STABILITY OF MASS TRANSFER FROM MASSIVE GIANTS

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ABSTRACT

The mass transfer in binaries with massive donors and compact companions, when the donors rapidly evolve after their main sequence, is one of the dominant formation channels of merging double stellar-mass black hole binaries. This mass transfer was previously postulated to be unstable and was expected to lead to a common envelope event. The common envelope event then would end with either double black hole formation, or with the merger of the two stars. We re-visit the stability of this mass transfer, and find that for a large range of the binary orbital separations this mass transfer is stable. This newly found stability allows us to reconcile the theoretical rate for double black hole binary mergers predicted by population synthesis studies, and the empirical rate obtained by LIGO. Furthermore, the stability of the mass transfer leads to the formation of ultra-luminous X-ray sources. The theoretically predicted formation rates of ultra-luminous X-ray sources powered by a stellar-mass BH, as well as the range of produced X-ray luminosity, can explain the observed bright ultraluminous X-ray sources.

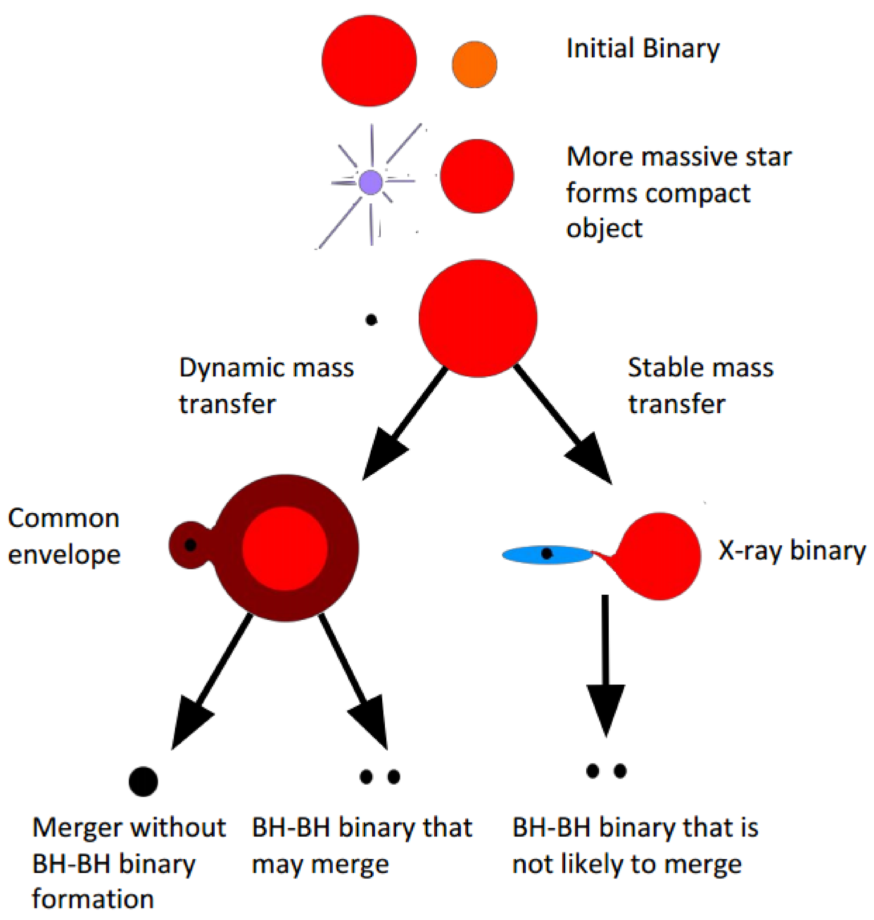
SCENARIO

With the detections of gravitational waves, it has become very important to understand and verify the proposed formation channels of black hole - black hole (BH-BH) binaries.

Currently there are two theoretically dominant formation channels:

1. The two stars are initially quickly rotating, so they never enter a giant phase, evolving directly to compact objects [5, 6].
2. The stars undergo dynamic mass transfer (MT) and go through at least one common envelope phase during evolution [1].

Our focus is on the second formation channel.



This BH-BH formation channel requires the system to enter at least one common envelope phase.

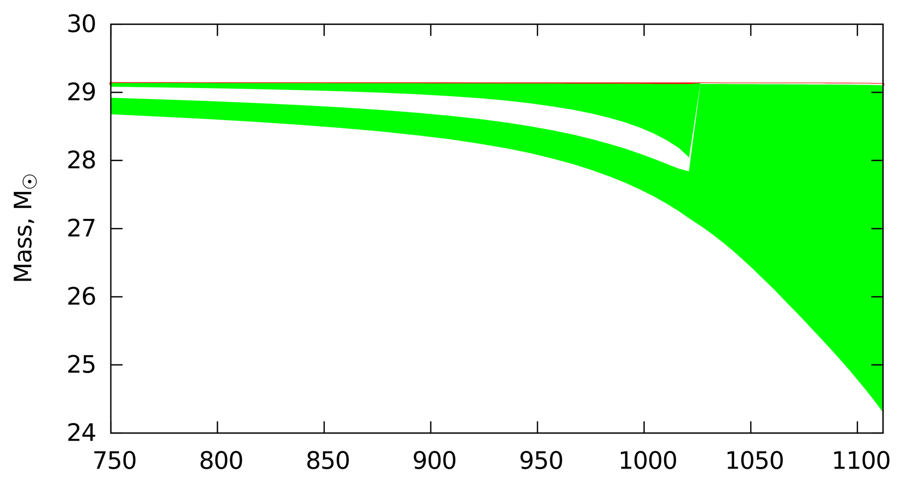
Using conventional MT stability criterion, this evolution is dynamically unstable and must result in a common envelope event.

Using self-consistent MT framework [8], we find that there is a range of binaries that are stable.

MT STABILITY/INSTABILITY BORDERS

1. Expansion Instability (R_S): This instability appears in donors, that at the moment of RLOF, experience fast thermal-timescale expansion. Donors larger than R_S at RLOF will not experience expansion instability.
2. Convection Instability (R_U): Donors with sufficiently developed convective envelope can experience this instability. Donors with a radius greater than R_U at the onset of RLOF will experience convection instability.

If the donor star lies between $R_S \leq R_d \leq R_U$, they do not experience unstable MT and are unlikely to experience the common envelope phase.



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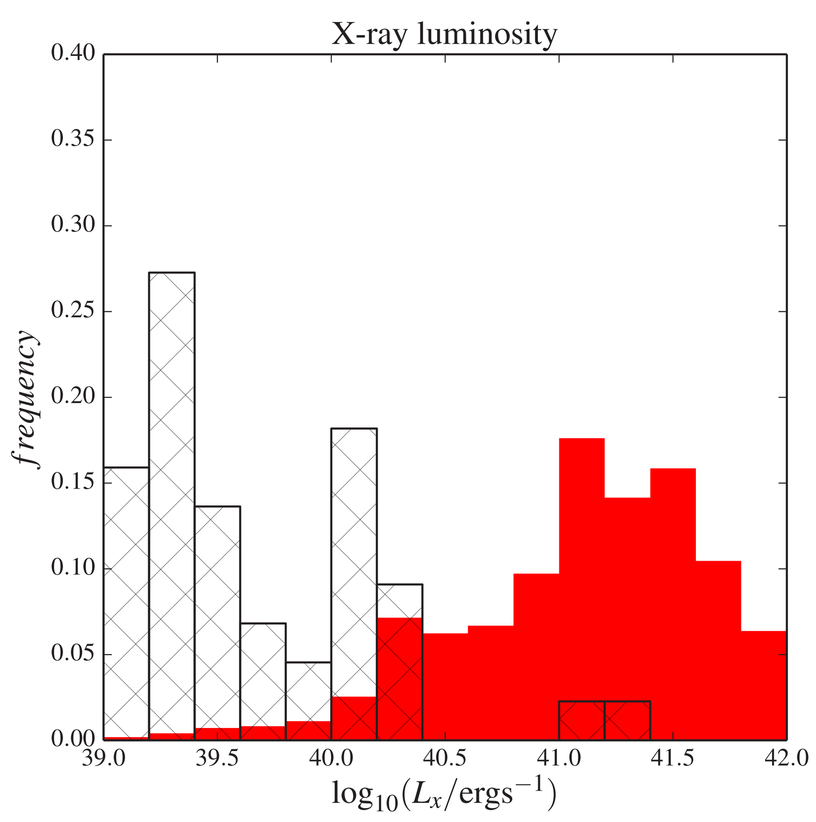
The development of the convective envelope that leads to convective instability (shaded area) for a 30 solar mass giant with 0.1 solar metallicity. Below 1004 Solar radii, this star has stable MT. Above 1111 Solar radii at RLOF, it is always unstable.

NEW FATE: ULTRA LUMINOUS X-RAY SOURCES

With the stable mass transfer, the binaries appear as X-ray sources and produce very high MT rates resulting in very large X-ray luminosities and appear as ULXs.



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Our systems predominantly produce bright ULXs with luminosities beyond 10^{40} ergs/s (shown as red histogram in Figure, while the observed ULXs from [2] are shown as hatched area).

Our theoretical formation rate is 0.2-2 bright ULXs per star formation rate of 1 $M_\odot yr^{-1}$. This is in agreement with the observed formation rate of bright ULXs, which can be as low as 0.4 [4], but also can be as high as 4 bright ULXs per star formation rate of 1 $M_\odot yr^{-1}$ if beaming is present [3].

WHICH BINARIES ARE STABLE NOW?

Using Modules for Experiments in Stellar Astrophysics (MESA), we tested systems with an already formed BH and a giant donor at various masses and metallicities.

$M_{d,ZAMS}$	M_{BH}	R_S	$M_{d,S}$	R_U	$M_{d,U}$
$Z = 0.1Z_\odot$					
20	7	Stable		686-721	19.6
30	7	44-51	29.4	1004-1111	29.1-29.2
40	7	309-354	38.6	1260-1327	38.6-38.7
60	7	Unstable			
60	10	346-364	56.8	1705-1790	56.8
60	12	140-156	56.8	1768-1879	56.8
80	7	Unstable			
80	10	Stable		2217-2241	74.5
80	12	134-155	74.6	2122-2176	74.5
$Z = Z_\odot$					
20	7	Stable		729-743	19.6
30	7	Stable		1144-1174	26.6
40	7	Stable		1381-1434	32.5
60	10	Stable		2035-2172	41.0
60	12	Stable		2009-2057	41.0
80	10	Stable		Stable	
80	14	Stable		Stable	

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A table of critical values for MT stability. Any system labelled as "stable" for the expansion instability is always stable prior to developing a convective envelope. Any system that is also labelled as "stable" for convective instability is always stable. Any system that is listed as "unstable" for expansion instability is always unstable.

$M_{d'S'}$, $M_{d'U}$ is the mass of the donor when they reach the instability boundary.
R_S is the expansion instability borders. The lower value is the largest radius with unstable MT and the upper value is the smallest value with stable MT.
R_U is the convective instability borders. The lower value is the largest radius with stable MT and the upper value is the smallest value with unstable MT.

The found stability of the mass transfer reduces the theoretically expected rate of BH-BH mergers to a merger rate of 220 Gpc^{-3} yr^{-1}, making it closer the current empirical LIGO estimate of of 9-240 Gpc^{-3} yr^{-1} [9].

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