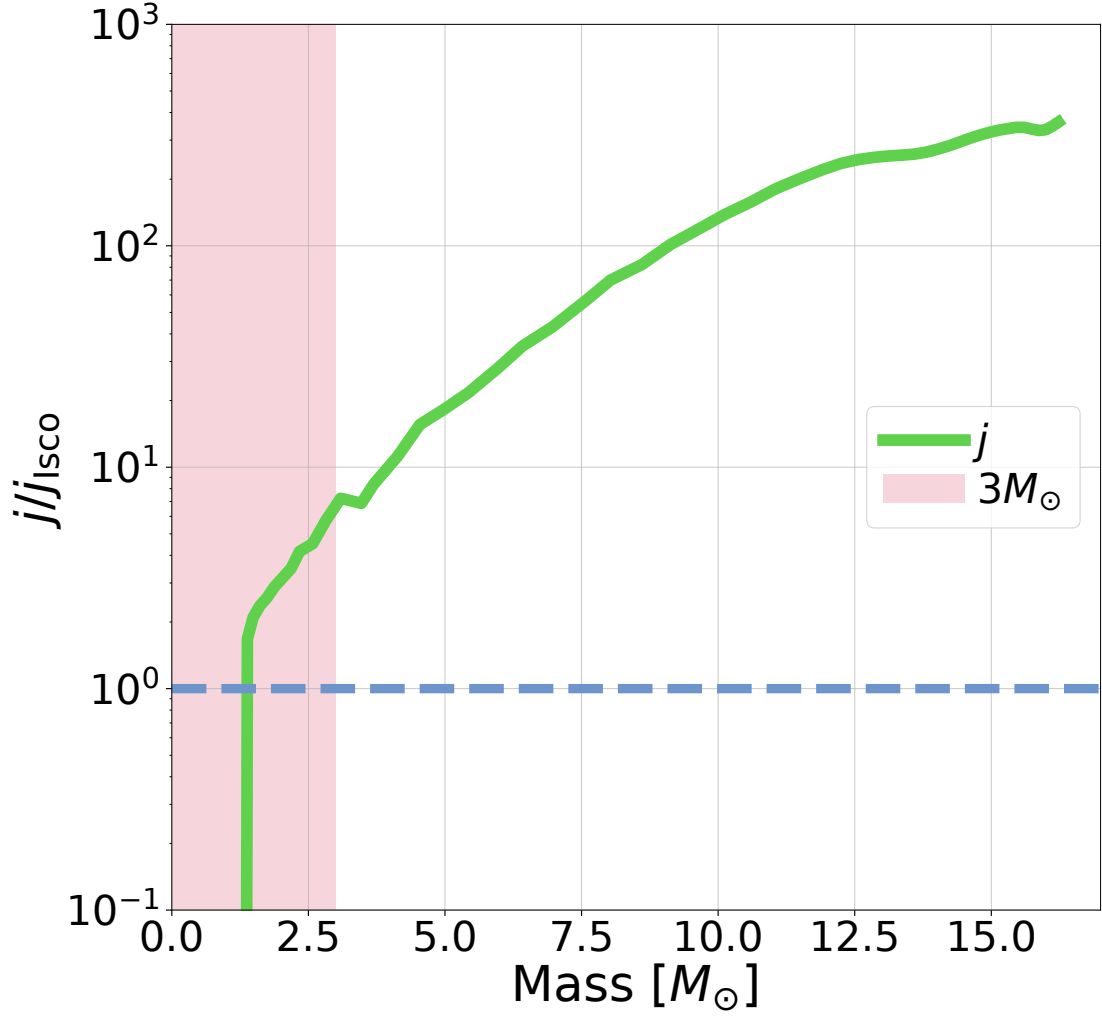


Figure 3.8: The normalized specific angular momentum content j/j_{isco} of the stellar core at the end of the simulation is shown in mass coordinates (green curve). The profile is calculated by taking the spherical average about the center of mass in the FLASH simulation shown in Figure 3.7. Here j_{isco} is the specific angular momentum required for disk formation (dashed vertical line). We note that the simulated stellar model satisfies this condition for disk formation at all radii.

simulation shown in Figure 3.7. The specific angular momentum is shown in units of j_{isco} (Bardeen et al., 1972), the minimum specific angular momentum required for disk formation, and is plotted against the enclosed mass, which includes the NS. As expected, the specific angular momentum is above the critical limits $j/j_{\text{isco}}=1$ at all mass coordinates. We expect a BH to be formed when the NS reaches a mass of about $3M_{\odot}$ (pink shaded region in Figure 3.7). After the inevitable accretion-induced collapse of the NS, the expected outcome would then be a spinning BH surrounded by an accretion disk, which is reminiscent of central engine models for gamma-ray burst (GRB) sources (Aloy et al., 2000; Fryer and Woosley, 1998; Fryer and Heger, 2000; Gehrels et al., 2009; Gottlieb et al., 2022; Lee and Ramirez-Ruiz, 2007; MacFadyen and Woosley, 1999; MacFadyen et al., 2001; Mochkovitch et al., 1993; Rees, 1999; Woosley, 1993).

To calculate the accretion rate history of the accreting BH we follow the framework described in Batta and Ramirez-Ruiz (2019) and Bavera et al. (2020). Following the assumption that a BH is formed from the collapse of the innermost $3M_{\odot}$ of the stellar core, we presume that the rotating in-falling material free falls onto the recently formed BH without any pressure support and without mixing of radial layers. In this formalism the mass distribution $M(r)$ of the stellar core can be envisioned as a collection of shells with mass m_{shell} and angular frequency Ω_{shell} that fall one after the other. Assuming that the disk formed from the collapse of a shell (m_{shell} with $j > j_{\text{isco}}$) is accreted before the next shell collapses, as the viscous accretion timescale of the inner disk is shorter than the dynamical timescale of the collapsing shells, we can calculate the accretion rate onto the BH, while consistently evolving the BH’s mass and spin as material is amassed. The reader is referred to Bavera et al. (2020) for further details.

The resulting mass accretion rate is displayed in Figure 3.9. The peak accretion

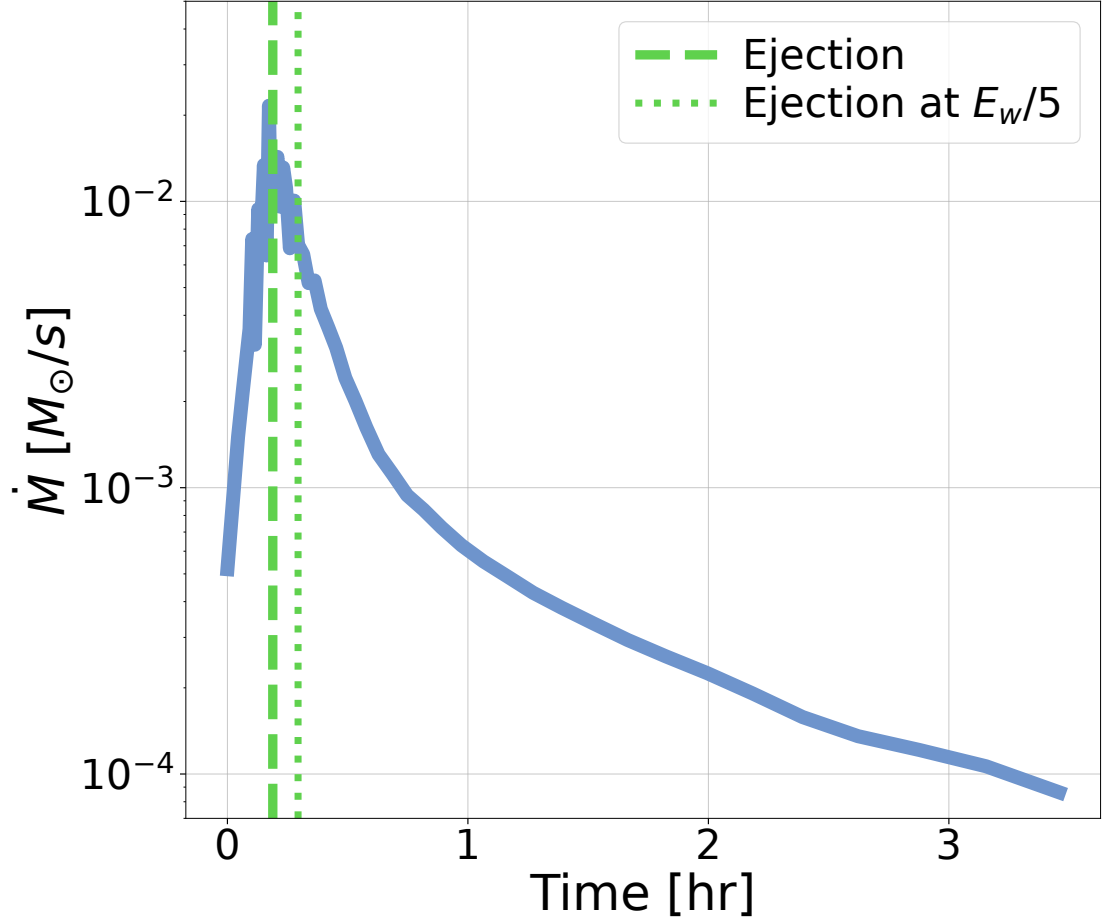


Figure 3.9: The accretion rate onto the newly formed BH as a function of time. The rotating in-falling core material is assumed to free fall without any pressure support and without mixing of radial layers. A disk is presumed to form from the collapse of every infalling shell and then subsequently accreted before the next shell collapses, as described in [Bavera et al. \(2020\)](#). When feedback from the accretion disk is taken into account, we show that it can unbind the infalling material on timescales that are comparable to the peak accretion time. The two ejection timescales shown as vertical lines are introduced in Figure 3.10.

luminosity is, as expected, well below that expected for most collapsar models ($\gtrsim 10^{-1} M_{\odot}/\text{s}$; Fryer and Woosley, 1998; MacFadyen and Woosley, 1999) and the central engine is foreseen to be longer lived than the typical duration of long GRBs ($\approx 20 \text{ s}$; Gehrels et al., 2009). This is expected as the core of the primary star is not highly evolved and thus remains much less compact at the time of collapse.

The accretion activity might be, however, shortened when the feedback energy from the wind’s accretion luminosity is taken into consideration. It has been widely shown that general relativistic, magnetohydrodynamic simulations of accretion disks around rotating BHs (e.g., McKinney et al., 2012) commonly show the development of a magnetized wind outflow, which can introduce energy that can, in this case, be competently shared with the layers of the infalling core. Figure 3.10 shows how the accumulated energy injection from the wind may contribute to envelope ejection as the stellar material infalls and subsequently accretes. The feedback from accretion is assumed to launch a wind that shares energy E_w with the collapsing stellar material with an efficiency of 1% (0.2%). The envelope is expected to be ejected when the integrated energy from the wind is larger than the binding energy of the envelope (see the dashed lines in Figure 3.10). This provides us with a rough idea of the total energy available to unbind the star. The feedback energy from accretion would then stop the collapse and notably abbreviate the duration of the accretion event.

3.4.2 Ultra-long GRBs and Recombination Transients

In this section we present a short summary of what we have learned so far about the fate of LMC X-4. Figure 3.11 presents a schematic montage of the events in the life of the LMC X-4 system. This encourages us to present a preliminary account

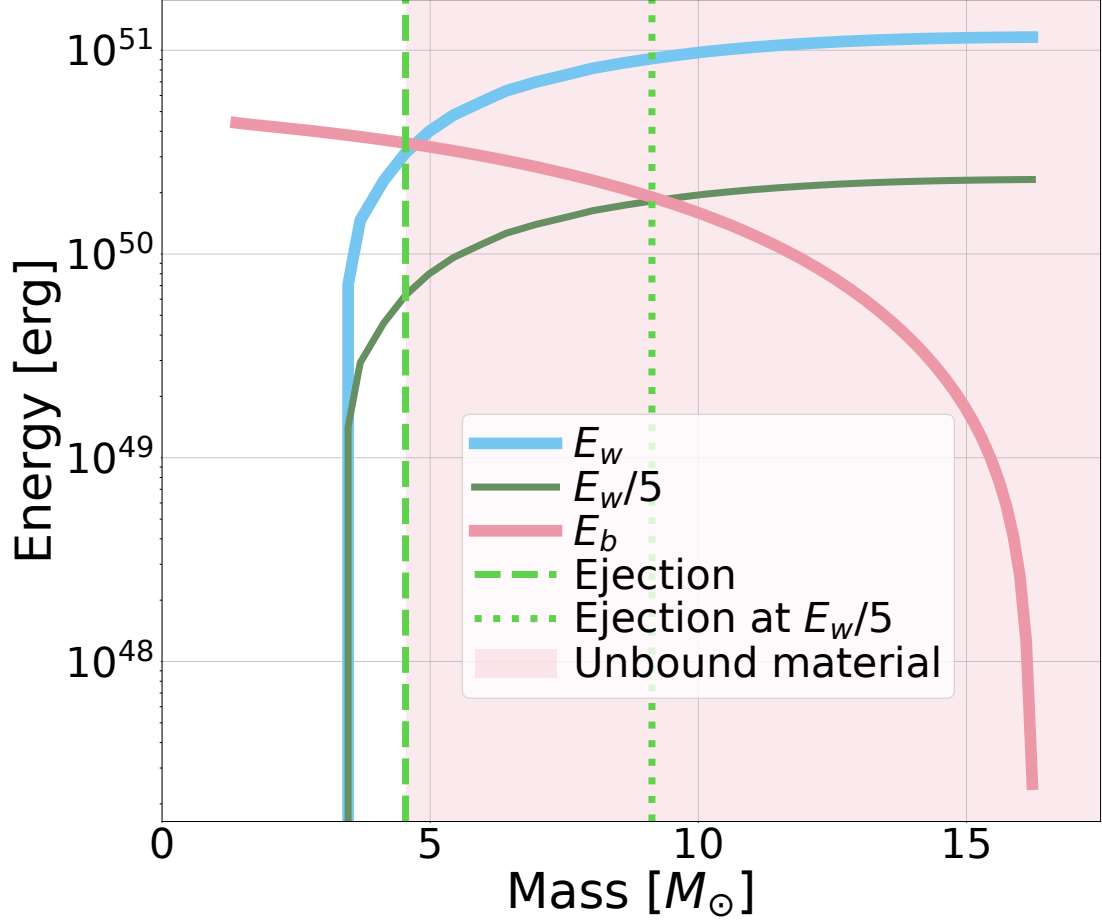


Figure 3.10: Relevant energy scales needed to estimate envelope unbinding during the accretion phase onto the newly formed BH. The binding energy of the rotating collapsing envelope, E_b , exterior to a given mass coordinate (pink) and the integrated wind accretion energy, E_w , expected to be shared with the infalling envelope (blue and dark green) are plotted against the mass coordinate of the post-merger model. The integrated energy required for ejection is uncertain. Here we assume two feedback efficiencies when calculating the fraction of energy that is shared with the collapsing stellar material. These are 1% (blue) and 0.2% (dark green), respectively. The formation of an accretion disk induces feedback, which in turn imposes a limit to the fraction of the star that can collapse and power an accretion event (dashed and dotted vertical lines).

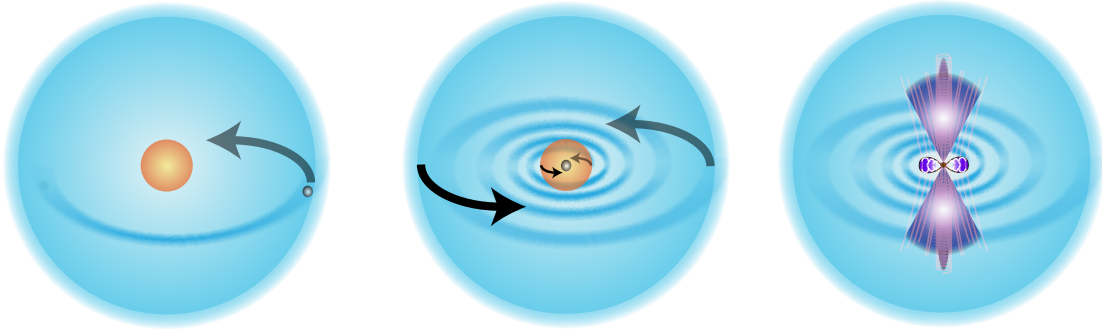


Figure 3.11: Diagram illustrating the post-merger evolution of the LMC X-4 system. After the primary fills its Roche lobe (represented by the blue sphere) and engulfs the NS (represented by the grey sphere), a merger event cannot be avoided (Figure 3.2). As the engulfment proceeds (Figure 3.7), the NS rapidly ($\approx 13.8\text{hr}$) sinks into the core (represented by the orange sphere). As a result, the core spins up due to shocks produced in the course of the inspiral. The further evolution of the rapidly rotating merger product can produce several interesting phenomena. The neutron star is expected to accrete a significant amount of mass to collapse to a BH. The rotating core, as it continues to collapse, will produce an accretion disk (Figure 3.8), which will likely also power and launch a relativistic jet.

of the effects of the ensuing accretion activity onto the central compact object. We also briefly describe the observational prospects for the near future. The NS at the center of the merger remnant quickly accretes a sizable amount of mass and is expected to collapse to a BH. The expected outcome would then be a spinning BH, orbited by a torus of stellar core debris. The binding energy of the orbiting debris and the spin of the BH are the two main energy reservoirs. It has become increasingly conspicuous that most plausible GRB progenitors (e.g., Gehrels et al., 2009; Izzard et al., 2004; Lee and Ramirez-Ruiz, 2007; Murguia-Berthier et al., 2017b; Rees, 1999) are expected to lead to a BH plus debris torus system with the overall energetics mainly determined by the mass and spin of the BH and the different masses left behind in the orbiting debris. This accretion process is expected to power and launch a relativistic jet, which will pierce through the primary star (e.g., Gottlieb et al., 2022; MacFadyen et al., 2001; Ramirez-Ruiz

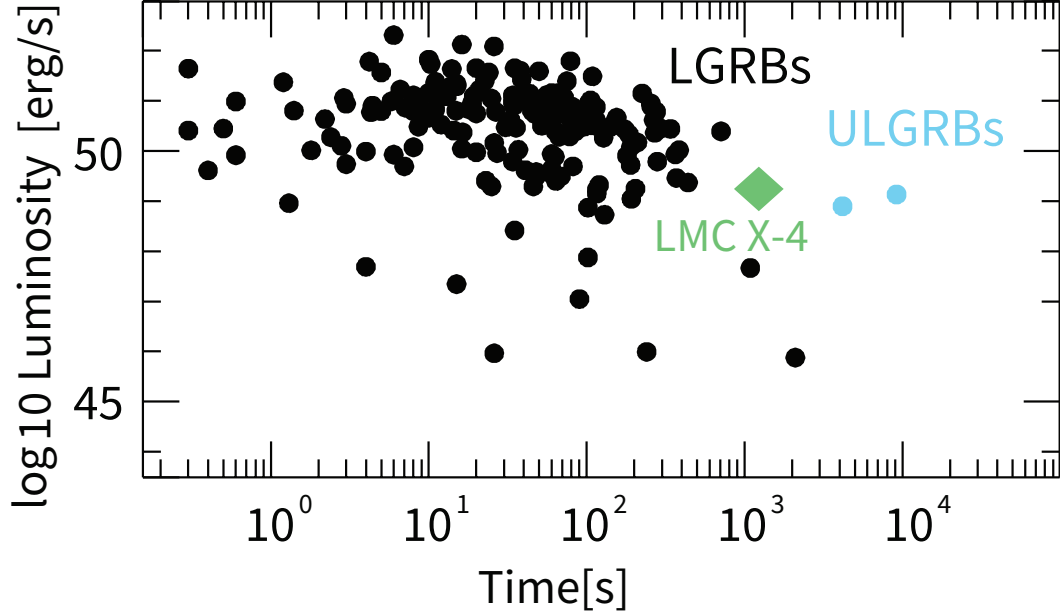


Figure 3.12: Luminosity as a function of the duration of high-energy transients adapted from [Levan et al. \(2014\)](#). For the GRB and ULGRB sources we plot t_{90} as the duration and the peak isotropic luminosity. The duration of the event assumes the ejection timescale determined by accretion feedback in Figure 3.9. The properties of the high-energy transient roughly coincide with those of the emerging class of ultra-long GRBs, such as GRB 101225A, GRB 111209A, and GRB 121027A.

[et al., 2002](#)). Energy dissipation within the jet is expected to produce γ -ray emission, which will eventually be detected as a GRB for on-axis observers.

The expected properties, including luminosities and decay timescales, are consistent with properties of ultra-long GRBs (ULGRBs; e.g., [Levan et al., 2014](#)). These ULGRBs attain peak X-ray luminosities of $\approx 10^{49}$ erg/s, have a duration on the order of a few hours, and have non-thermal spectra evocative of relativistically beamed emission. In Figure 3.12, we plot the peak timescale and luminosity of the high energy transient following the merger of LMC X-4. We calculate the beamed

luminosity of the jetted transient by assuming it traces the mass supply onto the BH, $L \propto \dot{M}c^2$ (Figure 3.9). We also assume that 1% of the accretion luminosity goes into high-energy radiation. It is thus enticing to identify ultra-long GRBs with the remarkable merger of a compact object and its stellar companion, with a small fraction of accretion energy going into a jetted outflow. This could be the less extreme example of a collapsar progenitor (MacFadyen and Woosley, 1999; Woosley, 1993).

A potential impediment for such relativistic outflows is the amount of entrained baryonic mass from the surrounding environment. In GRB models, high neutrino fluxes are capable of ablating baryonic mass from the surface of the disk at a rate $\dot{M}_{\text{wind}} \propto L_\nu^{5/3}$ (Qian and Woosley, 1996). Here L_ν is the neutrino luminosity, which, in turn, is expected to decrease with the mass accretion rate. Assuming that the poloidal field strength is restricted by the vigor of the convective motions, the magnetic luminosity scales as $L_{\text{wind}} \propto B^2 \propto L_\nu^{2/3}$ (Lee and Ramirez-Ruiz, 2007). As a result, the limiting bulk Lorentz factor of the outflow, $\Gamma \approx L_{\text{wind}}/(\dot{M}_{\text{wind}}c^2)$, decreases as L_ν^{-1} for neutrino-dominated accretion disks (Narayan et al., 2001). This reveals that the entrained baryonic mass is expected to be less severe in TZO than GRB environments.

If we were to venture a general classification scheme for the fate of HMXBs, on the hypothesis that the central engine involves a BH formed in the collapse of post-merger stellar cores (Everson et al., 2024a), we would surely expect the mass of the BH, the rate at which the gas is supplied to the BH (which will depend on the mass and evolutionary state of the primary star), the spin of the BH, and the orientation relative to our line of sight to all be essential parameters. For off-axis observers, we expect the mass ejected from the merger and the ensuing feedback to power an optical or infrared transient as it expands and becomes transparent

(Ivanova et al., 2013b; MacLeod et al., 2017b; Metzger et al., 2012; Soker and Tylenda, 2006). The detection of this post-merger transient would offer direct constraints on the properties of the outflow such as the total mass and velocity distribution. We expect that the ensuing accretion feedback, which will likely halt accretion, would help unbind most of the stellar envelope and thus produce a much brighter recombination transient than the one expected from the outflow conditions shown in Figure 3.5.

3.4.3 Previously discussed transients arising from TZO

Although some of the features discussed in § 3.4.2 were anticipated by previous theoretical discussions, the development and use of hydrodynamical simulations for modeling CE has allowed us to make an accurate determination of the total angular momentum content of the core, which we have robustly confirmed with analytical calculations (Everson et al., 2024a). We uncover here that the NS ends up being surrounded by dense core material with significant rotational support to power a long-lived accretion transient, with features that are evocative of GRB progenitors.

In a pioneering study, Chevalier (2012), motivated by the calculations of Fryer and Woosley (1998) in relation to the merger between a BH and a massive Helium star, postulated that CE events involving BHs or NSs could power strong explosions. The ensuing explosion, envisioned to be powered by mass accretion onto the compact object, is expected to easily unbind the entire envelope. In this scenario, the interaction of the rapidly moving envelope with the mass lost during the initial CE phase is predicted to produce a type IIn supernova. This scenario was thoughtfully extended by Schröder et al. (2020). They used radiative transfer

models of blast waves interacting with the CE ejecta in order to calculate the accompanying light curves. In both of these studies, the explosion driven by the coalescence of the compact object with the companion’s core was parameterized using straightforward energetic arguments and assumed to be shared roughly spherically with the envelope.

Another relevant study explored the fate of TŽOs with massive envelopes (Moriya, 2018), which are expected to be supported by nuclear reactions (Cannon, 1993). Moriya (2018)’s study examined the collapse of a TŽO after the star effectively runs out of fuel, as originally envisioned by Podsiadlowski et al. (1995). Moriya (2018) calculated the mass accretion onto the NS and concluded that a collapse to a BH was likely to occur. The consequences of this scenario depend sensitively on the angular momentum content of the envelope, which is assumed to be quasi-spherical (Podsiadlowski et al., 1995) and only likely to form a disk days after collapse (Moriya, 2018). Even in the most optimistic conditions (i.e., assuming prompt disk formation), the collapse of a hydrostatic TŽO is expected to power a transient with corresponding mass accretion rates $\lesssim 10^{-7} M_{\odot}/\text{s}$. As such, the luminosity of these transients are expected to be at least five orders of magnitude dimmer than those discussed in § 3.4.2 (Figure 3.9). Yet, they should be a natural end state in the evolution of quasi-static TŽOs.

3.4.4 Thin-envelope TŽOs

After nearly all of the stellar envelope has been unbound and ejected by the nascent BH, for systems with compact primaries such as LMC X-4, an alternative type of steady-state merger product may be possible: the thin-envelope TŽO (TETŽO) as proposed by Everson et al. (2024a). The TETŽO is comprised of a central

BH accreting via disk surrounded by a diffuse, radiation supported, remnant envelope with $\lesssim 1\%$ of the envelope’s initial mass, that is powered by the BH’s accretion luminosity. The TETŻO is not unlike the classical TŻO, though rather than presenting similarly to a star in the optical bands, these would present as ultra-luminous X-ray sources with a lifetime of $\approx 10^4$ yrs (Everson et al., 2024a).

Thus, the fate of LMC X-4 is unlikely to lead to a configuration as a TŻO due to the effects of rotation as described above, but if any envelope remains after the series of transient events initiated by the merger, this and other close HMXBs may end their lives as something not altogether different from what Thorne & Żytkow envisioned nearly 50 years ago.

3.5 Summary

In this paper we investigate the long-term fate of high mass X-ray binaries with the objective of understanding whether a TŻO might be ultimately assembled. We present the results from a 3D hydrodynamical simulation aimed at studying the fate of LMC X-4, a tight high mass X-ray binary system, after the primary star fills its Roche lobe and engulfs the NS companion (Figure 3.11). The salient findings of this work are:

1. The NS, as a consequence of the merger, injects energy, mass, and angular momentum into the core of the primary star (Figure 3.3). Spiral shocks during the merger spin up the core of the primary star before the NS eventually settles into the core’s interior (Figure 3.7). LMC X-4 thus plainly develops into a hyper-accreting NS surrounded by a rotating stellar core, similar to a collapsar-like progenitor system (Figure 3.8).

2. The inspiraling NS, upon merging with the core, can accrete efficiently at high rates (Figure 3.9), subsequently collapsing into a BH. This accretion process is expected to power and launch a relativistic jet, which will pierce through the envelope of the primary star and trigger a bright transient with a luminosity and duration typical of an ultra-long GRB (Figure 3.12). Such high-energy transients can be uncovered by observers along the jet axis.
3. Significant post-merger accretion feedback will unavoidably unbind the vast majority of the surrounding envelope, powering an optical or infrared transient as the material expands, recombines and becomes transparent. The detection of this transient, which will be available to observers at all directions, would offer direct constraints on the conditions and flow properties of this highly uncertain phase of high-mass X-ray binary evolution.
4. After most of the stellar envelope is ejected by the newly formed BH, we expect a thin-envelope TŻO to form, as predicted by [Everson et al. \(2024a\)](#). This short-lived source ($\approx 10^4$ yrs) will manifest as an ultra-luminous X-ray source. As such, the canonical framework for TŻO formation via common envelope evolution needs to be revisited. This is due to the fact that the post-merger angular momentum content of the material is, for all merging binaries ([Everson et al., 2024a](#)), high enough to break spherical symmetry and produce a centrifugally supported accretion disk.

3.6 Supplementary details on the initial stellar model and global simulations

In Figure 3.2 we plot the evolution of the stellar surface for the $18M_{\odot}$ stellar companion in LMC X-4, as calculated by MESA using the mean LMC metallicity of $[\text{Fe}/\text{H}]=-0.42$, from “today” to “CE onset”. In Figure 3.13 we show the convective velocity according to mixing length theory, the specific nuclear energy generation rate and the H and He mass-fraction profiles as a function of the radial coordinate. The MESA model corresponding to the primary’s structure today (left panel) has a convective core mass of $7.9 M_{\odot}$ and a radius of $1.5 R_{\odot}$, consistent with Falanga et al. (2015a)’s 1σ observational constraints. At the time of CE onset (right panel), the MESA model’s convective core has a mass of $6.2 M_{\odot}$ and radius of $1.3 R_{\odot}$. The radial coordinate at which the $\alpha = (E_{\text{grav}}/\Delta E_{\text{orb}}) = 1$ condition is satisfied is shown as a vertical dashed line in the right panel of Figure 3.13.

When the system enters into a CE phase, the stellar companion has a luminosity of $6.8 \times 10^4 L_{\odot}$. Shortly after, the NS is found to be completely engulfed within the companion’s non-convective envelope. Owing to gas drag, the NS will spiral towards the companion’s core. We follow the global hydrodynamic evolution from CE onset up to the NS settling into the stellar core in our FLASH simulation. Figures 3.3 and 3.14 show the NS spiral-in phase in both the orbital and meridional planes, respectively. Chevalier (1993, 1996) argued that steady-state TŻOs may not be able to form since, during the spiral-in phase, accretion onto the NS is likely to occur in the neutrino-dominated regime rather than the widely discussed Eddington-limited regime. In Appendix 3.7 that follows we explore this assertion and investigate the applicability of the known hydrostatic solutions.

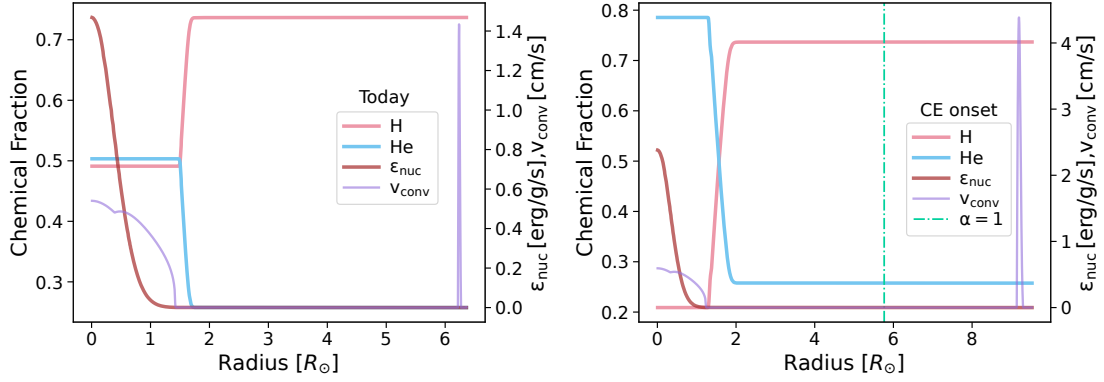


Figure 3.13: Stellar structure profiles for the $18 M_{\odot}$ MESA model presented in Figure 3.2. Plotted are the specific nuclear energy generation rate (in units of $10^5 \text{ erg g}^{-1} \text{ s}^{-1}$), the convective velocity according to mixing length theory (in units of 10^5 cm s^{-1}), and the H and He mass-fraction profiles as a function of radial coordinate. The left and right panels show the interior properties of the companion as inferred “today” by Falanga et al. (2015a) and at the time of mapping into the FLASH simulation, respectively. The radial coordinate at which the $\alpha = 1$ condition is satisfied is shown as a green vertical dashed line in the right panel.

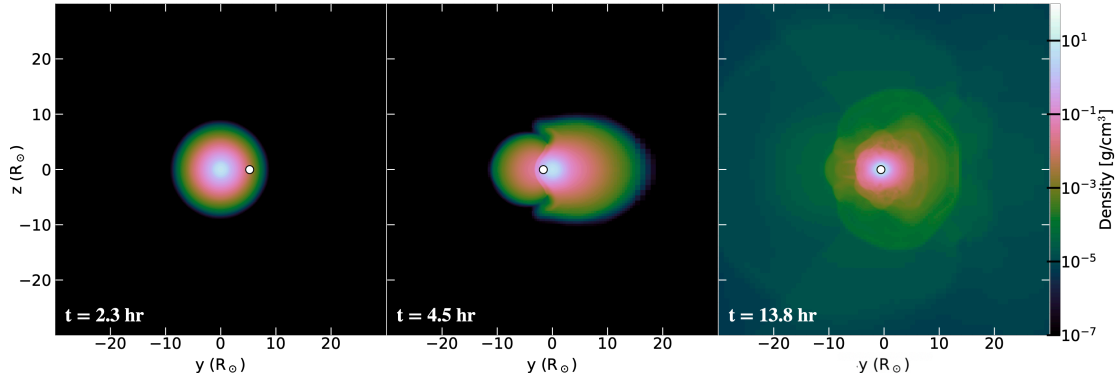


Figure 3.14: Two dimensional slices of the logarithm of gas density in the meridional plane (y - z) at three different times during the spiral-in phase (2.3hr, 4.5hr and 13.8hr). The upper panels in Figure 3.3 show the corresponding density slices in the orbital plane (y - x). Animations available at: <https://tinyurl.com/hydrosims>

3.7 On the applicability of equilibrium TŻO solutions

HMXB LMC X-4 consists of a NS orbiting a O8 III companion star with $L \approx 5 \times 10^4 L_\odot$ in a 1.4 day orbit (Falanga et al., 2015a). LMC X-4 has a characteristic X-ray luminosity of $L_x \approx 2 \times 10^{38} \text{ erg s}^{-1} \approx 10^5 L_\odot$, close to the Eddington limit for neutron stars. When the massive stellar companion completely fills its Roche lobe (Figure 3.2), the mass-transfer rate onto the neutron star will exceed the Eddington limit ($\approx 10^{-8} M_\odot/\text{yr}$) by several orders of magnitude. Unless the majority of the energy goes into neutrinos, the neutron star will not be able to accrete most of the transferred mass, such that the excess mass will form a quasi-hydrostatic structure around the NS (Chevalier, 1993).

There are two main difficulties to reach the classical equilibrium solutions initially envisioned by Thorne and Żytkow (1977) and Cannon (1993). First, the motion of the NS through the envelope will sweep away any equilibrium structure that might form around the NS. Second, as the NS sinks into the stellar core, the mass accretion is expected to increase much faster than the time it takes hydrostatic equilibrium to be attained. Not to mention that the mass accretion rate will unavoidably exceed $10^1 M_\odot/\text{yr}$ (Figure 3.6) and, under these circumstances, rapid accretion with significant neutrino losses can not be prevented (Chevalier, 1996; Fryer et al., 1996). Be that as it may, we note as a caveat that a self-consistent calculation of the formation of a TŻO has not been performed, in particular at accretion rates between the Eddington limit, $\dot{M}_{\text{Edd}} \approx 10^{-8} M_\odot/\text{yr}$, and the neutrino-cooling limit $\dot{M}_\nu \approx 10^4 \dot{M}_{\text{Edd}} \approx 10^{-4} M_\odot/\text{yr}$ (Houck and Chevalier, 1991). In what follows, we show that the formation of TŻOs during CE considerably

bridges this luminosity gap.

Two types of hydrostatic TŻO solutions arise based on the type of energy source at the base of the compact core. For TŻOs embedded in moderately massive envelopes, the main energy source is thought to be limited by the self-regulatory balance between gravity and radiation pressure (Cannon, 1993). In more massive envelopes, the generation of $e^- - e^+$ pairs results in a reduction of the Eddington limit, and the luminosity necessary to satisfy stability must therefore be made up by nuclear reactions (Biehle, 1991, 1994; Cannon, 1993). There is a gap in luminosity between the two types of solutions.¹ Envelopes supported by accretion have luminosities between $10^4 - 5 \times 10^4 L_\odot$ while envelopes supported by nuclear reactions attain luminosities very close to $10^5 L_\odot$.

Figure 3.15 show how temperature varies with density at the base of a given steady state TŻO solution as calculated by Cannon (1993). For these cases, the luminosity and temperature are connected simply through the reaction rates. The steady-burning phase in this regime is expected to be terminated when the supply of seed elements is exhausted and the rp-process becomes inefficient. This depends strongly on convection, which is rather uncertain under these conditions. It is, however, expected that as the accretion rate increases by orders of magnitude above the Eddington rate, a radiative zone is likely to develop at the base of the envelope and the supply of fuel to the burning region is expected to be cut off (Chevalier, 1996; Fryer et al., 1996).

As the mass accretion rate continues to increase, the core region progressively heats up until neutrino losses become the dominant energy mechanism, and neutrino runaway becomes inescapable (Houck and Chevalier, 1991). In Figure 3.15 we

¹We note that Farmer et al. (2023) neglected energy generation by nuclear heating in their static TŻO models.

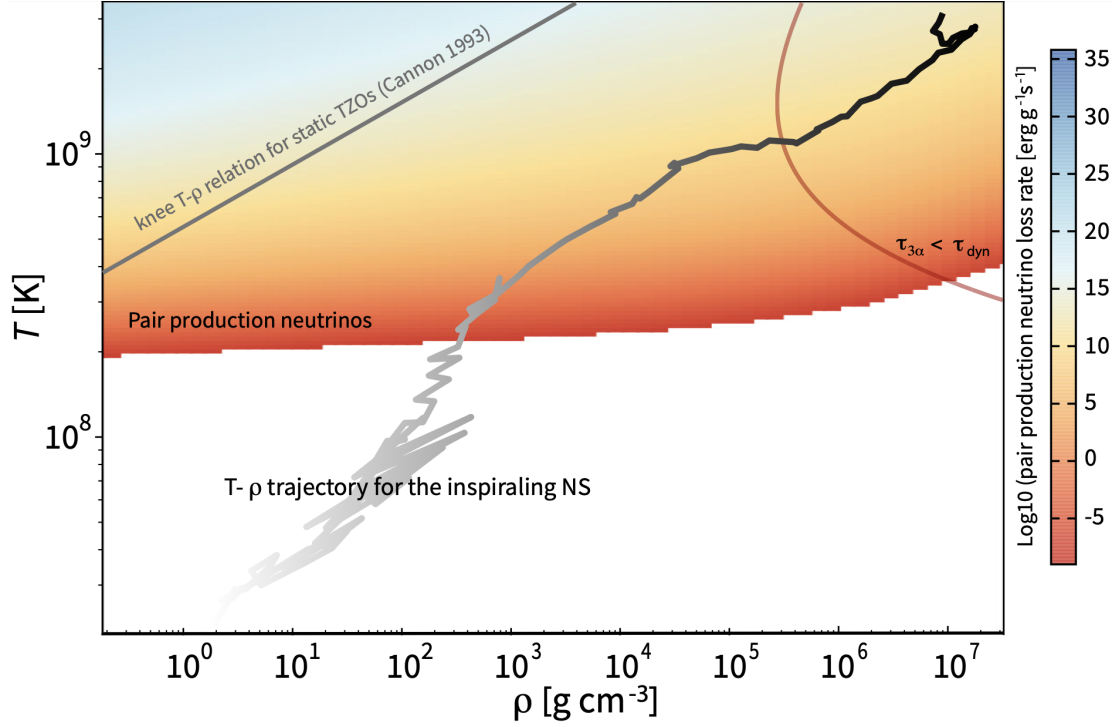


Figure 3.15: ρ – T parameter space relevant to TZO hydrostatic solutions and the spiral-in phase of a NS during CE. The grey line shows how temperature varies with density at the base of static TZO solutions (Cannon, 1993). The spiral-in trajectory starts at comparatively low temperature and less dense material (lower corner) and becomes hotter and denser (upper corner) as the NS sinks into the core. The neutrino emission is dominated by electron-positron pair production process, which are computed for solar metallicity material according to the fit formulae of Itoh et al. (1996).

show the thermodynamic properties along the spiral-in trajectory of the NS, as inferred using our global hydrodynamical calculations. The $\rho - T$ conditions at the point-mass accretion boundary ($\approx 0.1R_\odot$), which is significantly smaller than the gravitational radius, are extrapolated to the NS surface using the analytical solutions derived by [Chevalier \(1996\)](#). The NS spiral-in trajectory begins, as expected, at significantly higher densities than the ones supported by the steady state TŻO solutions. The temperature and density at the start of the spiral-in phase are near the limit in which pair emissivity dominates the neutrino emission.² As soon as the accretion rate reaches $\gtrsim 10^{-1}M_\odot/\text{yr}$, neutrino runaway becomes inescapable. This is observed to take place at around 2.3h (Figures 3.3 and 3.14). In brief, the considerations given here show that even during the spiral-in phase, the TŻO equilibrium conditions are difficult to reach. Once the NS settles into the core and collapse ensues, the corresponding accretion rates are reminiscent of those expected to take place in gamma-ray burst progenitor systems ([Fryer et al., 1999b](#); [Popham et al., 1999](#)).

Figure 3.15, also presents the $\rho - T$ parameter space relevant to He ignition. This is particularly relevant when the NS enters the companion’s core region. In this region, the timescale on which the He material can react, $\tau_{\text{dyn}} = (G\rho)^{-1/2}$, starts being comparable to the burning timescale ([Khokhlov and Ergma, 1986](#)) and the material can not expand swiftly enough to quench burning ([Holcomb et al., 2013](#); [Rosswog et al., 2009](#)). The fate of the envelope material is mainly governed by the competition between dynamical nuclear heating and neutrino cooling ([Rosswog et al., 2008](#)). This regime was initially explored by [Fryer et al. \(1999a\)](#) and more recently by [Fernández and Metzger \(2013\)](#). The broad implication is that the

²The neutrino emission is computed for solar metallicity material according to the fit formulae of [Itoh et al. \(1996\)](#) as coded by F. Timmes: <https://cococubed.com/>

energy associated with dynamical burning is not expected to prevent the NS merging with the companion's core or to significantly alter the accretion flow during the collapse of the companion's core onto the NS (MacFadyen et al., 2001).

As we have described here, our rationalization of the principal physical considerations of the formation of TŻOs via CE evolution combines some generally accepted features with some more speculative physical ingredients. What is more valuable, though considerably harder to achieve, is to refine models like the one presented here to the point of resolving the properties of the flow near the accreting NS. What we can hope of our current modeling is that it will help us in this endeavor.

Chapter 4

Thin-Envelope Thorne–Żytkow Objects: A New Evolutionary Paradigm

4.1 Introduction

As discussed previously, a Thorne–Żytkow object (TŻO) is a speculative stellar merger product originally proposed by [Thorne and Żytkow \(1975\)](#) and further developed by [Thorne and Żytkow \(1977\)](#), consisting of a compact object embedded within the center of a massive star. Classical Thorne–Żytkow objects were originally envisioned as stars containing an accreting neutron star or black hole at their centers, where accretion rather than nuclear fusion provides the dominant energy source. In the classical TŻO framework, the compact object accretes approximately spherically from the surrounding stellar material. Unlike ordinary stars, which are primarily powered by nuclear fusion, red giant TŻOs are expected to be supported largely by accretion energy, whereas supergiant TŻOs may instead derive most

of their luminosity from nuclear burning near the base of the convective envelope (Cannon et al., 1992), with accretion acting as a secondary energy source (Thorne and Żytkow, 1975).

Since their original conception, TŻOs have received renewed attention owing to both observational and theoretical developments. Proposed formation channels include CE mergers in isolated binaries (Podsiadlowski et al., 1995), supernova-kick-induced collisions (Hirai and Podsiadlowski, 2022), and dynamical interactions in dense stellar environments (see Everson et al., 2024a, for a review and detailed references). Among these, CE mergers between a compact object and an evolved stellar companion have long been regarded as one of the most promising pathways because they naturally produce compact object–core mergers within extended stellar envelopes and are expected to occur at appreciable rates (Podsiadlowski et al., 1995). However, the classical TŻO picture contains an important inconsistency. The foundational equilibrium models assume a nearly non-rotating, quasi-spherical accretion flow surrounding the embedded compact object, yet CE inspiral is inherently a highly dynamical and rotational process. As discussed in §3.4 and illustrated in Figure 3.8, orbital decay, shocks, and hydrodynamic torques deposit substantial angular momentum into both the envelope and the stellar core. Even modest post-merger rotation can strongly alter the structure of the remnant, breaking spherical symmetry and favoring the formation of a centrifugally supported accretion disk rather than sustained spherical accretion.

These results suggest that the post-merger evolution of CE systems may differ fundamentally from the canonical steady-state TŻO paradigm. Instead of producing a long-lived, spherically accreting compact object embedded within a massive envelope, the merger remnant may undergo rapid disk accretion accompanied by energetic feedback capable of ejecting a substantial fraction of the surrounding

envelope. In this picture, the merger may power high-energy transients such as ultra-long gamma-ray bursts while simultaneously producing a lower-energy red transient associated with envelope ejection. This motivates a broader investigation of angular momentum transport and post-merger accretion physics across the CE merger population, while also providing a natural framework for placing the hydrodynamical results from Chapter 3 into the broader context of TŻO formation theory. Building on the simulations presented above, the following sections explore how rotational support constrains the formation of classical TŻOs and examine alternative outcomes, including thin-envelope Thorne–Żytkow objects (TETŻOs).

4.2 Common Envelope Merger Outcomes: Black Holes versus Neutron Stars

To place the results from Chapter 3 within the broader population of CE interactions, it is necessary to determine which systems successfully eject their envelopes and survive the CE phase, and which instead proceed toward compact object–core mergers. Among the merger systems, an additional distinction must be made between cases in which the stellar core is disrupted and those in which it remains intact. This distinction is particularly important because systems that retain an intact core may provide the conditions necessary for quasi-spherical accretion and therefore represent the most promising progenitors of classical TŻOs.

Figure 4.1 reproduces Figure 1 from [Everson et al. \(2024a\)](#) and illustrates a landscape of MESA models spanning a range of stellar masses and radii, organized according to three distinct CE interaction outcomes: successful CE ejection (beige), mergers with core disruption (brown), and mergers in which the core remains

intact (coral). All stellar models assume solar metallicity and span masses from 5 to $40 M_{\odot}$. The left panel shows systems with a neutron star (NS) companion, while the right panel shows systems with a black hole (BH) companion. In both panels, the white star marks the forward-evolved LMC X-4 stellar model discussed in Chapter 3. The NS panel adopts the observed companion mass of $1.57 M_{\odot}$, while the BH panel assumes a companion mass of $6.6 M_{\odot}$.

Mapping these interaction outcomes across parameter space makes it possible to identify the regions most favorable for classical TŻO formation and to place the LMC X-4 progenitor model within the broader population of CE merger systems. The models also trace bottom-to-top evolutionary tracks as stellar radii increase during post-main-sequence evolution, accompanied by a slight leftward shift resulting from wind-driven mass loss.

To understand the outcomes shown in Figure 4.1, it is first necessary to describe the onset and evolution of the CE phase. During its evolution, the evolved star, hereafter referred to as the primary, expands until it eventually fills its Roche lobe, initiating mass transfer onto the compact object companion, hereafter referred to as the secondary. As the mass transfer becomes dynamically unstable, the secondary is engulfed within the primary’s envelope and the CE phase begins. The secondary then inspirals through the envelope while experiencing drag forces that extract orbital energy and angular momentum, driving continued orbital decay. As the orbit shrinks, the released orbital energy is deposited into the surrounding envelope, playing a central role in determining whether the envelope can ultimately be unbound.

The subsequent evolution generally leads to one of two outcomes: successful envelope ejection or merger with the stellar core. The α -formalism provides a useful first-order approximation for distinguishing systems expected to survive the

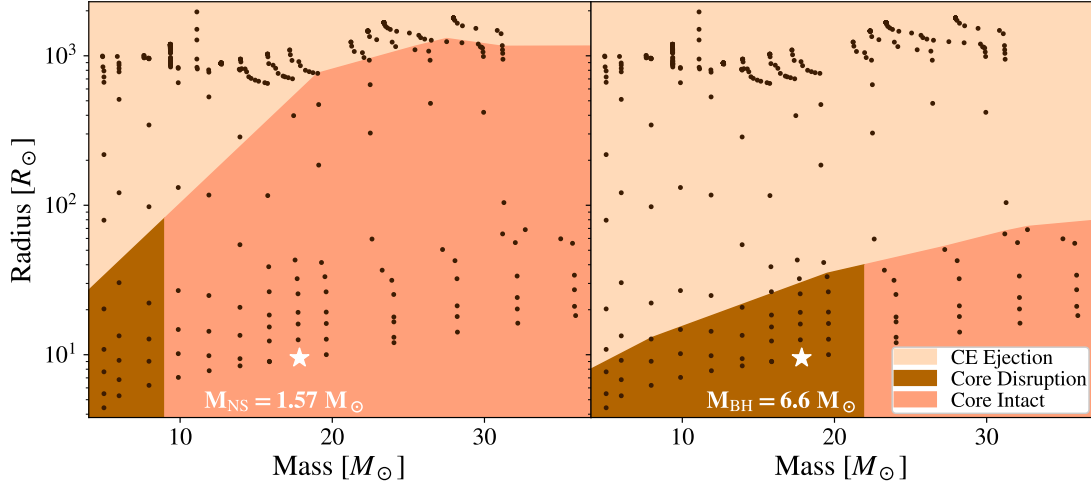


Figure 4.1: Reproduced from [Everson et al. \(2024a\)](#). Stellar masses and radii for a population of CE interaction outcomes modeled with MESA are shown as dark brown dots. The left panel displays systems with a neutron star (NS) companion, where the white star represents the forward-evolved LMC X-4 model from Chapter ?? with the observed $1.57 M_{\odot}$ NS companion. The right panel displays systems with black hole (BH) companions, with the white star again representing the LMC X-4 stellar model but assuming a $6.6 M_{\odot}$ BH companion. Systems above the CE ejection boundary successfully eject their envelopes and survive the CE phase (beige region), while systems below the boundary undergo merger. Among the merger systems, brown denotes cases in which the stellar core is disrupted, whereas coral denotes systems in which the core remains intact following merger.

CE phase from those that proceed toward merger. In the context of the MESA calculations shown in Figure 4.1, these estimates are used to map CE outcomes across the broader parameter space and to place the forward-evolved LMC X-4 model from Chapter 3 within this larger population of interacting systems.

The $\alpha = 1$ formalism compares the orbital energy released during inspiral, ΔE_{orb} , with the binding energy of the envelope, E_{bind} (Everson et al., 2024a). The released orbital energy is given by

$$\Delta E_{\text{orb}} = \frac{GM_1 M_2}{2a_0} - \frac{GM_{\text{enc}} M_2}{2a_{\text{final}}}, \quad (4.1)$$

while the envelope binding energy is defined as

$$E_{\text{bind}} = \int_{M_{\text{core}}}^{M_{\star}} -\frac{GM(r)}{r} dm. \quad (4.2)$$

The physical interpretation is that if sufficient orbital energy is deposited into the envelope such that

$$\alpha \Delta E_{\text{orb}} \geq E_{\text{bind}}, \quad (4.3)$$

the envelope can be successfully ejected. Otherwise, if the binding energy exceeds the available deposited energy, the envelope largely remains bound and the secondary continues inspiraling toward the stellar core. The parameter α characterizes the efficiency with which the released orbital energy contributes to unbinding the envelope and accounts for uncertainties in how orbital energy is transferred into envelope ejection. The value of α remains uncertain and likely depends on the properties of the donor star as we will argue in the next chapter. Here, we adopt the conservative assumption of $\alpha = 1$, corresponding to perfectly efficient conversion of orbital energy into envelope ejection.

With this framework established, we can now revisit the two evolutionary pathways introduced earlier: successful CE ejection and compact object–core merger. Systems within the CE ejection regime in Figure 4.1 (beige region) possess sufficient released orbital energy to unbind the envelope according to the $\alpha = 1$ formalism. In these systems, the envelope is ejected before the secondary reaches the stellar core, preventing a merger from occurring. As a result, this evolutionary pathway is not expected to produce classical TŻOs. Instead, these systems are more likely to evolve into compact post-CE binaries.

The merger regime consists of systems below the CE ejection boundary (brown and coral regions in Figure 4.1), where the released orbital energy is insufficient to unbind the envelope. In these systems, the secondary continues inspiraling until it reaches the stellar core, making compact object–core merger unavoidable. These merger systems can be further divided into disruptive and non-disruptive cases.

To understand the criterion for core disruption, it is first necessary to define the tidal disruption radius, R_{dis} , and compare it with the stellar core radius, R_{core} . The tidal disruption radius represents the separation at which the tidal forces from the secondary become strong enough to disrupt the core material. Following [Everson et al. \(2024a\)](#), the mass ratio between the secondary and the stellar core is defined as

$$q_c = \frac{M_2}{M_{\text{core}}}. \quad (4.4)$$

Core disruption occurs when the tidal disruption radius exceeds the stellar core radius, which approximately corresponds to the condition $q_c > 1$, meaning that the secondary is more massive than the stellar core. In this regime, the core is tidally disrupted before an intact compact object–core merger can occur, leading to the formation of a rotationally supported accretion disk. Systems containing

BH companions are more likely to undergo disruptive mergers because their larger companion masses make the condition $q_c > 1$ more readily satisfied.

To satisfy the criterion for non-disruptive, core-intact mergers, the mass ratio must instead satisfy $q_c < 1$. In these systems, the stellar core remains centrally concentrated because it is not tidally disrupted during merger. Historically, non-disruptive, core-intact mergers have been regarded as the most promising progenitor pathway for classical TŻOs, as the resulting configuration more closely resembles the spherically symmetric neutron-star-in-envelope structures assumed in canonical TŻO models (Cannon et al., 1992; Podsiadlowski et al., 1995; Thorne and Żytkow, 1977).

However, as discussed previously in Chapter 3, perfectly spherical accretion is unlikely due to the effects of angular momentum. Even when the core remains intact, angular momentum deposited during inspiral can substantially spin up the merger remnant, making accretion disk formation likely even in the non-disruptive case. This motivates a more detailed hydrodynamical investigation of angular momentum transport during merger.

Figure 4.1 therefore provides broader context for the hydrodynamical simulations presented in Chapter 3. The white star systems correspond to the same forward-evolved LMC X-4 models and simulation framework used in that work and are used here to probe representative merger outcomes across the CE landscape. In the NS case, the merger is non-disruptive and the stellar core remains intact, whereas in the BH case the larger companion mass leads to a disruptive merger. These distinctions motivate the detailed hydrodynamical comparison explored in the following section.

4.3 Testing the Merger Paradigm with Hydrodynamical Simulations

The merger paradigm is further explored using two hydrodynamical simulations based on the MESA models denoted by the white stars in Figure 4.1. These simulations build directly on the FLASH setup presented in Chapter 3, which was developed to model the CE inspiral of the LMC X-4 system (see Section 3.3.1). The NS model is identical to the simulation presented in Chapter 3, while the BH case adopts the same setup but replaces the secondary with a $6.6 M_{\odot}$ point mass and includes the corresponding adjustment to the initial Keplerian velocity. Aside from these modifications, the simulations are otherwise unchanged. As described previously, the simulations begin at the onset of CE evolution and follow the subsequent inspiral of the secondary through the stellar envelope.

Figure 4.2 shows density snapshots during the inspiral. The top row corresponds to the BH case at 2.4 hr and 3.3 hr, while the bottom row corresponds to the NS case at 4.6 hr and 5.5 hr. The black circle denotes the tidal disruption radius, the black X marks the center of mass of the primary, and the white circle outlined in black represents the secondary. In both simulations, the secondary ultimately reaches and merges with the stellar core. However, the resulting core response differs substantially between the two systems. In the BH case, the secondary strongly disrupts the core, whereas in the NS case the core remains comparatively intact and experiences only modest perturbation.

This difference follows directly from the disruption criterion discussed previously. The BH model has $q_c \approx 3/2$, satisfying the condition for core disruption, whereas the NS model has $q_c \approx 1/3$, corresponding to a non-disruptive merger in which the stellar core remains intact.

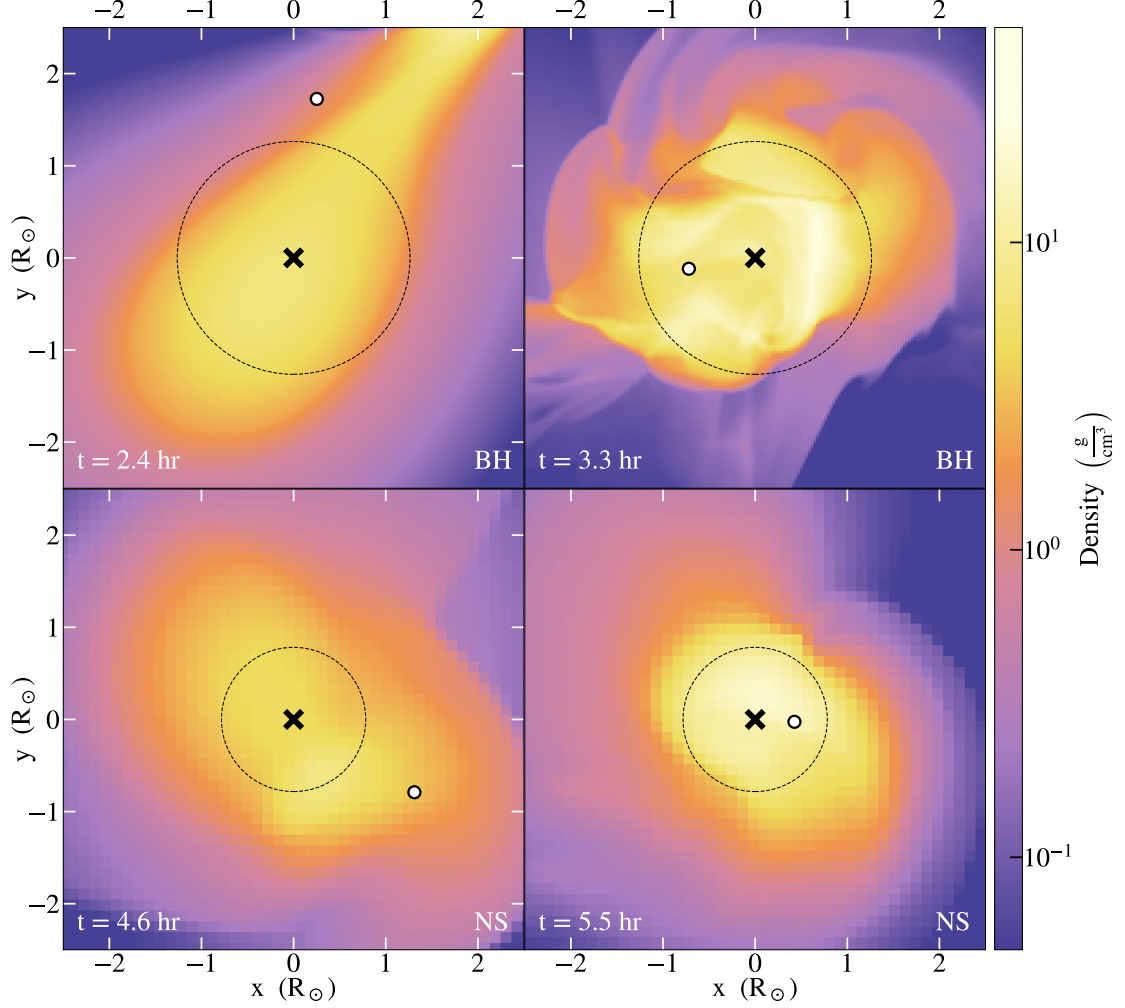


Figure 4.2: Reproduced from [Everson et al. \(2024a\)](#). Density snapshots during inspiral for the BH case (top row) at 2.4 hr and 3.3 hr, and for the NS case (bottom row) at 4.6 hr and 5.5 hr. The black circle denotes the tidal disruption radius, the black X marks the center of mass of the primary, and the white circle outlined in black represents the secondary. In both simulations, the secondary inspirals toward and merges with the stellar core. The BH case exhibits significant tidal disruption of the core, whereas the NS case undergoes a non-disruptive merger in which the core remains comparatively intact.

These simulations provide a direct test of the merger outcomes predicted by the $\alpha = 1$ and q_c criteria discussed in the previous section. While the population-level analysis predicts whether a system is expected to undergo core disruption, the hydrodynamical simulations make it possible to follow the detailed gas dynamics throughout inspiral and merger. This is particularly important because the analytic criteria alone do not determine whether the post-merger remnant satisfies the physical assumptions required for classical TŻO formation. The simulations shown here therefore build directly on the hydrodynamical framework introduced in Chapter 3, allowing the analytic predictions to be tested in a fully dynamical setting.

The BH simulation behaves consistently with the expectations of the disruptive merger regime. As the more massive secondary approaches the stellar core, strong tidal forces deform and ultimately disrupt the central structure, rather than preserving a centrally concentrated core surrounded by approximately spherical inflow as envisioned in classical TŻO models. The disrupted material acquires substantial angular momentum from the orbital motion of the secondary and is therefore expected to develop strong rotational support and form an accretion disk.

The NS case behaves differently. Although the secondary perturbs and modestly deforms the stellar core, the core itself remains largely intact throughout the simulation. Historically, this type of merger has been viewed as a promising classical TŻO progenitor because preserving the core provides conditions more favorable for quasi-spherical accretion (e.g., Podsiadlowski et al., 1995). However, the simulations indicate that maintaining an intact core alone is not sufficient. During inspiral, shocks and gravitational torques transfer orbital angular momentum into the surrounding material and spin up the merger remnant. As a result, even

the non-disruptive case is not expected to maintain the slowly rotating central conditions required to prevent accretion disk formation.

Furthermore, both systems exceed the j_{isco} criterion discussed by [Everson et al. \(2024a\)](#), implying that accretion disk formation is unavoidable. The key distinction therefore may not simply be whether the stellar core survives the merger, but whether sufficiently low-angular-momentum conditions can be maintained following inspiral. Classical TŻO models assume long-term quasi-spherical accretion onto the embedded compact object, which requires minimal rotational support in the central regions of the remnant. The hydrodynamical results instead suggest that maintaining these conditions may be difficult because angular momentum is naturally redistributed throughout the system during inspiral and merger.

This conclusion is also consistent with the results presented in Chapter 3. In the LMC X-4 simulation, the inspiraling NS transferred substantial orbital angular momentum into the central regions of the star through shocks generated during merger, spinning up the core and producing conditions favorable for accretion disk formation. The resulting feedback was predicted to remove a large fraction of the surrounding envelope material, suggesting that the remnant evolves away from a classical TŻO configuration. Rather than producing a compact object embedded within a massive envelope undergoing long-term quasi-spherical accretion, these systems may instead evolve toward the thin-envelope TŻO scenario discussed in the following section.

These results therefore motivate moving beyond a simple disruptive versus non-disruptive classification and toward understanding how angular momentum transport modifies post-merger evolution. The following section examines these implications in the broader context of classical TŻO and thin-envelope TŻO formation.

4.4 Thin-Envelope TŻOs as the Natural Outcome of Binary Interactions

As discussed previously, classical TŻO formation assumes a NS embedded within the stellar interior undergoing approximately spherical or quasi-spherical accretion. However, the hydrodynamical results presented in the previous section suggest that maintaining these conditions may be difficult in CE merger systems. During inspiral, orbital angular momentum is transferred into the surrounding material through shocks and gravitational torques, spinning up the central regions and breaking the spherical symmetry assumed in classical TŻO models. The resulting accretion flow is instead expected to become rotationally supported and form an accretion disk. In addition, the feedback generated by this accretion process can remove a large fraction of the surrounding envelope material. The traditional CE-to-TŻO pathway therefore appears unlikely, motivating the need for an alternative post-merger configuration.

Rather than eliminating the TŻO framework entirely, these effects may instead redirect the evolution toward an alternative steady-state structure containing a thin yet optically thick envelope. This configuration, referred to here as a Thin-Envelope TŻO (TETŻO), is expected to arise through the following sequence of events: CE inspiral, merger with the stellar core, collapse of the NS into a BH through accretion, disk-powered feedback, removal of most of the stellar envelope, and retention of a small fraction of envelope gas surrounding the compact remnant.

The results from Chapter 3 support this picture. In the LMC X-4 simulation, the inspiraling NS deposited substantial angular momentum into the central regions of the star and produced conditions favorable for accretion disk formation and

strong feedback. The subsequent evolution was predicted to remove most of the surrounding envelope rather than preserve a massive stellar structure around the compact object. The merger remnant therefore evolves away from the classical TŻO picture and toward a thin-envelope configuration.

The structure of a TETŻO consists of a low-mass residual envelope, containing $\lesssim 1\%$ of the original envelope mass, surrounding a central BH accreting through a disk. Unlike the massive envelopes of classical TŻOs, the remaining material forms a diffuse, radiation-supported structure. The residual envelope can survive because feedback removes most, but not all, of the surrounding gas. [Everson et al. \(2024a\)](#) argued that this outcome is favored in systems where the deposited energy is insufficient to completely unbind the remaining envelope, particularly for systems with companions in the early post-main-sequence phase. The remnant therefore reaches a state in which a small amount of material remains gravitationally bound while the majority of the envelope has already been ejected.

Figure 4.3 illustrates the expected TETŻO structure. The central BH accretes through a disk with radius $R_{\text{in}} \approx R_{\odot}$, while the diffuse optically thick envelope extends to $R_{\tau} \approx 10^3 R_{\odot}$, corresponding to the radius where the material transitions from optically thick to optically thin. Although the envelope mass is small, its large radial extent results from the diffuse structure supported by radiation pressure generated through accretion. Unlike classical TŻOs, which assume approximately spherical accretion onto an embedded NS surrounded by a massive stellar envelope, the TETŻO is powered by disk accretion onto an embedded BH within a diffuse low-mass envelope.

The observational properties of TETŻOs are also expected to differ significantly from those of classical TŻOs. Rather than resembling ordinary stars, these systems are predicted to appear as compact, luminous X-ray sources powered by accretion

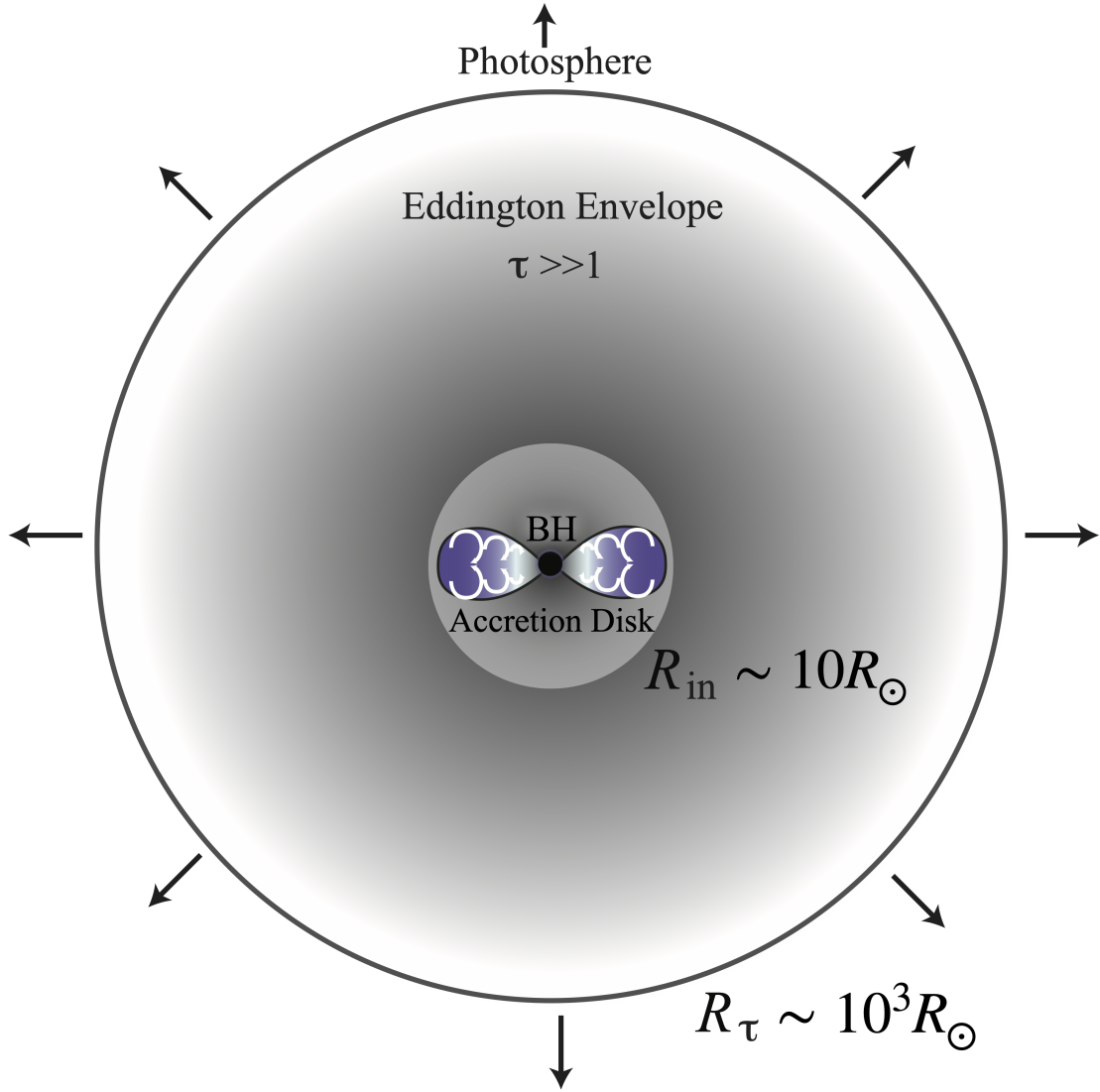


Figure 4.3: Reproduced from [Everson et al. \(2024a\)](#). Schematic illustration of the expected TETZO structure. The central BH accretes through a disk with characteristic radius R_{in} , while a diffuse optically thick envelope extends outward to the photosphere at radius R_{τ} .

onto the central BH. Using a framework similar to that adopted for classical TŻOs, characteristic quantities such as the luminosity, photospheric temperature, and lifetime can be estimated. The luminosity is expected to approach the Eddington limit,

$$L_{\text{TETZO}} = L_{\text{Edd}} = 10^{39} \left(\frac{M_{\text{bh}}}{10M_{\odot}} \right) \text{ erg/s} \quad (4.5)$$

which is approximately an order of magnitude larger than the luminosities expected for classical TŻOs. This increase arises because the central engine is now a BH rather than a NS, resulting in a correspondingly larger Eddington limit. The corresponding photospheric temperature is estimated to be

$$T_{\text{ph}} \approx \left(\frac{L_{\text{Edd}}}{4\pi R_{\tau=1}^2} \right)^{1/4} \approx 9 \times 10^5 \left(\frac{M_{\text{bh}}}{10M_{\odot}} \right)^{1/4} \left(\frac{M_{\text{env}}}{5 \times 10^{-3} M_{\odot}} \right)^{-1/4} \text{ K} \quad (4.6)$$

placing the emission primarily in the soft X-ray regime. Unlike classical TŻOs, which are expected to resemble cool supergiant stars, TETŻOs are predicted to be substantially hotter systems powered directly by accretion onto the embedded BH. The lifetime of a TETŻO can be estimated as

$$\tau = \frac{M_{\text{env}}}{\dot{M}} = 2 \times 10^4 \left(\frac{M_{\text{bh}}}{10M_{\odot}} \right)^{-1} \left(\frac{M_{\text{env}}}{5 \times 10^{-3} M_{\odot}} \right) \left(\frac{\epsilon}{0.1} \right) \text{ yr.} \quad (4.7)$$

which is approximately two orders of magnitude shorter than the expected lifetime of a classical TŻO. This shorter lifetime is a direct consequence of the significantly smaller amount of envelope material available to sustain long-term accretion.

Because of these properties, it is possible that TETŻOs have already been observed but classified as other types of accreting systems. For example, [Everson et al. \(2024a\)](#) suggested that several ultraluminous X-ray (ULX) sources in NGC 925 exhibit luminosities and photon temperatures similar to those predicted

for TETŻOs. With an estimated formation rate of roughly 10^{-3} systems per galaxy per year, nearby galaxies may plausibly host several such objects at any given time.

4.5 Summary

In conclusion, CE binary interactions naturally redistribute orbital angular momentum throughout inspiral and merger. The hydrodynamical results discussed here suggest that this redistribution fundamentally alters the post-merger evolution and redirects the system away from the classical TŻO structure originally envisioned by Kip Thorne and Anna Żytkow. Rather than producing a long-lived compact object embedded within a massive envelope undergoing quasi-spherical accretion, the merger instead evolves toward a rotationally supported configuration characterized by disk accretion and strong feedback.

These results suggest that TETŻOs may represent the more natural endpoint of CE-driven TŻO formation. In this picture, angular momentum transport during inspiral prevents the long-term quasi-spherical accretion required to sustain a classical TŻO, while simultaneously driving the removal of most of the stellar envelope. The remaining bound material forms a diffuse, optically thick envelope surrounding an accreting compact remnant, producing a qualitatively different steady-state configuration and observational signature.

Chapter 5

Hydrodynamic Response of Mildly Evolved Common Envelope Donors in Luminous Red Novae

Abstract

Luminous red novae trace unstable binary interactions in which common-envelope evolution can produce either a stellar merger or a surviving binary following envelope ejection. Recent population studies suggest that a substantial fraction of these systems originate from mildly evolved donors whose structures occupy an intermediate regime between simplified polytropic envelopes and the highly stratified giant stars commonly studied in classical common-envelope calculations. We present a suite of three-dimensional hydrodynamic simulations of mildly evolved donors interacting with embedded companions spanning a range of mass ratios and central density concentrations. We show that the hydrodynamic evolution is strongly regulated by the donor central concentration, parameterized by the

ratio $\rho_c/\bar{\rho}$. Donors with similar values of $\rho_c/\bar{\rho}$ exhibit qualitatively similar inspiral morphologies and mass-ejection histories despite substantial differences in stellar mass and radius. Systems with relatively modest central concentration evolve through rapid inspiral dominated by local orbital-energy deposition, while more centrally concentrated donors develop prolonged expansion-driven phases in which shocks, circulation flows, and large-scale envelope motions efficiently redistribute deposited energy and angular momentum throughout the star. In this regime, the envelope itself becomes dynamically important in driving continued mass loss long after the rapid plunge-in phase has slowed substantially. These results challenge semi-analytic models of luminous red novae that assume nearly instantaneous envelope ejection and estimate ejection efficiencies using simple orbital-energy balance arguments. Instead, our simulations suggest that the observable diversity of luminous red novae may depend not only on the total ejecta mass, but also on the temporal structure of the outflow, including the transition between impulsive envelope ejection and prolonged wind-like or multi-stage mass-loss evolution.

5.1 Introduction

A common-envelope interaction occurs when one star in a binary expands and engulfs its companion, initiating rapid orbital inspiral and strong hydrodynamic coupling between the embedded companion and the donor envelope (Iben and Livio, 1993; Ivanova et al., 2013a; Paczynski, 1976b; Ricker and Taam, 2012a; Soberman et al., 1997; Taam et al., 1978a). These interactions can produce two qualitatively different outcomes: successful envelope ejection leading to binary survival, or continued inspiral culminating in stellar merger (Klencki et al., 2021; MacLeod et al., 2018b; Pavlovskii et al., 2017; Podsiadlowski et al., 2001; Soberman et al.,

1997). Common-envelope interactions are widely believed to power luminous red novae (LRNe), a class of optical and infrared transients associated with eruptive mass ejection during unstable binary interaction and coalescence (Blagorodnova et al., 2021, 2017; Bond et al., 2003; Cai et al., 2019; Kaminski and Blagorodnova, 2026; Kulkarni et al., 2007; Kurtenkov et al., 2015; Martini et al., 1999; Munari et al., 2002; Pastorello et al., 2019b; Smith et al., 2016; Soker and Tylenda, 2003; Stritzinger et al., 2020; Tylenda et al., 2011).

Recent binary-population synthesis studies have shown that a substantial fraction of LRN-producing systems originate from mildly evolved donors undergoing unstable mass transfer during the early stages of post-main-sequence expansion (Twum et al., 2026). In this regime, the inspiral is expected to proceed toward merger rather than successful envelope ejection and long-term binary survival (e.g., Hutchinson-Smith et al., 2024). These donors occupy an intermediate structural regime between zero-age main-sequence stars and stars with highly stratified envelopes, making them particularly valuable for studying the hydrodynamic response of stars to embedded companions. Their envelopes are sufficiently extended to undergo strong dynamical interaction while remaining only moderately centrally concentrated, placing these systems in a transition regime where the global hydrodynamic response remains strongly coupled to the stellar interior.

This regime is also particularly well suited for three-dimensional hydrodynamical calculations (e.g., Everson et al., 2024b; Hutchinson-Smith et al., 2024; Wu et al., 2020). Stars with highly stratified envelopes develop extreme density contrasts that are computationally challenging to resolve and tend to localize the hydrodynamic response to the outermost layers of the star (e.g., Ivanova et al., 2013a; MacLeod et al., 2017b; Röpke and De Marco, 2023). Mildly evolved donors instead exhibit more moderate values of the ratio of central to average density,

$\rho_c/\bar{\rho}$, making them both more computationally tractable and more conducive to efficiently coupling the perturbation generated by the embedded companion to the stellar interior (e.g., [Everson et al., 2025](#)). As a result, relatively small changes in stellar structure can produce large differences in inspiral dynamics, shock formation, and mass ejection.

This sensitivity to stellar central concentration has also emerged in studies of tidal disruption events (e.g., [Bush et al., 2025](#); [Law-Smith et al., 2019](#); [Law-Smith et al., 2020a](#); [Liu et al., 2025](#)). Three-dimensional simulations have shown that many disruption outcomes can be organized primarily by the ratio of central to average density, $\rho_c/\bar{\rho}$, enabling the construction of numerical libraries parameterized by stellar central concentration rather than stellar mass and radius alone ([Law-Smith et al., 2020a](#)). In contrast to tidal disruption events, where the perturbation is externally driven, common-envelope interactions involve a lower-mass companion inspiraling within the donor envelope, depositing energy and angular momentum throughout the stellar interior ([Röpke and De Marco, 2023](#)). Here we investigate how the hydrodynamic evolution of common-envelope inspiral varies across donors spanning a range of $\rho_c/\bar{\rho}$, with particular emphasis on whether systems with similar central concentration exhibit comparable inspiral morphologies and mass-ejection histories despite differences in stellar mass and radius ([Everson et al., 2020](#); [Law-Smith et al., 2020a](#)). We focus on mildly evolved donors undergoing merger-driven inspiral with embedded companions spanning a range of mass ratios motivated by the population synthesis models of [Twum et al. \(2026\)](#).

The efficiency and duration of envelope ejection during common-envelope evolution remain highly uncertain ([De Marco et al., 2003](#); [Livio and Soker, 1988](#); [Passy et al., 2012](#); [Ricker and Taam, 2012a](#); [Sandquist et al., 1998](#)). In particular, it remains unclear how efficiently orbital energy couples to the envelope and over

what timescales mass loss proceeds. Additional processes, including recombination-powered outflows (Ivanova et al., 2013a) and jet feedback from the embedded companion (Dori et al., 2023; Soker, 2015, 2024), may further accelerate envelope removal or alter the late-time evolution of the interaction.

Our goal is to determine how donor structure regulates inspiral dynamics and mass ejection during the hydrodynamic evolution leading to luminous red novae. Many models used to interpret the light curves of luminous red novae assume that the bulk of the envelope mass is ejected impulsively over only a few dynamical timescales following the onset of inspiral (Ivanova et al., 2013b; MacLeod et al., 2017b). Whether this assumption applies across the full diversity of LRN progenitors remains uncertain, particularly for donors whose internal structure may regulate the timescale and character of mass ejection in ways not captured by simple orbital-energy balance arguments.

To explore this connection, we utilize the grid of donor stars from Twum et al. (2026), constructed using the one-dimensional stellar evolution code MESA (Jermyn et al., 2023; Paxton et al., 2011a, 2013a, 2015a, 2019; Paxton et al., 2018), to survey the landscape of central concentration among mildly evolved donors. From this grid, we select donor models spanning a representative range of $\rho_c/\bar{\rho}$ and simulate their common-envelope evolution using FLASH (Fryxell et al., 2000b), a three-dimensional adaptive mesh refinement hydrodynamics code. We additionally perform comparison calculations involving donors with similar values of $\rho_c/\bar{\rho}$ but substantially different masses and evolutionary states to test the extent to which central concentration governs the hydrodynamic evolution. By following the inspiral self-consistently in three dimensions, we investigate how donor central concentration regulates the inspiral dynamics, hydrodynamic response, and temporal distribution of mass ejection during common-envelope evolution.

The paper is structured as follows. Section 2 introduces the stellar evolution and population synthesis models of [Twum et al. \(2026\)](#) used to map the landscape of donor central concentration, with particular emphasis on the regime occupied by mildly evolved progenitors. Section 3 presents the hydrodynamical simulations, introducing the primary donor models and the FLASH setup, and explores the inspiral dynamics and mass-ejection histories across a range of companion mass ratios. Section 4 discusses the implications of our results for common-envelope evolution and luminous red novae. Appendix 5.5 presents additional comparison simulations involving donors with similar values of $\rho_c/\bar{\rho}$ but different masses and evolutionary states, while Appendix 5.6 summarizes the donor masses and radii adopted in previous global common-envelope simulations and places the present models within the broader landscape of common-envelope calculations.

5.2 Demographics of Mildly Evolved Common-Envelope Donors

We adopt the binary population synthesis framework presented by [Twum et al. \(2026\)](#), which combines rapid binary evolution calculations using COMPAS ([Mandel et al., 2025](#); [Riley et al., 2022b](#); [Stevenson et al., 2017](#)) with detailed stellar structure models to follow interacting binaries undergoing unstable mass transfer and common-envelope evolution. In this work, we specifically adopt the binary population model based on the orbital distributions inferred for massive binaries by [Sana et al. \(2012\)](#), referred to as the SANA model in [Twum et al. \(2026\)](#). This model includes distributions in primary mass, orbital period, and mass ratio and produces the largest fraction of interacting systems originating from mildly evolved donors

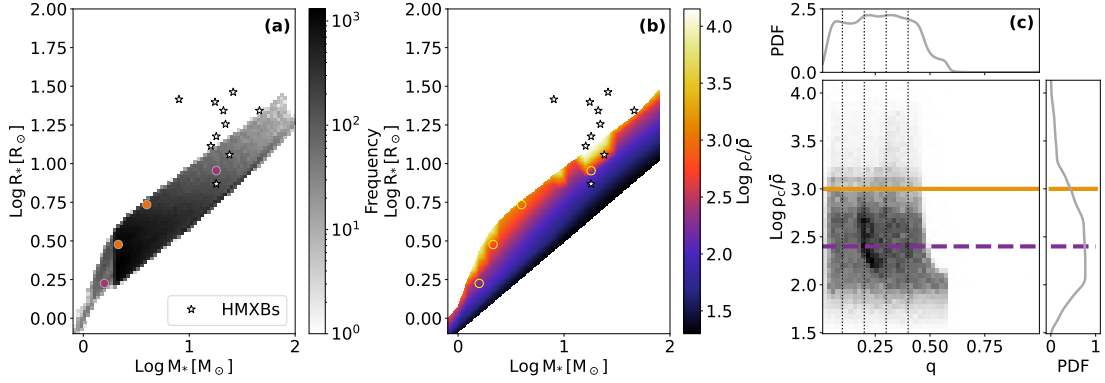


Figure 5.1: Binary interactions involving unstable mass transfer obtained from the binary population synthesis calculations of [Twum et al. \(2026\)](#). Panel *a*: Distribution of mildly evolved (Zone I) donors in the mass-radius plane. Panel *b*: Distribution of the ratio of central to average density, $\rho_c/\bar{\rho}$, across the mass-radius plane for the mildly evolved donor population. In panels *a* and *c*. Symbols indicate the subset of donor models selected for the three-dimensional hydrodynamical simulations. Panel *c*: Joint distribution of binary mass ratio, q , and donor central concentration, $\rho_c/\bar{\rho}$, for mildly evolved common-envelope donors. The masses and radii of eclipsing high-mass X-ray binaries (HMXBs) studied by [Falanga et al. \(2015b\)](#) are shown as star symbols. The simulated models (orange and purple) span the characteristic range of structural and binary properties occupied by the majority of mildly evolved common-envelope donors.

among the population models explored in that work. Systems are evolved until the onset of unstable mass transfer, at which point they are classified according to the evolutionary state and internal structure of the donor star. Of particular relevance here are the mildly evolved donors identified as Zone I systems in [Twum et al. \(2026\)](#). These correspond to binaries that initiate unstable mass transfer shortly after leaving the main sequence, before developing highly stratified envelopes. Under the [Sana et al. \(2012\)](#) binary parameter distributions, mildly evolved donors constitute approximately 27.4% of the predicted common-envelope interactions associated with luminous red novae, making them one of the dominant progenitor channels.

Mildly evolved donors occupy a relatively narrow evolutionary window in which the stellar envelope has expanded beyond the zero-age main sequence but has not yet developed the extreme density stratification characteristic of later evolutionary stages. Their envelopes remain only moderately centrally concentrated, allowing the hydrodynamic response to remain globally coupled to the stellar interior. This makes these systems particularly valuable for studying the response of common-envelope donors to embedded inspiral.

To characterize the internal structure of these donors, we compute the ratio of central to average density, $\rho_c/\bar{\rho}$, across the donor population. [Figure 5.1](#) shows the distribution of mildly evolved donors in the mass-radius plane together with the corresponding distribution of $\rho_c/\bar{\rho}$. Mildly evolved donors populate a transition regime where relatively small changes in stellar evolution produce substantial changes in stellar central concentration. Most of these donors occupy an intermediate structural regime with $10^2 \lesssim \rho_c/\bar{\rho} \lesssim 10^3$. For comparison, a $\Gamma = 5/3$ polytrope has $\rho_c/\bar{\rho} = 5.8$, while a $\Gamma = 4/3$ polytrope has $\rho_c/\bar{\rho} = 73$ ([Law-Smith et al., 2020a](#)), whereas highly stratified giant envelopes can reach

$$\rho_c/\bar{\rho} \gtrsim 10^6 \text{ (MacLeod et al., 2012)}$$

The donor structures are calculated using the one-dimensional stellar evolution code MESA (Jermyn et al., 2023; Paxton et al., 2011a, 2013a, 2015a, 2019; Paxton et al., 2018) following the methodology described in Twum et al., 2026. To capture the diversity of common-envelope donors associated with luminous red novae, Twum et al., 2026 constructed extensive grids of stellar evolution models spanning initial masses from 0.08 to $100M_{\odot}$ at solar metallicity ($Z = 0.02$). Low- and intermediate-mass stars (0.08 - $7.9M_{\odot}$) were evolved using the MESA 7M_premis_to_AGB test suite, which follows stellar evolution from the pre-main-sequence phase through the asymptotic giant branch. These calculations adopt a mixing length parameter of 1.73 and include Reimers and Blocker prescriptions for RGB and AGB mass loss, respectively. Intermediate- and high-mass stars were evolved using the 12M_pre_ms_to_core_collapse configurations, following stellar evolution from the zero-age main sequence to core collapse.

From this library, we select mildly evolved systems undergoing unstable mass transfer shortly after leaving the main sequence. The corresponding donor structures are extracted from the MESA stellar evolution calculations at evolutionary stages representative of the onset of unstable interaction and are subsequently mapped into the three-dimensional hydrodynamical simulations described in Section 5.3. For each donor, we extract the radial density, pressure, temperature, and composition profiles needed to initialize the hydrodynamical calculations.

The subset of donor models selected for the three-dimensional simulations is indicated by open symbols in Figure 5.1. These models span the characteristic range of $\rho_c/\bar{\rho}$ occupied by the majority of mildly evolved progenitors while sampling a broad range of donor masses and companion mass ratios. The simulation suite is designed to isolate the role of stellar central concentration by comparing systems

with substantially different donor masses but similar values of $\rho_c/\bar{\rho}$, as well as systems with fixed donor structure and varying companion mass ratio. This allows us to systematically explore how stellar central concentration regulates inspiral dynamics, shock formation, and mass ejection during common-envelope evolution. Details of the three-dimensional hydrodynamical calculations are presented in Section 5.3. For comparison, Figure 5.1 also includes observed high-mass -ray binaries hosting neutron stars, which are expected to evolve into common-envelope systems once the massive donor fills its Roche lobe and unstable mass transfer leads to the engulfment of the neutron star within the expanding envelope (Hutchinson-Smith et al., 2024).

5.3 Hydrodynamical Simulations

5.3.1 FLASH Setup

The one-dimensional donor structures generated with MESA are imported into the three-dimensional hydrodynamical framework using FLASH version 4.32 (Fryxell et al., 2000b). For each donor, the radial density, pressure, temperature, and composition profiles are interpolated onto a Cartesian adaptive mesh refinement grid to initialize the stellar envelope in hydrostatic equilibrium. The hydrodynamical evolution is computed using the numerical framework developed for stellar disruption and merger calculations by Guillochon et al. (2009) and Guillochon and Ramirez-Ruiz (2013), later extended to follow detailed thermodynamic and compositional evolution in three dimensions (Bush et al., 2025; Law-Smith et al., 2017; Law-Smith et al., 2020a; Wu et al., 2020). The simulations employ the extended Helmholtz equation of state (Timmer and Swesty, 2000), which allows us

to consistently evolve the thermodynamic state of the gas throughout the inspiral.

Our simulation suite is designed to isolate the role of donor central concentration in regulating common-envelope hydrodynamics. The primary calculations focus on two representative donor families spanning contrasting values of $\rho_c/\bar{\rho}$ (Figure 5.1). The first consists of an $18M_\odot$ donor with moderate central concentration, $\rho_c/\bar{\rho} = 251$, while the second consists of a $2.14M_\odot$ donor with substantially higher central concentration, $\rho_c/\bar{\rho} = 962$. For each donor, we consider embedded companions with mass ratios $q \equiv M_\bullet/M_*$ between 0.1 and 0.4, where M_* is the mass of the donor and $M_\bullet$ is the mass of the inspiraling companion. This allows us to explore how inspiral dynamics and mass ejection vary with binary mass ratio at fixed donor structure. Additional comparison calculations involving donors with similar values of $\rho_c/\bar{\rho}$ but different masses and evolutionary states are presented in Appendix 5.5.

Before introducing the embedded companion, each donor model is first mapped into FLASH and evolved in isolation for several donor dynamical timescales. The simulations are performed in a three-dimensional Cartesian domain with an 8^3 block grid structure and adaptive mesh refinement. The finest refinement level corresponds to a minimum cell size of $\lesssim R_*/10^2$, where R_* is the radius of the donor, consistent with the resolution required to achieve convergence in both the inspiral trajectory and mass-ejection evolution (Hutchinson-Smith et al., 2024; Law-Smith et al., 2020a; Wu et al., 2020). During the relaxation procedure, the embedded companion is introduced as a point mass initially placed at rest near the donor surface. Its orbital velocity is then gradually increased until reaching the local circular Keplerian value, allowing the donor envelope to adjust smoothly to the presence of the companion. Once the relaxation phase is complete, the donor has settled into hydrostatic equilibrium on the computational grid and the subsequent inspiral trajectory of the embedded companion is evolved self-consistently (Wu

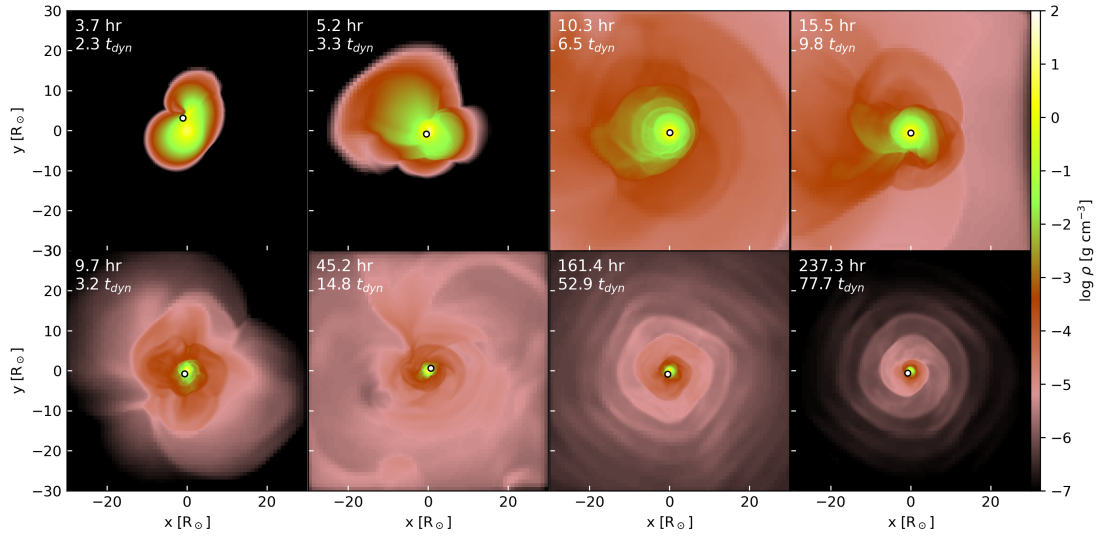


Figure 5.2: Time evolution of the mid-plane density for the two representative $q = 0.1$ simulations. The moderately concentrated $18M_{\odot}$ donor (top panels) with $\rho_c/\bar{\rho} = 251$ undergoes rapid inspiral over only a few dynamical timescales, after which the orbital separation decreases more gradually as the embedded companion settles near the core radius of the donor. The more centrally concentrated $2.14M_{\odot}$ donor (bottom panels) with $\rho_c/\bar{\rho} = 962$ evolves over tens of dynamical timescales and settles into a quasi-stationary orbit while the donor envelope undergoes substantial expansion. Mass loss continues throughout this extended phase for hundreds of dynamical timescales, ultimately leading to the ejection of most of the donor envelope. Animations available at: <https://tinyurl.com/hydrosims>

et al., 2020). Additional details regarding the numerical implementation, relaxation procedure, and hydrodynamic scheme can be found in Hutchinson-Smith et al. (2024) and Everson et al. (2024b).

To further test the extent to which the hydrodynamic evolution is governed by stellar central concentration rather than donor mass alone, we perform additional comparison calculations involving donors with similar values of $\rho_c/\bar{\rho}$ but different masses and evolutionary states. These include a $1.58M_\odot$ donor with $\rho_c/\bar{\rho} = 260$, comparable to the $18M_\odot$ donor, and a $3.97M_\odot$ donor with $\rho_c/\bar{\rho} = 940$, comparable to the $2.14M_\odot$ donor. For these comparison models, we focus on the $q = 0.1$ cases, which are presented in Appendix 5.5. These calculations allow us to directly assess whether systems with similar central concentration exhibit similar hydrodynamic evolution despite substantial differences in donor mass.

5.3.2 Dynamical Inspiral at Fixed Companion Mass Ratio

We first compare the hydrodynamic evolution of the two representative donor families at fixed companion mass ratio, $q = 0.1$, thereby isolating the role of donor structure while holding the relative companion mass fixed. Figure 5.2 compares the mid-plane density evolution of both systems at comparable times measured in units of the donor dynamical timescale. This comparison highlights how increasing donor central concentration alters the global hydrodynamic response during inspiral, leading to qualitatively different shock structures, envelope expansion, and mass-ejection behavior.

The two calculations exhibit qualitatively different inspiral and mass-ejection histories. In the moderately concentrated $18M_\odot$ donor (*bottom* panels In Figure 5.2), the embedded companion inspirals rapidly through the envelope over

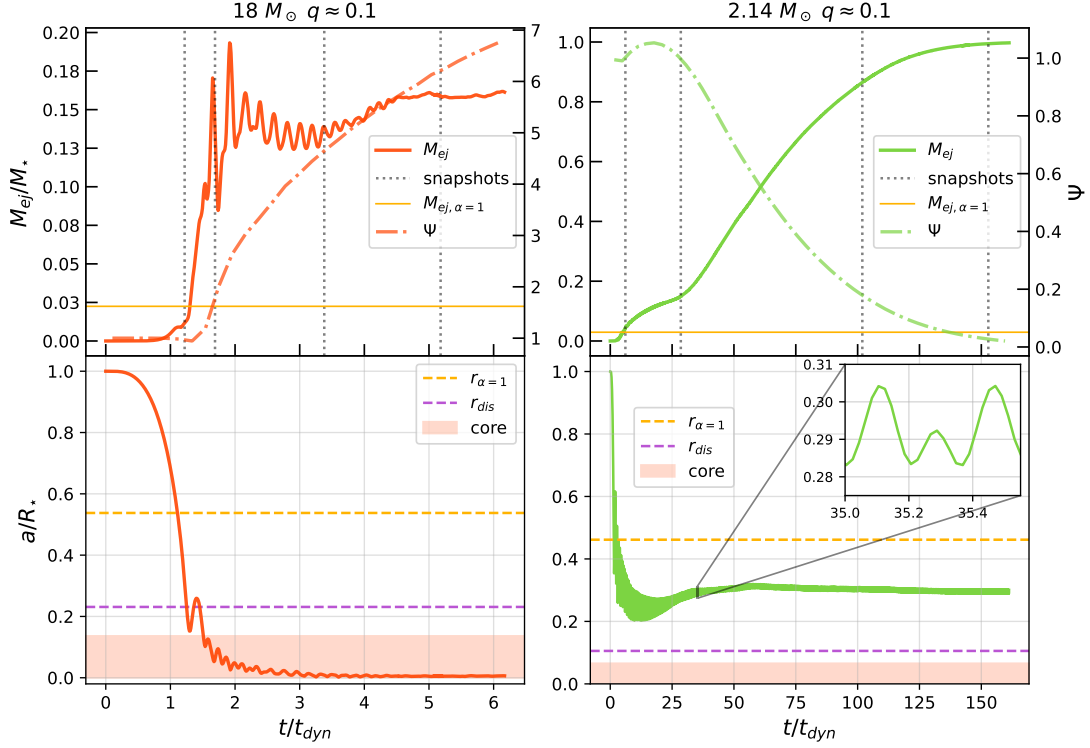


Figure 5.3: Time evolution, in units of the dynamical timescale of the donor, representative $q = 0.1$ simulations for the moderately concentrated $18M_{\odot}$ donor with $\rho_c/\bar{\rho} = 251$ (left) and the high-central-concentration $2.14M_{\odot}$ donor with $\rho_c/\bar{\rho} = 962$ (right). The top panels show the cumulative ejected mass, normalized to the initial donor mass, together with the evolution of the enclosed-mass response parameter Ψ . Horizontal solid lines indicate the ejecta mass predicted by the standard α -formalism assuming $\alpha = 1$. Vertical dotted lines mark the times corresponding to the hydrodynamical snapshots shown in Figure ???. The bottom panels show the orbital separation of the embedded companion normalized to the donor radius, a/R_* . The horizontal dashed line indicates the characteristic radius at which the released orbital energy equals the binding energy of the overlying envelope in the $\alpha = 1$ formalism, while the purple dashed line marks the tidal disruption radius assuming a zero-age main-sequence companion (Twum et al., 2026). The shaded region denotes the donor's core region.

only a few donor dynamical timescales. Following this initial plunge, the orbital separation continues to decrease gradually as the companion settles near the core radius of the donor. As the companion inspirals toward the core, it deposits orbital energy and angular momentum into the donor envelope through shocks and spiral density waves, unbinding only a modest fraction of the envelope material. Most of the hydrodynamic response therefore occurs during the initial inspiral phase, after which the large-scale donor structure evolves comparatively little.

By contrast, the more centrally concentrated $2.14M_{\odot}$ donor (*bottom* panels in Figure 5.2) undergoes a much more prolonged evolution. The companion inspirals over tens of donor dynamical timescales before settling into a quasi-stationary orbit. Soon after the initial inspiral phase is completed, the donor envelope begins to expand on progressively larger scales, driving sustained mass loss for hundreds of dynamical timescales and ultimately ejecting most of the envelope. In this case, the slowing of the inspiral marks not the end of the hydrodynamic response, but the onset of a prolonged expansion-driven mass-loss phase.

We quantify these evolutionary differences in Figure 5.3, which shows the unbound mass and companion separation as functions of time, in units of the donor dynamical timescale, for both $q = 0.1$ simulations. We follow [Hutchinson-Smith et al. \(2024\)](#) and define the ejected mass as gas with positive total specific energy, computed as the sum of the specific kinetic and gravitational potential energies, excluding the internal energy contribution. To quantify the hydrodynamic response of the donor envelope, we introduce the dimensionless enclosed-mass response parameter,

$$\Psi \equiv \frac{M(< a)}{M_0(< a)}, \quad (5.1)$$

where $M(< a)$ is the donor mass enclosed within the instantaneous orbital separa-

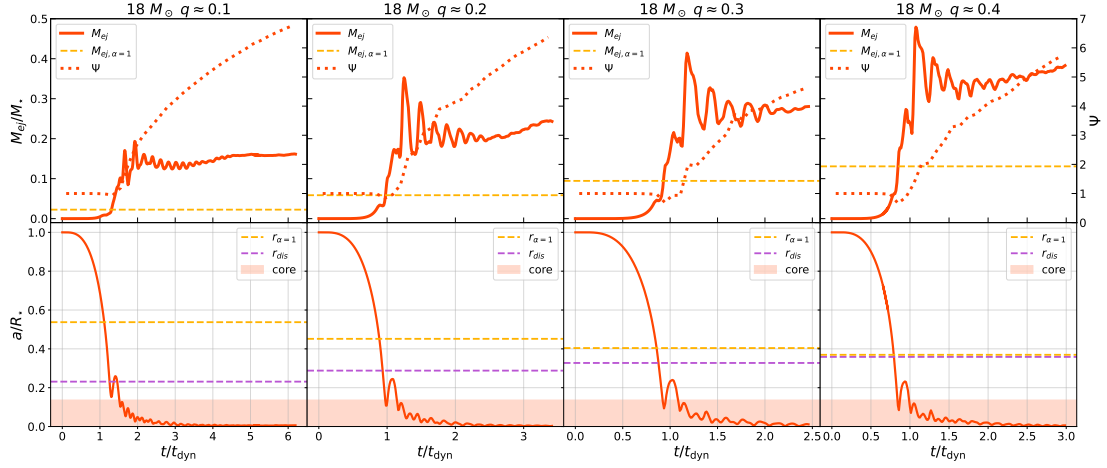


Figure 5.4: Time evolution of the moderately concentrated $18M_{\odot}$ donor with $\rho_c/\bar{\rho} = 251$ for companion mass ratios spanning $q = 0.1$ – 0.4 . The panels show the cumulative ejected mass, enclosed-mass response parameter Ψ , and orbital separation as functions of time in units of the donor dynamical timescale. All models exhibit qualitatively similar inspiral evolution, with the embedded companion rapidly inspiraling toward the donor core over only a few dynamical timescales. The total ejected mass increases systematically with companion mass ratio, although the ratio between the simulated ejecta mass and the $\alpha = 1$ prediction does not increase with q . Line styles and additional quantities are defined as in Figure 5.3.

tion, a , of the embedded companion and $M_0(< a)$ is the enclosed mass at the same radius in the original unperturbed donor profile. This quantity directly measures how the donor redistributes mass during the inspiral. Values of $\Psi < 1$ correspond to envelope expansion and rarefaction interior to the companion orbit, while $\Psi > 1$ indicates compression or contraction.

The evolution of Ψ provides a useful diagnostic for understanding the global hydrodynamic response of the donor and helps explain the markedly different mass-ejection histories of the two systems. The $18M_{\odot}$ donor (*right* panels in Figure 5.3) ejects material primarily during the initial rapid inspiral and subsequently reaches an approximately steady ejecta mass. Throughout this evolution, Ψ remains greater than unity, indicating that the donor contracts as the companion inspirals and continues to compress until the embedded object settles near the donor core.

In this regime, the interaction primarily perturbs the local envelope surrounding the companion, depositing orbital energy and angular momentum into a relatively confined region and unbinding only a modest fraction of the donor mass.

By contrast, the $2.14M_{\odot}$ donor (*left* panels in Figure 5.3) exhibits an initial contraction phase during the early dynamical inspiral, followed by a sustained decrease in Ψ once the inspiral slows. This transition marks the onset of large-scale envelope expansion, during which the donor continues to unbind material over hundreds of dynamical timescales. As the envelope expands and redistributes mass on progressively larger scales, the ejecta mass continues to increase long after the initial inspiral phase has ended, ultimately leading to the ejection of most of the donor envelope.

Also shown in Figure 5.3 is the radius at which the embedded companion is expected to undergo tidal disruption. Following Twum et al. (2026), we assume disruption occurs once the inspiraling companion encounters an enclosed donor density comparable to roughly half of its own average density, as expected for a zero-age main-sequence accretor. Once this condition is reached, we assume the companion is tidally disrupted, halting further inspiral and terminating additional orbital energy deposition into the envelope.

For comparison, we also indicate the characteristic radius predicted by the standard α -formalism (Webbink, 1984), assuming $\alpha = 1$, at which the released orbital energy equals the binding energy of the overlying envelope. In both models, this characteristic radius is reached promptly during the initial dynamical inspiral phase, broadly consistent with expectations from simple orbital-energy balance arguments applied to a frozen stellar structure. However, the subsequent hydrodynamic evolution alters the mass-ejection history substantially. While the moderately concentrated donor ejects only a modest fraction of its envelope after

reaching this stage, the highly concentrated donor undergoes continued large-scale expansion that drives prolonged mass loss and ultimately unbinds most of the envelope. These calculations demonstrate that the hydrodynamic response of the donor can significantly modify the mass ejection relative to predictions based solely on instantaneous orbital-energy deposition.

5.3.3 Dependence on Companion Mass Ratio

We now investigate how the common-envelope evolution changes with companion mass ratio for fixed donor structure. Figure 5.4 shows the evolution of the moderately concentrated $18M_{\odot}$ donor with $\rho_c/\bar{\rho} = 251$ for companion mass ratios spanning $q = 0.1$ – 0.4 .

All simulations exhibit qualitatively similar inspiral evolution. In each case, the embedded companion rapidly inspirals through the donor envelope over only a few dynamical timescales before settling near the donor core. The inspiral trajectories remain remarkably similar despite the factor of four variation in companion mass, indicating that the global hydrodynamic evolution is largely set by the donor structure. In all models, the inspiral proceeds well beyond the characteristic $\alpha = 1$ radius predicted by the standard energy formalism.

While the overall inspiral morphology remains qualitatively similar across the suite, increasing companion mass ratio leads to systematically stronger shocks, more rapid envelope expansion, and larger total ejecta masses as additional orbital energy and angular momentum are deposited into the donor during inspiral. However, the ratio of the simulated ejecta mass to the corresponding $\alpha = 1$ energy-balance estimate does not increase systematically with q . This suggests that the additional orbital energy released by more massive companions is not converted solely into

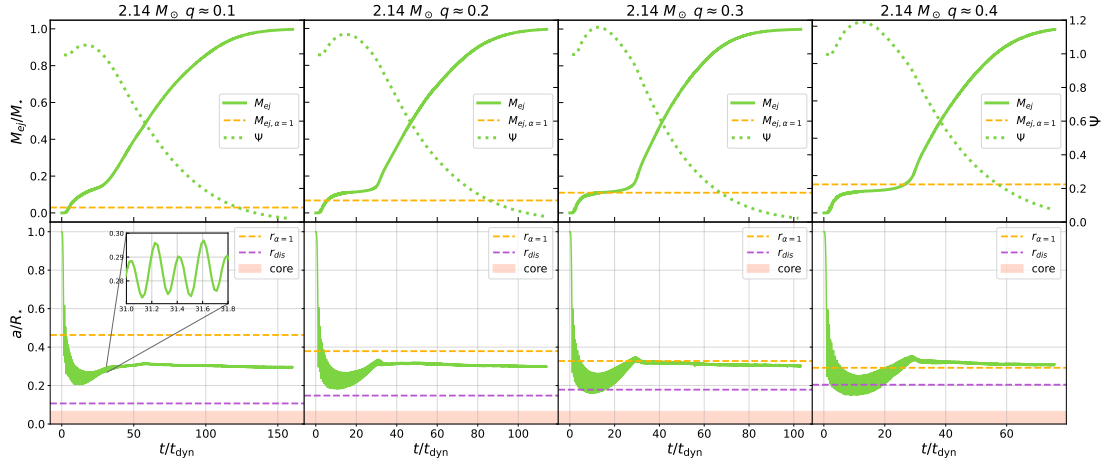


Figure 5.5: Time evolution of the high-central-concentration $2.14M_{\odot}$ donor with $\rho_c/\bar{\rho} = 962$ for companion mass ratios spanning $q = 0.1$ – 0.4 . The panels show the cumulative ejected mass, enclosed-mass response parameter Ψ , and orbital separation as functions of time in units of the donor dynamical timescale. In all models, the inspiral undergoes an initial dynamical contraction phase followed by a transition to prolonged envelope expansion once the companion settles into a quasi-stationary orbit. The subsequent evolution is dominated by sustained hydrodynamic expansion and continued mass loss over tens to hundreds of dynamical timescales, ultimately leading to the ejection of most of the donor envelope largely independent of companion mass ratio. Line styles and additional quantities are defined as in Figure 5.3.

direct envelope unbinding, but is increasingly redistributed through shocks, large-scale hydrodynamic expansion, and internal restructuring of the donor, allowing the interaction to couple more efficiently to deeper and more tightly bound layers of the envelope.

The evolution of Ψ remains qualitatively similar across the full range of mass ratios. In all cases, Ψ increases substantially during the inspiral, indicating that the donor contracts as the embedded companion penetrates deeper into the envelope. These calculations therefore suggest that, for donors with modest central concentration, the companion mass ratio primarily regulates the efficiency of mass ejection while the overall character of the inspiral is determined by the donor structure itself.

The high-central-concentration suite ($\rho_c/\bar{\rho} = 962$) tells a markedly different story. In contrast to the $18M_\odot$ donor, all simulations involving the $2.14M_\odot$ donor exhibit a prolonged two-stage evolution across the full range of companion mass ratios (Figure 5.5). The embedded companion initially undergoes rapid inspiral over several dynamical timescales, during which the donor contracts and Ψ increases modestly above unity. This early plunge-in phase is followed by a transition to large-scale envelope expansion once the inspiral slows and the companion settles into a quasi-stationary orbit.

After this transition, the subsequent evolution becomes dominated by global hydrodynamic expansion rather than continued orbital decay. In all models, Ψ decreases steadily as the donor envelope expands, driving sustained mass loss over tens to hundreds of dynamical timescales and ultimately ejecting most of the envelope largely independent of companion mass ratio.

While the overall hydrodynamic evolution remains qualitatively similar across the suite, increasing companion mass ratio primarily accelerates the envelope

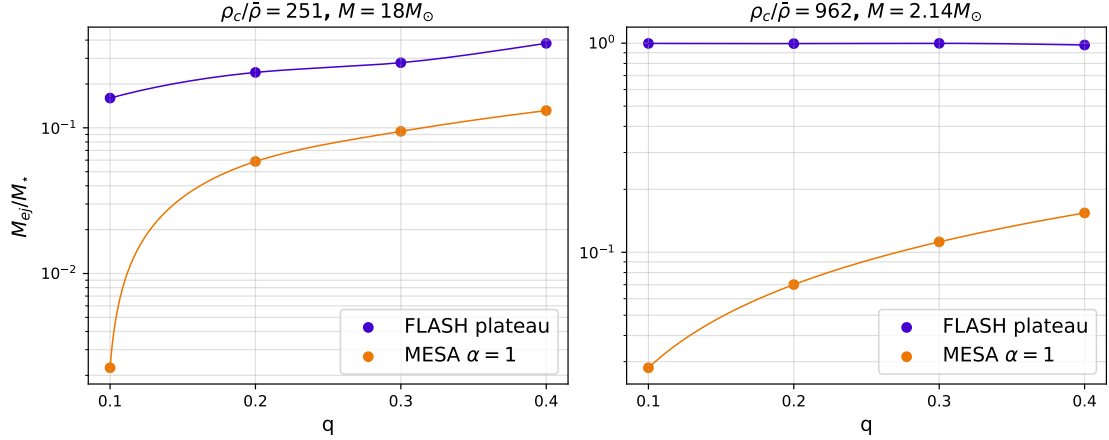


Figure 5.6: Comparison between the total ejecta mass obtained from the hydrodynamical simulations and the predictions of the standard α -formalism assuming $\alpha = 1$. The left panel shows the moderately concentrated donor suite, while the right panel shows high-central-concentration donor suite. The moderately concentrated donors broadly follow the orbital-energy scaling expected from the inspiral, although the simulations consistently eject more mass than predicted by the simple energy formalism. By contrast, the high-central-concentration donor suite ejects most of the donor envelope largely independent of companion mass ratio due to prolonged hydrodynamic expansion following the inspiral phase.

expansion and mass-loss evolution. More massive companions inject orbital energy and angular momentum into the donor more rapidly, generating stronger shocks and driving faster large-scale expansion, such that near-complete envelope ejection is reached on progressively shorter timescales.

In both donor suites, the tidal disruption radius increases with companion mass because more massive main-sequence companions have lower mean densities and are therefore disrupted at larger orbital separations within the donor envelope.

5.3.4 Hydrodynamic Mass Ejection Beyond the α -Formalism

Figure 5.6 compares the total ejecta mass obtained from the hydrodynamical simulations to the predictions of the standard α -formalism assuming $\alpha = 1$. The left panel shows the high-central-concentration donor suite, while the right panel

shows the moderately concentrated donor suite.

For the moderately concentrated donors, the total ejecta mass increases systematically with companion mass ratio and broadly follows the scaling expected from the orbital-energy budget. In these systems, the inspiral proceeds rapidly toward the donor core. As a result, orbital energy deposited after the inspiral passes the nominal $\alpha = 1$ radius can continue to unbind progressively deeper layers of the donor envelope. However, the released energy is insufficient to eject all material exterior to the companion once the inspiral reaches the most tightly bound inner regions of the donor. The hydrodynamical simulations therefore consistently eject more mass than predicted by the simple energy formalism, while still retaining a clear dependence on the orbital energy released during inspiral. This behavior is broadly consistent with the findings of [Hutchinson-Smith et al. \(2024\)](#), who similarly found that hydrodynamic evolution can enhance envelope ejection beyond the predictions of simple instantaneous energy-balance arguments.

The comparison breaks down qualitatively for the high-central-concentration donor suite. In these systems, the simulations eject nearly the entire donor envelope over the full range of companion mass ratios, while the $\alpha = 1$ formalism predicts substantially smaller ejecta masses. Once the inspiral settles into a quasi-stationary orbit, the subsequent evolution becomes dominated by large-scale hydrodynamic expansion of the donor envelope. In this regime, the donor itself performs much of the work required to unbind the envelope as expansion redistributes energy and drives prolonged mass loss over hundreds of dynamical timescales. The total ejecta mass is therefore no longer determined primarily by instantaneous orbital-energy deposition, but instead by the global hydrodynamic response of the donor.

These conclusions may be altered substantially for main-sequence companions, whose lower mean densities make them susceptible to tidal disruption before

reaching the smallest orbital separations within the donor envelope (Twum et al., 2026). In such systems, the inspiral and associated orbital-energy deposition terminate once the companion is disrupted, potentially preventing the onset of the prolonged expansion-driven phase identified in the high-central-concentration donor suite. By contrast, compact companions such as white dwarfs, neutron stars, and black holes can survive to much smaller radii, allowing continued inspiral and sustained energy deposition deep within the donor envelope.

5.4 Discussion, Lessons Learned, and Observational Implications

5.4.1 Hydrodynamic Evolution in the Context of Common-Envelope Simulations

The common-envelope literature has historically focused on highly extended RGB, AGB, and red-supergiant donors with radii spanning tens to hundreds of solar radii (Iaconi et al., 2017, 2018; Ohlmann et al., 2016; Passy et al., 2012; Reichardt et al., 2019; Ricker and Taam, 2012b). As summarized in Appendix 5.6, relatively few global simulations have explored the intermediate regime of mildly evolved donors with moderate central concentration considered here. Early hydrodynamical studies frequently employed idealized polytropic structures or simplified envelope models (e.g., Passy et al., 2012), whereas more recent calculations increasingly map one-dimensional stellar-evolution models directly into three-dimensional hydrodynamic simulations (Iaconi et al., 2017, 2018; Ohlmann et al., 2016; Reichardt et al., 2019; Ricker and Taam, 2012b).

Despite substantial differences in numerical methods, resolution, and donor

structure, these simulations reveal several common hydrodynamic features. In most calculations, the interaction begins with a rapid dynamical inspiral during which the embedded companion transfers orbital energy and angular momentum to the surrounding envelope through shocks, gravitational torques, and hydrodynamic drag. This initial plunge-in phase is typically followed by a substantial slowing of the inspiral as the local envelope around the companion becomes increasingly disturbed and partially evacuated. Many simulations subsequently develop long-lived oscillatory or quasi-periodic orbital evolution in which the companion continues orbiting within a partially bound envelope over many dynamical timescales (Iaconi et al., 2017; Passy et al., 2012; Reichardt et al., 2019). These studies suggest that the outcome of the interaction is not determined solely by the orbital energy released during the initial plunge-in, but by the hydrodynamic state in which the inspiral ultimately stalls near the inner regions of the donor. Once the local envelope surrounding the companion becomes sufficiently disturbed, shocks, circulation flows, and large-scale envelope motions can redistribute deposited energy and angular momentum increasingly efficiently throughout the star (Everson et al., 2025). The hydrodynamic response during this post-plunge evolution is often highly complex, with large-scale shocks, anisotropic outflows, envelope expansion, fallback, and recombination-driven cooling all contributing to the continued redistribution of energy and momentum throughout the envelope (Ivanova et al., 2013a; Lau et al., 2022). As a result, many simulations find that orbital-energy deposition during the initial dynamical inspiral alone is insufficient to unbind the full envelope, and that the subsequent hydrodynamic evolution over many dynamical timescales plays a critical role in determining the final ejecta mass and long-term fate of the system. However, these conclusions have largely emerged from simulations of highly extended giant envelopes, where the envelope dynamical timescales are long

and the outer layers are only weakly bound.

5.4.2 Hydrodynamic Evolution Regulated by Donor Central Concentration

The simulations presented here explore this hydrodynamic evolution in a structurally distinct regime characterized by moderately evolved donors with central density contrasts of $\rho_c/\bar{\rho} \approx 10^2 - 10^3$ (Figure 5.1). This range begins above the most centrally concentrated simple polytropic structures, but extends to density contrasts well below those of highly evolved giant envelopes. Within this intermediate regime, the donor central concentration emerges as a key parameter governing the global hydrodynamic response of the interaction (Everson et al., 2020; Law-Smith et al., 2020a). Additional comparison simulations presented in Appendix 5.5 further support this interpretation by demonstrating that donors with substantially different masses and evolutionary states, but similar values of $\rho_c/\bar{\rho}$, exhibit qualitatively similar inspiral morphologies and mass-ejection histories. Importantly, these similarities emerge despite significant differences in the detailed stellar structure of the donor models, suggesting that $\rho_c/\bar{\rho}$ captures a physically important aspect of how the envelope couples hydrodynamically to the inspiraling companion. Systems with relatively modest central concentration, whose structures remain closer to polytropic envelopes, tend to evolve through a rapid inspiral toward the inner regions of the donor, with the evolution remaining largely dominated by local orbital-energy deposition during the dynamical plunge-in phase (e.g., Passy et al., 2012). By contrast, increasing central concentration leads to progressively stronger global envelope response as the inspiral slows and the local hydrodynamic drag around the companion weakens.

This transition toward slower, expansion-driven evolution bears some resemblance to the quasi-stationary outflow picture discussed by [Ivanova and Chaichenets \(2011\)](#), in which envelope ejection during common-envelope evolution may proceed through prolonged large-scale outflows rather than instantaneous dynamical unbinding. In our simulations, however, this behavior emerges naturally from the hydrodynamic coupling between the inspiral and the global envelope response, without requiring an explicit separation between instantaneous and stationary ejection phases. In this regime, shocks, circulation flows, and large-scale expansion can redistribute deposited energy and angular momentum more efficiently throughout the star (Figure 5.2).

The simulations explored here therefore appear to probe a progression in hydrodynamic behavior with increasing donor central concentration. At low concentration, the evolution is dominated by rapid inspiral driven by strong local drag with comparatively limited global envelope response (Figure 5.4). At intermediate concentration, the slowing inspiral allows increasingly efficient hydrodynamic communication throughout the donor, driving large-scale expansion and efficient envelope ejection (Figure 5.5). At still larger central concentration, the development of a strongly condensed inner structure increasingly decouples the inspiral from the outer envelope, reducing communication between the inner and outer regions of the star and returning the interaction toward the more classical extended-envelope regime in which the final outcome depends sensitively on where the companion ultimately parks within the donor (e.g., [Ohlmann et al., 2016](#)).

A final important caveat is that essentially all of the hydrodynamic regimes discussed here assume that the embedded companion behaves as a point mass throughout the interaction. In reality, the survival of the companion may itself depend sensitively on its internal structure and compactness (e.g., [Twum et al.,](#)

2026). Extended main-sequence companions may undergo tidal disruption or substantial mass loss before reaching the deepest stages of inspiral, potentially altering or even terminating the subsequent hydrodynamic evolution (Figures 5.4 and 5.5). Consequently, the mass-ejection histories and large-scale envelope responses identified here may not only reflect the structure of the donor, but, in systems where the interaction appears to terminate prematurely, could also provide indirect constraints on the compactness and survivability of the embedded companion.

5.4.3 Implications for Envelope Ejection and Luminous Red Novae

The current understanding of luminous red novae increasingly favors a picture in which the observed diversity of LRNe reflects the complex and time-dependent hydrodynamic evolution of the binary interaction itself rather than a single universal ejection mechanism (Kaminski and Blagorodnova, 2026). In particular, observations increasingly point toward prolonged pre-maximum mass loss, multiple ejection episodes, and extended interaction between successive outflows, implying that the envelope response can remain dynamically active over many orbital or dynamical timescales. This emerging observational framework aligns naturally with the hydrodynamic complexities we have identified for donors spanning different evolutionary states and central density concentrations.

The simulations presented here suggest that the time dependence of mass ejection may be as important observationally as the total ejecta mass itself. In systems with relatively low central density concentration, where the evolution is dominated by rapid inspiral and strong local drag (MacLeod and Ramirez-

Ruiz, 2015a; MacLeod et al., 2017a; Rosselli-Calderon et al., 2024; Yarza et al., 2023), the envelope response remains closely tied to the instantaneous release of orbital energy, producing comparatively impulsive mass ejection on dynamical timescales, similar to the rapid plunge-in behavior seen in lower-concentration or polytropic-envelope simulations (Passy et al., 2012; Ricker and Taam, 2012b). At intermediate central concentration, however, the slowing inspiral allows increasingly efficient hydrodynamic communication throughout the donor, leading to prolonged expansion-driven evolution in which the envelope itself continues driving mass loss long after the rapid plunge-in phase has slowed substantially (Figure 5.5). In this regime, the outflow transitions from a predominantly impulsive ejection event toward a more sustained wind-like or multi-stage mass-loss history.

The importance of the mass-ejection history is also emphasized by LRN light-curve modeling, which shows that the observable properties of these transients depend sensitively on the ejecta mass, velocity, launching radius, and the interaction between dynamically ejected material and pre-existing outflows (Matsumoto and Metzger, 2022b). At still larger central concentration, corresponding to the highly extended giant envelopes explored in many previous common-envelope simulations (Iaconi et al., 2017, 2018; Lau et al., 2022; Ohlmann et al., 2016; Reichardt et al., 2019), the inspiral timescale again becomes long compared to the local dynamical time of the envelope, and the evolution returns to a regime in which envelope ejection proceeds gradually over many dynamical timescales before the companion reaches the deepest layers of the donor (MacLeod et al., 2022; Twum et al., 2026).

This progression in hydrodynamic behavior may therefore provide a natural framework for understanding the diversity of luminous red nova outbursts (Kaminski and Blagorodnova, 2026; Matsumoto and Metzger, 2022b; Twum et al., 2026). In this picture, the observable properties of LRNe depend not only on the total

ejecta mass (e.g., MacLeod et al., 2017b), but also on the temporal structure of the outflow itself, including whether the interaction produces an impulsive shell, a prolonged wind-like phase, or multiple successive ejection episodes. Systems in the intermediate regime identified here may be particularly well suited for generating long-lived outbursts, extended photospheric evolution, and complex circumstellar environments powered by continued shocks and interaction between successive phases of mass ejection.

5.5 Comparison Simulations at Fixed Stellar Central Concentration

To further isolate the role of donor central concentration, we compare simulations involving stars with substantially different masses and evolutionary states but similar values of $\rho_c/\bar{\rho}$. Figure 5.7 compares the inspiral evolution and cumulative mass ejection for two such pairs of systems: a $1.58M_\odot$ donor with $\rho_c/\bar{\rho} \approx 260$ compared to the $18M_\odot$ donor, and a $3.97M_\odot$ donor with $\rho_c/\bar{\rho} \approx 940$ compared to the $2.14M_\odot$ donor. All models shown correspond to the $q = 0.1$ simulations.

Despite large differences in donor mass, radius, and detailed stellar structure, systems with similar values of $\rho_c/\bar{\rho}$ exhibit remarkably similar hydrodynamic evolution. In the lower-central-concentration comparison pair ($18M_\odot$ and $1.58M_\odot$), both systems undergo continued inspiral toward the inner regions of the donor with comparatively limited prolonged expansion-driven evolution. By contrast, the higher-central-concentration pair ($2.14M_\odot$ and $3.97M_\odot$) both transition into quasi-stationary orbital evolution accompanied by sustained expansion-driven mass loss after the rapid plunge-in phase. In both comparison pairs, the overall inspiral

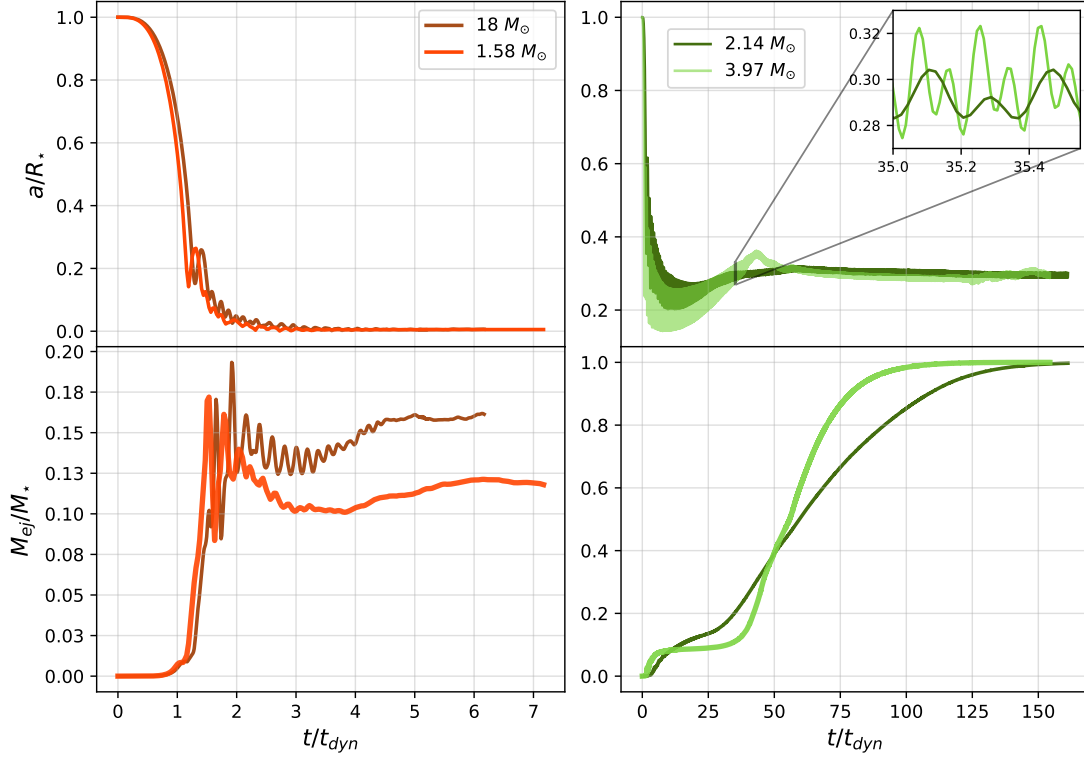


Figure 5.7: Comparison of simulations involving donors with similar central density contrasts but substantially different masses and evolutionary states. Top panels show the orbital separation evolution normalized by the donor radius, while bottom panels show the cumulative unbound mass fraction normalized by the total donor mass as a function of time normalized by the donor dynamical timescale. Despite significant differences in stellar mass and detailed envelope structure, systems with similar values of $\rho_c/\bar{\rho}$ exhibit qualitatively similar inspiral morphologies and mass-ejection histories, supporting the interpretation that donor central concentration regulates the global hydrodynamic response during common-envelope evolution.

morphology and character of the mass-ejection history closely resemble one another once normalized by the donor dynamical timescale, stellar radius, and total mass.

Importantly, realistic stellar models with similar values of $\rho_c/\bar{\rho}$ are not structurally self-similar. Unlike polytropic stellar models, which are self-similar by construction, realistic stellar evolution models with comparable values of $\rho_c/\bar{\rho}$ can possess substantially different density gradients, entropy profiles, and envelope structures. The similarity of the resulting hydrodynamic evolution therefore suggests that the central-to-average density ratio captures a physically important aspect of how the donor envelope couples to the inspiraling companion and redistributes deposited energy and angular momentum during the interaction.

The most significant differences between the comparison models appear primarily in the late-time mass-ejection histories. In particular, the more centrally concentrated systems develop prolonged expansion-driven evolution that can continue ejecting mass long after the rapid inspiral phase has slowed substantially. Nevertheless, the overall qualitative agreement between systems with similar $\rho_c/\bar{\rho}$ supports the interpretation that donor central concentration acts as a key organizing parameter governing the global hydrodynamic response during common-envelope evolution.

5.6 Donor Structures in Previous Common-Envelope Simulations

The initial donor masses and radii adopted in previous global common-envelope simulations are summarized in Figure 5.8. Existing calculations have predominantly focused on evolved RGB, AGB, and red-supergiant donors with large radii and

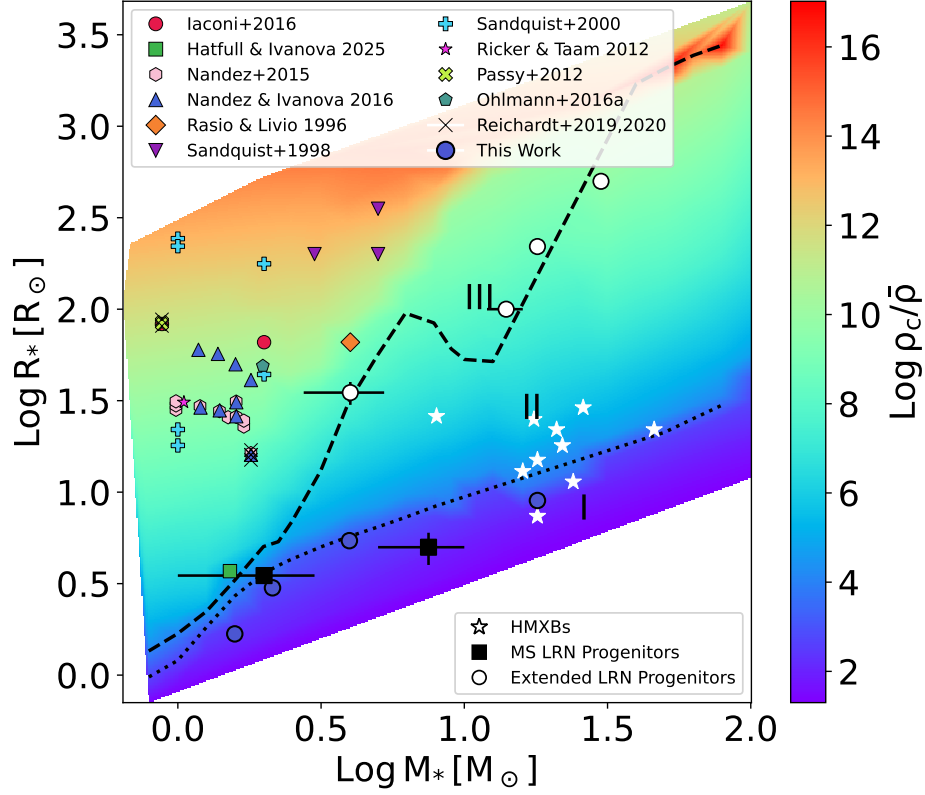


Figure 5.8: Initial donor masses and radii adopted in previous global common-envelope simulations compared to the donor models studied in this work (*blue circle* symbols). Literature simulations primarily probe evolved RGB, AGB, and red-supergiant donors with large radii, while the present models occupy a distinct regime of mildly evolved progenitors with intermediate central concentration. The masses and radii of eclipsing high-mass x-ray binaries studied by Falanga et al. (2015b) are shown as white star symbols. The background color indicates the central-to-average density ratio, $\rho_c/\bar{\rho}$, highlighting that the present study explores a region of donor structure that has been comparatively underrepresented in previous three-dimensional common-envelope calculations. The dotted and dashed lines delineate the three evolutionary regimes identified by Twum et al. (2026). Binary population demographics based on the Sana et al. (2012) initial binary distributions suggest that approximately 27.4%, 11.7%, and 58.2% of systems undergoing unstable mass transfer populate Zones I, II, and III, respectively. Observed LRN progenitors with pre-explosion imaging are plotted for comparison (Matsumoto and Metzger, 2022a). From left to right, in order of increasing inferred mass, these include V1309 Scorpii, M31LRN2015, V838 Monocerotis, M101-OT2015, SN Hunt248, and AT 2018bwo. These progenitors are either main-sequence progenitors (*black squares*; Zone I) or extended progenitors (*white dots*; Zones II and III).

strongly stratified envelopes (Iaconi et al., 2017, 2018; Nandez and Ivanova, 2016; Nandez et al., 2015; Passy et al., 2012; Rasio and Livio, 1996; Reichardt et al., 2019, 2020; Ricker and Taam, 2012b; Sandquist et al., 2000). By contrast, the mildly evolved progenitors studied in this work occupy a comparatively underexplored region of parameter space, with smaller radii at fixed mass and intermediate central concentration.

This distinction is important because the hydrodynamic response to inspiral depends not only on the total envelope binding energy, but also on how the donor structure regulates the redistribution of deposited energy and angular momentum during and after the dynamical plunge-in phase. In highly extended giant envelopes, the inspiral often evolves toward a regime in which the companion becomes increasingly decoupled from the outer envelope as the local density rises and the inspiral slows near the condensed inner regions of the donor. By contrast, the moderately evolved progenitors considered here remain sufficiently coupled to the global envelope.

The background color in Figure 5.8 indicates the central-to-average density ratio, $\rho_c/\bar{\rho}$, illustrating how the present models bridge the transition between low-concentration structures and the highly stratified envelopes of classical giant-star common-envelope simulations. The intermediate regime studied here appears particularly favorable for prolonged expansion-driven mass loss and efficient global hydrodynamic response, phenomena that are less apparent in both the low-concentration rapid-inspiral limit and the highly stratified giant-envelope regime. The figure also highlights the three qualitative evolutionary regimes identified by Twum et al. (2026).

Part II

The Evolution of Galactic Bar Structure

Chapter 6

Galaxy Zoo Bar Lengths: A Catalogue of Measurements from *Hubble Space Telescope* Images and the Evolution of Galactic Bar Structure at $z < 1$

Abstract

Understanding the role of galactic scale bars in disk galaxy evolution requires detailed measurements of bar properties across galaxies hosting bars at many redshifts. We present measurements of bar lengths and widths in a sample of 8230 disk galaxies from *Hubble Space Telescope* (*HST*) Legacy surveys. The highest-redshift barred galaxies in the sample have $z \sim 3$; most have $z \leq 1$. Using a mass-complete sample from the COSMOS field, we examine bar properties and

evolution within $0.25 < z < 1$ in galaxies with stellar mass $\log(M_*/M_\odot) \geq 9.5$. The lowest-mass galaxies in our sample have similar star formation rate (SFR) distributions whether or not they host bars. For galaxies with $\log(M_*/M_\odot) \geq 10$, barred galaxies are more likely to be quiescent or quenched, consistent with bars mainly participating in slow quenching processes. The median physical bar length increases with increasing stellar mass. Relative bar lengths and widths (as a fraction of disk radius) peak at stellar mass $\log(M_*/M_\odot) \sim 10.25$, and change together with mass such that the median ratio, a proxy for bar strength, does not significantly change with stellar mass. Bars in our sample tend to be slightly ($\approx 13\%$) weaker at higher redshift. Quiescent and quenching galaxies have longer and wider bars than those in galaxies on or above the star-forming sequence, especially at lower redshift and higher masses; at the low-mass end of our sample, starburst galaxies host relatively longer and stronger bars. Our findings are consistent with other results from studies at both higher and lower redshift, cementing the fundamental importance of bars in disk galaxy evolution.

6.1 Introduction

Galactic-scale bars, which are found in a significant fraction of disk galaxies out to at least $z \sim 4$ (from over 50% at $z \leq 0.5$ to $\sim 14\%$ at $2 < z < 3$; *e.g.*, Geron et al., 2025; Le Conte et al., 2024; Sheth et al., 2008), seem to be engines of galaxy evolution in several ways. In simulations, the density of the host dark matter halo significantly affects the bar rotation speed (Debattista and Sellwood, 1998), and bars can stabilize their host disks over long evolutionary times (for reviews of bar dynamics, see Athanassoula 2013 and Sellwood 2014). Both simulations (*e.g.*, Kraljic et al., 2012) and observations (*e.g.*, de Sá-Freitas et al., 2025) find that

most bars are long-lived (> 1 Gyr). Bars can exchange angular momentum with other baryonic components in the galaxy, including stars and gas both inside the bar region and in galaxy rings, contributing to the formation of spiral arms and overall disk galaxy evolution (Athanasoula, 2003; Bournaud et al., 2005; Pfenniger and Friedli, 1991; Sellwood, 1981; Sparke and Sellwood, 1987). Bars may also exchange angular momentum with the halo (Athanasoula, 2003; Debattista and Sellwood, 1998), although this may not be a significant effect in the latter half of the Universe (Pérez et al., 2012). Bars also contribute to supermassive black hole growth (Galloway et al., 2015; Garland et al., 2024).

Observationally, bars tend to be found in redder disk galaxies (Masters et al., 2011; Nair and Abraham, 2010), and barred galaxies are more gas-poor than disk galaxies at similar stellar masses and colors (Masters et al., 2012). This effect may be stronger in galaxies with stronger bars, possibly because stronger bars are more efficient at angular momentum exchange and gas consumption (Buta et al., 2005). For example, bars are associated with increased supermassive black hole accretion (Galloway et al., 2015; Garland et al., 2024). The presence of a bar may also affect the break structure of the host disk, especially in systems with smaller bulges (Kim et al., 2014). In local galaxy studies, bars appear different in late-type and early-type disks (Aguerri et al., 2009; Erwin, 2005; Hoyle et al., 2011; Laurikainen et al., 2007), and bars seem to have more local than global influence on their host galaxies (Seidel et al., 2015), particularly on stars and gas in the nuclear region (Seidel et al., 2016). In the overall disk galaxy population, the fraction of galaxies with bars varies with redshift, stellar mass, and star formation rate (*e.g.*, Cameron et al., 2010, and references therein).

Despite the fraction of bars in disk galaxies being well-studied in the local Universe and out to relatively high redshift (Abraham et al., 1999; Cameron et al.,

2010; de Vaucouleurs et al., 1991; Elmegreen et al., 2004; Espejo Salcedo et al., 2025; Euclid Collaboration et al., 2025b; Geron et al., 2025; Guo et al., 2025; Jogee et al., 2004; Le Conte et al., 2024; Masters et al., 2012; Melvin et al., 2014; Nair and Abraham, 2010; Sheth et al., 2008; Simmons et al., 2014), detailed studies of bar length and strength have been more limited to the local Universe (Erwin, 2005; Hoyle et al., 2011; Kim et al., 2014) until relatively recently (Kim et al., 2021; Le Conte et al., 2025). Most findings indicate no, or little, evolution in bar lengths, which may be due at higher redshift to more complex bar origins (Fragkoudi et al., 2025; Kraljic et al., 2012). Here we select a sample of 8,230 disk galaxies using Galaxy Zoo morphological classifications of *Hubble Space Telescope* legacy surveys (Simmons et al., 2017; Willett et al., 2017), then measure and examine their detailed bar properties.

In Section 6.2 we describe the selection of a sample of disk galaxies and measurement of bar properties. In Section 6.3 we select a subset of these galaxies from the COSMOS survey and describe the ancillary data used in subsequent analysis. We present and discuss our results in Sections 6.4 and 6.5. Throughout this paper all cross-matched catalogues use the nearest positional match within $3''$, we use the AB magnitude system, and where necessary we adopt a cosmology consistent with Λ CDM, with $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega = 0.7$ (Bennett et al., 2013).

6.2 Galaxy Zoo Bar Lengths

Galaxy Zoo Hubble (GZH; Willett et al., 2017, hereafter W17) collected detailed morphological classifications of 119,849 galaxies originally imaged in 4 legacy surveys (GOODS, Giavalisco et al. 2004; GEMS, Rix et al. 2004; COSMOS,

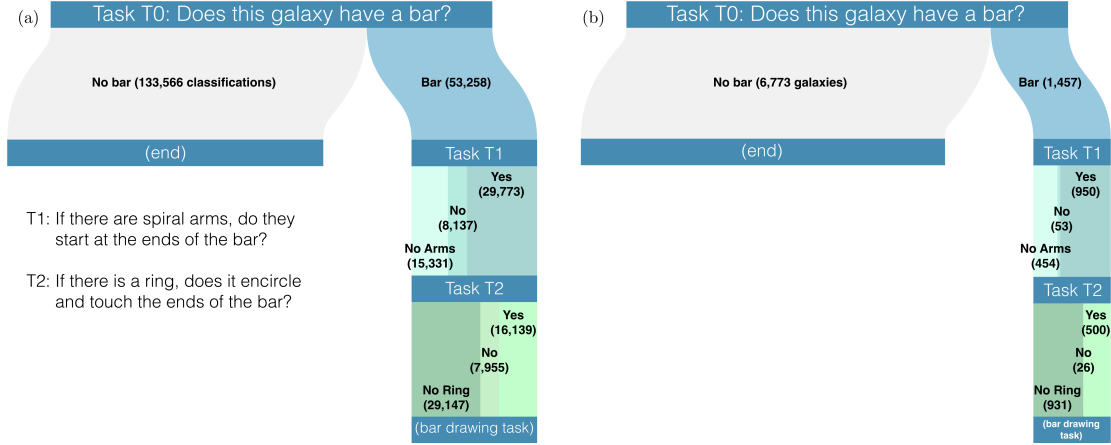


Figure 6.1: Demographics of the Galaxy Zoo Bar Lengths sample, based on (a) raw classification counts and (b) plurality classification for each galaxy. In each panel, the full classification tree (Table 1) is shown. Each node in each diagram (dark blue horizontal bars with white text inset) represents a task in the classification tree. The paths between tasks represent each possible answer to the task above it, and they flow to the next task shown to a classifier who gives that response. From the initial task, the classification ends if the classifier indicates the galaxy is unbarred; otherwise, they answer two further questions and complete a drawing task, with no further branches of the classification tree. In panel (a) on the left, the width of each path is proportional to the number of raw classifications received for each response, for any galaxy. In panel (b) on the right, we apply a label to each galaxy based on the plurality (highest vote fraction) answer to each task, with ties broken by entering the galaxy into the “Yes” category for that task. For example, in panel (b), a galaxy is considered barred if at least 50% of classifiers answered “Yes” to task T0. For a task with more than 2 answer choices, the plurality need not reach the 50% threshold. This visualization is a useful overview of the morphologies of the disk galaxies in this dataset.

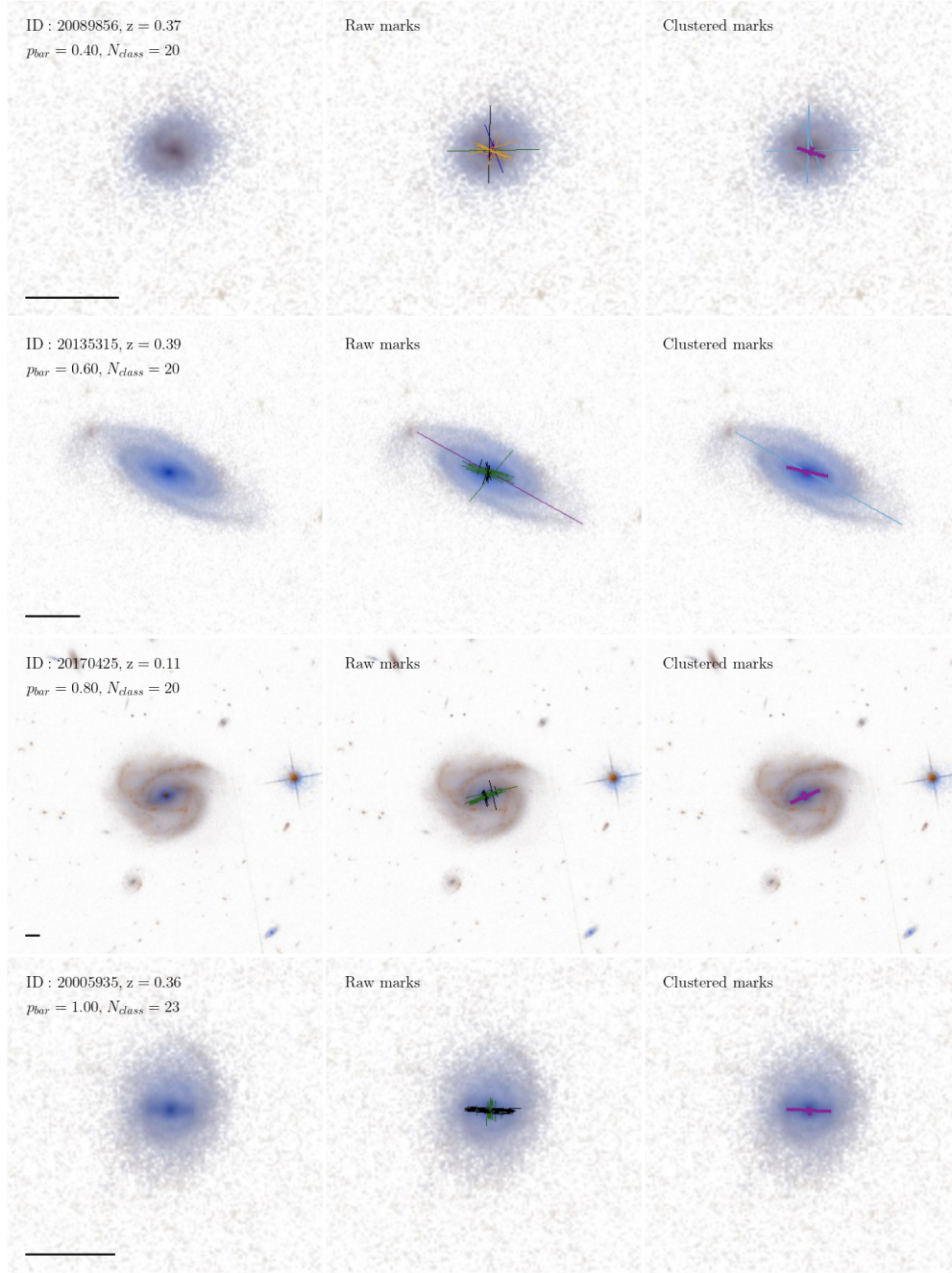


Figure 6.2: Example images from the Galaxy Zoo Bar Lengths project (left column), with markings by individual classifiers shown as thin lines (middle column) and clustered markings of bar length and width shown in thick purple lines (right column). Marks in the middle column are color-grouped by final cluster membership. Light blue marks in the right column indicate low-confidence clusters (typically containing outlier marks). Agglomeration with median combination of line parameters is robust to outliers that *do* fall within a high-confidence cluster and often produces accurate measurements even at values of p_{bar} below our selection threshold (*e.g.*, top row).

Table 6.1: Main workflow for Galaxy Zoo Bar Lengths.

Task	Question	Responses	Next
T0	<i>Does this galaxy have a bar?</i>	Yes	T1
		No	end
T1	<i>If there are spiral arms, do they start at the ends of the bar?</i>	Yes	T2
		No	T2
		No spiral arms	T2
T2	<i>If there is a ring, does it encircle and touch the ends of the bar?</i>	Yes	T3
		No	T3
		No ring	T3
T3	<i>Draw 1 line through the length and 1 line through the width of the bar.</i>	(line markings)	end

Note. All classifiers answer the initial task; if a classifier indicates that a bar is present, they are asked to further classify the spiral arms (if present), ring (if present), and then to draw the length and width of the bar on the galaxy image. At each stage, classifiers have access to “Help” text with further description and example images.

Scoville et al. 2007; AEGIS, Davis et al. 2007). The GZH project identifies galaxies with bars, but does not otherwise measure the properties of bars. The same is the case for the Galaxy Zoo CANDELS project (GZC; Simmons et al., 2017, hereafter S17), which classified galaxies at rest-frame optical wavelengths to higher redshift using images from CANDELS (Grogin et al., 2011; Koekemoer et al., 2011). We used the GZH and GZC classifications to select a sample of disk galaxies within which additional bar properties could potentially be measured.

To select this subsample of galaxies from GZH, we used an early version of the weighted vote fractions published in W17 and S17. Following previous studies that examined barred galaxies in different Galaxy Zoo samples (Galloway et al., 2015; Masters et al., 2012; Melvin et al., 2014; Simmons et al., 2014), we selected galaxies that classifiers had marked as likely not-edge-on disk galaxies in the first two questions in the GZH or GZC question tree (we used the same questions in each tree). Specifically, we required that a galaxy be marked as having “features” by at least 40% of weighted classifiers, $p_{\text{features}} \geq 0.4$, and that at least half of

classifiers had indicated the galaxy was not edge-on, $p_{\text{not-edge-on}} \geq 0.5$. We further selected galaxies where there was at least some indication that the galaxy might have a bar, $p_{\text{bar}} \geq 0.2$. These selections are intended to be relatively inclusive to allow for more conservative subsequent selections, while also minimising the inclusion of subjects for which asking classifiers about bar properties would be nonsensical. These requirements resulted in the selection of 8,230 galaxies (5,965 from GZH-COSMOS, 906 from GZH-AEGIS, 610 from GZH-GEMS, 367 from GZH-GOODS, and 382 from GZC).

The detailed bar-related properties of this disk galaxy sample were collected in the Galaxy Zoo Bar Lengths (GZBL) project¹, created using the Zooniverse Project Builder². The project presented volunteer classifiers with a galaxy image, which could be toggled to display an inverted-colormap image. These galaxy images were duplicates of the color images presented in their origin GZ projects, except further zoomed in to focus on each galaxy (by 40% for GZH images and 60% for GZC images). Each classifier was asked to complete up to 4 tasks for each galaxy. First, classifiers were asked to confirm whether the galaxy had a bar. If the classifier indicated the galaxy was unbarred, another galaxy was presented. If the classifier said the galaxy was barred, they were then asked further questions about the bar’s relation to spiral arms (if present) and a ring (if present), and then asked to draw lines on the image to mark the bar’s length and width. The classifier could optionally access “Help” text including examples of each galaxy type and bar markings. The full bar-length measurement workflow for the project is listed in Table 6.1.

The GZBL project launched on the 28th of July, 2015, with the goal of collecting

¹zooniverse.org/projects/vrooje/galaxy-zoo-bar-lengths/

²zooniverse.org/lab

at least 20 classifications per galaxy image. Between the launch date and the 14th of January, 2016, GZBL collected 171,206 classifications from 2,694 registered classifiers and 730 not-logged-in IP addresses. (Each unique not-logged-in IP address was treated as a distinct classifier in our analysis.) A subsequent workflow, active between the 18th of February and the 13th of April, 2016, collected 10,952 further bar markings (task T3 only) for 1,336 subjects with marginal bar vote percentages p_{bar} for the initial task, such that further markings were required to confidently identify the consensus bar measurement. Overall, the project collected 187,431 bar-length workflow classifications of 8,230 galaxies from GZC (382 galaxies) and GZH (7,848 galaxies) over an approximately 9-month period. Of these, 607 (0.3%) were duplicate classifications of the same subject by the same classifier, and were removed from subsequent analysis. Excluding duplicate classifications, the average classification count per subject was 22.7; the median was 21. The overall distribution of classifications for the full sample is shown in Figure 6.1.

Following the completion of the classification phase of the project for this workflow, the classifications were combined to produce an aggregated classification for each galaxy. For the question tasks (T0, T1, and T2), we computed the percentage of classifiers who gave each possible answer. For the drawing task (T3), we used agglomerative clustering to compute the bar lengths and widths. Specifically, we used a hierarchical method with the Ward distance indicator to cluster line markings based on (x_1, y_1, r, θ) , where (x_1, y_1) is the image coordinate of the leftmost endpoint of the line segment, r is the length of the line, and θ is the angle between the line and the $+x$ axis. The distance that defines a cluster of line markings for each galaxy, d_{max} , is defined to be the maximum distance at which the number of markings in any cluster does not exceed the number of classifiers who were presented with the marking task.

For each cluster, we use the fraction of classifiers whose marks ended up in that cluster as a measure of cluster reliability, and consider only clusters where more than 30% of classifiers’ markings are included to be real clusters. In 81% of galaxies where at least 6 classifiers were asked to measure bar lengths, this clustering method and reliability selection returns 2 clusters of line markings, which we take to indicate the bar length and width. In more rare cases where there are 3 or more clusters for a galaxy, we rank the clusters according to the fraction of classifiers’ line marks included in the cluster, considering only the 2 most reliable clusters in further analysis.

In each cluster, we combine markings by using the median of each of the (x_1, y_1) and (x_2, y_2) coordinates denoting each line endpoint. Using the median of the markings generally leads to bar lengths and widths that are within 10 degrees of perpendicular. We take the marking with the longest length to be the bar length, and the shortest to be the bar width.

Figure 6.2 shows examples of galaxies with individual classifier markings and aggregated markings. We also visually inspected all 7,608 galaxies with bar markings, to assess overall data quality. The quality of marks is generally very high, consistent with a past Galaxy Zoo study of bar lengths at lower redshift using ground-based data (Hoyle et al., 2011). The Ward distance used in our agglomerative clustering, as well as the method chosen to determine d_{max} , tend to include some marks which are moderate outliers in the main clusters. Taking the median of values within a cluster is far more effective at avoiding outlier influence than using mean values.

For example, out of the 500 disk galaxies with the highest combined “bulge prominence” (a weighted combination of all possible responses to the Galaxy Zoo question assessing the strength of a central bulge in not-edge-on, featured galaxies;

see [Masters et al. 2019](#) for its first use), approximately 25% of images had some (typically one or two) outlier marks where classifiers missed or misinterpreted the project’s explicit instructions to ignore the bulge in the bar markings. Of those, only 12 galaxies (2.4%) had a clustered width measurement that differed from an expert (BDS) assessment of width; those differences were small ($< 5\%$). Length measurements were unaffected. Given that this subset of galaxies is among the most likely to show outlier contamination, our overall outlier contamination is likely considerably below this level ($< 2\%$, based on further spot checks).

The aggregated classifications for each galaxy are shown in Table 6.2. We report the Zooniverse subject ID for each galaxy as well as its ID in the original Galaxy Zoo project from which the galaxy image was drawn (*i.e.*, either GZH or GZC). We also report the pixel scale of the classified color images and the URLs for both the standard and inverted images presented in the classification interface. The latter are included in the full version of the tables at <http://data.galaxyzoo.org> but are not printed in the manuscript table due to their length.

For the question tasks, the column name contains the task number and a readable description of the question and relevant quantity. For example, in the first task (T0; “Does this galaxy have a bar?”), we report the fraction of classifiers who indicated the galaxy does have a bar (“Yes”), the fraction of classifiers who indicated the galaxy does not have a bar (“No”), and the total number of classifiers who answered the question. The three column names for this question thus are:

`t0_has_bar_yes_frac`

`t0_has_bar_no_frac`

`t0_has_bar_count`

Table 6.2: Classifications and bar measurements for the full sample galaxies classified in the bar-length workflow in the Galaxy Zoo Bar Lengths project.

DATA COLUMN NAME	SUBJECTS					
subject_id	466952	466954	466955	472198	472199	492867 ...
OBJID_prev_GZ	20041145	20041171	20041181	50013522	50013555	GDS_18760 ...
RA	149.9273072	149.9484361	149.9686391	188.9995104	189.1104491	53.0452995 ...
Dec	1.9383032	1.9321485	1.9306812	62.2397809	62.314795	-27.7441006 ...
scale_arcsec_per_pixel	0.01011	0.01011	0.01289	0.02241	0.01205	0.00849 ...
n_class_total	19	20	22	21	20	25 ...
t0_has_bar_count	19	20	22	21	20	25 ...
t0_has_bar_yes_frac	0.47	0.55	0.0	0.24	0.55	0.12 ...
t0_has_bar_no_frac	0.53	0.45	1.0	0.76	0.45	0.88 ...
t1_spiral_arms_attached_count	9	11	0	5	11	3 ...
t1_spiral_arms_attached_yes_frac	1.0	0.91		0.6	0.18	0.0 ...
t1_spiral_arms_attached_no_frac	0.0	0.0		0.2	0.09	0.67 ...
t1_spiral_arms_attached_no_spiral_arms_frac	0.0	0.09		0.2	0.73	0.33 ...
t2_ring_attached_count	9	11	0	5	11	3 ...
t2_ring_attached_yes_frac	0.33	0.36		0.6	0.0	0.33 ...
t2_ring_attached_no_frac	0.11	0.27		0.0	0.09	0.0 ...
t2_ring_attached_no_ring_frac	0.56	0.36		0.4	0.91	0.67 ...
t3_bar_length_class_count	10	10	0	5	11	3 ...
n_lines_highprob	3	2	0	2	2	2 ...
length_p_true_positive	0.60	1.0		1.0	0.82	1.0 ...
length_x1	209.4	196.2		184.4	186.0	175.4 ...
length_y1	236.2	262.1		209.0	225.0	188.0 ...
length_x2	247.9	249.7		222.2	241.1	231.6 ...
length_y2	157.3	135.8		206.0	232.0	231.0 ...
angle_length	-17.7	67.0		4.5	-8.2	-37.4 ...
length_line_dist_pix	87.8	137.2		37.9	55.5	70.8 ...
width_p_true_positive	0.6	1.0		1.0	0.91	1.0 ...
width_x1	216.9	197.1		203.4	212.3	194.4 ...
width_y1	204.5	186.0		201.1	237.5	216.8 ...
width_x2	230.9	258.6		204.4	219.2	216.4 ...
width_y2	186.0	203.5		214.1	218.0	192.0 ...
angle_width	50.8	-15.9		-85.6	64.1	48.4 ...
width_line_dist_pix	23.2	63.9		13.0	20.7	33.1 ...
angle_length_width	68.5	82.9		90.1	72.3	85.8 ...
bar_length_arcsec	0.887	1.387		0.850	0.669	0.601 ...
bar_width_arcsec	0.235	0.646		0.292	0.249	0.281 ...
i_gal	61.4	10.1	43.2	42.9	43.7	31.3 ...
delta_bar	4.0	81.9		23.3	-55.4	-52.2 ...
psi_bar	72.5	-1.0		-66.8	16.9	33.6 ...
length_deproject_factor	1.008	1.016		1.066	1.272	1.110 ...
width_deproject_factor	2.015	1.000		1.315	1.038	1.055 ...

Note. The data for each galaxy includes information that can be used to uniquely identify it in several data sets (this project as well as the earlier versions of Galaxy Zoo from which each galaxy was selected), the pixel scale of the images presented for classification in the project, the classification counts and fractions for each question in the classification tree, and information on the clustered bar measurements, including the bar length and width, where enough classifiers indicated the presence of a bar and marked its length and width to allow the agglomerative clustering to produce a result (where this is not the case, the values are blank). The complete version of this table is available in electronic form and at <http://data.galaxyzoo.org>. The printed table shows a transposed subset of the full table to illustrate its format and content. The complete version also includes the URLs for the galaxy images classified.

For the line measurement task (T3), we report the number of classifiers who marked the galaxy image and the number of clustered line measurements resulting from the agglomerative clustering described above. For galaxies where a bar length and width was measured, we report for both bar length and width the number of marks in that cluster as a percentage of the number of classifiers who were presented with the marking task (an indication of the likelihood the cluster is reliable), the clustered endpoint coordinates, the distance between endpoint coordinates of each line in pixels, and the angle (in degrees) between the bar length and width lines. We additionally use the pixel scale of each image to convert the bar length and width measurements to arcseconds, and report these as `bar_length_arcsec` and `bar_width_arcsec`. As described above, all coordinates use the median of the individual marks in the cluster.

6.2.1 Correction for projection effects

Assuming disk galaxies would be observed as circular if viewed face-on, it is possible to de-project the measured bar lengths and widths using the angle of inclination (i) of the disk relative to the plane of the sky, the angle of the observed disk major axis (θ) and the angles of the measured bar length (α) and width (β). Defining the relative difference between the bar length and disk major axis as $\delta \equiv \alpha - \theta$ and the relative width angle as $\psi \equiv \beta - \theta$, the factor required to correct the bar length for projection effects is

$$f_{\text{length}} = \sqrt{\cos^2 \delta + \frac{\sin^2 \delta}{\cos^2 i}},$$

and similarly for the width

$$f_{\text{width}} = \sqrt{\cos^2 \psi + \frac{\sin^2 \psi}{\cos^2 i}}.$$

In general, we use θ and i values derived from position angles and axis ratios from the ACS-GC catalog (Griffith et al., 2012), which provides a relatively uniform set of measurements across the different fields of the *HST*-ACS legacy surveys. The angles are measured from fitted light profiles (using GALFIT; Peng et al., 2002, 2010a), which are often less affected by bright asymmetric features (such as bars) than other methods of determining angles, centroids and sizes. These values were verified by comparing them to those measured using Source Extractor (Bertin and Arnouts, 1996) in the different surveys where available (Caldwell et al., 2008; Giavalisco, 2012; Leauthaud et al., 2007). Where the values differed substantially (3% of galaxies with high-confidence bar markings), each image was visually assessed and the survey catalog values were used if the ACS-GC values were obviously incorrect. For GZC sources, which are not included in the ACS-GC, we used measurements from the survey catalogs (Galametz et al., 2013; Guo et al., 2013; Nayyeri et al., 2017). The values of `i_gal`, `delta_bar`, `psi_bar`, `length_deproject_factor` and `width_deproject_factor` are included in the GZBL catalog.

We present here the full catalog of classifications and bar measurements for the GZBL project so that readers can perform their own analyses, perhaps using different thresholds than we describe below. We recommend that those pursuing their own investigations with this data require a minimum number of bar markings in order to select a sample of bars (at whatever threshold) with high confidence

length and width measurements. We suggest a minimum of 6 classifiers must mark bar measurements for the clustering algorithm to work as expected. We further suggest that users set a reasonable threshold on the angle between length and width lines, *e.g.*, requiring that the lines be within $\pm 15^\circ$ of perpendicular.

6.2.2 Purity and completeness

In order to select barred galaxies, we choose a threshold of the bar vote percentage p_{bar} . In practice, this requires consideration of the trade offs between sample completeness (percentage of all barred galaxies that end up in our sample) and sample purity (percentage of galaxies in the selected sample that have bars). To assess purity and completeness in our sample, we performed expert classification on 500 galaxies selected from the full GZBL sample to uniformly span the full range of bar classifications, $0 \leq p_{\text{bar}} \leq 1$. Two classifiers (THS and BDS) independently visually examined each of the 500 galaxies and assigned a classification of barred or unbarred. The independent classifications between the expert classifiers agreed very well: we report the average of their classifications, but note our analysis would not change were we to have used one or the other.

We used these classifications to determine purity and completeness for samples selected using a threshold on p_{bar} . Figure 6.3 shows both purity and completeness of barred samples as a function of the threshold value used to select the sample. We choose a threshold of $p_{\text{bar}} = 0.5$ when selecting a barred sample below. Using this threshold value selects a sample that is $\sim 85\%$ complete and $\sim 87\%$ pure.

Applying this threshold selects 1,457 barred galaxies. We show bar length vs bar width for all barred galaxies in GZBL in Figure 6.4. The figure also shows the full width at half-maximum (FWHM) of the point-spread function (PSF) of

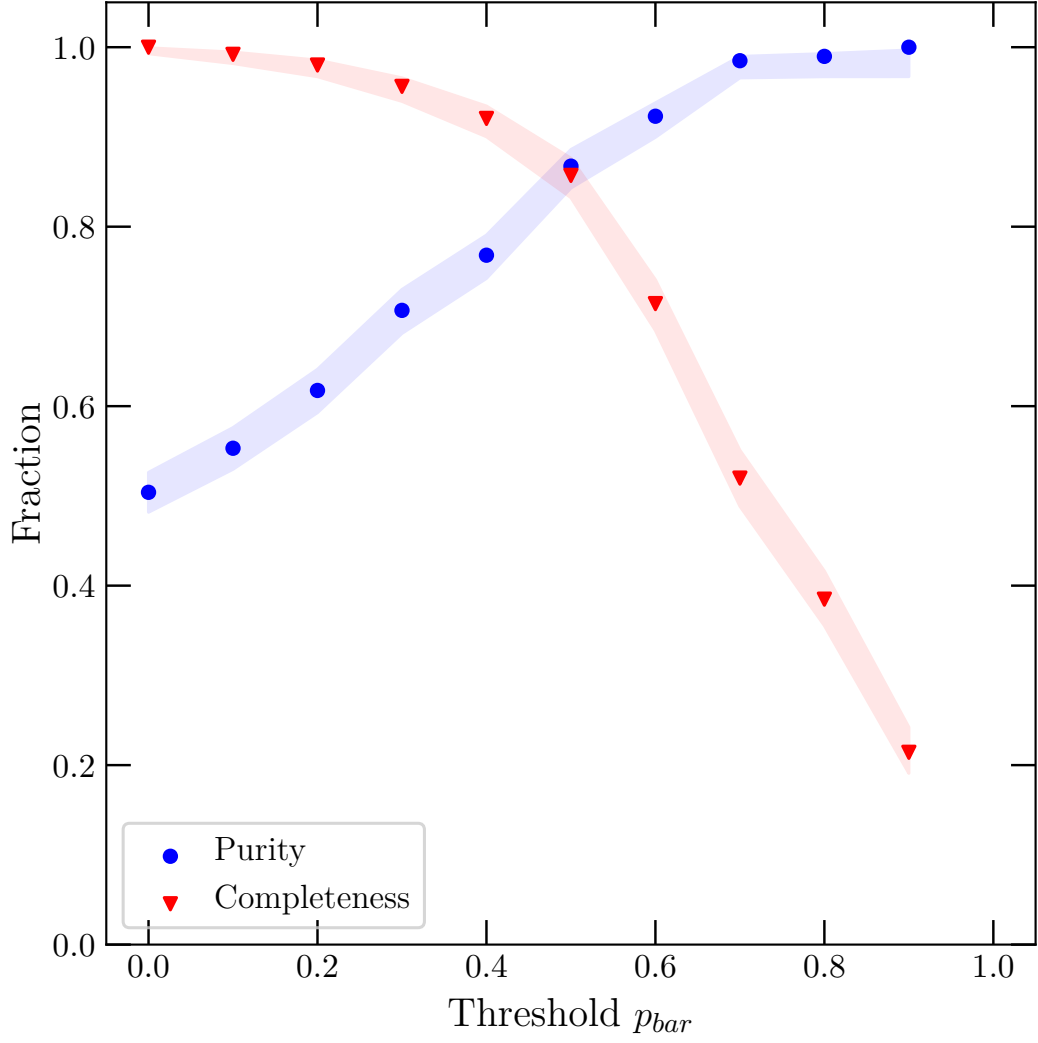


Figure 6.3: Purity (blue circles) and completeness (red triangles) of samples as a function of the p_{bar} threshold used to select the barred sample from within the full set of disk galaxies examined in Galaxy Zoo Bar Lengths. As the threshold is raised, the sample becomes more pure (less contaminated by unbarred galaxies) but less complete. Considering these tradeoffs, we choose a threshold of $p_{\text{bar}} = 0.5$ to select a barred galaxy sample.

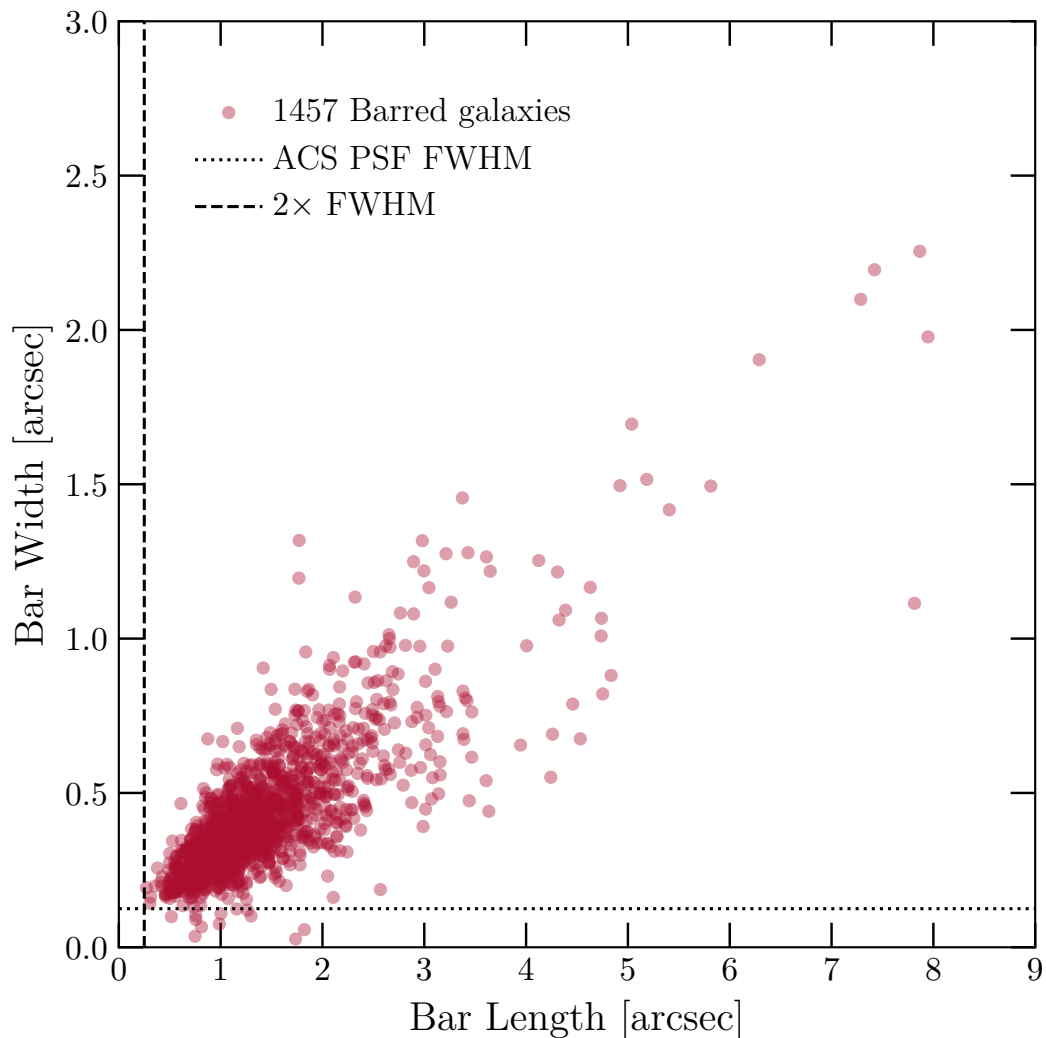


Figure 6.4: Bar width versus length for all bars in the Galaxy Zoo Bar Lengths project that meet the definition of barred described in Section 6.2.2. The dotted line at constant bar width shows the FWHM size of the *HST* ACS point-spread function, the minimum size we might expect to measure a bar width; the dashed line at constant length shows twice this value, the minimum size at which we would resolve a bar. Most bars are very well resolved. Bar length and width generally correlate, with a median length-width ratio of ~ 3 . From within the full sample of barred galaxies in GZBL we further analyze the subset that have well-measured additional properties from data sets in the COSMOS field (described further in Section 6.3).

the Advanced Camera for Surveys (ACS) in $I_{AB,F814W}$ as a line of constant width. The constant-length line is twice the FWHM, which indicates the minimum size at which we would expect to resolve a bar. A bar with a shorter length than this would likely not be detected. If a bar was long enough to be resolved but physically narrower than the PSF FWHM, its measured width would be limited to approximately the FWHM size. Most bars meeting the other measurement criteria described above are well resolved. We discuss resolution effects further in Section 6.5.

The median bar length is ~ 3 times the bar width, regardless of how large the galaxy appears on the sky. There is substantial range of values around the median, and axis ratio is an imperfect proxy for dynamically-defined bar strength. Nevertheless, this median axis ratio is that of a strong bar (Abraham and Merrifield, 2000; Jogee et al., 2004; Sheth et al., 2008), consistent with previous studies using this p_{bar} threshold to select barred galaxy samples (Galloway et al., 2015; Masters et al., 2011, 2012; Melvin et al., 2014).

Of those galaxies with $p_{\text{bar}} > 0.5$ and bar lengths and widths within $\pm 15^\circ$ of perpendicular, the highest-redshift galaxies in the catalogue have photometric redshifts (Hartley et al., 2013) $z \sim 2.8$, overlapping with the spectroscopically-confirmed high- z bars found in surveys using *JWST* (e.g., Guo et al., 2023; Le Conte et al., 2024). Owing in large part to the wavelength coverage of the largest *HST* surveys, most of the secure bar measurements in our catalogue have $z \leq 1$. Therefore, in the next section we choose a subset of the catalogue for further investigation.

The median bar length is ~ 3 times the bar width, regardless of how large the galaxy appears on the sky. There is substantial range of values around the median, and axis ratio is an imperfect proxy for dynamically-defined bar strength.

Nevertheless, this median axis ratio is that of a strong bar (Abraham and Merrifield, 2000; Jogee et al., 2004; Sheth et al., 2008), consistent with previous studies using this p_{bar} threshold to select barred galaxy samples (Galloway et al., 2015; Masters et al., 2011, 2012; Melvin et al., 2014).

Of those galaxies with $p_{\text{bar}} > 0.5$ and bar lengths and widths within $\pm 15^\circ$ of perpendicular, the highest-redshift galaxies in the catalogue have photometric redshifts (Hartley et al., 2013) $z \sim 2.8$, overlapping with the spectroscopically-confirmed high- z bars found in surveys using *JWST* (e.g., Guo et al., 2023; Le Conte et al., 2024). Owing in large part to the wavelength coverage of the largest *HST* surveys, most of the secure bar measurements in our catalogue have $z \leq 1$. Therefore, in the next section we choose a subset of the catalogue for further investigation.

6.3 COSMOS

Above we describe and present the whole data set for GZBL, which includes *HST* images from multiple surveys observing in non-uniform bands across multiple fields. For the analysis that follows we focus on the measurements made in the COSMOS ACS imaging data (Koekemoer et al., 2007; Leauthaud et al., 2007). The COSMOS ACS imaging used in the project has 0.05 arcsec/pixel resolution and covers approximately 1.8 square degrees in F814W to a depth of $I_{AB,F814W} = 27.2$ (5σ point-source depth). At $z \approx 1$, the minimum resolved size of features is approximately 1 kpc. Of the 8,230 total galaxies in GZBL, 5,965 are galaxies from the COSMOS ACS imaging. Of the total COSMOS subsample of disk galaxies, 1,083 are barred according to our criterion.

Considerable ancillary data exists for galaxies in the COSMOS field. We make

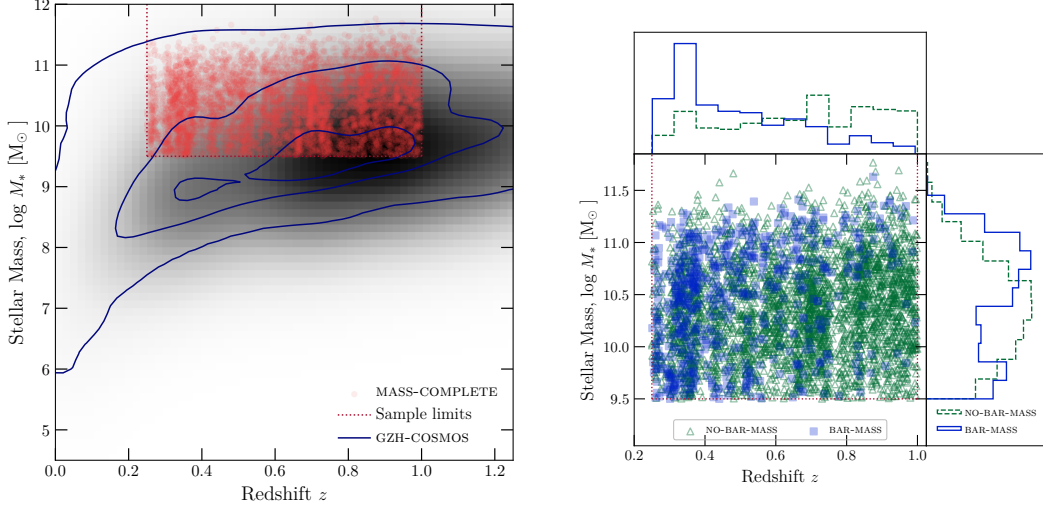


Figure 6.5: Rest-frame galaxy stellar mass versus redshift. At left, the full COSMOS sample used here (Section 6.3; Leauthaud et al., 2007; Muzzin et al., 2013a,b; Weaver et al., 2022) is shown as a grayscale density plot. Solid blue contours show the subset of COSMOS galaxies examined in the GZH project (W17). From this GZH-COSMOS parent sample, disk galaxies falling within the MASS-COMPLETE sample (limits drawn by the dotted red lines) are shown as red circles. The figure at right is zoomed to show only the limits of the MASS-COMPLETE sample, with barred galaxies shown as filled blue squares and unbarred galaxies shown as open green triangles, and normalized mass and redshift distributions of the BAR-MASS and NO-BAR-MASS samples shown as blue solid and green dashed lines, respectively. The BAR-MASS-WT and NO-BAR-MASS-WT samples are then defined with weights such that the weighted (M_*, z) distributions are statistically indistinguishable (Section 6.3.1).

use of stellar masses (M_*), star formation rates (SFRs), and rest-frame colors from these catalogues. Specifically, we draw mostly from the “classic” COSMOS2020 catalogue (Weaver et al., 2022), using a combination of redshifts from zCOSMOS (lilly07) and photometric redshifts where spectra from zCOSMOS are not available. We also use the results of spectral energy distribution (SED) fitting to source star formation rates and stellar masses, choosing the LePhare (Arnouts et al., 2002; Ilbert et al., 2006) values where the quality of SED fit was good. If not, we choose the EAZY (Brammer et al., 2008) values, if those have good fit quality. In the first instance, we draw reduced χ^2_ν values from the COSMOS2020 column `lp_chi2_best`; in the second, we derive χ^2_ν as `ez_z_phot_chi2 / ez_nusefilt`. In both cases, we find that a requirement of $\chi^2_\nu < 3$ adequately selects good fits. In cases where neither SED fit from COSMOS2020 meets these criteria, we use the older values from the K_s -selected catalogue of Muzzin et al. (2013a,b), requiring that `USE` = 1 as a criterion for data inclusion. We further require available measurements of galaxy radii from the ACS-based photometric catalog (Leauthaud et al., 2007)³, and additionally apply the requirement that there be a physically reasonable range of rest-frame colors ($0.0 < U - V < 2.7$ and $-0.2 < V - J < 2.3$). Note that rest-frame UVJ colors are only available from the EAZY SED fits, so these are used if the EAZY fit met the $\chi^2_\nu < 3$ threshold, and otherwise we use the values from Muzzin et al. (2013a,b).

While choosing a single catalogue and fit method would have been simpler, it would also have unnecessarily eliminated a small fraction of the data sources in COSMOS with measured bar lengths and widths. We note that the differences in redshifts, stellar masses, and SFRs between these 3 sources of SED fits to the same

³That catalog was produced using a version of the COSMOS *HST* imaging drizzled to 0.03 arcsec pixel⁻¹ resolution. We have corrected for this difference between the two imaging pixel scales when performing analysis involving lengths originally measured in image pixels.

galaxies are generally small and lie within the typical uncertainties. For example, $\Delta z < 0.1$ for approximately 99%, or < 0.05 for over 93%, of disk galaxies within the volume limit we define below and with good fits between the 3 catalogues. The cascading selection criteria lead to us using SED fit parameters from LePhare approximately 96% of the time, with COSMOS2020 EAZY fits supplementing another 1% and the Muzzin et al. fits providing the remaining 3%. For UVJ colors, COSMOS2020 provides 94% of rest-frame values, with Muzzin et al. providing the remainder. None of our qualitative results below would change if we were to make different catalogue selections within reasonable data quality thresholds.

These combined requirements select 175,615 well-measured galaxies at all redshifts, masses and colors in the COSMOS field. COSMOS2020 has a considerably fainter flux limit than that applied to select galaxies for inclusion in GZH ($I_{AB,F814W} < 23.5$; see Section 2.1 of W17). The COSMOS sample with reliable masses, colors and radii includes 67,772 galaxies from the main GZH-COSMOS sample and 5,245 galaxies from the GZBL-COSMOS sample (of which 940 are barred according to our criterion). As our GZBL-COSMOS sample is selected from GZH, the galaxies included in this analysis are drawn from the brighter, highly complete portion of the full COSMOS2020 data sets. Figure 6.5 shows the basic properties of the COSMOS sample and the subset analyzed in GZBL.

6.3.1 A cleaner, more complete sample of disks

The selection of the GZBL sample from the GZH parent sample was relatively inclusive by design: while it was selected to include galaxies in which a bar might plausibly be measured, it did not exclude any galaxies that might have a high “featured” vote fraction p_{features} due to non-disk structures such as mergers, shells,

or dust lanes in elliptical galaxies. For the analysis below, we use a stricter selection on disk galaxies by excluding features such as these. The disk selection uses the GZH classification question “Is there anything odd?” (task T06 in Figure 4 of W17) and its follow-up answers (task T08 in W17). These are designed to identify irregular, disturbed, merging, and gravitationally lensed galaxies, as well as dust lanes and rings. The variety of possible features and the need to remove non-disk interlopers from the sample *without* removing disks themselves (which may be irregular and have features such as dust lanes and rings) led to a compound set of selection criteria. The specific criteria are given in Table 6.3; thresholds were chosen after extensive visual confirmation that using these values led to a clean yet relatively complete sample of disks. Our qualitative results below are not strongly dependent on the choice of threshold value, although some criteria are essential, such as ensuring spiral and bar features are not included in the general selection of “odd” galaxies.

From within this cleaner disk sample in GZH-COSMOS, we selected a sample of unbarred disk galaxies using the bar question in that project, “Is there a sign of a bar feature through the center of the galaxy?” (task T03 in Figure 4 of W17). Specifically, we require that the weighted fraction of classifiers who answered “Yes” was no greater than 20%, where at least 8 classifiers answered the question. The latter requirement is due to the branched nature of the GZH question tree and the position of the bar question as a third-tier question. This selects 5,777 not-edge-on, unbarred disk galaxies from GZH-COSMOS. Applying the same disk selection to the GZBL-COSMOS barred sample described above yields 926 barred disks.

We wish to examine the evolution of bars to $z \sim 1$, which is the maximum redshift at which *HST* imagery in the COSMOS field is dominated by rest-frame optical wavelengths. The redshift limit is also a key requirement for both examining

star-formation properties in galaxies and collecting reliable bar measurements (*e.g.*, Melvin et al., 2014; Sheth et al., 2008; Speltin et al., 2008). We thus require a sample that is relatively complete in mass over a large redshift range. We therefore define a disk galaxy sample within $0.25 \leq z \leq 1$ and $\log(M_*/M_\odot) \geq 9.5$. This volume-limited, MASS-COMPLETE sample, shown as enlarged red circles in both panels of Figure 6.5, contains **6,683** disk galaxies from GZH-COSMOS, of which **3,565** are unbarred disks (selected according to the criteria described above) and **624** are barred disks from GZBL-COSMOS. The remainder did not meet the criteria for secure classification into either the barred or unbarred sample. We hereafter refer to these subsamples of unbarred and barred disk galaxies within the MASS-COMPLETE sample as the NO-BAR-MASS and BAR-MASS sample, respectively. We examine the BAR-MASS sample in the majority of the analysis below.

Controlling for mass and redshift differences

Figure 6.5 shows that the stellar mass distributions of the BAR-MASS and NO-BAR-MASS samples are significantly different. This is a selection effect due to the incidence of strong bars being higher in galaxies with higher stellar mass (Cameron et al., 2010; Masters et al., 2012; Melvin et al., 2014; Sheth et al., 2008) at all redshift sampled here. In those analyses below which compare barred to unbarred galaxies, we correct for this effect and for differences in the samples' redshift distributions by applying a weight to each galaxy such that the weighted (M_*, z) distributions are statistically indistinguishable. We refer to the weighted samples below as the BAR-MASS-WT and NO-BAR-MASS-WT samples.

The weighting method has the advantage of considering every galaxy in the volume-limited samples, with proportionate weights set to control for mass and redshift differences. Weighted sample counts are calculated by summing the

assigned weights; the maximum weight for any galaxy is 1.0. As there are more unbarred than barred galaxies in all parts of (M_*, z) parameter space, this method does not downweight any barred galaxies. The effective sample sizes of the BAR-MASS-WT and NO-BAR-MASS-WT samples are 624.0 and 641.8, respectively. The median redshift and stellar mass of the matched samples are $z_{\text{med}} = 0.49$ and $M_{*, \text{med}} = 2.9 \times 10^{10} M_{\odot}$.

We note that, in the analysis below, none of our qualitative results would have changed had we chosen subsets of the NO-BAR-MASS galaxies to match the BAR-MASS (M_*, z) distributions instead of using weighted samples. We also verified that none of our qualitative results change if we consider a much more restrictive axis ratio such that only very face-on galaxies are included. As this needlessly reduces our sample size (by about half, depending on the threshold), we retain our full samples below.

We note that the FWHM of the ACS point-spread function varies slightly in physical units over the redshift range in the MASS-COMPLETE sample, from $0.3 \leq \text{FWHM} \leq 0.6$ kpc. Morphological determinations are sensitive to resolved features larger than the FWHM, typically with sizes at least 2 times the FWHM size. In the analysis below, we are thus sensitive to bars with length $\gtrsim 1$ kpc at all redshifts considered. This means we are less sensitive to small bars compared to studies examining very nearby galaxies (*e.g.*, Erwin, 2005; Erwin, 2019). This selection bias informs our mass limits above.

6.3.2 Additional useful quantities: relative bar sizes and $\delta \log SFR$

Having measured bar properties, selected galaxy samples from COSMOS2020 within the volume limit, and controlled for the differences in stellar mass and redshift between barred and unbarred populations, we must define a few further quantities before continuing.

Firstly, we combine the *HST*-based measurements of galaxy size with the physical bar lengths (L_{bar}) and widths (W_{bar}) to define the relative bar length (ℓ_{rel}) and relative bar width (ω_{rel}) as a fraction of disk size,

$$\ell_{\text{rel}} \equiv \frac{L_{\text{bar}}}{2 \times r_{90}} \quad \text{and} \quad \omega_{\text{rel}} \equiv \frac{W_{\text{bar}}}{2 \times r_{90}} \quad (6.1)$$

where r_{90} is the 90% *F814W* flux radius (Leauthaud et al., 2007) of the galaxy. This flux radius encompasses most of the disk and is far less influenced by fluctuations in central concentration (*e.g.*, due to bulges or bars) than radii which only consider smaller fractions of the galaxy light (Graham, 2019). Choosing r_{90} over the more commonly-used half-light radius thus considerably reduces the possibility of introducing a correlation between relative bar size and other galaxy properties which also correlate with bulge strength (such as star-forming properties).

Secondly, we seek a parameter which quantifies a galaxy’s star-forming status compared to the population. The star formation rate of a “typical” star-forming galaxy depends on stellar mass and redshift (best seen in studies of the star-forming sequence, *e.g.*, Aird et al., 2019; Noeske et al., 2007; Peng et al., 2010b). Over the range in (M_*, z) parameter space of our samples, these dependencies may complicate our analysis and wash out real trends and differences. Aird et al. (2019)

measured the dependence of the $SFR - M_*$ relation on both stellar mass and redshift (their Equation 8). This allows us to predict, for each galaxy in our sample, the star formation rate that the galaxy would have, $SFR_{\text{seq,mid}}$, if it were in the middle of the star-forming sequence. The ratio between this hypothetical “mid-sequence” value and the galaxy’s observed SFR (or the difference, in log),

$$\delta \log SFR \equiv \log SFR - \log SFR_{\text{seq,mid}} \quad (6.2)$$

gives a value that measures the offset between the galaxy’s SFR and the star-forming sequence, and which accounts for the dependency of the sequence on both M_* and z . Positive values of $\delta \log SFR$ are above the midpoint of the sequence, and negative values are below it.

Using $\delta \log SFR$, we also adopt the definitions of star-forming categories {Starburst, On Sequence, Sub-Sequence, Quiescent-high, Quiescent-low} recommended by [Aird et al. \(2019\)](#), and apply these to both the BAR-MASS-WT and NO-BAR-MASS-WT samples. Table 6.4 presents weighted sample counts and fractions for both samples in all categories. In general, there are relatively few quiescent galaxies in our volume-limited, (M_*, z) -controlled samples, so we combine the two Quiescent categories into a single category for the rest of the analysis.

6.4 Star formation Properties of barred versus unbarred galaxies

To analyze the distribution of star formation activity between barred and unbarred galaxies, we use both rest-frame colors and SFR measurements, as each captures slightly different physical processes. Specifically, rest-frame colors generally reflect

Table 6.3: Selection of disks in the COSMOS subsample.

SELECTION	CRITERIA
1 is_featured	$\text{gzh_t01_smooth_or_features_a02_features_or_disk_weighted_fraction} \geq 0.4$
2 not_clumpy	$\text{gzh_t12_clumpy_a02_no_weighted_fraction} \geq 0.3 \ \&\& \ \text{gzh_t12_clumpy_total_weight} \geq 8$
3 not_edge_on	$\text{gzh_t02_edgeon_a02_no_weighted_fraction} \geq 0.5 \ \&\& \ \text{gzh_t02_edgeon_total_weight} \geq 8$
4 not_artifact	$\text{gzh_t01_smooth_or_features_a03_star_or_artifact_weighted_fraction} \leq 0.5$
5 is_odd_only	$\text{gzh_t06_odd_a01_yes_weighted_fraction} \geq 0.3 \ \&\& \ \text{gzh_t08_odd_feature_total_weight} \geq 6 \ \&\& \ ((\text{gzh_t04_spiral_total_weight} \geq 6 \ \&\& \ \text{gzh_t03_bar_a01_bar_weighted_fraction} < 0.3 \ \&\& \ \text{gzh_t04_spiral_a01_spiral_weighted_fraction} < 0.4) \ \ \text{gzh_t04_spiral_total_weight} < 6)$
6 merger	$\text{gzh_t08_odd_feature_a06_merger_weighted_fraction} \geq 0.35$
7 strong_arc	$\text{gzh_t06_odd_a01_yes_weighted_fraction} \geq 0.5 \ \&\& \ \text{gzh_t08_odd_feature_a02_lens_or_arc_weighted_fraction} \geq 0.3$
8 all_odd	$\text{is_odd_only} \ \&\& \ (\text{merger} \ \ \text{strong_arc})$
9 clean_disks	$\text{is_featured} \ \&\& \ \text{not_clumpy} \ \&\& \ \text{not_edge_on} \ \&\& \ \text{not_artifact} \ \&\& \ \text{!all_odd}$
10 disks_unbarred	$\text{clean_disks} \ \&\& \ \text{gzh_t03_bar_a01_bar_weighted_fraction} \leq 0.2 \ \&\& \ \text{gzh_t03_bar_total_weight} \geq 8$
11 disks_barred	$\text{clean_disks} \ \&\& \ \text{t0_has_bar_yes_frac} \geq 0.5$

Note. The complex selection criteria uses weighted vote fractions from GZH (W17) and, for selection of a barred subsample, bar vote fraction from GZBL. The final selections are made up of a number of criteria, designed to select a sample of featured, not-edge-on galaxies (1–4) and then identify different types of “features” which are not related to disks but rather to other disturbances to a smooth, symmetric light profile, such as mergers and gravitational lenses (5–7). Those selections are then combined to select a disk sample (8–9), from which clean samples of unbarred (10) and barred (11) galaxies are selected.

Table 6.4: Sample counts, percentages, and confidence intervals on percentages for the volume-limited, weighted samples BAR-MASS-WT and NO-BAR-MASS-WT in each star-forming category.

SF CLASS	BAR-MASS-WT				NO-BAR-MASS-WT			
	Count	Per cent	.68 CI	.95 CI	Count	Per cent	.68 CI	.95 CI
			(per cent)				(per cent)	
STARBURST	87.0	13.9%	+1.5 −1.3	+2.9 −2.5	122.5	19.1%	+1.6 −1.4	+3.2 −2.8
ON SEQUENCE	249.0	39.9%	+2.0 −1.9	+3.9 −3.8	312.0	48.6%	+2.0 −2.0	+3.9 −3.8
SUB-SEQUENCE	200.0	32.1%	+1.9 −1.8	+3.8 −3.5	157.4	24.5%	+1.8 −1.6	+3.5 −3.2
QUIESCENT-HIGH	63.0	10.1%	+1.3 −1.1	+2.6 −2.1	40.2	6.3%	+1.1 −0.8	+2.1 −1.6
QUIESCENT-LOW	25.0	4.0%	+0.9 −0.6	+1.8 −1.3	9.8	1.5%	+0.6 −0.3	+1.3 −0.7
QUIESCENT (combined)	88.0	14.1%	+1.5 −1.3	+3.0 −2.5	50.0	7.8%	+1.2 −0.9	+2.3 −1.8

Note. See Section 6.3.2 for the definition of each sample. As the samples are weighted to match their mass and redshift distributions, the count values need not be integers. Both 68% and 95% confidence intervals on population fractions are given, using binomial confidence intervals (Cameron, 2011). These distributions and counts are visualized in Figure 6.7b, although in that figure and the rest of the analysis the 2 quiescent categories defined according to the method of Aird et al. (2019) are combined into a single category to improve counting statistics. The fractions for mass-and-redshift-matched barred and unbarred galaxies do not overlap within their 95% confidence intervals for the On-Sequence, Sub-Sequence, or combined Quiescent star-forming categories.

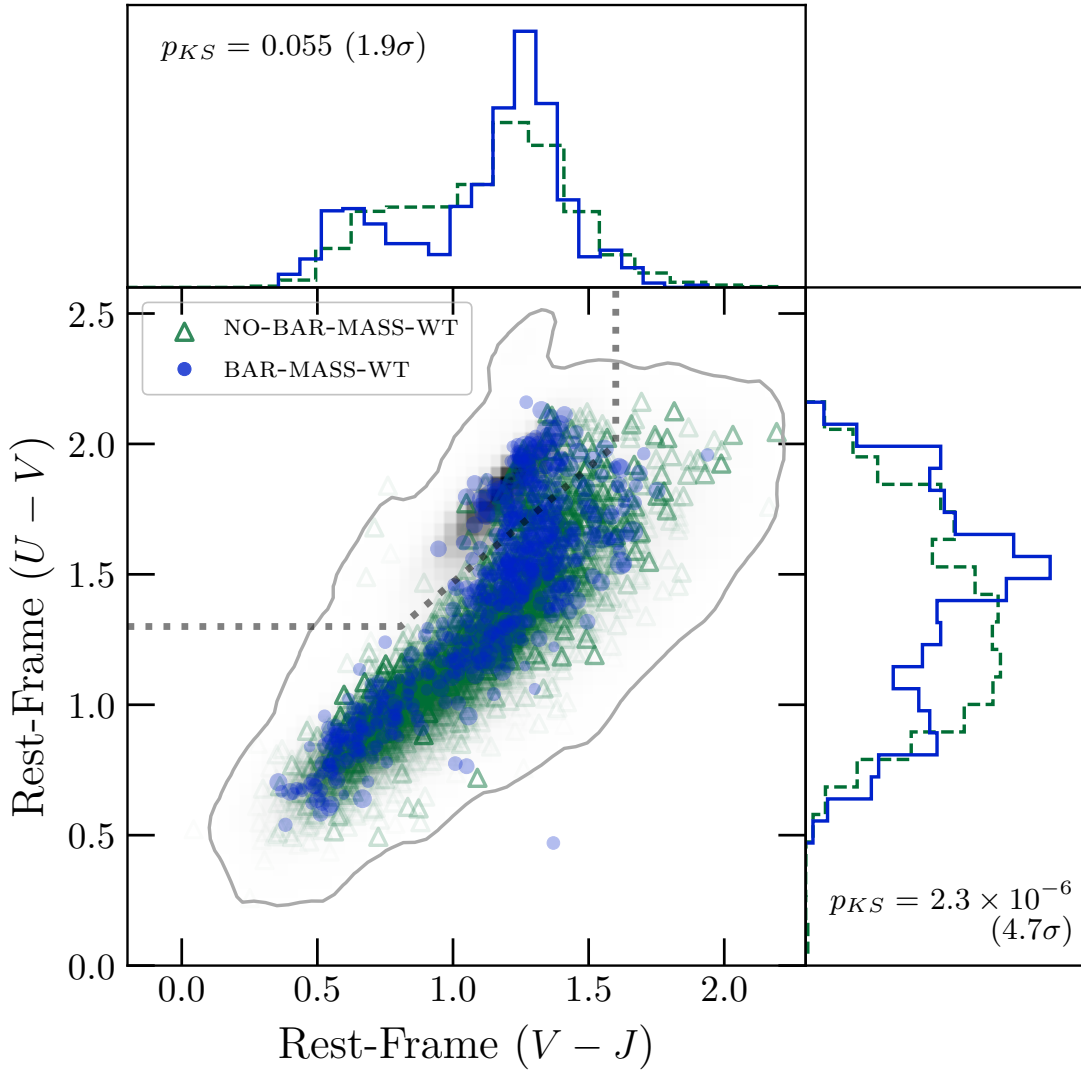


Figure 6.6: Rest-frame $U - V$ versus $V - J$. The gray density plot shows all galaxies (of all morphologies) COSMOS within the boundaries of the MASS-COMPLETE sample; the gray contour encloses 99% of COSMOS galaxies. Points show COSMOS disk galaxies analyzed by the Galaxy Zoo Bar Lengths project, split into BAR-MASS (blue circles) and NO-BAR-MASS (green triangles) sub-samples. For both sub-samples, the opacity of each point is scaled according to its weight, such that the weighted BAR-MASS-WT and NO-BAR-MASS-WT samples have statistically indistinguishable stellar mass and redshift distributions. For barred galaxies, the size of the point is proportional to the fractional bar length ℓ_{rel} . The dashed line separates passively-evolving (top-left region) and star-forming galaxies (from Williams et al., 2009, $z \geq 0.5$ coefficients). Histograms of $U - V$ and $V - J$ for the BAR-MASS-WT (blue solid lines) and NO-BAR-MASS-WT (green dashed lines) distributions are also shown: even controlling for stellar mass and redshift, barred and unbarred galaxies have different color distributions.

a combination of a galaxy’s current star formation rate and longer-term star formation history, while SFRs more directly trace recent star-forming activity on shorter timescales.

Figure 6.6 shows rest-frame $U - V$ versus $V - J$ colors for barred and unbarred galaxies in the MASS-COMPLETE sample. We show the weighted samples, BAR-MASS-WT and NO-BAR-MASS-WT visualising the weight of each source with the opacity of the point representing it. We adopt the definition of passively evolving versus actively star forming from Williams et al., 2009, shown as dotted lines in Figure 6.6, and additionally show the density plot and outer 99% contour for the full COSMOS2020 data set (*i.e.*, galaxies of any morphology) within the mass and redshift limits of the MASS-COMPLETE sample. The passive-active definition in Williams et al. evolves slightly between $z < 0.5$ and $z \geq 0.5$. Figure 6.6 shows the diagonal separation for $z \geq 0.5$, and below we apply labels based on the definition appropriate to each galaxy’s redshift.

The majority of disk galaxies in our sample are actively star forming, with a smaller fraction of disks passively evolving. Barred galaxies exhibit different rest-frame color distributions compared to unbarred counterparts, even after controlling for mass and redshift. Specifically, barred galaxies are underrepresented in intermediate $U - V$ and $V - J$ space. The differences between distributions are larger and more statistically significant in $U - V$ than $V - J$: according to a 2-sided Kolmogorov-Smirnov test (KS; Kolmogorov, 1933; Massey Jr., 1951; Smirnov, 1939, 1948)⁴ between BAR-MASS-WT and NO-BAR-MASS-WT, $p_{KS,U-V} = 2.3 \times 10^{-6}$ (4.7σ) versus $p_{KS,V-J} = 0.055$ (1.9σ).

⁴Applying the KS test to weighted samples is straightforward, by measuring distribution distances using weights rather than integer counts to compute cumulative fractions. Estimating p values uses weighted sample sizes, rounded to the nearest integer value. As no source in either sample has a weight above 1.0, this estimate of significance tends to be conservative.

Using the active-versus-passive galaxy criteria from Williams et al. (2009) to separate actively star-forming versus passively-evolving galaxies reveals that the differences in color distributions originate in the active locus. For the passive sub-samples, we cannot rule out the null hypothesis that the barred and unbarred galaxies are drawn from the same parent sample ($p_{KS,U-V} = 0.98$ versus $p_{KS,V-J} = 0.42$ when considering only the passive subsamples at all redshifts). For the “active” galaxies, the color differences in $U - V$ remain statistically significant ($p_{KS,U-V} = 7.7 \times 10^{-4}$, 3.4σ , versus $p_{KS,V-J} = 0.076$, 1.8σ) despite the drop in sample size.

A star-forming galaxy’s position in the active region of the UVJ diagram depends on many physical properties, including stellar mass (with more massive galaxies moving towards the redder end of the region because they emit more light from previous generations of star formation), current SFR (Patel et al., 2011) and dust extinction along the line of sight (Williams et al., 2009). The latter would make a larger difference in the subset of galaxies which is less face-on in our samples. To assess whether orientation might drive the observed color differences, we examined a version of Figure 6.6 that included only face-on disks (assuming intrinsically circular disks and requiring axis ratios $b/a \geq 0.8$), as well as a version where axis ratio was not thresholded but instead controlled for in a 3-way ($M_* - z - b/a$) weighting. The same trends remained apparent; the statistical significance increased slightly (*e.g.*, from 4.7 to 4.9σ for $U - V$ and 1.9 to 2.5σ for $V - J$ when considering the $(M_* - z - b/a)$ -weighted subsample), suggesting that dust-related orientation effects may play a small role in observed differences, but do not dominate the results.

The BAR-MASS-WT and NO-BAR-MASS-WT samples are weighted so as to control for stellar mass and the effect of observing at different evolutionary epochs. The

color difference therefore cannot be due to differences in mass or redshift between barred and unbarred samples. The declining bar fraction with increasing redshift in the overall galaxy population (*e.g.*, Melvin et al., 2014; Sheth et al., 2008, both of which examined bar fractions in the COSMOS-*HST* field) means there are fewer galaxies in either sample in the higher-redshift panel of Figure 6.6. While this makes the UVJ color gap in the active locus more visually evident in the $0.5 < z \leq 1.0$ scatter plot, the smaller sample size also decreases the statistical significance in that bin. Further examination of possible trends with redshift is warranted, and will be addressed in Section 6.5. For now, we will compare the SED-fitting-based SFR properties of barred and unbarred galaxies.

The left panel of Figure 6.7 shows that both barred and unbarred disk galaxies span the full range of stellar masses and SFRs within the volume-limited COSMOS2020 sample. As discussed in Section 6.3.1 above, the peak value of the mass-matched distributions at $\log(M_*/M_\odot) \sim 10.7$ is at least partially due to selection effects. As expected, disk galaxies undersample the quiescent portions of the parameter space compared to all galaxies in the volume, although both barred and unbarred disks are present below the star-formation sequence. Barred galaxies slightly overpopulate the portion of the diagram just below the star-forming sequence compared to their unbarred counterparts.

The binned medians in this panel show that, at stellar masses $M_* \gtrsim 10^{10} M_\odot$, the barred disk population’s median SFR decreases to just below that of the unbarred disk population.

To investigate this further, the right panel of Figure 6.7 plots each galaxy’s offset from the star-forming sequence ($\delta \log SFR$), which removes the redshift and mass dependence of the primary SFR– M_* relation. We confirm that barred galaxies are more likely to lie below the star forming sequence than unbarred galaxies.

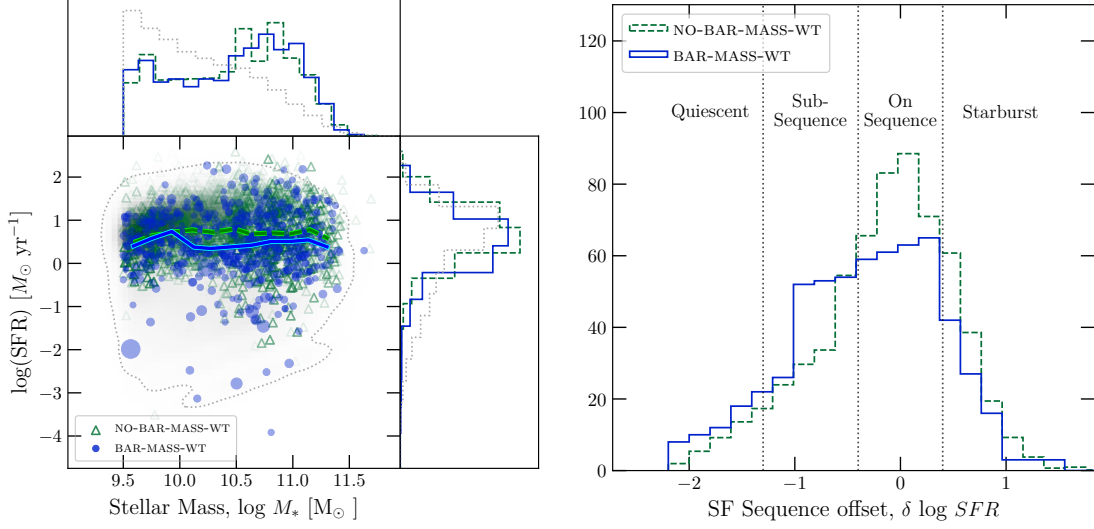


Figure 6.7: Left: star formation rate versus stellar mass for barred (blue circles) and unbarred (green triangles) disk galaxies, as well as for the overall COSMOS sample within the mass and redshift limits (gray 2D histogram and outer 99% dotted contour). The size of each barred-galaxy point is scaled to the relative bar length, as in Figure 6.6. Each point’s opacity is scaled according to its weight, such that the points represent the weighted BAR-MASS-WT and NO-BAR-MASS-WT samples. Binned medians for the BAR-MASS-WT and NO-BAR-MASS-WT samples are shown as blue solid and green dashed lines, respectively. Axis histograms show weighted sample counts for barred (blue solid) and unbarred (green dashed) disks, and all galaxies (grey dotted) in the volume limit. Both samples occupy the full range of all galaxies, although there are relatively few disk galaxies with features such as spiral arms and bars that are both low-mass and off the star-forming sequence. Right: distribution of positions of BAR-MASS-WT and NO-BAR-MASS-WT galaxies relative to where they would be expected if they were in the middle of the star-forming sequence at their stellar mass and redshift, according to the method of Aird et al. (2019). The lowest-value bin includes galaxies with $\delta \log \text{SFR}$ lower than that value (highly quiescent galaxies). Generally, there is an excess of barred versus unbarred disk galaxies below the star-forming sequence. These categories will be used for analysis in sections below.

The overall distributions are significantly different ($p_{\text{KS}} = 1.6 \times 10^{-6}$, or 4.8σ significance). Table 6.4 shows this numerically: while the weighted sample counts in the Starburst category are consistent between barred and unbarred disks within their 95% confidence intervals, this is not the case for any of the On Sequence, Sub-Sequence, or combined Quiescent categories. There are proportionally fewer barred galaxies compared to unbarred on the star-forming sequence, and proportionally more barred than unbarred below the sequence.

As indicated by the left panel of Figure 6.7, this difference is mass-dependent: the SFR distributions of barred and unbarred disk galaxies are statistically indistinguishable for the subset with $\log(M_*/M_\odot) \leq 10.0$ ($p_{\text{KS}} = 0.69$, 0.4σ), whereas for both $10.0 < \log(M_*/M_\odot) \leq 10.5$ and $\log(M_*/M_\odot) > 10.5$ the distributions are inconsistent with being drawn from the same parent distribution ($p_{\text{KS}} = 1.3 \times 10^{-5}$ and 2.6×10^{-5} , respectively; both are $> 4\sigma$ significance).

This relative over-representation of barred galaxies on the low-SFR side is consistent with previous studies finding that bars play a role in accelerating the quenching process, in both simulations and observations. For example, bars are efficient engines of angular momentum transfer, driving gas inflows in simulations (*e.g.*, Athanassoula, 1992; Athanassoula et al., 2013) which lead to central star formation and eventual quenching (Carles et al., 2016).

Observationally, strong bars are associated with an overall HI gas deficiency (Fraser-McKelvie et al., 2020b; Masters et al., 2012), and show ionisation properties consistent with low star-formation efficiency (Krishnarao et al., 2020). There is often a change in SFR along the bar itself (Fraser-McKelvie et al., 2020a; Geron et al., 2024), a finding which depends on mass in a way that is consistent with simulations (Carles et al., 2016) and with our results. The impact of the bar on the host galaxy increases when a strong bar is also a slow rotator (Geron et al.,

2024).

From the wider view offered by this sample (Figure 6.7), bars are clearly associated with quenching of the overall galaxy, at larger stellar masses ($M_* \geq 10^{10} M_\odot$). This interpretation is supported by prior work that discusses specific pathways through the green valley for galaxies with different morphologies and structures (*e.g.*, Bremer et al., 2018; Geron et al., 2021; Mukundan et al., 2025; Noeske et al., 2007; Schawinski et al., 2014; Smethurst et al., 2015). In particular, our results are consistent with past studies finding that the quenching of galaxies associated with bars is relatively slow (*e.g.*, Kelvin et al., 2018; Nogueira-Cavalcante et al., 2018), causing barred disks to “pile up” in the green valley compared to unbarred galaxies. This, and the associated higher fraction of quenched barred galaxies, shows up in the UVJ diagram (Figure 6.6) as a decrement in the $U - V$ and $V - J$ colors just blueward of the transition to the passive region, with a corresponding increase in barred galaxies at or above (redward of) the transition, compared to the distribution of colors of unbarred disk galaxies.

6.5 Overall properties of bars in galaxies at $0.25 <$

$$z < 1$$

The goal of this section is to examine the structural properties of bars – including bar length L_{bar} , relative bar length ℓ_{rel} , relative bar width ω_{rel} , and length-to-width ratio $L_{\text{bar}}/W_{\text{bar}}$ (an imperfect measure of bar strength) – and their connection to host galaxy properties such as redshift, stellar mass, and SFR.

In Section 6.2.2, we noted that a small fraction of clearly detected bars have

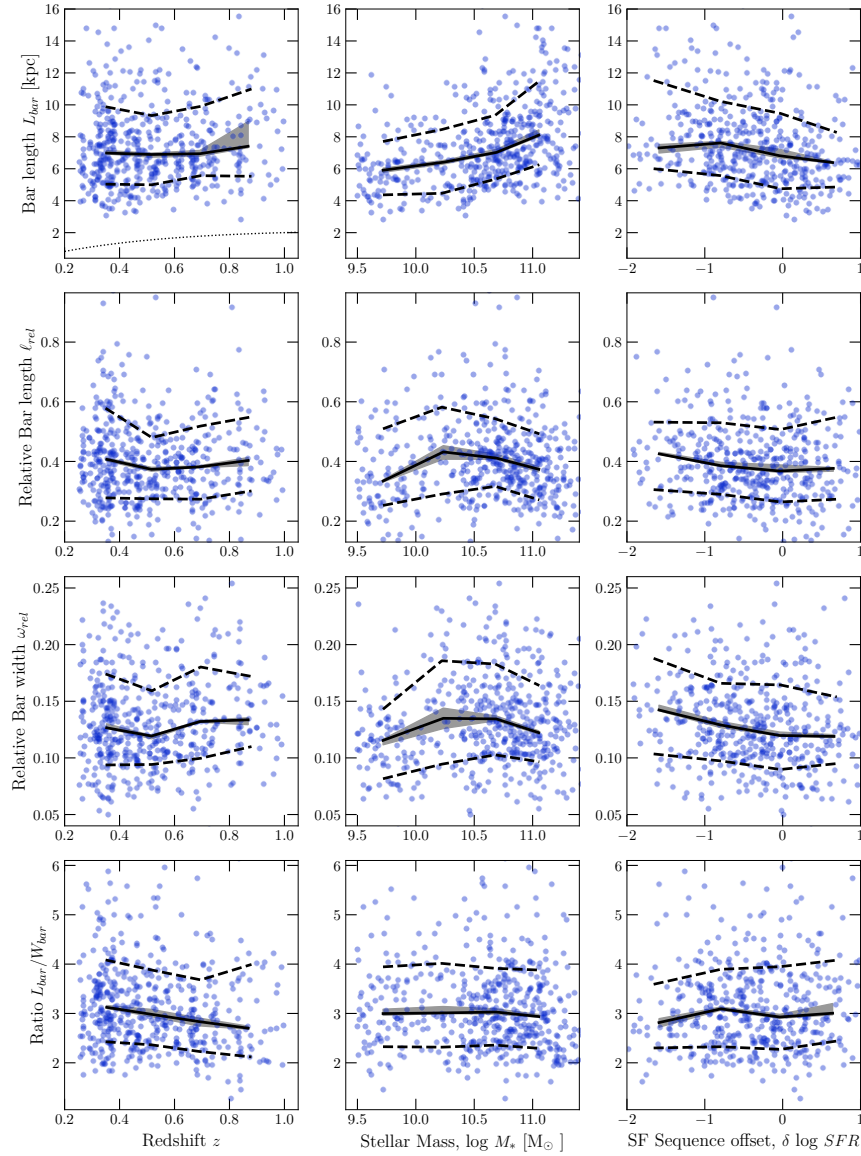


Figure 6.8: Properties of bars in the subset of the BAR-MASS sample with bar width $W_{\text{bar}} > 1.5$ kpc (blue circles) versus galaxy properties. From top to bottom, y -axes show bar length in kpc, relative bar length ℓ_{rel} , relative bar width ω_{rel} , and length-to-width ratio $L_{\text{bar}}/W_{\text{bar}}$ (a measure of bar strength). From left to right, x -axes show redshift z , stellar mass M_* , and offset from the star-forming sequence $\delta \log SFR$. Solid lines show binned median bar property values, with 95% confidence intervals on the median, estimated by varying binning and resampling 1,000 times within ± 0.1 in each x -axis value, shown as gray shaded regions. Dashed lines enclose the central 68% of galaxies in each bin. In the top left panel, the dotted line shows the evolution of $2 \times \text{PSF FWHM}$ (*i.e.*, the minimum resolvable bar length) with redshift. There are some statistically significant trends in the median values, although these differences are much smaller than the width of the overall population distributions.

width measurements indicating the physical widths may not be well resolved (also see Figure 6.4). If a bar narrower than the FWHM of the PSF is smeared out to the PSF size, this could introduce a bias such that strength measurements including bar widths may be affected by these broadened bars. In the GZBL-COSMOS data examined here, this effect is mild, but still present. Thus, in the analysis below, we further restrict the BAR-MASS sample to those bars where the width measurement is $W_{\text{bar}} > 1.5$ kpc, which is resolved by the *HST* ACS PSF at all redshifts.

This reduces the sample size to 484 barred galaxies. We have verified that our qualitative conclusions below do not change for reasonable choices of resolution threshold. Given that the bar length exceeds the width by definition, enforcing resolution via bar widths is more conservative than requiring well resolved lengths.

6.5.1 Overall trends with galaxy properties

Figure 6.8 presents the trends of four bar properties: absolute bar length (L_{bar} , in kpc), relative bar length (ℓ_{rel}), relative bar width (ω_{rel}), and length-to-width ratio ($L_{\text{bar}}/W_{\text{bar}}$), as functions of redshift (z), stellar mass (M_*), and offset from the star-forming sequence midpoint ($\delta \log SFR$). The length-to-width ratio also serves as a measure for bar strength that correlates well to other measures (Laurikainen et al., 2007; Laurikainen and Salo, 2002; Laurikainen et al., 2002), where larger ratios equate to stronger bars.

Dashed lines on the figure trace the width of the distribution, enclosing 68% of barred galaxies in that bin. We also compute binned median values and show these on the figure. Variances on the median are generally smaller than the line width, so we estimate uncertainties on medians by varying bin edges within a reasonable tolerance (drawn randomly from a uniform distribution 20% of the bin width in

each quantity), resampling the bins 1,000 times. The shaded regions around the binned medians represent the 95% confidence interval on the median determined via this method.⁵

The median physical bar length of the overall sample is $\langle L_{\text{bar}} \rangle_{\text{med}} = 7.0$ kpc. The top left panel of Figure 6.8 also shows a dotted line representing the physical size of twice the FWHM of the *HST* ACS PSF, an estimate of the minimum length we can resolve in the BAR-MASS sample. We do not find significant evolution of the median physical bar length (represented by the solid black line) within this dataset. This observation agrees with Kim et al., 2021, who use a sample of 379 galaxies within $0.2 < z < 0.84$ to show that there is similarly no significant evolution of physical bar length within their redshift range. Our median L_{bar} value agrees with the mean value of Kim et al. within their standard deviation; both are about twice as long as the mean physical length of bars measured with *JWST* at $1 \leq z \leq 4$ (Le Conte et al., 2025), and significantly larger than the minimum resolvable bar length at all redshifts.

Within our sample, the median relative length ℓ_{rel} also shows no significant evolution with redshift across all redshift bins ($\langle \ell_{\text{rel}} \rangle_{\text{med}} = 0.407^{+0.004}_{-0.006}$ in the lowest-redshift bin versus $\langle \ell_{\text{rel}} \rangle_{\text{med}} = 0.403^{+0.010}_{-0.017}$ in the highest-redshift bin). This is consistent with the mean and standard deviations of the similar-redshift sample of Kim et al. and the higher-redshift sample of Le Conte et al., implying a stable “typical” relative bar length across at least 9 Gyr of cosmic time, over which period the size of disk galaxies evolves significantly (which reconciles a factor of two evolution in physical size but no evolution in relative size).

⁵These confidence intervals/uncertainties are usually larger than the formal variance on the median, but are still relatively small (sometimes $< 1\%$). In the rest of the discussion, we sometimes quote median values with more decimal places than we would ordinarily consider significant, in order to quote non-zero uncertainties on the median.

The median bar width ω_{rel} also appears marginally stable, with the relative width in the lowest redshift bin ($0.127^{+0.004}_{-0.0005}$) just consistent with that of the highest redshift bin ($0.135^{+0.002}_{-0.004}$) within the 95% uncertainties. While neither the slight decrease in median ℓ_{rel} nor the slight increase in median ω_{rel} with z is statistically significant, the length-to-width ratio ($L_{\text{bar}}/W_{\text{bar}}$) shows a decrease with increasing redshift on the median of approximately 13% ($3.12^{+0.04}_{-0.02}$ to $2.70^{+0.04}_{-0.02}$), within the 95% uncertainties. This may imply that bars typically develop as slightly weaker instabilities at higher redshifts, and strengthen over time. This is consistent with bars in the population becoming stronger over time as long-lived bars absorb angular momentum (Athanasoula et al., 2013). It is also potentially consistent with the slightly lower ellipticities of bars at $z > 1$ measured by Le Conte et al. (2025), where their average corrected ellipticity of ≈ 0.5 would correspond to a length-to-width ratio of ≈ 2 . However, the inherent uncertainties that Le Conte et al. carefully describe in their measurements, as well as differences in methods and mass completeness between studies, mean that further work would be required to quantify the evolution of bar strength across these epochs. There is also considerable range in values of both relative length and width among populations at all redshifts, including those sampled in this work.

In a recent analysis of the Auriga simulations (Grand et al., 2017, 2019), Fragkoudi et al. (2025) find that most bars initially develop at shorter relative lengths, then lengthen as they age; however, bars that form at higher redshifts (including the high end of our redshift range) tend to form at longer relative lengths, which then stay at approximately the same ℓ_{rel} as the system ages. The relative consistency in lengths across the redshift range of our sample may be consistent with this combination of bars strengthening as they age, but a higher proportion of newer, weaker bars at higher redshifts. Fragkoudi et al. define the bar strength

of their simulated galaxies as the $m = 2$ Fourier mode of the surface density, A_2 , and find that bars that develop early remain at similar strengths throughout their evolution, whereas bars that develop later may slowly increase their strength (their Figure 3). We cannot determine the bar ages of this sample (although perhaps further data could enable this, *e.g.*, using the method described by de Sá-Freitas et al., 2025), so we cannot separate the general trend in the lower left panel of Figure 6.8 into younger and older bars. However, the trend is shallow enough and the differences in method and galaxy mass coverage are complex enough that our results may be consistent with those of Fragkoudi et al.

Note that this trend in median $L_{\text{bar}}/W_{\text{bar}}$ values (and all trends reported here), while significant compared to the bootstrapped uncertainty on the median, is small compared to the overall width of the distribution of $L_{\text{bar}}/W_{\text{bar}}$ values: the changes are subtle compared to the variety within the population. Kim et al., 2021 found that mean bar strength has no significant evolution with redshift, over approximately the same redshift range we probe. We would note that there is a slight decrease in their mean bar strength with increasing redshift in Figure 7 of Kim et al., but as variances on means are generally much larger than variances on medians, their claim of a lack of significance in the mean trend is consistent with our finding of a change in the median value that is real, but small compared to the distribution width. Differences between the bar strengths of Kim et al., 2021 and the bar strength results of this study may also be due in part to the difference in our bar strength definitions, since Kim et al., 2021 defines the bar strength using two methods: Fourier amplitude (A_2) and an estimate of torque parameter (Q_b), rather than our method of simply taking the ratio $L_{\text{bar}}/W_{\text{bar}}$.

We find more notable trends when examining these 4 properties (L_{bar} , ℓ_{rel} , ω_{rel} , $L_{\text{bar}}/W_{\text{bar}}$) as functions of stellar mass compared to the slight (or no) trends

with redshift. The median physical bar length increases by 37% across the full range of stellar mass (from $5.91^{+0.13}_{-0.13}$ to $8.10^{+0.33}_{-0.10}$ kpc from lower to higher mass). The direction of this trend is expected given that higher-mass galaxies tend to have larger bars (Hoyle et al., 2011; Kim et al., 2021). While there is a slight increase in the slope of the correlation at higher stellar masses, we do not observe the same strongly broken trend as Erwin (2019), who found that bar lengths in lower-redshift galaxies have a nearly constant mean length in galaxies with mass up to just above $10^{10} M_{\odot}$, with lengths increasing steeply with mass in more massive galaxies. Interestingly, we observe a median trend between physical bar length and galaxy stellar mass more consistent with that of Erwin if we include bars with narrow widths that may not be well resolved at these redshifts (*i.e.*, if we skip the conservative resolution cuts described at the start of this Section). This suggests that the change in the shape of the trend may be largely due to narrower bars, to which Erwin (2019) was far more sensitive owing to the high physical resolution of the dataset used in that study.

The stellar mass at which we observe a slight additional increase in bar length is slightly higher than the break mass found by Erwin; both are similar to the mass at which other bar properties transition (*e.g.*, Kruk et al., 2017; Nair and Abraham, 2010) given the evolution of the galaxy mass function between those studies’ and our samples’ redshifts (Driver et al., 2022; Shuntov et al., 2025; Weigel et al., 2016). This mass also corresponds to the mass range beyond which quiescence tends to onset and the “red sequence” begins to dominate the galaxy population versus the “blue cloud” (Kauffmann et al., 2003; Smethurst et al., 2015).

The median relative bar length increases by about 30% up to $\log(M_*/M_{\odot}) \sim 10.25$, then decreases again towards higher stellar masses. The difference between this trend and the trend in physical bar length illustrates the importance of

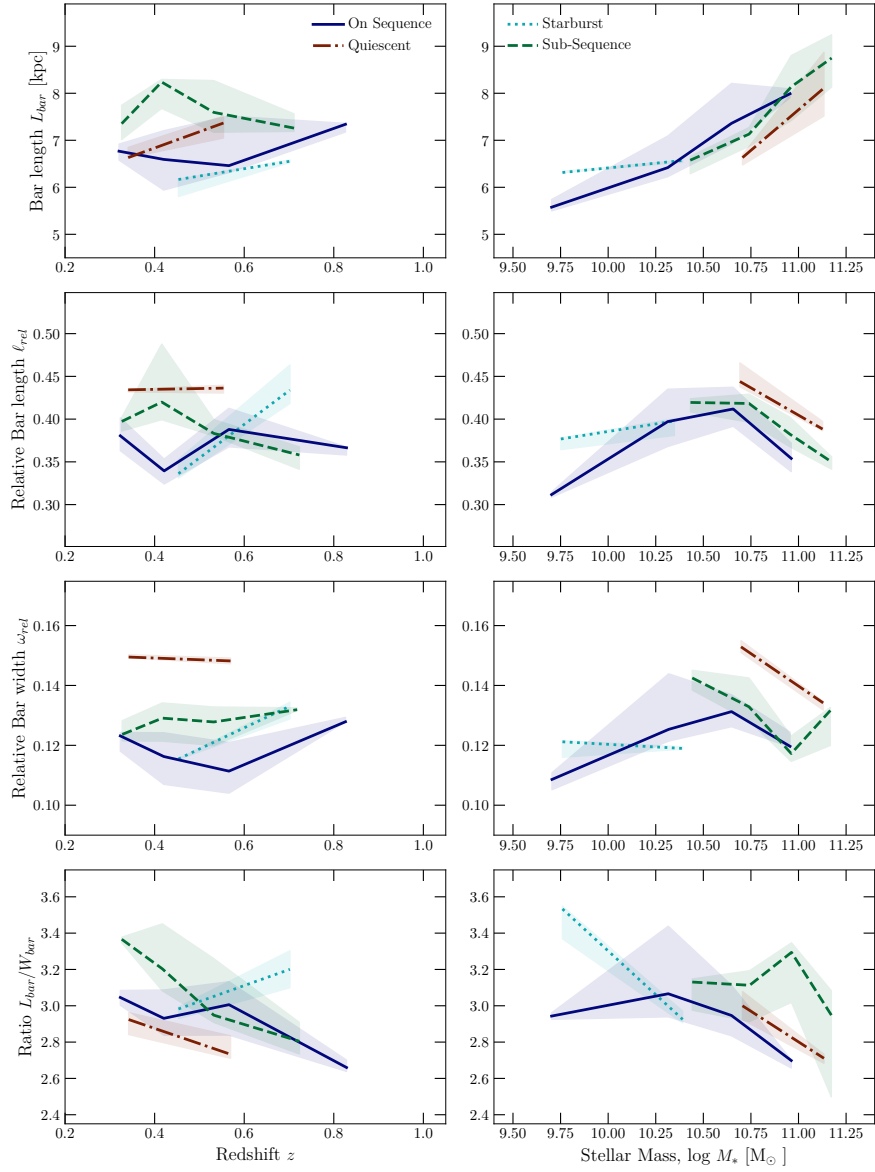


Figure 6.9: Bar length L_{bar} (top), relative bar length ℓ_{rel} (upper middle), relative bar width ω_{rel} (lower middle), and bar strength (bottom) versus redshift z (left) and stellar mass M_* (right) within the subset of the BAR-MASS sample with $W_{\text{bar}} > 1.5$ kpc. The sample has been split by star-forming status, with each galaxy assigned to be starburst (cyan dotted), on the star-forming sequence (blue solid), sub-sequence (green dashed), or quiescent (red dot-dashed) based on its position on the $SFR-M_*$ diagram relative to the centre of the star-forming sequence at its stellar mass and redshift ($\delta \log SFR$). Many $\delta \log SFR$ -based differences with redshift disappear when comparing galaxies at the same stellar masses across the star-forming categories, but there are still some statistically significant median differences between galaxies in different star-formation categories at a given stellar mass and a given redshift.

considering the overall galaxy size in consideration of bar lengths: physical bar length increases faster than galaxy disk size with mass, except at the highest masses in the sample, where the 90-per-cent radii of $M_* \sim 10^{11} \text{ M}_\odot$ disks are large enough that the relative bar size is smaller even though the bar is also physically longer. Relative bar width shows a similar median trend, increasing by about 17% to the same mass and falling back slightly at the highest masses. The median ratio $L_{\text{bar}}/W_{\text{bar}}$ with stellar mass is consistent with no change (*e.g.*, $3.00^{+0.09}_{-0.04}$ in the lowest-mass bin versus $2.94^{+0.04}_{-0.01}$ in the highest), indicating no significant change in bar strength with increasing stellar mass.

Jang et al. (2025) predicts that bars in lower-mass disk-dominated galaxies should be weaker than bars in higher mass galaxies, directly contradicting our finding here. However, Jang et al. focused on bar development in the absence of bulges, a restriction we have not imposed on our data. Most of our disk galaxies have at least some bulge. Therefore, this discrepancy may reflect a dependence on bulges in the formation and evolution of bars, as well as the uncertainty around observational proxies derived from images compared to the more direct dynamical measurements that are possible when using simulated data.

Our findings generally align well with those of past observational studies. At low redshift, bars tend to be longer (both in physical size and relative to the disk size) in more massive (Erwin, 2005), redder (Hoyle et al., 2011) galaxies. Kim et al. (2021) similarly find that bar lengths scale with host galaxy mass at the same redshifts as this work, giving further support to the fact that bars and disks co-evolve with each other and maintain their relative proportions. In studies of very nearby galaxies, bar lengths tend to vary with morphological T-type in the same way as luminosity varies with morphology (*e.g.*, Erwin, 2005; Menéndez-Delmestre et al., 2007), so our higher-redshift results are qualitatively similar to lower-redshift

results. A more detailed comparison with these studies is complicated by the very different selection methods used in studies of local galaxies, which we cannot replicate (*e.g.*, sensitivity to much smaller bars using space-based instruments to observe the local Universe, as in both [Erwin 2005](#) and [Menéndez-Delmestre et al. 2007](#)). The lack of change in our indicator of bar strength with stellar mass is qualitatively consistent with low-redshift studies which use similar strength metrics ([Laurikainen et al., 2007](#); [Whyte et al., 2002](#)).

The trends with $\delta \log SFR$ highlight the possible presence of structural differences in bars as a function of star-forming activity. We find that L_{bar} decreases as $\delta \log SFR$ increases (from $7.30^{+0.21}_{-0.32}$ kpc in the combined Quiescent category to $6.39^{+0.06}_{-0.04}$ kpc in the Starburst category), and the same is true for both ℓ_{rel} (from $0.425^{+0.005}_{-0.001}$ to $0.377^{+0.003}_{-0.009}$) and ω_{rel} (from $0.142^{+0.004}_{-0.001}$ to $0.119^{+0.002}_{-0.001}$). Galaxies lying on or above the star-forming sequence host bars that are shorter and narrower than those in quenching or quiescent galaxies.

The decrease in relative width is slightly larger than the decrease in relative length across the star-forming categories. These trends combine such that the median $L_{\text{bar}}/W_{\text{bar}}$ *increases* very slightly from lowest to highest $\delta \log SFR$, by about 7% (from $2.82^{+0.08}_{-0.09}$ in the combined Quiescent category to $3.01^{+0.20}_{-0.03}$ in the Starburst category). In our definition, larger ratios correspond to stronger, more elongated bars. This means that galaxies above the star-forming sequence tend to host physically shorter but slightly stronger bars, while galaxies in the combined “Quiescent” category host weaker, rounder bars. The slope of the change is not continuous across star-forming categories, and differences between any two categories are small. As with all other trends we observe, the statistically significant changes in median values are much smaller than the scatter within the overall population. In the lower right panel of Figure 6.8, the upper dashed line indicating

the 84th percentile of the distributions also trends toward stronger bars with higher $\delta \log SFR$, but there is no clear trend in the lower line tracing the 16th percentile of the distribution.

Our results connecting bar structure to $\delta \log SFR$ add to the broader context in which bars are tied in complex ways to the regulation of star formation.

For example, [Géron et al. \(2024\)](#) combined a bar strength definition from Galaxy Zoo DESI classifications (in which “strong” and “weak” bars are distinguished by their visual prominence) with spatially resolved spectroscopy to show that strong bars in star-forming galaxies enhance star formation in their centers ([an effect predicted by theoretical work, e.g., Sellwood, 2014](#)) and just beyond the bar-ends, while suppressing it along the bar arms. They further found that this effect is strongest for slow, strong bars, suggesting that bar kinematics as well as morphology influence how and where star formation occurs. [Mengistu et al. \(2026\)](#) further found that bars’ effect on host galaxy star formation is strongest on shorter timescales versus other secular processes. Both analyses were limited to nearby galaxies ($z < 0.06$) owing to the observational constraints involved.

Our photometric finding that galaxies above the star-forming sequence host shorter but proportionally slightly stronger bars is complementary to the results from [Géron et al. \(2024\)](#), potentially illustrating how [Géron et al.](#)’s more localized star formation patterns may show up in the more global view of star formation patterns across the full range of $\delta \log SFR$. However, given that $\delta \log SFR$ is also correlated with stellar mass (*e.g.*, [Figure 6.7](#)), and that both star formation rate and stellar mass evolve with redshift, it may be useful to disentangle these quantities further while also examining bar properties.

6.5.2 A closer look at bar properties with star formation

In Figure 6.9, we investigate how bar structure varies within $\delta \log SFR$ categories by examining median L_{bar} , ℓ_{rel} , ω_{rel} , and $L_{\text{bar}}/W_{\text{bar}}$ ratio as functions of redshift and stellar mass (as in Figure 6.8), but now separated by star formation status. The 95% confidence intervals on median values use the same bootstrapping method as the uncertainties in Figure 6.8.

As expected, there are not enough bars at low mass or high redshift hosted in quiescent galaxies to confidently discuss median trends; likewise for starburst galaxies at both redshift extremes and at high stellar mass.

At the lower redshifts in the sample ($z \lesssim 0.6$), galaxies with lower star formation activity (“Sub-Sequence” and “Quiescent”) tend to host bars that are both longer and wider than galaxies on or above the star-forming sequence. In terms of physical length, the Sub-Sequence galaxies (which are in the region of the $SFR - M_*$ plot known as the “green valley”) are the only category that shows a significant difference in median L_{bar} versus galaxies on the star-forming sequence. Bars in quenching/green-valley galaxies are $\approx 0.6^{+0.4}_{-0.4}$ kpc longer than bars in galaxies on the star-forming sequence at $z \approx 0.32$, and $\approx 1.6^{+0.8}_{-0.7}$ kpc longer than those in galaxies on the sequence at $z \approx 0.42$.

This redshift difference represents an evolutionary time of 0.84 Gyr, and the time between the median redshift in the $z \approx 0.42$ bin and the next-highest redshift bin (with a combined median across both categories of $z \approx 0.55$) is 0.94 Gyr. Quenching on fast (< 1 Gyr) and intermediate (< 2 Gyr) timescales does occur in disk galaxies (*e.g.*, Smethurst et al., 2015), and bars can affect their galaxies’ overall star formation on these timescales (*e.g.*, Mengistu et al., 2026). Bar strength can also vary significantly in individual galaxies over timescales less than

1 Gyr (Fragkoudi et al., 2025), so it is possible for galaxies to both transition from star forming to quenching and substantially change their bar properties across redshift bins sampled here. The relative bar lengths between “On Sequence” and “Sub-Sequence” are also different at lower redshifts, more so than the relative widths, such that the ratio $L_{\text{bar}}/W_{\text{bar}}$ is significantly higher for sub-sequence galaxies at the lowest redshifts in the sample than for any other category ($3.37^{+0.01}_{-0.02}$ for sub-sequence galaxies versus $3.05^{+0.04}_{-0.04}$ for on-sequence galaxies at $z \approx 0.32$).

Comparing the “Sub-Sequence” and “On Sequence” bar lengths as a function of stellar mass adds further context: the masses of barred disk galaxies that are quenching are typically higher than those of barred star-forming disks, and the trend of increasing physical bar lengths with increasing stellar mass is consistent between both sub-sample. The trend in $L_{\text{bar}}/W_{\text{bar}}$ with stellar mass is partially consistent where the quenching and on-sequence galaxies overlap. A galaxy on the star-forming sequence that begins quenching at a stellar mass of $M_* = 10^{10} M_{\odot}$ could potentially continue to grow while its SFR falls slightly below the sequence and reach the typical mass of the lowest-mass bin for sub-sequence galaxies in Figure 6.9, but it would need most of the time elapsed between the highest and lowest redshift bins in our sample to do so. Together, these indicate that the differences between these subsamples as a function of redshift are likely at least partially due to the fact that quenching tends to onset in higher-mass barred galaxies.

However, mass effects alone likely do not explain this. Barred galaxies in the combined Quiescent category have typical stellar masses at least as high as the Sub-Sequence barred galaxies, and their bar lengths are lower than both on-sequence and sub-sequence galaxies at the same masses. The relative lengths of quiescent bars are higher than those of bars in galaxies on the star-forming sequence, though

not necessarily than those of bars in galaxies that are still quenching. The relative bar widths in quiescent galaxies are significantly higher than bars in any of the other star-forming categories. This results in $L_{\text{bar}}/W_{\text{bar}}$ ratios substantially below those of bars in sub-sequence galaxies at $z \lesssim 0.6$, and consistently slightly below (though only marginally different from) those of bars on the star-forming sequence. At the higher stellar masses where we sample Quiescent, Sub-Sequence, and On Sequence barred galaxies, there is generally a progression whereby the median relative lengths and widths of bars in star-forming galaxies are smaller than those of quenching galaxies at a given stellar mass, which are themselves smaller than those of quenched galaxies at a given stellar mass. These differences mostly divide out when examining $L_{\text{bar}}/W_{\text{bar}}$ as a function of stellar mass: $L_{\text{bar}}/W_{\text{bar}}$ between star formation categories within the same overlapping mass range has relatively high uncertainties and does not show an obvious progression, nor does it preserve the ordering of categories.

At higher redshifts ($z \gtrsim 0.6$), most differences between $\delta \log SFR$ categories are not statistically significant (with the caveat that we do not have enough quiescent barred galaxies at higher redshifts to reliably determine median bar properties). The only exception is the Starburst category, whose bars are slightly longer relative to their (lower mass and more compact) host galaxies than those in on-sequence or sub-sequence galaxies. The right column of Figure 6.9 shows that this is driven by lower-mass galaxies. Bars in starburst galaxies are longer, wider, and stronger (via $L_{\text{bar}}/W_{\text{bar}}$) than galaxies on the star-forming sequence, but only at the lowest masses we sample (the median mass of a starburst galaxy in this bin is $\log(M_*/M_\odot) = 9.76$).

The offsets in bar properties between galaxies of the same mass and redshift but different star-forming status indicate that bar structure may be directly connected

to a galaxy’s level of star formation and consequently, its evolutionary state. However, our study echoes the results of many others (*e.g.*, [Fraser-McKelvie et al., 2020a,b](#); [Géron et al., 2024](#); [Mengistu et al., 2026](#)) in finding that the link between bar evolution and the regulation of star formation is likely to be complex.

For example, it is well known that galaxy interactions—such as mergers and close fly-bys—can trigger bursts of star formation (*e.g.*, [Barton et al., 2000](#); [Di Matteo et al., 2007](#); [O’Ryan et al., 2025](#); [Shah et al., 2022](#)). These episodes tend to occur over relatively short dynamical timescales and produce characteristic and asymmetric morphological features (*e.g.*, [Ellison et al., 2008](#); [Lotz et al., 2004, 2008a,b](#); [Patton et al., 2013](#)). Interaction-triggered bars are more likely to form both longer and stronger bars ([Fragkoudi et al., 2025](#)), although whether they are short- or long-lived depends somewhat on the dynamical stability of the pre-interaction disk ([Kraljic et al., 2012](#)).

However, merging systems are morphologically excluded from this study, so those events cannot explain the trends we observe unless the merger-induced differences persist until after visual merger signatures have relaxed ([Lotz et al., 2008a](#)). This is certainly possible for some galaxies in the sample, but it is unlikely to explain all the effects we see. To understand the internal set of processes likely dominating our results, [Géron et al. \(2024\)](#) provide a useful point of comparison. Their results outline a sequence of events echoing the “bar continuum” proposed by [Géron et al. \(2021\)](#). Combining that proposal with our results and those of the simulations mentioned above is consistent with a scenario in which a strong bar forms, drives gas inward along its length, and boosts star formation in the center and near the bar-ends. Over time, this contributes to global quenching of the galaxy, leading to somewhat weaker, more extended bars in quiescent systems. This timeline implies multiple timescales for bar-driven evolution, most of which

differ from the shorter and more transient bursts of star formation expected from fly-by interactions.

Enhanced AGN activity would also be expected to be associated with the presence of a relatively young bar in the above scenario. While this was an unsettled debate for many years (*e.g.*, Cheung et al., 2015; Galloway et al., 2015; Lee et al., 2012; Martini et al., 2003), there is now clear evidence for an increase in the AGN fraction in barred galaxies (Garland et al., 2024; La Marca et al., 2026). The enhancement is stronger in more strongly barred systems (Garland et al., 2024), and is more associated with the lower- and moderate-luminosity AGN that are more likely to be triggered via secular processes than the higher-luminosity growth seen as a result of interactions and mergers (La Marca et al., 2026). Examining the joint role of AGN and star-formation status in bar evolution is out of scope for this work, but this will be possible in future, larger samples that retain their statistical power for examining AGN fractions in different star-formation subcategories of AGN host galaxy.

The redshift range of the BAR-MASS sample spans approximately 5 Gyr of cosmic time. Our findings of modest differences in median bar properties as functions of redshift and mass, with some complexities in the differences between barred galaxies at different levels of star-formation, provide observational evidence consistent with the picture in which bar growth, gas inflows, and quenching proceed together via both secular processes at multiple timescales and more rapid externally-driven events.

6.6 Summary

In this study, we investigate how bar presence and structure relates to star formation activity in disk galaxies across cosmic time. Using bar length and width measurements and galaxy classifications from Galaxy Zoo, we analyze a mass-complete sample of barred and unbarred galaxies in the COSMOS survey over the redshift range $0.25 < z < 1$ and with stellar masses $\log(M_*/M_\odot) \geq 9.5$. Our analysis focuses on whether barred galaxies differ systematically from their unbarred counterparts in terms of star-forming properties, and how bar lengths and other structural properties evolve with stellar mass, redshift and distance from the star-forming sequence. The key findings of this work are as follows:

1. After controlling for differences in redshift and stellar mass distributions, the star-formation rates of barred galaxies are significantly lower than those of unbarred galaxies, on average. In particular, at stellar masses $\log(M_*/M_\odot) \gtrsim 10$, barred galaxies are more likely to occupy the “green valley”, just below the star-forming sequence, or be quiescent. This is consistent with bars being associated with relatively slow quenching processes, and with the presence of a bar contributing to the observed scatter in the star-forming sequence.
2. The median bar length relative to disk length does not evolve over the redshifts we probe, but the median length-to-width ratio, a proxy for bar strength, shows a trend with redshift, decreasing 13% from the lowest to highest redshift of the sample. The median bar at higher redshift is slightly weaker/less elongated than at lower redshift. This is broadly consistent with recent theoretical work.
3. Median physical bar length (in kpc) increases with stellar mass for galaxies,

by nearly 40% across our stellar mass range. This finding is similar to that of previous studies of lower-redshift barred galaxies.

4. In relative terms, bars are at their proportionally longest *and* widest at $\log(M_*/M_\odot) \sim 10.25$, and both quantities change with mass such that the median bar strength is consistent with no significant change across the mass range of our sample.
5. Median bar lengths and widths also change as a function of star-formation rate, such that quiescent and quenching galaxies have the longest and widest bars (relative to their host disks) compared to galaxies both on and above the star-forming sequence. Given that quiescent and quenching (sub-sequence) galaxies also predominantly have higher stellar masses, this finding is generally consistent with bars contributing to the secular decline of star formation in massive disk galaxies over time. However, more rapid quenching due to processes such as galaxy fly-bys (which can cause bar formation) is not ruled out, and some of the complexities in the differences in median bar properties with redshift and stellar mass indicate that more rapid quenching timescales are likely also present in our sample.
6. Starburst galaxies, which mainly populate the low-mass end of the overall population, show an increase in physical and relative length, as well as length-to-width ratio, compared to galaxies at the lowest masses in the sample that are on the star-forming sequence.
7. While there are complexities in bar properties with redshift and stellar mass after separating the barred population into star-forming categories, the persistence of an overall sequence in relative bar lengths and widths from

actively star forming to quiescent systems suggest that bar properties evolve alongside and participate in overall galaxy evolution.

Together, these results support a picture in which bar-driven secular processes play a measurable role in the quenching of disk galaxies. Past theoretical work has shown that bars offer a structural route to quenching, and past observations of bar and galaxy kinematics have found clear indications of bar-associated changes to local star formation. In this context, our results imply that bars at least partially drive and record a galaxy’s transition from actively star-forming to quiescent.

While all the median differences and trends we report here are statistically significant, it is important to note that the overall variations of the population (or sub-population) distributions are generally much wider than the median trends. There is still potentially much to learn about disk galaxy evolution within this scatter.

In recent years, the study of bar features in disk galaxies has moved forward via a combination of advanced simulations and multiple observational techniques, including imaging studies of larger samples and targeted dynamical work. Looking forward, a new generation of high-resolution surveys (*e.g.*, *JWST*-driven surveys such as CEERS, [Finkelstein et al. 2025](#), and COSMOS-Web, [Casey et al. 2023](#); as well as surveys with *Euclid*, [Euclid Collaboration et al. 2025a](#), and *Roman*, [Akeson et al. 2019](#); [Spergel et al. 2015](#)), as well as Adaptive-Optics-assisted ground-based surveys using instruments such as MUSE, promise to bring us spatially-resolved star-formation insights on large samples of barred and unbarred disk galaxies at rest-frame optical and infrared wavelengths across many Gyr of cosmic time. Among other discoveries, these will determine whether the global trends we observe here align with the smaller-scale bar effects described by current kinematic studies.

Data Availability

The full catalogue from the Galaxy Zoo Bar Lengths project, including bar measurements across all *HST* surveys covered and links to all subject images classified, will be available at <https://data.galaxyzoo.org> and <https://doi.org/10.5281/zenodo.19614348> upon publication of this manuscript.

Bibliography

- Abraham, R. G. and M. R. Merrifield (Dec. 2000). “Explorations in Hubble Space: A Quantitative Tuning Fork”. In: 120, pp. 2835–2842. DOI: [10.1086/316877](https://doi.org/10.1086/316877).
- Abraham, R. G. et al. (Sept. 1999). “The evolution of barred spiral galaxies in the Hubble Deep Fields North and South”. In: 308, pp. 569–576. DOI: [10.1046/j.1365-8711.1999.02766.x](https://doi.org/10.1046/j.1365-8711.1999.02766.x).
- Aguerri, J. A. L., J. Méndez-Abreu, and E. M. Corsini (Feb. 2009). “The population of barred galaxies in the local universe. I. Detection and characterisation of bars”. In: 495, pp. 491–504. DOI: [10.1051/0004-6361:200810931](https://doi.org/10.1051/0004-6361:200810931).
- Aird, J., A. L. Coil, and A. Georgakakis (Apr. 2019). “X-rays across the galaxy population - III. The incidence of AGN as a function of star formation rate”. In: 484.3, pp. 4360–4378. DOI: [10.1093/mnras/stz125](https://doi.org/10.1093/mnras/stz125).
- Akeson, Rachel et al. (Feb. 2019). “The Wide Field Infrared Survey Telescope: 100 Hubbles for the 2020s”. In: *arXiv e-prints*, arXiv:1902.05569, arXiv:1902.05569. DOI: [10.48550/arXiv.1902.05569](https://doi.org/10.48550/arXiv.1902.05569).
- Aloy, M. A. et al. (Mar. 2000). “Relativistic Jets from Collapsars”. In: 531.2, pp. L119–L122. DOI: [10.1086/312537](https://doi.org/10.1086/312537).
- Arnouts, S. et al. (Jan. 2002). “Measuring the redshift evolution of clustering: the Hubble Deep Field South”. In: 329.2, pp. 355–366. DOI: [10.1046/j.1365-8711.2002.04988.x](https://doi.org/10.1046/j.1365-8711.2002.04988.x).

- Athanassoula, E. (Nov. 1992). “Morphology of bar orbits”. In: 259, pp. 328–344.
- (June 2003). “What determines the strength and the slowdown rate of bars?”. In: 341, pp. 1179–1198. DOI: [10.1046/j.1365-8711.2003.06473.x](https://doi.org/10.1046/j.1365-8711.2003.06473.x).
- (2013). “Bars and secular evolution in disk galaxies: Theoretical input”. In: *Secular Evolution of Galaxies*. Ed. by Jesús Falcón-Barroso and Johan H. Knapen. Cambridge, UK: Cambridge University Press, p. 305. DOI: [10.48550/arXiv.1211.6752](https://doi.org/10.48550/arXiv.1211.6752).
- Athanassoula, E., R. E. G. Machado, and S. A. Rodionov (Mar. 2013). “Bar formation and evolution in disc galaxies with gas and a triaxial halo: morphology, bar strength and halo properties”. In: 429, pp. 1949–1969. DOI: [10.1093/mnras/sts452](https://doi.org/10.1093/mnras/sts452).
- Bardeen, James M., William H. Press, and Saul A. Teukolsky (Dec. 1972). “Rotating Black Holes: Locally Nonrotating Frames, Energy Extraction, and Scalar Synchrotron Radiation”. In: 178, pp. 347–370. DOI: [10.1086/151796](https://doi.org/10.1086/151796).
- Barton, Elizabeth J., Margaret J. Geller, and Scott J. Kenyon (Feb. 2000). “Tidally Triggered Star Formation in Close Pairs of Galaxies”. In: 530.2, pp. 660–679. DOI: [10.1086/308392](https://doi.org/10.1086/308392).
- Batta, Aldo and Enrico Ramirez-Ruiz (Apr. 2019). “Accretion Feedback from newly-formed black holes and its implications for LIGO Sources”. In: *arXiv e-prints*, arXiv:1904.04835, arXiv:1904.04835. DOI: [10.48550/arXiv.1904.04835](https://doi.org/10.48550/arXiv.1904.04835).
- Bavera, Simone S. et al. (Mar. 2020). “The origin of spin in binary black holes. Predicting the distributions of the main observables of Advanced LIGO”. In: 635, A97, A97. DOI: [10.1051/0004-6361/201936204](https://doi.org/10.1051/0004-6361/201936204).
- Beasor, Emma R. et al. (Sept. 2018). “A critical re-evaluation of the Thorne-Żytkow object candidate HV 2112”. In: 479.3, pp. 3101–3105. DOI: [10.1093/mnras/sty1744](https://doi.org/10.1093/mnras/sty1744).

- Belczynski, Krzysztof, Vassiliki Kalogera, and Tomasz Bulik (June 2002). “A Comprehensive Study of Binary Compact Objects as Gravitational Wave Sources: Evolutionary Channels, Rates, and Physical Properties”. In: 572.1, pp. 407–431. DOI: [10.1086/340304](https://doi.org/10.1086/340304).
- Bennett, C. L. et al. (Oct. 2013). “Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results”. In: 208, 20, p. 20. DOI: [10.1088/0067-0049/208/2/20](https://doi.org/10.1088/0067-0049/208/2/20).
- Bertin, E. and S. Arnouts (June 1996). “SExtractor: Software for source extraction.” In: 117, pp. 393–404.
- Bethe, Hans A. and G. E. Brown (Oct. 1998). “Evolution of Binary Compact Objects That Merge”. In: 506.2, pp. 780–789. DOI: [10.1086/306265](https://doi.org/10.1086/306265).
- Biehle, Garrett T. (Oct. 1991). “High-Mass Stars with Degenerate Neutron Cores”. In: 380, p. 167. DOI: [10.1086/170572](https://doi.org/10.1086/170572).
- (Jan. 1994). “Observational Prospects for Massive Stars with Degenerate Neutron Cores”. In: 420, p. 364. DOI: [10.1086/173566](https://doi.org/10.1086/173566).
- Blagorodnova, N., J. Klencki, O. Pejcha, et al. (2021). In: 653, A134. DOI: [10.1051/0004-6361/202140525](https://doi.org/10.1051/0004-6361/202140525). URL: <https://doi.org/10.1051/0004-6361/202140525>.
- Blagorodnova, N., R. Kotak, J. Polshaw, et al. (2017). In: *ApJ* 834, p. 107. DOI: [10.3847/1538-4357/834/2/107](https://doi.org/10.3847/1538-4357/834/2/107). URL: <https://doi.org/10.3847/1538-4357/834/2/107>.
- Bond, H. E., A. Henden, Z. G. Levay, et al. (2003). In: *Natur* 422, p. 405. DOI: [10.1038/nature01508](https://doi.org/10.1038/nature01508). URL: <https://doi.org/10.1038/nature01508>.
- Bournaud, F., F. Combes, and B. Semelin (Nov. 2005). “The lifetime of galactic bars: central mass concentrations and gravity torques”. In: 364, pp. L18–L22. DOI: [10.1111/j.1745-3933.2005.00096.x](https://doi.org/10.1111/j.1745-3933.2005.00096.x).

- Brammer, G. B., P. G. van Dokkum, and P. Coppi (Oct. 2008). “EAZY: A Fast, Public Photometric Redshift Code”. In: 686, 1503-1513, pp. 1503–1513. DOI: [10.1086/591786](https://doi.org/10.1086/591786).
- Bremer, M. N. et al. (May 2018). “Galaxy and Mass Assembly (GAMA): Morphological transformation of galaxies across the green valley”. In: 476.1, pp. 12–26. DOI: [10.1093/mnras/sty124](https://doi.org/10.1093/mnras/sty124).
- Brown, G. E. (Feb. 1995). “Neutron Star Accretion and Binary Pulsar Formation”. In: 440, p. 270. DOI: [10.1086/175268](https://doi.org/10.1086/175268).
- Bush, Rewa Clark et al. (Sept. 2025). “Black Hole Survival Guide: Searching for Stars in the Galactic Center that Endure Partial Tidal Disruption”. In: 990.1, L7, p. L7. DOI: [10.3847/2041-8213/adejde](https://doi.org/10.3847/2041-8213/adejde).
- Buta, R. et al. (Aug. 2005). “The Distribution of Bar and Spiral Arm Strengths in Disk Galaxies”. In: 130, pp. 506–523. DOI: [10.1086/431251](https://doi.org/10.1086/431251).
- Cai, Y. Z., A. Pastorello, M. Fraser, et al. (2019). In: 632, p. L6. DOI: [10.1051/0004-6361/201936749](https://doi.org/10.1051/0004-6361/201936749). URL: <https://doi.org/10.1051/0004-6361/201936749>.
- Caldwell, John A. R. et al. (Jan. 2008). “GEMS Survey Data and Catalog”. In: *The Astrophysical Journal Supplement Series* 174, pp. 136–144. DOI: [10.1086/521080](https://doi.org/10.1086/521080).
- Cameron, E. (June 2011). “On the Estimation of Confidence Intervals for Binomial Population Proportions in Astronomy: The Simplicity and Superiority of the Bayesian Approach”. In: 28, pp. 128–139. DOI: [10.1071/AS10046](https://doi.org/10.1071/AS10046).
- Cameron, E. et al. (Nov. 2010). “Bars in early- and late-type discs in COSMOS”. In: 409, pp. 346–354. DOI: [10.1111/j.1365-2966.2010.17314.x](https://doi.org/10.1111/j.1365-2966.2010.17314.x).
- Cannon, R. C. (Aug. 1993). “Massive Thorne-Żytkow Objects - Structure and Nucleosynthesis”. In: 263, p. 817. DOI: [10.1093/mnras/263.4.817](https://doi.org/10.1093/mnras/263.4.817).

- Cannon, R. C. et al. (Feb. 1992). “The Structure and Evolution of Thorne-Zytkow Objects”. In: 386, p. 206. DOI: [10.1086/171006](https://doi.org/10.1086/171006).
- Carles, Christian et al. (Nov. 2016). “The mass dependence of star formation histories in barred spiral galaxies”. In: 463.1, pp. 1074–1087. DOI: [10.1093/mnras/stw2056](https://doi.org/10.1093/mnras/stw2056).
- Casey, Caitlin M. et al. (Sept. 2023). “COSMOS-Web: An Overview of the JWST Cosmic Origins Survey”. In: 954.1, 31, p. 31. DOI: [10.3847/1538-4357/acc2bc](https://doi.org/10.3847/1538-4357/acc2bc).
- Chernov, S.V. (2020). “Orbital Decay in High-Mass X-Ray Binaries”. In: *Astronomy Reports* 64, pp. 425–433. DOI: [10.1134/S1063772920050017](https://doi.org/10.1134/S1063772920050017).
- Cheung, E. et al. (Feb. 2015). “Galaxy Zoo: Are bars responsible for the feeding of active galactic nuclei at $0.2 < z < 1.0$?” In: 447, pp. 506–516. DOI: [10.1093/mnras/stu2462](https://doi.org/10.1093/mnras/stu2462).
- Chevalier, Roger A. (July 1993). “Neutron Star Accretion in a Stellar Envelope”. In: 411, p. L33. DOI: [10.1086/186905](https://doi.org/10.1086/186905).
- (Mar. 1996). “Neutrino-cooled Accretion: Rotation and Stellar Equation of State”. In: 459, p. 322. DOI: [10.1086/176895](https://doi.org/10.1086/176895).
- (June 2012). “Common Envelope Evolution Leading to Supernovae with Dense Interaction”. In: 752.1, L2, p. L2. DOI: [10.1088/2041-8205/752/1/L2](https://doi.org/10.1088/2041-8205/752/1/L2).
- Choi, Jieun et al. (2016). “MESA Isochrones and Stellar Tracks (MIST). I: Solar-Scaled Models”. In: *ApJ* 823.2, p. 102.
- Choudhury, S. et al. (2021). In: 507, pp. 4752–4763.
- Davis, M. et al. (May 2007). “The All-Wavelength Extended Groth Strip International Survey (AEGIS) Data Sets”. In: 660, pp. L1–L6. DOI: [10.1086/517931](https://doi.org/10.1086/517931).
- De, Soumi et al. (July 2020). “Common Envelope Wind Tunnel: The Effects of Binary Mass Ratio and Implications for the Accretion-driven Growth of LIGO Binary Black Holes”. In: 897.2, 130, p. 130. DOI: [10.3847/1538-4357/ab9ac6](https://doi.org/10.3847/1538-4357/ab9ac6).

- De Marco, Orsola et al. (Feb. 2003). “Three-dimensional simulations of the common envelope phase of a red giant”. In: *Revista Mexicana de Astronomia y Astrofisica Conference Series*. Vol. 15. Revista Mexicana de Astronomia y Astrofisica Conference Series, pp. 34–38.
- de Sá-Freitas, Camila et al. (June 2025). “Bar ages derived for the first time in nearby galaxies: Insights into secular evolution from the TIMER sample”. In: 698, A5, A5. DOI: [10.1051/0004-6361/202453367](https://doi.org/10.1051/0004-6361/202453367).
- de Vaucouleurs, G. et al. (1991). *Third Reference Catalogue of Bright Galaxies. Volume I: Explanations and references. Volume II: Data for galaxies between 0^h and 12^h . Volume III: Data for galaxies between 12^h and 24^h* . Springer, New York, NY.
- Debattista, V. P. and J. A. Sellwood (Jan. 1998). “Dynamical Friction and the Distribution of Dark Matter in Barred Galaxies”. In: 493, pp. L5–L8. DOI: [10.1086/311118](https://doi.org/10.1086/311118).
- Di Matteo, P. et al. (June 2007). “Star formation efficiency in galaxy interactions and mergers: a statistical study”. In: 468.1, pp. 61–81. DOI: [10.1051/0004-6361:20066959](https://doi.org/10.1051/0004-6361:20066959).
- Dori, Noam, Ealeal Bear, and Noam Soker (Sept. 2023). “Wobbling Jets in Common Envelope Evolution”. In: 954.2, 143, p. 143. DOI: [10.3847/1538-4357/aced97](https://doi.org/10.3847/1538-4357/aced97).
- Dotter, Aaron (2016). “MESA Isochrones and Stellar Tracks (MIST) 0: Methods for the construction of stellar isochrones”. In: *ApJS* 222, p. 8.
- Driver, Simon P. et al. (June 2022). “Galaxy And Mass Assembly (GAMA): Data Release 4 and the $z < 0.1$ total and $z < 0.08$ morphological galaxy stellar mass functions”. In: 513.1, pp. 439–467. DOI: [10.1093/mnras/stac472](https://doi.org/10.1093/mnras/stac472).

- Ellison, Sara L. et al. (May 2008). “Galaxy Pairs in the Sloan Digital Sky Survey. I. Star Formation, Active Galactic Nucleus Fraction, and the Mass-Metallicity Relation”. In: 135.5, pp. 1877–1899. DOI: [10.1088/0004-6256/135/5/1877](https://doi.org/10.1088/0004-6256/135/5/1877).
- Elmegreen, B. G., D. M. Elmegreen, and A. C. Hirst (Sept. 2004). “A Constant Bar Fraction out to Redshift $z \sim 1$ in the Advanced Camera for Surveys Field of the Tadpole Galaxy”. In: 612, pp. 191–201. DOI: [10.1086/422407](https://doi.org/10.1086/422407).
- Erwin, P. (Nov. 2005). “How large are the bars in barred galaxies?” In: 364, pp. 283–302. DOI: [10.1111/j.1365-2966.2005.09560.x](https://doi.org/10.1111/j.1365-2966.2005.09560.x).
- Erwin, Peter (Nov. 2019). “What determines the sizes of bars in spiral galaxies?” In: 489.3, pp. 3553–3564. DOI: [10.1093/mnras/stz2363](https://doi.org/10.1093/mnras/stz2363).
- Espejo Salcedo, J. M. et al. (Aug. 2025). “Galaxy morphologies at cosmic noon with JWST: A foundation for exploring gas transport with bars and spiral arms”. In: 700, A42, A42. DOI: [10.1051/0004-6361/202554725](https://doi.org/10.1051/0004-6361/202554725).
- Euclid Collaboration et al. (Mar. 2025a). “Euclid Quick Data Release (Q1) – Data release overview”. In: *arXiv e-prints*, arXiv:2503.15302, arXiv:2503.15302. DOI: [10.48550/arXiv.2503.15302](https://doi.org/10.48550/arXiv.2503.15302).
- Euclid Collaboration et al. (Mar. 2025b). “Euclid Quick Data Release (Q1), A first look at the fraction of bars in massive galaxies at $z < 1$ ”. In: *arXiv e-prints*, arXiv:2503.15311, arXiv:2503.15311. DOI: [10.48550/arXiv.2503.15311](https://doi.org/10.48550/arXiv.2503.15311).
- Everson, Rosa Wallace, Morgan MacLeod, and Enrico Ramirez-Ruiz (Jan. 2025). “The Energy Sharing Timescale in an Analytic Framework for Common Envelope Hydrodynamics”. In: 979.1, L11, p. L11. DOI: [10.3847/2041-8213/ada0ae](https://doi.org/10.3847/2041-8213/ada0ae).
- Everson, Rosa Wallace et al. (Aug. 2020). “Common Envelope Wind Tunnel: Range of Applicability and Self-similarity in Realistic Stellar Envelopes”. In: 899.1, 77, p. 77. DOI: [10.3847/1538-4357/aba75c](https://doi.org/10.3847/1538-4357/aba75c).

- Everson, Rosa Wallace et al. (Aug. 2024a). “Rethinking Thorne–Żytkow Object Formation: Assembly via Common Envelope in Field Binaries”. In: 971.2, 132, p. 132. DOI: [10.3847/1538-4357/ad595e](https://doi.org/10.3847/1538-4357/ad595e).
- (Aug. 2024b). “Rethinking Thorne Żytkow Object Formation: Assembly via Common Envelope in Field Binaries”. In: 971.2, 132, p. 132. DOI: [10.3847/1538-4357/ad595e](https://doi.org/10.3847/1538-4357/ad595e).
- Falanga, M et al. (2015a). “Ephemeris, orbital decay, and masses of ten eclipsing high-mass X-ray binaries”. In: *A&A* 577, p. 130. ISSN: 14320746. DOI: [10.1051/0004-6361/201425191](https://doi.org/10.1051/0004-6361/201425191).
- (May 2015b). “Ephemeris, orbital decay, and masses of ten eclipsing high-mass X-ray binaries”. In: 577, A130, A130. DOI: [10.1051/0004-6361/201425191](https://doi.org/10.1051/0004-6361/201425191).
- Farmer, R. et al. (Sept. 2023). “Observational predictions for Thorne–Żytkow objects”. In: 524.2, pp. 1692–1709. DOI: [10.1093/mnras/stad1977](https://doi.org/10.1093/mnras/stad1977).
- Fernández, Rodrigo and Brian D. Metzger (Feb. 2013). “Nuclear Dominated Accretion Flows in Two Dimensions. I. Torus Evolution with Parametric Microphysics”. In: 763.2, 108, p. 108. DOI: [10.1088/0004-637X/763/2/108](https://doi.org/10.1088/0004-637X/763/2/108).
- Finkelstein, Steven L. et al. (Apr. 2025). “The Cosmic Evolution Early Release Science Survey (CEERS)”. In: 983.1, L4, p. L4. DOI: [10.3847/2041-8213/adbbd3](https://doi.org/10.3847/2041-8213/adbbd3).
- Fragkoudi, Francesca et al. (Apr. 2025). “Bar formation and evolution in the cosmological context: inputs from the Auriga simulations”. In: 538.3, pp. 1587–1608. DOI: [10.1093/mnras/staf389](https://doi.org/10.1093/mnras/staf389).
- Fragos, Tassos et al. (Oct. 2019). “The Complete Evolution of a Neutron-star Binary through a Common Envelope Phase Using 1D Hydrodynamic Simulations”. In: 883.2, L45, p. L45. DOI: [10.3847/2041-8213/ab40d1](https://doi.org/10.3847/2041-8213/ab40d1).

- Fraser-McKelvie, Amelia et al. (July 2020a). “SDSS-IV MaNGA: spatially resolved star formation in barred galaxies”. In: 495.4, pp. 4158–4169. DOI: [10.1093/mnras/staa1416](https://doi.org/10.1093/mnras/staa1416).
- Fraser-McKelvie, Amelia et al. (Nov. 2020b). “SDSS-IV MaNGA: The link between bars and the early cessation of star formation in spiral galaxies”. In: 499.1, pp. 1116–1125. DOI: [10.1093/mnras/staa2866](https://doi.org/10.1093/mnras/staa2866).
- Fryer, C. L. and S. E. Woosley (July 1998). “Helium Star/Black Hole Mergers: A New Gamma-Ray Burst Model”. In: 502.1, pp. L9–L12. DOI: [10.1086/311493](https://doi.org/10.1086/311493).
- Fryer, Chris et al. (May 1999a). “What Can the Accretion-induced Collapse of White Dwarfs Really Explain?” In: 516.2, pp. 892–899. DOI: [10.1086/307119](https://doi.org/10.1086/307119).
- Fryer, Chris L., Willy Benz, and Marc Herant (Apr. 1996). “The Dynamics and Outcomes of Rapid Infall onto Neutron Stars”. In: 460, p. 801. DOI: [10.1086/177011](https://doi.org/10.1086/177011).
- Fryer, Chris L. and Alexander Heger (Oct. 2000). “Core-Collapse Simulations of Rotating Stars”. In: 541.2, pp. 1033–1050. DOI: [10.1086/309446](https://doi.org/10.1086/309446).
- Fryer, Chris L., S. E. Woosley, and Dieter H. Hartmann (Nov. 1999b). “Formation Rates of Black Hole Accretion Disk Gamma-Ray Bursts”. In: 526.1, pp. 152–177. DOI: [10.1086/307992](https://doi.org/10.1086/307992).
- Fryxell, B. et al. (Nov. 2000a). “FLASH: An Adaptive Mesh Hydrodynamics Code for Modeling Astrophysical Thermonuclear Flashes”. In: 131, pp. 273–334. DOI: [10.1086/317361](https://doi.org/10.1086/317361).
- (Nov. 2000b). “FLASH: An Adaptive Mesh Hydrodynamics Code for Modeling Astrophysical Thermonuclear Flashes”. In: 131.1, pp. 273–334. DOI: [10.1086/317361](https://doi.org/10.1086/317361).

- Galametz, A. et al. (June 2013). “CANDELS Multiwavelength Catalogs: Source Identification and Photometry in the CANDELS UKIDSS Ultra-deep Survey Field”. In: 206, 10, p. 10. DOI: [10.1088/0067-0049/206/2/10](https://doi.org/10.1088/0067-0049/206/2/10).
- Gallegos-Garcia, Monica et al. (Oct. 2022). “Do High-spin High-mass X-Ray Binaries Contribute to the Population of Merging Binary Black Holes?” In: 938.2, L19, p. L19. DOI: [10.3847/2041-8213/ac96ef](https://doi.org/10.3847/2041-8213/ac96ef).
- Galloway, M. A. et al. (Apr. 2015). “Galaxy Zoo: the effect of bar-driven fuelling on the presence of an active galactic nucleus in disc galaxies”. In: 448, pp. 3442–3454. DOI: [10.1093/mnras/stv235](https://doi.org/10.1093/mnras/stv235).
- Garland, Izzy L. et al. (Aug. 2024). “Galaxy Zoo DESI: large-scale bars as a secular mechanism for triggering AGNs”. In: 532.2, pp. 2320–2330. DOI: [10.1093/mnras/stae1620](https://doi.org/10.1093/mnras/stae1620).
- Gehrels, N., E. Ramirez-Ruiz, and D. B. Fox (Sept. 2009). “Gamma-Ray Bursts in the Swift Era”. In: 47.1, pp. 567–617. DOI: [10.1146/annurev.astro.46.060407.145147](https://doi.org/10.1146/annurev.astro.46.060407.145147).
- Géron, Tobias et al. (Nov. 2021). “Galaxy zoo: stronger bars facilitate quenching in star-forming galaxies”. In: 507.3, pp. 4389–4408. DOI: [10.1093/mnras/stab2064](https://doi.org/10.1093/mnras/stab2064).
- Géron, Tobias et al. (Oct. 2024). “The Effects of Bar Strength and Kinematics on Galaxy Evolution: Slow Strong Bars Affect Their Hosts the Most”. In: 973.2, 129, p. 129. DOI: [10.3847/1538-4357/ad66b7](https://doi.org/10.3847/1538-4357/ad66b7).
- Géron, Tobias et al. (July 2025). “Galaxy Zoo CEERS: Bar Fractions Up to $z \sim 4.0$ ”. In: 987.1, 74, p. 74. DOI: [10.3847/1538-4357/add7d0](https://doi.org/10.3847/1538-4357/add7d0).
- Giavalisco, M. (Sept. 2012). “VizieR Online Data Catalog: GOODS Source Catalogs release r2.0z (Giavalisco+ 2008)”. In: *VizieR Online Data Catalog*, II/318, pp. II/318.

- Giavalisco, M. et al. (Jan. 2004). “The Great Observatories Origins Deep Survey: Initial Results from Optical and Near-Infrared Imaging”. In: 600, pp. L93–L98. DOI: [10.1086/379232](https://doi.org/10.1086/379232).
- Gottlieb, Ore et al. (Mar. 2022). “Black hole to breakout: 3D GRMHD simulations of collapsar jets reveal a wide range of transients”. In: 510.4, pp. 4962–4975. DOI: [10.1093/mnras/stab3784](https://doi.org/10.1093/mnras/stab3784).
- Graham, Alister W. (Oct. 2019). “ R_e . I. Understanding galaxy sizes, associated luminosity densities, and the artificial division of the early-type galaxy population”. In: 36, e035, e035. DOI: [10.1017/pasa.2019.23](https://doi.org/10.1017/pasa.2019.23).
- Grand, Robert J. J. et al. (May 2017). “The Auriga Project: the properties and formation mechanisms of disc galaxies across cosmic time”. In: 467.1, pp. 179–207. DOI: [10.1093/mnras/stx071](https://doi.org/10.1093/mnras/stx071).
- Grand, Robert J. J. et al. (Dec. 2019). “Gas accretion and galactic fountain flows in the Auriga cosmological simulations: angular momentum and metal redistribution”. In: 490.4, pp. 4786–4803. DOI: [10.1093/mnras/stz2928](https://doi.org/10.1093/mnras/stz2928).
- Griffith, R. L. et al. (May 2012). “The Advanced Camera for Surveys General Catalog: Structural Parameters for Approximately Half a Million Galaxies”. In: 200, 9, p. 9. DOI: [10.1088/0067-0049/200/1/9](https://doi.org/10.1088/0067-0049/200/1/9).
- Grogin, N. A. et al. (Dec. 2011). “CANDELS: The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey”. In: 197, 35, p. 35. DOI: [10.1088/0067-0049/197/2/35](https://doi.org/10.1088/0067-0049/197/2/35).
- Guillochon, James and Enrico Ramirez-Ruiz (Apr. 2013). “Hydrodynamical Simulations to Determine the Feeding Rate of Black Holes by the Tidal Disruption of Stars: The Importance of the Impact Parameter and Stellar Structure”. In: 767.1, 25, p. 25. DOI: [10.1088/0004-637X/767/1/25](https://doi.org/10.1088/0004-637X/767/1/25).

- Guillochon, James et al. (Nov. 2009). “Three-dimensional Simulations of Tidally Disrupted Solar-type Stars and the Observational Signatures of Shock Breakout”. In: 705.1, pp. 844–853. DOI: [10.1088/0004-637X/705/1/844](https://doi.org/10.1088/0004-637X/705/1/844).
- Guo, Y. et al. (Aug. 2013). “CANDELS Multi-wavelength Catalogs: Source Detection and Photometry in the GOODS-South Field”. In: 207, 24, p. 24. DOI: [10.1088/0067-0049/207/2/24](https://doi.org/10.1088/0067-0049/207/2/24).
- Guo, Yuchen et al. (Mar. 2023). “First Look at $z > 1$ Bars in the Rest-frame Near-infrared with JWST Early CEERS Imaging”. In: 945.1, L10, p. L10. DOI: [10.3847/2041-8213/acacfb](https://doi.org/10.3847/2041-8213/acacfb).
- Guo, Yuchen et al. (June 2025). “The Abundance and Properties of Barred Galaxies out to $z \sim 4$ Using JWST CEERS Data”. In: 985.2, 181, p. 181. DOI: [10.3847/1538-4357/adc8a7](https://doi.org/10.3847/1538-4357/adc8a7).
- Halevi, Goni et al. (Feb. 2023). “Density Profiles of Collapsed Rotating Massive Stars Favor Long Gamma-Ray Bursts”. In: 944.2, L38, p. L38. DOI: [10.3847/2041-8213/acb702](https://doi.org/10.3847/2041-8213/acb702).
- Hartley, W. G. et al. (June 2013). “Studying the emergence of the red sequence through galaxy clustering: host halo masses at $z \sim 2$ ”. In: 431, pp. 3045–3059. DOI: [10.1093/mnras/stt383](https://doi.org/10.1093/mnras/stt383).
- Hirai, Ryosuke and Philipp Podsiadlowski (Dec. 2022). “Neutron stars colliding with binary companions: formation of hypervelocity stars, pulsar planets, bumpy superluminous supernovae and Thorne-Żytkow objects”. In: 517.3, pp. 4544–4556. DOI: [10.1093/mnras/stac3007](https://doi.org/10.1093/mnras/stac3007).
- Holcomb, Cole et al. (July 2013). “Conditions for Successful Helium Detonations in Astrophysical Environments”. In: 771.1, 14, p. 14. DOI: [10.1088/0004-637X/771/1/14](https://doi.org/10.1088/0004-637X/771/1/14).

- Houck, John C. and Roger A. Chevalier (July 1991). “Steady Spherical Hypercritical Accretion onto Neutron Stars”. In: 376, p. 234. DOI: [10.1086/170272](https://doi.org/10.1086/170272).
- Hoyle, B. et al. (Aug. 2011). “Galaxy Zoo: bar lengths in local disc galaxies”. In: 415, pp. 3627–3640. DOI: [10.1111/j.1365-2966.2011.18979.x](https://doi.org/10.1111/j.1365-2966.2011.18979.x).
- Hoyle, F. and R. A. Lyttleton (Jan. 1939). “The effect of interstellar matter on climatic variation”. In: *Proceedings of the Cambridge Philosophical Society* 35.3, p. 405. DOI: [10.1017/S0305004100021150](https://doi.org/10.1017/S0305004100021150).
- Hutchinson-Smith, Tenley et al. (Dec. 2024). “Rethinking Thorne Żytkow Object Formation: The Fate of X-Ray Binary LMC X-4 and Implications for Ultra-long Gamma-Ray Bursts”. In: 977.2, 196, p. 196. DOI: [10.3847/1538-4357/ad88f3](https://doi.org/10.3847/1538-4357/ad88f3).
- Iaconi, Roberto et al. (Feb. 2017). “The common envelope binary interaction: simulations with adaptive mesh refinement”. In: 464.4, pp. 4028–4044. DOI: [10.1093/mnras/stw2569](https://doi.org/10.1093/mnras/stw2569).
- Iaconi, Roberto et al. (July 2018). “The effect of a wider initial separation on common envelope binary interaction simulations”. In: 477.3, pp. 3409–3427. DOI: [10.1093/mnras/sty825](https://doi.org/10.1093/mnras/sty825).
- Iben, I. J. and M. Livio (1993). In: *PASP* 105, p. 1373. DOI: [10.1086/133321](https://doi.org/10.1086/133321). URL: <https://doi.org/10.1086/133321>.
- Ilbert, O. et al. (Oct. 2006). “Accurate photometric redshifts for the CFHT legacy survey calibrated using the VIMOS VLT deep survey”. In: 457.3, pp. 841–856. DOI: [10.1051/0004-6361:20065138](https://doi.org/10.1051/0004-6361:20065138).
- Itoh, Naoki et al. (Feb. 1996). “Neutrino Energy Loss in Stellar Interiors. VII. Pair, Photo-, Plasma, Bremsstrahlung, and Recombination Neutrino Processes”. In: 102, p. 411. DOI: [10.1086/192264](https://doi.org/10.1086/192264).
- Ivanova, N. and S. Chaichenets (Apr. 2011). “Common Envelope: Enthalpy Consideration”. In: 731.2, L36, p. L36. DOI: [10.1088/2041-8205/731/2/L36](https://doi.org/10.1088/2041-8205/731/2/L36).

- Ivanova, N. et al. (Feb. 2013a). “Common envelope evolution: where we stand and how we can move forward”. In: 21, 59, p. 59. DOI: [10.1007/s00159-013-0059-2](https://doi.org/10.1007/s00159-013-0059-2).
- Ivanova, N. et al. (Jan. 2013b). “Identification of the Long-Sought Common-Envelope Events”. In: *Science* 339.6118, p. 433. DOI: [10.1126/science.1225540](https://doi.org/10.1126/science.1225540).
- Izzard, Robert G., Enrico Ramirez-Ruiz, and Christopher A. Tout (Mar. 2004). “Formation rates of core-collapse supernovae and gamma-ray bursts”. In: 348.4, pp. 1215–1228. DOI: [10.1111/j.1365-2966.2004.07436.x](https://doi.org/10.1111/j.1365-2966.2004.07436.x).
- Jang, Dajeong, Woong-Tae Kim, and Yun Hee Lee (Sept. 2025). “Conditions for Bar Formation in Bulgeless Disk Galaxies”. In: *arXiv e-prints*, arXiv:2509.07353, arXiv:2509.07353. DOI: [10.48550/arXiv.2509.07353](https://doi.org/10.48550/arXiv.2509.07353).
- Jermyn, Adam S. et al. (Mar. 2023). “Modules for Experiments in Stellar Astrophysics (MESA): Time-dependent Convection, Energy Conservation, Automatic Differentiation, and Infrastructure”. In: 265.1, 15, p. 15. DOI: [10.3847/1538-4365/acae8d](https://doi.org/10.3847/1538-4365/acae8d).
- Jogee, S. et al. (Nov. 2004). “Bar Evolution over the Last 8 Billion Years: A Constant Fraction of Strong Bars in the GEMS Survey”. In: 615, pp. L105–L108. DOI: [10.1086/426138](https://doi.org/10.1086/426138).
- Kaminski, Tomasz and Nadejda Blagorodnova (May 2026). “Red novae, their progenitors, and remnants”. In: *arXiv e-prints*, arXiv:2605.17005, arXiv:2605.17005.
- Kauffmann, Guinevere et al. (May 2003). “The dependence of star formation history and internal structure on stellar mass for 10^5 low-redshift galaxies”. In: 341.1, pp. 54–69. DOI: [10.1046/j.1365-8711.2003.06292.x](https://doi.org/10.1046/j.1365-8711.2003.06292.x).

- Kelvin, Lee S. et al. (July 2018). “Galaxy and Mass Assembly (GAMA): variation in galaxy structure across the green valley”. In: 477.3, pp. 4116–4130. DOI: [10.1093/mnras/sty933](https://doi.org/10.1093/mnras/sty933).
- Khokhlov, A. M. and E. V. Ergma (May 1986). “Peculiar Type-I Supernovae - Explosive Helium Burning in a Low-Mass Accreting White Dwarf”. In: *Soviet Astronomy Letters* 12, pp. 152–154.
- Kim, T. et al. (Feb. 2014). “Unveiling the Structure of Barred Galaxies at $3.6\ \mu\text{m}$ with the Spitzer Survey of Stellar Structure in Galaxies (S⁴G). I. Disk Breaks”. In: 782, 64, p. 64. DOI: [10.1088/0004-637X/782/2/64](https://doi.org/10.1088/0004-637X/782/2/64).
- Kim, Taehyun et al. (Dec. 2021). “Cosmic Evolution of Barred Galaxies up to z 0.84”. In: 922.2, 196, p. 196. DOI: [10.3847/1538-4357/ac2300](https://doi.org/10.3847/1538-4357/ac2300).
- Klencki, J. et al. (2021). In: 645, A54. DOI: [10.1051/0004-6361/202038707](https://doi.org/10.1051/0004-6361/202038707). URL: <https://doi.org/10.1051/0004-6361/202038707>.
- Koekemoer, A. M. et al. (Sept. 2007). “The COSMOS Survey: Hubble Space Telescope Advanced Camera for Surveys Observations and Data Processing”. In: 172, pp. 196–202. DOI: [10.1086/520086](https://doi.org/10.1086/520086).
- Koekemoer, A. M. et al. (Dec. 2011). “CANDELS: The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey The Hubble Space Telescope Observations, Imaging Data Products, and Mosaics”. In: 197, 36, p. 36. DOI: [10.1088/0067-0049/197/2/36](https://doi.org/10.1088/0067-0049/197/2/36).
- Kolmogorov, A. N. (1933). “Sulla determinazione empirica di una legge di distribuzione”. In: *Giorn Dell’inst Ital Degli Att* 4, pp. 89–91.
- Kraljic, K., F. Bournaud, and M. Martig (Sept. 2012). “The Two-phase Formation History of Spiral Galaxies Traced by the Cosmic Evolution of the Bar Fraction”. In: 757, 60, p. 60. DOI: [10.1088/0004-637X/757/1/60](https://doi.org/10.1088/0004-637X/757/1/60).

- Krishnarao, Dhanesh et al. (Aug. 2020). “The Effect of Bars on the Ionized ISM: Optical Emission Lines from Milky Way Analogs”. In: 898.2, 116, p. 116. DOI: [10.3847/1538-4357/ab9fa3](https://doi.org/10.3847/1538-4357/ab9fa3).
- Kruk, S. J. et al. (Aug. 2017). “Galaxy Zoo: finding offset discs and bars in SDSS galaxies”. In: 469, pp. 3363–3373. DOI: [10.1093/mnras/stx1026](https://doi.org/10.1093/mnras/stx1026).
- Kulkarni, S. R., E. O. Ofek, A. Rau, et al. (2007). In: *Natur* 447, p. 458. DOI: [10.1038/nature05822](https://doi.org/10.1038/nature05822). URL: <https://doi.org/10.1038/nature05822>.
- Kurtenkov, A. A., P. Pessev, T. Tomov, et al. (2015). In: 578, p. L10. DOI: [10.1051/0004-6361/201526564](https://doi.org/10.1051/0004-6361/201526564). URL: <https://doi.org/10.1051/0004-6361/201526564>.
- La Marca, A. et al. (Mar. 2026). “Galactic bars and active galactic nucleus fuelling in the second half of cosmic history”. In: 707, A152, A152. DOI: [10.1051/0004-6361/202556236](https://doi.org/10.1051/0004-6361/202556236).
- Lau, Mike Y. M. et al. (Apr. 2022). “Common-envelope evolution in massive stars: effects of recombination energy and radiation pressure”. In: 512.4, pp. 4665–4680. DOI: [10.1093/mnras/stac049](https://doi.org/10.1093/mnras/stac049).
- Laurikainen, E. et al. (Oct. 2007). “Properties of bars and bulges in the Hubble sequence”. In: 381, pp. 401–417. DOI: [10.1111/j.1365-2966.2007.12299.x](https://doi.org/10.1111/j.1365-2966.2007.12299.x).
- Laurikainen, Eija and Heikki Salo (Dec. 2002). “Bar strengths in spiral galaxies estimated from 2MASS images”. In: 337.3, pp. 1118–1138. DOI: [10.1046/j.1365-8711.2002.06008.x](https://doi.org/10.1046/j.1365-8711.2002.06008.x).
- Laurikainen, Eija, Heikki Salo, and Pertti Rautiainen (Apr. 2002). “Comparison of bar strengths in active and non-active galaxies”. In: 331.4, pp. 880–892. DOI: [10.1046/j.1365-8711.2002.05243.x](https://doi.org/10.1046/j.1365-8711.2002.05243.x).

- Law-Smith, Jamie, James Guillochon, and Enrico Ramirez-Ruiz (Sept. 2019). “The Tidal Disruption of Sun-like Stars by Massive Black Holes”. In: 882.2, L25, p. L25. DOI: [10.3847/2041-8213/ab379a](https://doi.org/10.3847/2041-8213/ab379a).
- Law-Smith, Jamie et al. (June 2017). “Low-mass White Dwarfs with Hydrogen Envelopes as a Missing Link in the Tidal Disruption Menu”. In: 841.2, 132, p. 132. DOI: [10.3847/1538-4357/aa6ffb](https://doi.org/10.3847/1538-4357/aa6ffb).
- Law-Smith, Jamie A. P. et al. (Dec. 2020a). “Stellar Tidal Disruption Events with Abundances and Realistic Structures (STARS): Library of Fallback Rates”. In: 905.2, 141, p. 141. DOI: [10.3847/1538-4357/abc489](https://doi.org/10.3847/1538-4357/abc489).
- Law-Smith, Jamie A. P. et al. (Nov. 2020b). “Successful Common Envelope Ejection and Binary Neutron Star Formation in 3D Hydrodynamics”. In: *arXiv e-prints*, arXiv:2011.06630, arXiv:2011.06630. DOI: [10.48550/arXiv.2011.06630](https://doi.org/10.48550/arXiv.2011.06630).
- Le Conte, Zoe A. et al. (May 2024). “A JWST investigation into the bar fraction at redshifts $1 \leq z \leq 3$ ”. In: 530.2, pp. 1984–2000. DOI: [10.1093/mnras/stae921](https://doi.org/10.1093/mnras/stae921).
- (Nov. 2025). “The evolution of the bar fraction and bar lengths in the last 12 billion years”. In: DOI: [10.1093/mnras/staf2010](https://doi.org/10.1093/mnras/staf2010).
- Leauthaud, A. et al. (Sept. 2007). “Weak Gravitational Lensing with COSMOS: Galaxy Selection and Shape Measurements”. In: 172, pp. 219–238. DOI: [10.1086/516598](https://doi.org/10.1086/516598).
- Lee, G.-H. et al. (May 2012). “Do Bars Trigger Activity in Galactic Nuclei?” In: 750, 141, p. 141. DOI: [10.1088/0004-637X/750/2/141](https://doi.org/10.1088/0004-637X/750/2/141).
- Lee, William H. and Enrico Ramirez-Ruiz (Apr. 2006). “Accretion Modes in Collapsars: Prospects for Gamma-Ray Burst Production”. In: 641.2, pp. 961–971. DOI: [10.1086/500533](https://doi.org/10.1086/500533).
- (Jan. 2007). “The progenitors of short gamma-ray bursts”. In: *New Journal of Physics* 9.1, p. 17. DOI: [10.1088/1367-2630/9/1/017](https://doi.org/10.1088/1367-2630/9/1/017).

- Levan, A. J. et al. (Jan. 2014). “A New Population of Ultra-long Duration Gamma-Ray Bursts”. In: 781.1, 13, p. 13. DOI: [10.1088/0004-637X/781/1/13](https://doi.org/10.1088/0004-637X/781/1/13).
- Levesque, E. M. et al. (Sept. 2014). “Discovery of a Thorne-Zytkow object candidate in the Small Magellanic Cloud.” In: 443, pp. L94–L98. DOI: [10.1093/mnrasl/slu080](https://doi.org/10.1093/mnrasl/slu080).
- Levine, Alan M, Saul A Rappaport, and Goce Zojcheski (2000). “Orbital Decay in LMC X-4”. In: *ApJ* 541.1, pp. 194–202. ISSN: 0004-637X. DOI: [10.1086/309398](https://doi.org/10.1086/309398).
- Liotine, Camille et al. (Mar. 2023). “The Missing Link between Black Holes in High-mass X-Ray Binaries and Gravitational-wave Sources: Observational Selection Effects”. In: 946.1, 4, p. 4. DOI: [10.3847/1538-4357/acb8b2](https://doi.org/10.3847/1538-4357/acb8b2).
- Liu, Chang, Ricardo Yarza, and Enrico Ramirez-Ruiz (Jan. 2025). “Repeating Partial Tidal Encounters of Sun-like Stars Leading to Their Complete Disruption”. In: 979.1, 40, p. 40. DOI: [10.3847/1538-4357/ad9b0b](https://doi.org/10.3847/1538-4357/ad9b0b).
- Liu, Q. Z., J. van Paradijs, and E. P. J. van den Heuvel (Sept. 2006). “Catalogue of high-mass X-ray binaries in the Galaxy (4th edition)”. In: 455.3, pp. 1165–1168. DOI: [10.1051/0004-6361:20064987](https://doi.org/10.1051/0004-6361:20064987).
- Livio, Mario and Noam Soker (June 1988). “The Common Envelope Phase in the Evolution of Binary Stars”. In: 329, p. 764. DOI: [10.1086/166419](https://doi.org/10.1086/166419).
- Lotz, J. M., J. Primack, and P. Madau (July 2004). “A New Nonparametric Approach to Galaxy Morphological Classification”. In: 128, pp. 163–182. DOI: [10.1086/421849](https://doi.org/10.1086/421849).
- Lotz, J. M. et al. (Dec. 2008a). “Galaxy merger morphologies and time-scales from simulations of equal-mass gas-rich disc mergers”. In: 391, pp. 1137–1162. DOI: [10.1111/j.1365-2966.2008.14004.x](https://doi.org/10.1111/j.1365-2966.2008.14004.x).

- Lotz, J. M. et al. (Jan. 2008b). “The Evolution of Galaxy Mergers and Morphology at $z \sim 1.2$ in the Extended Groth Strip”. In: 672, pp. 177–197. DOI: [10.1086/523659](https://doi.org/10.1086/523659).
- Maccarone, Thomas J. and Selma E. de Mink (May 2016). “Large proper motion of the Thorne-Żytkow object candidate HV 2112 reveals its likely nature as foreground Galactic S-star”. In: 458.1, pp. L1–L5. DOI: [10.1093/mnrasl/slw004](https://doi.org/10.1093/mnrasl/slw004).
- MacFadyen, A. I. and S. E. Woosley (Oct. 1999). “Collapsars: Gamma-Ray Bursts and Explosions in “Failed Supernovae””. In: 524.1, pp. 262–289. DOI: [10.1086/307790](https://doi.org/10.1086/307790).
- MacFadyen, A. I., S. E. Woosley, and A. Heger (Mar. 2001). “Supernovae, Jets, and Collapsars”. In: 550.1, pp. 410–425. DOI: [10.1086/319698](https://doi.org/10.1086/319698).
- MacLeod, Morgan, Kishalay De, and Abraham Loeb (Oct. 2022). “Dusty, Self-obscured Transients from Stellar Coalescence”. In: 937.2, 96, p. 96. DOI: [10.3847/1538-4357/ac8c31](https://doi.org/10.3847/1538-4357/ac8c31).
- MacLeod, Morgan, James Guillochon, and Enrico Ramirez-Ruiz (Oct. 2012). “The Tidal Disruption of Giant Stars and their Contribution to the Flaring Supermassive Black Hole Population”. In: 757.2, 134, p. 134. DOI: [10.1088/0004-637X/757/2/134](https://doi.org/10.1088/0004-637X/757/2/134).
- MacLeod, Morgan, Eve C. Ostriker, and James M. Stone (Dec. 2018a). “Bound Outflows, Unbound Ejecta, and the Shaping of Bipolar Remnants during Stellar Coalescence”. In: 868.2, 136, p. 136. DOI: [10.3847/1538-4357/aae9eb](https://doi.org/10.3847/1538-4357/aae9eb).
- (Aug. 2018b). “Runaway Coalescence at the Onset of Common Envelope Episodes”. In: 863.1, 5, p. 5. DOI: [10.3847/1538-4357/aacf08](https://doi.org/10.3847/1538-4357/aacf08).

- MacLeod, Morgan and Enrico Ramirez-Ruiz (Apr. 2015a). “Asymmetric Accretion Flows within a Common Envelope”. In: 803.1, 41, p. 41. DOI: [10.1088/0004-637X/803/1/41](https://doi.org/10.1088/0004-637X/803/1/41).
- (Jan. 2015b). “On the Accretion-fed Growth of Neutron Stars during Common Envelope”. In: 798.1, L19, p. L19. DOI: [10.1088/2041-8205/798/1/L19](https://doi.org/10.1088/2041-8205/798/1/L19).
- MacLeod, Morgan et al. (Mar. 2017a). “Common Envelope Wind Tunnel: Coefficients of Drag and Accretion in a Simplified Context for Studying Flows around Objects Embedded within Stellar Envelopes”. In: 838.1, 56, p. 56. DOI: [10.3847/1538-4357/aa6117](https://doi.org/10.3847/1538-4357/aa6117).
- MacLeod, Morgan et al. (Feb. 2017b). “Lessons from the Onset of a Common Envelope Episode: the Remarkable M31 2015 Luminous Red Nova Outburst”. In: 835.2, 282, p. 282. DOI: [10.3847/1538-4357/835/2/282](https://doi.org/10.3847/1538-4357/835/2/282).
- Mandel, Ilya et al. (June 2025). “Rapid stellar and binary population synthesis with COMPAS: methods paper II”. In: *arXiv e-prints*, arXiv:2506.02316, arXiv:2506.02316. DOI: [10.48550/arXiv.2506.02316](https://doi.org/10.48550/arXiv.2506.02316).
- Martini, P., R. M. Wagner, A. Tomaney, et al. (1999). In: *AJ* 118, p. 1034. DOI: [10.1086/300951](https://doi.org/10.1086/300951). URL: <https://doi.org/10.1086/300951>.
- Martini, P. et al. (June 2003). “Circumnuclear Dust in Nearby Active and Inactive Galaxies. II. Bars, Nuclear Spirals, and the Fueling of Active Galactic Nuclei”. In: 589, pp. 774–782. DOI: [10.1086/374685](https://doi.org/10.1086/374685).
- Massey Jr., Frank J. (1951). “The Kolmogorov-Smirnov Test for Goodness of Fit”. In: *Journal of the American Statistical Association* 46.253, pp. 68–78. DOI: [10.1080/01621459.1951.10500769](https://doi.org/10.1080/01621459.1951.10500769). URL: <https://www.tandfonline.com/doi/abs/10.1080/01621459.1951.10500769>.
- Masters, K. L. et al. (Mar. 2011). “Galaxy Zoo: bars in disc galaxies”. In: 411, pp. 2026–2034. DOI: [10.1111/j.1365-2966.2010.17834.x](https://doi.org/10.1111/j.1365-2966.2010.17834.x).

- Masters, K. L. et al. (Aug. 2012). “Galaxy Zoo and ALFALFA: atomic gas and the regulation of star formation in barred disc galaxies”. In: 424, pp. 2180–2192. DOI: [10.1111/j.1365-2966.2012.21377.x](https://doi.org/10.1111/j.1365-2966.2012.21377.x).
- Masters, Karen L. et al. (Aug. 2019). “Galaxy Zoo: unwinding the winding problem - observations of spiral bulge prominence and arm pitch angles suggest local spiral galaxies are winding”. In: 487.2, pp. 1808–1820. DOI: [10.1093/mnras/stz1153](https://doi.org/10.1093/mnras/stz1153).
- Matsumoto, Tatsuya and Brian D. Metzger (Oct. 2022a). “Light-curve Model for Luminous Red Novae and Inferences about the Ejecta of Stellar Mergers”. In: *The Astrophysical Journal* 938.1, p. 5. ISSN: 1538-4357. DOI: [10.3847/1538-4357/ac6269](https://doi.org/10.3847/1538-4357/ac6269). URL: <http://dx.doi.org/10.3847/1538-4357/ac6269>.
- (Oct. 2022b). “Light-curve Model for Luminous Red Novae and Inferences about the Ejecta of Stellar Mergers”. In: 938.1, 5, p. 5. DOI: [10.3847/1538-4357/ac6269](https://doi.org/10.3847/1538-4357/ac6269).
- McKinney, Jonathan C., Alexander Tchekhovskoy, and Roger D. Blandford (July 2012). “General relativistic magnetohydrodynamic simulations of magnetically choked accretion flows around black holes”. In: 423.4, pp. 3083–3117. DOI: [10.1111/j.1365-2966.2012.21074.x](https://doi.org/10.1111/j.1365-2966.2012.21074.x).
- Melvin, T. et al. (Mar. 2014). “Galaxy Zoo: an independent look at the evolution of the bar fraction over the last eight billion years from HST-COSMOS”. In: 438, pp. 2882–2897. DOI: [10.1093/mnras/stt2397](https://doi.org/10.1093/mnras/stt2397).
- Menéndez-Delmestre, K. et al. (Mar. 2007). “A Near-Infrared Study of 2MASS Bars in Local Galaxies: An Anchor for High-Redshift Studies”. In: 657, pp. 790–804. DOI: [10.1086/511025](https://doi.org/10.1086/511025).
- Mengistu, Petra et al. (Apr. 2026). “The effects of bar strength and kinematics on galaxy evolution II: The global and local impacts of slow-strong bars”. In: DOI: [10.1093/mnras/stag561](https://doi.org/10.1093/mnras/stag561).

- Metzger, B. D., D. Giannios, and D. S. Spiegel (Oct. 2012). “Optical and X-ray transients from planet-star mergers”. In: 425.4, pp. 2778–2798. DOI: [10.1111/j.1365-2966.2012.21444.x](https://doi.org/10.1111/j.1365-2966.2012.21444.x).
- Mochkovitch, R. et al. (Jan. 1993). “Gamma-ray bursts as collimated jets from neutron star/black hole mergers”. In: 361.6409, pp. 236–238. DOI: [10.1038/361236a0](https://doi.org/10.1038/361236a0).
- Moriya, Takashi J. (Mar. 2018). “Explosions of Thorne-Żytkow objects”. In: 475.1, pp. L49–L51. DOI: [10.1093/mnrasl/sly005](https://doi.org/10.1093/mnrasl/sly005).
- Mukundan, Kavya et al. (Sept. 2025). “Bar fraction and its dependence on host galaxy properties in the local Universe”. In: 542.1, pp. 151–169. DOI: [10.1093/mnras/staf1143](https://doi.org/10.1093/mnras/staf1143).
- Munari, U., A. Henden, S. Kiyota, et al. (2002). In: 389, p. L51. DOI: [10.1051/0004-6361:20020715](https://doi.org/10.1051/0004-6361:20020715). URL: <https://doi.org/10.1051/0004-6361:20020715>.
- Murguía-Berthier, Ariadna et al. (Aug. 2017a). “Accretion Disk Assembly During Common Envelope Evolution: Implications for Feedback and LIGO Binary Black Hole Formation”. In: 845.2, 173, p. 173. DOI: [10.3847/1538-4357/aa8140](https://doi.org/10.3847/1538-4357/aa8140).
- Murguía-Berthier, Ariadna et al. (Feb. 2017b). “The Properties of Short Gamma-Ray Burst Jets Triggered by Neutron Star Mergers”. In: 835.2, L34, p. L34. DOI: [10.3847/2041-8213/aa5b9e](https://doi.org/10.3847/2041-8213/aa5b9e).
- Murguía-Berthier, Ariadna et al. (Oct. 2020). “On the Maximum Stellar Rotation to form a Black Hole without an Accompanying Luminous Transient”. In: 901.2, L24, p. L24. DOI: [10.3847/2041-8213/abb818](https://doi.org/10.3847/2041-8213/abb818).
- Muzzin, A. et al. (May 2013a). “A Public K_s -selected Catalog in the COSMOS/ULTRAVISTA Field: Photometry, Photometric Redshifts, and Stellar Population Parameters”. In: 206, 8, p. 8. DOI: [10.1088/0067-0049/206/1/8](https://doi.org/10.1088/0067-0049/206/1/8).

- Muzzin, A. et al. (Nov. 2013b). “The Evolution of the Stellar Mass Functions of Star-forming and Quiescent Galaxies to $z = 4$ from the COSMOS/UltraVISTA Survey”. In: 777, 18, p. 18. DOI: [10.1088/0004-637X/777/1/18](https://doi.org/10.1088/0004-637X/777/1/18).
- Nair, P. B. and R. G. Abraham (May 2010). “On the Fraction of Barred Spiral Galaxies”. In: 714, pp. L260–L264. DOI: [10.1088/2041-8205/714/2/L260](https://doi.org/10.1088/2041-8205/714/2/L260).
- Nandez, J. L. A. and N. Ivanova (Aug. 2016). “Common envelope events with low-mass giants: understanding the energy budget”. In: 460.4, pp. 3992–4002. DOI: [10.1093/mnras/stw1266](https://doi.org/10.1093/mnras/stw1266).
- Nandez, Jose L. A., Natalia Ivanova, and James C. Lombardi (June 2015). “V1309 Scorpii: Merger of a Contact Binary”. In: 806.2, 170, p. 170. DOI: [10.1088/0004-637X/806/2/170](https://doi.org/10.1088/0004-637X/806/2/170).
- Narayan, Ramesh, Tsvi Piran, and Pawan Kumar (Aug. 2001). “Accretion Models of Gamma-Ray Bursts”. In: 557.2, pp. 949–957. DOI: [10.1086/322267](https://doi.org/10.1086/322267).
- Nayyeri, H. et al. (Jan. 2017). “CANDELS Multi-wavelength Catalogs: Source Identification and Photometry in the CANDELS COSMOS Survey Field”. In: *The Astrophysical Journal Supplement Series* 228, 7, p. 7. DOI: [10.3847/1538-4365/228/1/7](https://doi.org/10.3847/1538-4365/228/1/7).
- Noeske, K. G. et al. (May 2007). “Star Formation in AEGIS Field Galaxies since $z=1.1$: The Dominance of Gradually Declining Star Formation, and the Main Sequence of Star-forming Galaxies”. In: 660.1, pp. L43–L46. DOI: [10.1086/517926](https://doi.org/10.1086/517926).
- Nogueira-Cavalcante, J. P. et al. (Jan. 2018). “Star formation quenching in green valley galaxies at $0.5 \lesssim z \lesssim 1.0$ and constraints with galaxy morphologies”. In: 473.1, pp. 1346–1358. DOI: [10.1093/mnras/stx2399](https://doi.org/10.1093/mnras/stx2399).
- O’Grady, Anna J. G. et al. (Oct. 2020). “Cool, Luminous, and Highly Variable Stars in the Magellanic Clouds from ASAS-SN: Implications for Thorne-Żytkow

- Objects and Super-asymptotic Giant Branch Stars”. In: 901.2, 135, p. 135. DOI: [10.3847/1538-4357/abafad](https://doi.org/10.3847/1538-4357/abafad).
- O’Ryan, David et al. (June 2025). “Time-scales for the effects of interactions on galaxy properties and SMBH growth”. In: 539.4, pp. 2967–2986. DOI: [10.1093/mnras/staf541](https://doi.org/10.1093/mnras/staf541).
- Ohlmann, Sophie T. et al. (Jan. 2016). “Hydrodynamic Moving-mesh Simulations of the Common Envelope Phase in Binary Stellar Systems”. In: 816, L9, p. L9. DOI: [10.3847/2041-8205/816/1/L9](https://doi.org/10.3847/2041-8205/816/1/L9).
- Özel, Feryal et al. (Sept. 2012). “On the Mass Distribution and Birth Masses of Neutron Stars”. In: 757.1, 55, p. 55. DOI: [10.1088/0004-637X/757/1/55](https://doi.org/10.1088/0004-637X/757/1/55).
- Paczynski, B. (Jan. 1976a). “Common Envelope Binaries”. In: *Structure and Evolution of Close Binary Systems*. Ed. by Peter Eggleton, Simon Mitton, and John Whelan. Vol. 73, p. 75.
- (Jan. 1976b). “Common Envelope Binaries”. In: *Structure and Evolution of Close Binary Systems*. Ed. by Peter Eggleton, Simon Mitton, and John Whelan. Vol. 73. IAU Symposium, p. 75.
- Passy, Jean-Claude et al. (Jan. 2012). “Simulating the Common Envelope Phase of a Red Giant Using SPH and Uniform Grid Codes”. In: 744, 52, p. 52. DOI: [10.1088/0004-637X/744/1/52](https://doi.org/10.1088/0004-637X/744/1/52).
- Pastorello, A., E. Mason, S. Taubenberger, et al. (2019b). In: 630, A75. DOI: [10.1051/0004-6361/201935999](https://doi.org/10.1051/0004-6361/201935999). URL: <https://doi.org/10.1051/0004-6361/201935999>.
- Patel, Shannon G. et al. (July 2011). “The Star-formation-rate-Density Relation at $0.6 < z < 0.9$ and the Role of Star-forming Galaxies”. In: 735.1, 53, p. 53. DOI: [10.1088/0004-637X/735/1/53](https://doi.org/10.1088/0004-637X/735/1/53).

- Patton, David R. et al. (June 2013). “Galaxy pairs in the Sloan Digital Sky Survey - VI. The orbital extent of enhanced star formation in interacting galaxies”. In: 433.1, pp. L59–L63. DOI: [10.1093/mnras/slt058](https://doi.org/10.1093/mnras/slt058).
- Pavlovskii, K. et al. (2017). In: *MNRAS* 465, p. 2092. DOI: [10.1093/mnras/stw2786](https://doi.org/10.1093/mnras/stw2786). URL: <https://doi.org/10.1093/mnras/stw2786>.
- Paxton, B., L. Bildsten, A. Dotter, et al. (2011a). In: *ApJS* 192, p. 3. DOI: [10.1088/0067-0049/192/1/3](https://doi.org/10.1088/0067-0049/192/1/3). URL: <https://doi.org/10.1088/0067-0049/192/1/3>.
- Paxton, B., M. Cantiello, P. Arras, et al. (2013a). In: *ApJS* 208, p. 4. DOI: [10.1088/0067-0049/208/1/4](https://doi.org/10.1088/0067-0049/208/1/4). URL: <https://doi.org/10.1088/0067-0049/208/1/4>.
- Paxton, B., P. Marchant, J. Schwab, et al. (2015a). In: *ApJS* 220, p. 15. DOI: [10.1088/0067-0049/220/1/15](https://doi.org/10.1088/0067-0049/220/1/15). URL: <https://doi.org/10.1088/0067-0049/220/1/15>.
- Paxton, B., R. Smolec, J. Schwab, et al. (2019). In: *ApJS* 243, p. 10. DOI: [10.3847/1538-4365/ab2241](https://doi.org/10.3847/1538-4365/ab2241). URL: <https://doi.org/10.3847/1538-4365/ab2241>.
- Paxton, Bill et al. (Jan. 2011b). “Modules for Experiments in Stellar Astrophysics (MESA)”. In: *ApJS* 192.1, p. 3. ISSN: 00670049. DOI: [10.1088/0067-0049/192/1/3](https://doi.org/10.1088/0067-0049/192/1/3).
- Paxton, Bill et al. (Aug. 2013b). “Modules for experiments in stellar astrophysics (MESA): Planets, oscillations, rotation, and massive stars”. In: *ApJS* 208.1, p. 4. ISSN: 00670049. DOI: [10.1088/0067-0049/208/1/4](https://doi.org/10.1088/0067-0049/208/1/4).
- Paxton, Bill et al. (Sept. 2015b). “Modules for Experiments in Stellar Astrophysics (MESA): Binaries, pulsations, and explosions”. In: *ApJS* 220.1, p. 15. ISSN: 00670049. DOI: [10.1088/0067-0049/220/1/15](https://doi.org/10.1088/0067-0049/220/1/15).
- Paxton, Bill et al. (Feb. 2018). “Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries, Element Diffusion, and Massive Star Explosions”. In: 234.2, 34, p. 34. DOI: [10.3847/1538-4365/aaa5a8](https://doi.org/10.3847/1538-4365/aaa5a8).

- Peng, C. Y. et al. (July 2002). “Detailed Structural Decomposition of Galaxy Images”. In: 124, pp. 266–293. DOI: [10.1086/340952](https://doi.org/10.1086/340952).
- (June 2010a). “Detailed Decomposition of Galaxy Images. II. Beyond Axisymmetric Models”. In: 139, pp. 2097–2129. DOI: [10.1088/0004-6256/139/6/2097](https://doi.org/10.1088/0004-6256/139/6/2097).
- Peng, Ying-jie et al. (Sept. 2010b). “Mass and Environment as Drivers of Galaxy Evolution in SDSS and zCOSMOS and the Origin of the Schechter Function”. In: 721.1, pp. 193–221. DOI: [10.1088/0004-637X/721/1/193](https://doi.org/10.1088/0004-637X/721/1/193).
- Pérez, I., J. A. L. Aguerri, and J. Méndez-Abreu (Apr. 2012). “Bar pattern speed evolution over the last 7 Gyr”. In: 540, A103, A103. DOI: [10.1051/0004-6361/201118396](https://doi.org/10.1051/0004-6361/201118396).
- Pfenniger, D. and D. Friedli (Dec. 1991). “Structure and dynamics of 3D N-body barred galaxies”. In: 252, pp. 75–93.
- Podsiadlowski, Ph., S. Rappaport, and E. Pfahl (Jan. 2001). “Binary Population Synthesis: Low- and Intermediate- Mass X-Ray Binaries”. In: *The Influence of Binaries on Stellar Population Studies*. Ed. by D. Vanbeveren. Vol. 264. Astrophysics and Space Science Library, p. 355. DOI: [10.1007/978-94-015-9723-4_26](https://doi.org/10.1007/978-94-015-9723-4_26).
- Podsiadlowski, Philipp, Robert C. Cannon, and Martin J. Rees (May 1995). “The evolution and final fate of massive Thorne-Zytkow objects”. In: 274.2, pp. 485–490. DOI: [10.1093/mnras/274.2.485](https://doi.org/10.1093/mnras/274.2.485).
- Popham, Robert, S. E. Woosley, and Chris Fryer (June 1999). “Hyperaccreting Black Holes and Gamma-Ray Bursts”. In: 518.1, pp. 356–374. DOI: [10.1086/307259](https://doi.org/10.1086/307259).
- Postnov, Konstantin A. and Lev R. Yungelson (May 2014). “The Evolution of Compact Binary Star Systems”. In: *Living Reviews in Relativity* 17.1, 3, p. 3. DOI: [10.12942/lrr-2014-3](https://doi.org/10.12942/lrr-2014-3).

- Qian, Y. -Z. and S. E. Woosley (Nov. 1996). “Nucleosynthesis in Neutrino-driven Winds. I. The Physical Conditions”. In: 471, p. 331. DOI: [10.1086/177973](https://doi.org/10.1086/177973).
- Qin, Ying et al. (Jan. 2019). “On the Origin of Black Hole Spin in High-mass X-Ray Binaries”. In: 870.2, L18, p. L18. DOI: [10.3847/2041-8213/aaf97b](https://doi.org/10.3847/2041-8213/aaf97b).
- Ramirez-Ruiz, Enrico, Annalisa Celotti, and Martin J. Rees (Dec. 2002). “Events in the life of a cocoon surrounding a light, collapsar jet”. In: 337.4, pp. 1349–1356. DOI: [10.1046/j.1365-8711.2002.05995.x](https://doi.org/10.1046/j.1365-8711.2002.05995.x).
- Rasio, Frederic A. and Mario Livio (Nov. 1996). “On the Formation and Evolution of Common Envelope Systems”. In: 471, p. 366. DOI: [10.1086/177975](https://doi.org/10.1086/177975).
- Rees, M. J. (Sept. 1999). “Some comments on triggers, energetics and beaming”. In: 138, pp. 491–497. DOI: [10.1051/aas:1999324](https://doi.org/10.1051/aas:1999324).
- Reichardt, T. A. et al. (2019). “Extending common envelope simulations from Roche lobe overflow to the nebular phase”. In: *MNRAS* 484, p. 631. DOI: [10.1093/mnras/sty3485](https://doi.org/10.1093/mnras/sty3485). URL: <https://doi.org/10.1093/mnras/sty3485>.
- Reichardt, T. A. et al. (2020). “The impact of recombination energy on simulations of the common-envelope binary interaction”. In: *MNRAS* 494, p. 5333. DOI: [10.1093/mnras/staa937](https://doi.org/10.1093/mnras/staa937). URL: <https://doi.org/10.1093/mnras/staa937>.
- Ricker, P. M. and R. E. Taam (2012a). In: *ApJ* 746, p. 74. DOI: [10.1088/0004-637X/746/1/74](https://doi.org/10.1088/0004-637X/746/1/74). URL: <https://doi.org/10.1088/0004-637X/746/1/74>.
- Ricker, Paul M. and Ronald E. Taam (Feb. 2012b). “An AMR Study of the Common-envelope Phase of Binary Evolution”. In: 746, 74, p. 74. DOI: [10.1088/0004-637X/746/1/74](https://doi.org/10.1088/0004-637X/746/1/74).
- Riley, Jeff et al. (Feb. 2022a). “Rapid Stellar and Binary Population Synthesis with COMPAS”. In: 258.2, 34, p. 34. DOI: [10.3847/1538-4365/ac416c](https://doi.org/10.3847/1538-4365/ac416c).
- (Feb. 2022b). “Rapid Stellar and Binary Population Synthesis with COMPAS”. In: 258.2, 34, p. 34. DOI: [10.3847/1538-4365/ac416c](https://doi.org/10.3847/1538-4365/ac416c).

- Rix, H.-W. et al. (June 2004). “GEMS: Galaxy Evolution from Morphologies and SEDs”. In: 152, pp. 163–173. DOI: [10.1086/420885](https://doi.org/10.1086/420885).
- Röpke, Friedrich K. and Orsola De Marco (Dec. 2023). “Simulations of common-envelope evolution in binary stellar systems: physical models and numerical techniques”. In: *Living Reviews in Computational Astrophysics* 9.1, 2, p. 2. DOI: [10.1007/s41115-023-00017-x](https://doi.org/10.1007/s41115-023-00017-x).
- Rosselli-Calderon, Alejandra et al. (Dec. 2024). “The Evolution of Binaries Embedded Within Common Envelopes”. In: 977.1, 16, p. 16. DOI: [10.3847/1538-4357/ad84ee](https://doi.org/10.3847/1538-4357/ad84ee).
- Rosswog, S., E. Ramirez-Ruiz, and W. R. Hix (Apr. 2009). “Tidal Disruption and Ignition of White Dwarfs by Moderately Massive Black Holes”. In: 695.1, pp. 404–419. DOI: [10.1088/0004-637X/695/1/404](https://doi.org/10.1088/0004-637X/695/1/404).
- Rosswog, Stephan et al. (July 2008). “Simulating black hole white dwarf encounters”. In: *Computer Physics Communications* 179.1-3, pp. 184–189. DOI: [10.1016/j.cpc.2008.01.031](https://doi.org/10.1016/j.cpc.2008.01.031).
- Safi-Harb, S. and H. Ögelman (1996). “MESA Isochrones and Stellar Tracks (MIST) 0: Methods for the construction of stellar isochrones”. In: 456, pp. L37–L40.
- Sana, Hugues et al. (2012). “Binary Interaction Dominates the Evolution of Massive Stars”. In: *Science* 337.6093, p. 444. DOI: [10.1126/science.1223344](https://doi.org/10.1126/science.1223344).
- Sandquist, Eric L., Ronald E. Taam, and Xian Chen (Jan. 2000). “Hydrodynamic calculations of common envelope evolution”. In: *New Astronomy* 4.7, pp. 313–321. DOI: [10.1016/S1384-1076\(99\)00076-4](https://doi.org/10.1016/S1384-1076(99)00076-4).
- Sandquist, Eric L. et al. (June 1998). “Common Envelope Evolution of Massive Binary Stars”. In: 500, pp. 909–922. DOI: [10.1086/305774](https://doi.org/10.1086/305774).

- Schawinski, K. et al. (May 2014). “The green valley is a red herring: Galaxy Zoo reveals two evolutionary pathways towards quenching of star formation in early- and late-type galaxies”. In: 440, pp. 889–907. DOI: [10.1093/mnras/stu327](https://doi.org/10.1093/mnras/stu327).
- Schröder, Sophie Lund et al. (Mar. 2020). “Explosions Driven by the Coalescence of a Compact Object with the Core of a Massive-star Companion inside a Common Envelope: Circumstellar Properties, Light Curves, and Population Statistics”. In: 892.1, 13, p. 13. DOI: [10.3847/1538-4357/ab7014](https://doi.org/10.3847/1538-4357/ab7014).
- Scoville, N. et al. (Sept. 2007). “The Cosmic Evolution Survey (COSMOS): Overview”. In: 172, pp. 1–8. DOI: [10.1086/516585](https://doi.org/10.1086/516585).
- Seidel, M. K. et al. (July 2015). “The BaLROG project - I. Quantifying the influence of bars on the kinematics of nearby galaxies”. In: 451, pp. 936–973. DOI: [10.1093/mnras/stv969](https://doi.org/10.1093/mnras/stv969).
- Seidel, M. K. et al. (Aug. 2016). “The BaLROG project - II. Quantifying the influence of bars on the stellar populations of nearby galaxies”. In: 460, pp. 3784–3828. DOI: [10.1093/mnras/stw1209](https://doi.org/10.1093/mnras/stw1209).
- Sellwood, J. A. (June 1981). “Bar instability and rotation curves”. In: 99, pp. 362–374.
- (Jan. 2014). “Secular evolution in disk galaxies”. In: *Reviews of Modern Physics* 86, pp. 1–46. DOI: [10.1103/RevModPhys.86.1](https://doi.org/10.1103/RevModPhys.86.1).
- Shah, Ekta A. et al. (Nov. 2022). “Investigating the Effect of Galaxy Interactions on Star Formation at $0.5 < z < 3.0$ ”. In: 940.1, 4, p. 4. DOI: [10.3847/1538-4357/ac96eb](https://doi.org/10.3847/1538-4357/ac96eb).
- Sheth, Kartik et al. (Mar. 2008). “Evolution of the Bar Fraction in COSMOS: Quantifying the Assembly of the Hubble Sequence”. In: 675.2, pp. 1141–1155. DOI: [10.1086/524980](https://doi.org/10.1086/524980).

- Shuntov, Marko et al. (Nov. 2025). “The stellar mass function of quiescent and star-forming galaxies and its dependence on morphology in COSMOS-Web”. In: *arXiv e-prints*, arXiv:2511.05259, arXiv:2511.05259.
- Simmons, B. D. et al. (Dec. 2014). “Galaxy Zoo: CANDELS barred discs and bar fractions”. In: 445, pp. 3466–3474. DOI: [10.1093/mnras/stu1817](https://doi.org/10.1093/mnras/stu1817).
- Simmons, B. D. et al. (Feb. 2017). “Galaxy Zoo: quantitative visual morphological classifications for 48 000 galaxies from CANDELS”. In: 464, pp. 4420–4447. DOI: [10.1093/mnras/stw2587](https://doi.org/10.1093/mnras/stw2587).
- Smethurst, R. J. et al. (June 2015). “Galaxy Zoo: evidence for diverse star formation histories through the green valley”. In: 450, pp. 435–453. DOI: [10.1093/mnras/stv161](https://doi.org/10.1093/mnras/stv161).
- Smirnov, Nickolay (1939). “Sur les écarts de la courbe de distribution empirique: Recueil Mathématique (Matematicheskii Sbornik), v”. In: *N.S.* 6, pp. 3–26.
- (1948). “Table for estimating the goodness of fit of empirical distributions”. In: *The annals of mathematical statistics* 19.2, pp. 279–281.
- Smith, N., J. E. Andrews, S. D. Van Dyk, et al. (2016). In: *MNRAS* 458, p. 950. DOI: [10.1093/mnras/stw219](https://doi.org/10.1093/mnras/stw219). URL: <https://doi.org/10.1093/mnras/stw219>.
- Soberman, G. E., E. S. Phinney, and E. P. J. van den Heuvel (1997). In: 327, p. 620.
- Soker, Noam (Feb. 2015). “Close Stellar Binary Systems by Grazing Envelope Evolution”. In: 800.2, 114, p. 114. DOI: [10.1088/0004-637X/800/2/114](https://doi.org/10.1088/0004-637X/800/2/114).
- (June 2024). “More Luminous Red Novae That Require Jets”. In: *Galaxies* 12.4, 33, p. 33. DOI: [10.3390/galaxies12040033](https://doi.org/10.3390/galaxies12040033).
- Soker, Noam and Romuald Tylanda (Jan. 2003). “Main-Sequence Stellar Eruption Model for V838 Monocerotis”. In: 582.2, pp. L105–L108. DOI: [10.1086/367759](https://doi.org/10.1086/367759).

- Soker, Noam and Romuald Tylenda (Dec. 2006). “Violent stellar merger model for transient events”. In: 373.2, pp. 733–738. DOI: [10.1111/j.1365-2966.2006.11056.x](https://doi.org/10.1111/j.1365-2966.2006.11056.x).
- Sparke, L. S. and J. A. Sellwood (Apr. 1987). “Dissection of an N-body bar”. In: 225, pp. 653–675. DOI: [10.1093/mnras/225.3.653](https://doi.org/10.1093/mnras/225.3.653).
- Speltinckx, T., E. Laurikainen, and H. Salo (Jan. 2008). “Comparison of bar strengths in optical and near-infrared for the OSUBSGS sample”. In: 383, pp. 317–329. DOI: [10.1111/j.1365-2966.2007.12548.x](https://doi.org/10.1111/j.1365-2966.2007.12548.x).
- Spergel, D. et al. (Mar. 2015). “Wide-Field InfrarRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report”. In: *arXiv e-prints*, arXiv:1503.03757, arXiv:1503.03757. DOI: [10.48550/arXiv.1503.03757](https://doi.org/10.48550/arXiv.1503.03757).
- Stevenson, Simon et al. (Apr. 2017). “Formation of the first three gravitational-wave observations through isolated binary evolution”. In: *Nature Communications* 8, 14906, p. 14906. DOI: [10.1038/ncomms14906](https://doi.org/10.1038/ncomms14906).
- Stritzinger, M. D., F. Taddia, M. Fraser, et al. (2020). In: 639, A104. DOI: [10.1051/0004-6361/202038019](https://doi.org/10.1051/0004-6361/202038019). URL: <https://doi.org/10.1051/0004-6361/202038019>.
- Taam, R. E., P. Bodenheimer, and J. P. Ostriker (1978a). In: *ApJ* 222, p. 269. DOI: [10.1086/156142](https://doi.org/10.1086/156142). URL: <https://doi.org/10.1086/156142>.
- (May 1978b). “Double core evolution. I. A 16 M sun star with a 1 M sun neutron-star companion.” In: 222, pp. 269–280. DOI: [10.1086/156142](https://doi.org/10.1086/156142).
- Thorne, K. S. and A. N. Żytkow (July 1975). “Red giants and supergiants with degenerate neutron cores.” In: 199, pp. L19–L24. DOI: [10.1086/181839](https://doi.org/10.1086/181839).
- (Mar. 1977). “Stars with degenerate neutron cores. I. Structure of equilibrium models.” In: 212, pp. 832–858. DOI: [10.1086/155109](https://doi.org/10.1086/155109).

- Timmes, F. X. and F. Douglas Swesty (Feb. 2000). “The Accuracy, Consistency, and Speed of an Electron-Positron Equation of State Based on Table Interpolation of the Helmholtz Free Energy”. In: 126.2, pp. 501–516. DOI: [10.1086/313304](https://doi.org/10.1086/313304).
- Tout, C. A. et al. (Nov. 2014). “HV2112, a Thorne-Zytkow object or a super asymptotic giant branch star.” In: 445, pp. L36–L40. DOI: [10.1093/mnrasl/flu131](https://doi.org/10.1093/mnrasl/flu131).
- Twum, Angela A. G. et al. (Feb. 2026). “The Landscape of Unstable Mass Transfer in Interacting Binaries and Its Imprint on the Population of Luminous Red Novae”. In: *arXiv e-prints*, arXiv:2602.10211, arXiv:2602.10211. DOI: [10.48550/arXiv.2602.10211](https://doi.org/10.48550/arXiv.2602.10211).
- Tylenda, R., M. Hajduk, T. Kamiński, et al. (2011). In: 528, A114. DOI: [10.1051/0004-6361/201016221](https://doi.org/10.1051/0004-6361/201016221). URL: <https://doi.org/10.1051/0004-6361/201016221>.
- van den Heuvel, E. P. J. (Jan. 1976). “Late Stages of Close Binary Systems”. In: *Structure and Evolution of Close Binary Systems*. Ed. by Peter Eggleton, Simon Mitton, and John Whelan. Vol. 73, p. 35.
- Weaver, J. R. et al. (Jan. 2022). “COSMOS2020: A Panchromatic View of the Universe to $z \sim 10$ from Two Complementary Catalogs”. In: 258.1, 11, p. 11. DOI: [10.3847/1538-4365/ac3078](https://doi.org/10.3847/1538-4365/ac3078).
- Webbink, R. F. (Feb. 1984). “Double white dwarfs as progenitors of R Coronae Borealis stars and type I supernovae.” In: 277, pp. 355–360. DOI: [10.1086/161701](https://doi.org/10.1086/161701).
- Weigel, Anna K., Kevin Schawinski, and Claudio Bruderer (June 2016). “Stellar mass functions: methods, systematics and results for the local Universe”. In: 459.2, pp. 2150–2187. DOI: [10.1093/mnras/stw756](https://doi.org/10.1093/mnras/stw756).

- Whyte, L. F. et al. (Nov. 2002). “Morphological classification of the OSU Bright Spiral Galaxy Survey”. In: 336.4, pp. 1281–1286. DOI: [10.1046/j.1365-8711.2002.05879.x](https://doi.org/10.1046/j.1365-8711.2002.05879.x).
- Willett, K. W. et al. (Feb. 2017). “Galaxy Zoo: morphological classifications for 120 000 galaxies in HST legacy imaging”. In: 464, pp. 4176–4203. DOI: [10.1093/mnras/stw2568](https://doi.org/10.1093/mnras/stw2568).
- Williams, R. J. et al. (Feb. 2009). “Detection of Quiescent Galaxies in a Bicolor Sequence from $Z = 0-2$ ”. In: 691, pp. 1879–1895. DOI: [10.1088/0004-637X/691/2/1879](https://doi.org/10.1088/0004-637X/691/2/1879).
- Woosley, S. E. (Mar. 1993). “Gamma-Ray Bursts from Stellar Mass Accretion Disks around Black Holes”. In: 405, p. 273. DOI: [10.1086/172359](https://doi.org/10.1086/172359).
- Wu, Samantha et al. (Sept. 2020). “The Art of Modeling Stellar Mergers and the Case of the B[e] Supergiant R4 in the Small Magellanic Cloud”. In: 901.1, 44, p. 44. DOI: [10.3847/1538-4357/abaf48](https://doi.org/10.3847/1538-4357/abaf48).
- Yarza, Ricardo et al. (Sept. 2023). “Hydrodynamics and Survivability during Post-main-sequence Planetary Engulfment”. In: 954.2, 176, p. 176. DOI: [10.3847/1538-4357/acbdfc](https://doi.org/10.3847/1538-4357/acbdfc).