Tidal Disruptions Due to Stellar Mass Black Hole Binaries: Modifying the Spin Magnitudes and Directions of LIGO Sources

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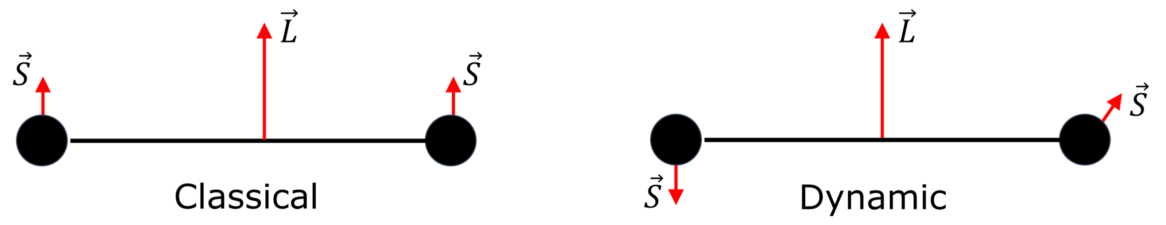
Introduction

Due to the recent detection of gravitational waves[1] (GWs), we know that black hole binaries (BHBs) are able to merge. Upon coalescence, BHBs produce GW signals that can be measured by the Laser Interferometer Gravitational-Wave Observatory (LIGO) group on Earth. Spin (S) is one such parameter that LIGO can estimate[2] and as such can be used to constrain their production site. When a BHB tidally disrupts a star, a significant fraction of the debris can be accreted by the binary, effectively altering the spin of the BH members. Therefore, although a dynamically formed BHB will initially have low randomly aligned spins, through these types of interactions their birth spins can be significantly altered both in direction and magnitude. The implications of our results will help us constrain the properties of BHBs in dense stellar systems in anticipation of an exciting decade ahead of us.

Formation Channels

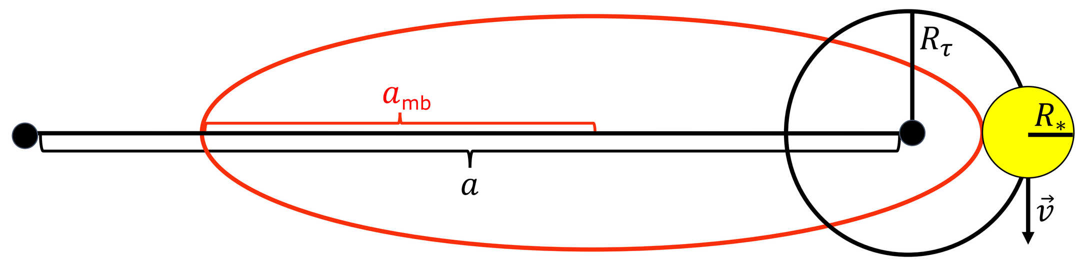
- Globular clusters can have about a thousand times denser stellar environments than our Milky Way.
- This crowded setting leads to interactions between inhabitants of the cluster and the formation of an assortment of exotic objects.
- One such object is a BHB that forms through multiple 3-body interactions, this is the dynamic formation channel of BHBs.
- Dynamic BHBs have randomly oriented BH spins due to the isotropic nature of interactions[3].
- When BHBs form through stellar evolution, this is the classical formation channel.
- Classical BHBs have aligned BH spins.



Unique Scenarios

- The outcomes of tidal interactions with BHBs in globular cluster depends on many different length scales in the initial conditions (ICs): stellar radius (R_*), binary separation (a), tidal radius (R_τ), and semi-major axis of most bound material (a_{mb}).
- These length scales can all be reduced to the ratio between R_τ and a.
- We have simulated three unique scenarios which varies this ratio using GADGET-3, a Smoothed Particle Hydrodynamics (SPH) code[4,5,6].

Single Scenario(SS)	Circumbinary Scenario(CS)	Overflow Scenario(OS)
$R_\tau \ll a$	$R_\tau \gg a$	$R_\tau \sim a$



Single Scenario

Stellar ICs	BHB ICs	Simulation ICs
• $M_* = 1\,M_\odot$ • $R_* = 1\,R_\odot$	• $M_{BH_1} = 15\,M_\odot$ • $M_{BH_2} = 15\,M_\odot$ • $a = 2$ AU • $e = 0.5$	• $R_\tau = 2.47\,R_\odot$ • $v_\infty = 10$ km/s • $i = \pi/3$

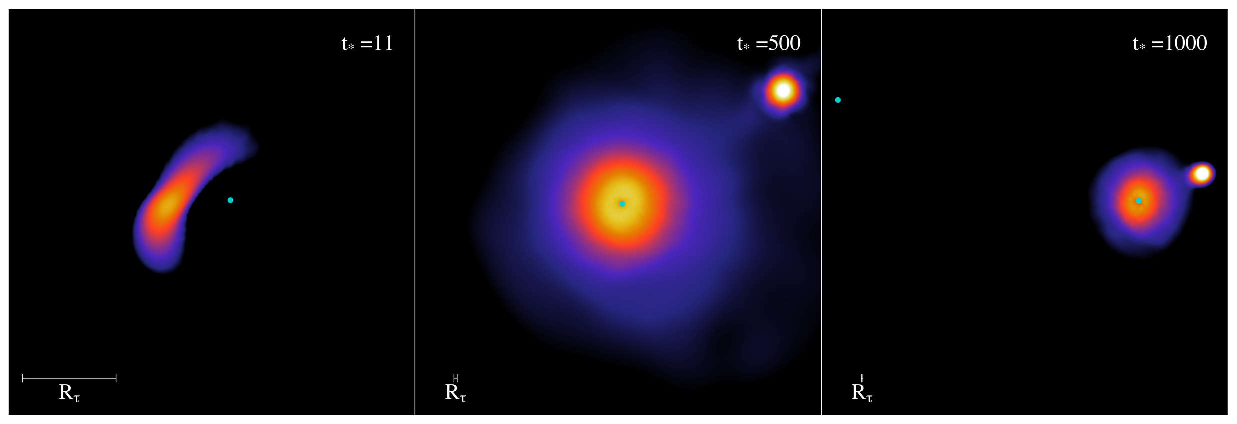


Figure 1: A simulation of the single scenario using GADGET-3. t_* is the dynamical time step of the star.

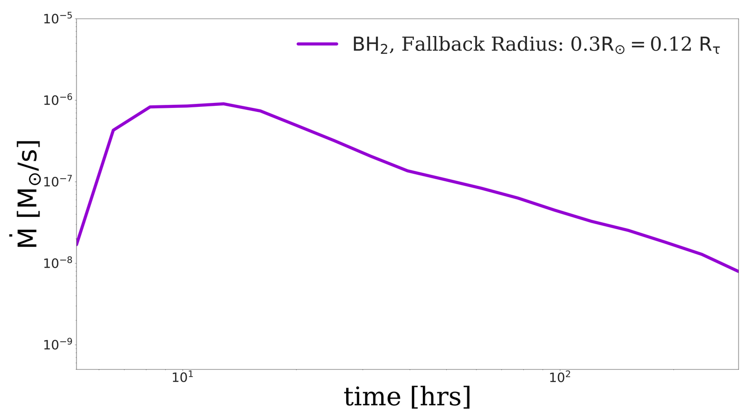


Figure 2: The accreted mass onto the BH that tidally disrupted the star.

Circumbinary Scenario

Stellar ICs	BHB ICs	Simulation ICs
• $M_* = 1\,M_\odot$ • $R_* = 43\,R_\odot$	• $M_{BH_1} = 15\,M_\odot$ • $M_{BH_2} = 15\,M_\odot$ • $a = 0.2$ AU • $e = 0.5$	• $R_\tau = 106.05\,R_\odot$ • $v_\infty = 30$ km/s • $i = \pi/4$

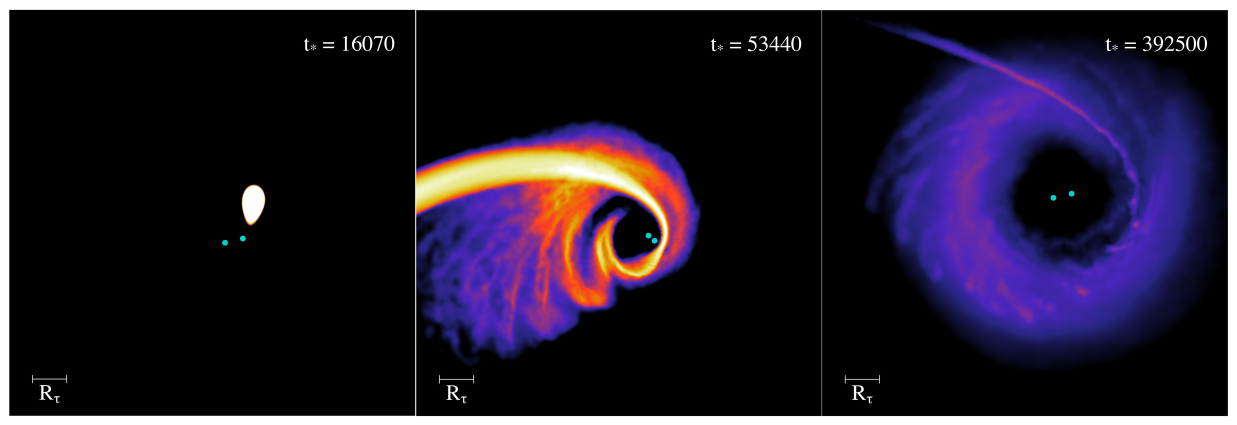


Figure 3: A simulation of the circumbinary scenario using GADGET-3. t_* is the dynamical time step of the star.

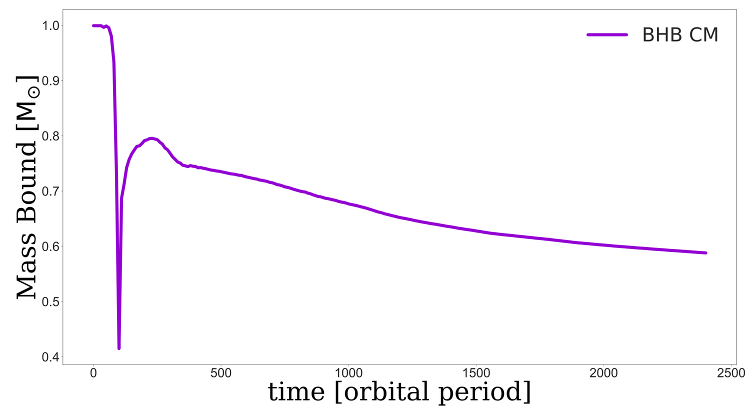


Figure 4: The stellar mass bound to the center of mass of the BHB. The final mass bound is taken as the mass of the disk.

Overflow Scenario

Stellar ICs	BHB ICs	Simulation ICs
• $M_* = 1\,M_\odot$ • $R_* = 1\,R_\odot$	• $M_{BH_1} = 15\,M_\odot$ • $M_{BH_2} = 15\,M_\odot$ • $a = 0.2$ AU • $e = 0.5$	• $R_\tau = 2.47\,R_\odot$ • $v_\infty = 20$ km/s • $i = \pi/3$

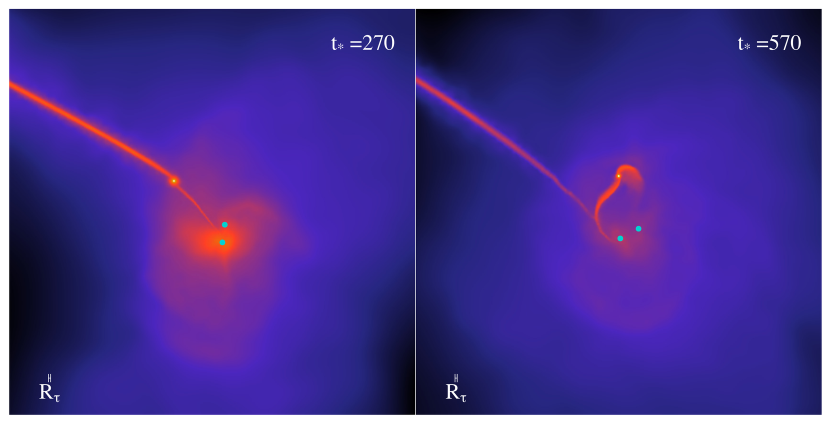


Figure 5: A simulation of the overflow scenario using GADGET-3. t_* is the dynamical time step of the star.

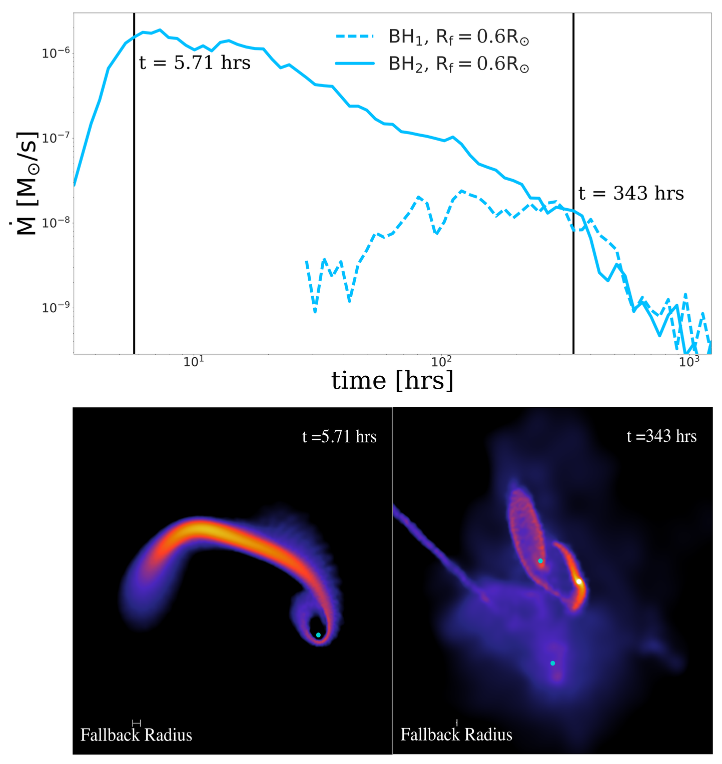


Figure 6: The accreted mass onto the BHB. The fallback radius (R_f) is the radius which $\dot{M}$ is calculated.

Massive Overflow Scenario

Stellar ICs	BHB ICs	Simulation ICs
• $M_* = 5\,M_\odot$ • $R_* = 6\,R_\odot$	• $M_{BH_1} = 10\,M_\odot$ • $M_{BH_2} = 10\,M_\odot$ • $a = 0.1$ AU • $e = 0.5$	• $R_\tau = 7.56\,R_\odot$ • $v_\infty = 30$ km/s • $i = \pi/3$

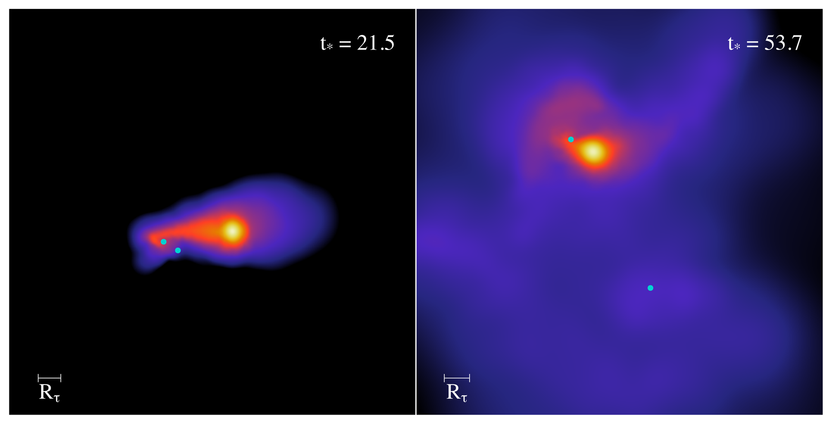


Figure 7: A simulation of the massive overflow scenario using GADGET-3. t_* is the dynamical time step of the star.

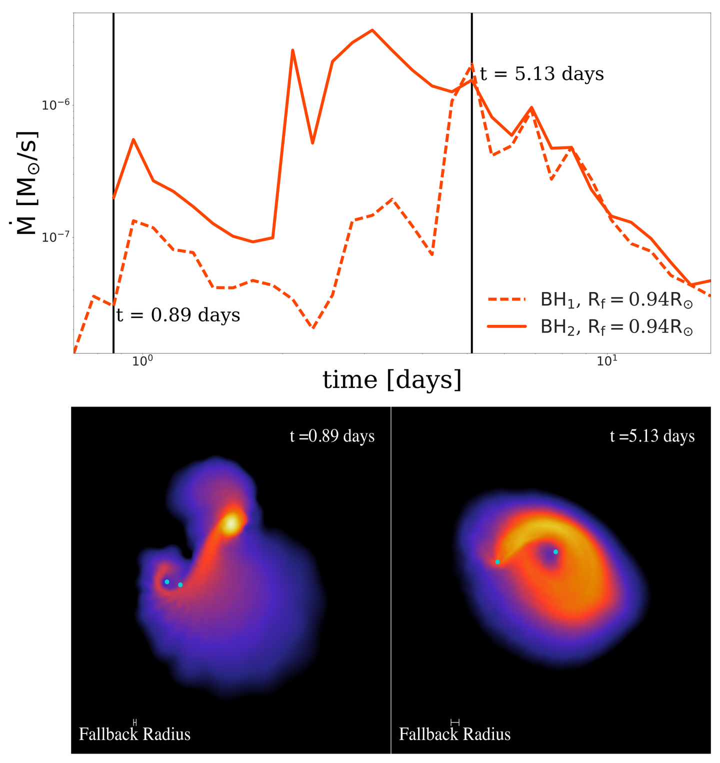


Figure 8: The accreted mass onto the BHB. The fallback radius (R_f) is the radius which $\dot{M}$ is calculated.

Results

SS		CS		OS		MOS	
BH_1	BH_2	BH_1	BH_2	BH_1	BH_2	BH_1	BH_2
$S_f = 0.00$	$S_f = 0.05$	$S_f = 0.07$	$S_f = 0.07$	$S_f = 0.01$	$S_f = 0.05$	$S_f = 0.29$	$S_f = 0.41$
$M_f = 15\,M_\odot$	$M_f = 15.23\,M_\odot$	$M_f = 15.31\,M_\odot$	$M_f = 15.31\,M_\odot$	$M_f = 15.05\,M_\odot$	$M_f = 15.21\,M_\odot$	$M_f = 10.93\,M_\odot$	$M_f = 11.44\,M_\odot$

- Relative spins of the BHs can be be significantly altered and aligned through tidal disruption events in the circumbinary and massive overflow scenarios.
- The CS accretes the mass evenly through viscous dissipation of the disk.
- As in the MOS, the mass of the BHB and the star must be comparable, otherwise spin up and alignment is negligible.

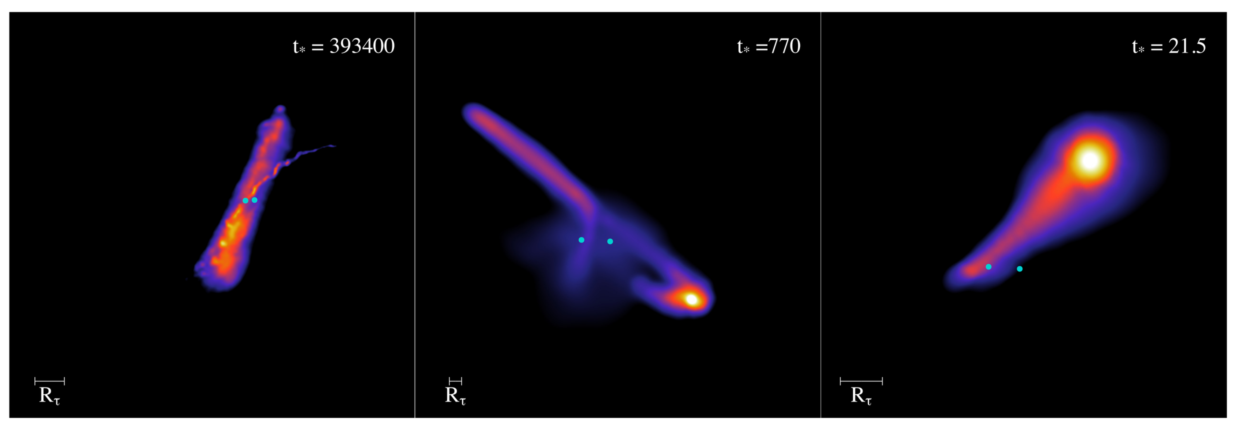


Figure 8: Side view of BHBs and the accretion disk. All angles are with respect to the orbital angular momentum of the binary. t_* is the dynamical time step of the star in each scenario. Left Panel: CS, 22°; Middle Panel: OS, 50°; Right Panel: MOS 48°;

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[1] Abbott, B. P. et al. 2016, Physical Review Letters, 116, 061102, 1602.03837; **[2]** Farr, W. M., Stevenson, S., Miller, M. C., Mandel, I., Farr, B., & Vecchio, A. 2017, Nature, 548, 426, 1706.01385; **[3]** C. L. Rodriguez, M. Zevin, C. Pankow, V. Kalogera, and F. A. Rasio, Astrophys. J. 832, L2 (2016); **[4]** Pakmor, R., Edelmann, P., Röpke, F. K., & Hillebrandt, W. 2012, MNRAS, 424, 2222, 1205.5806; **[5]** Gingold, R. A., & Monaghan, J. J. 1977, MNRAS, 181, 375; **[6]** Lucy, L. B. 1977, AJ, 82, 1013