Helium star donors to thermonuclear supernovae

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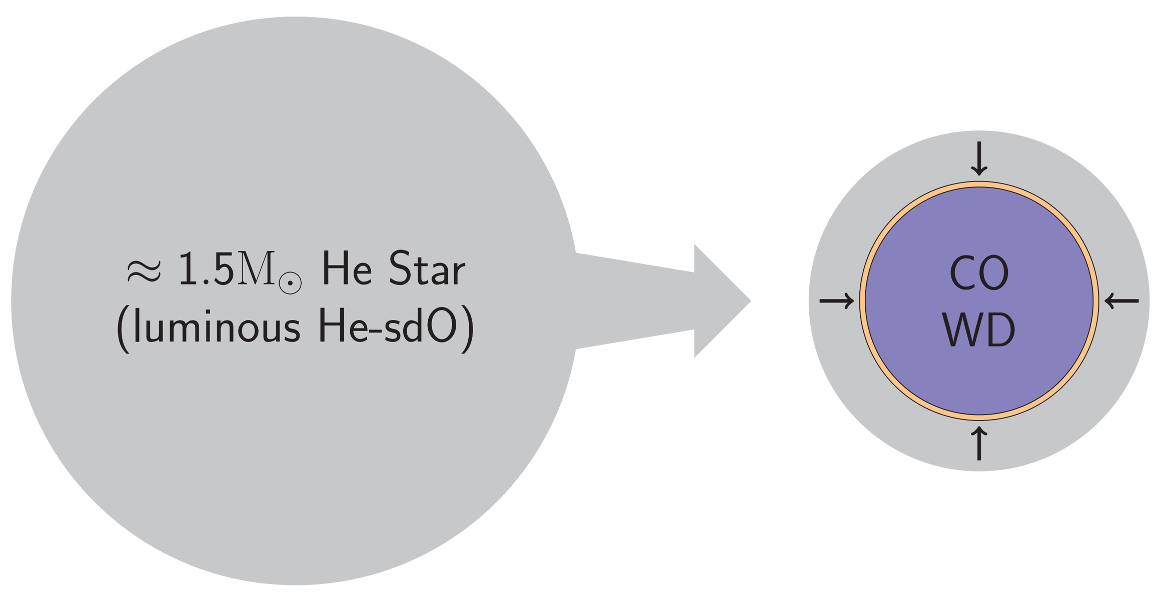
Abstract

We perform binary evolution calculations of helium star - carbon-oxygen white dwarf (CO WD) binaries using the stellar evolution code MESA. We focus on 1-2 $M_\odot$ He stars that undergo thermal-timescale mass transfer. We survey the initial binary parameters (orbital period, He star mass, and WD mass) and determine which systems can evolve towards thermonuclear supernovae. Our time-dependent calculations resolve the stellar structures of both binary components, which allows accurate detection of the occurrence of off-center carbon ignitions. We find systems that successfully reach explosion generally have orbital periods of hours; it will be useful to understand the MW population of He star - WD binaries with these properties. We also describe the observational appearance of these systems near the time of explosion as they may be detectable in pre-explosion images of supernovae.

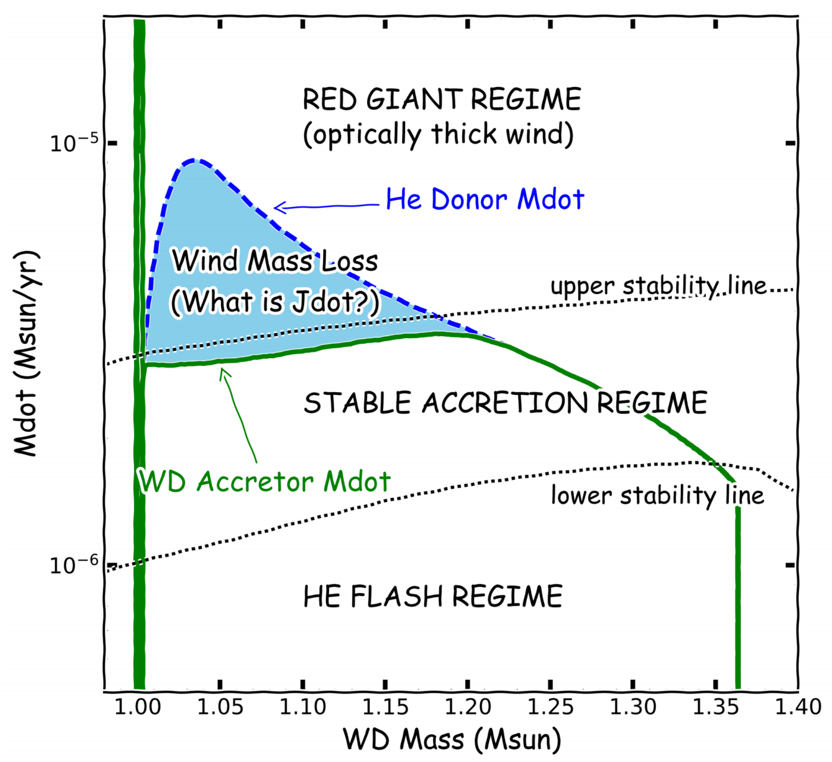
Binary scenario and mass transfer prescription

We consider He star - WD binaries at orbital periods such that the He star will fill its Roche lobe on the He giant branch. Yoon & Langer (2003) showed the resulting thermal-timescale He mass transfer can produce a Chandrasekhar mass WD.



Orbital period ~ hours

The WD may accrete helium stably within a narrow range of mass transfer rates. Below the lower stability line, the WD envelope experiences a thermal instability and undergoes helium flashes. Above the upper stability line, the WD cannot burn the accreted helium fast enough and expands to red giant dimensions. We invoke the optically thick wind theory, such that the WD loses the excess mass through an isotropic wind, and grows at the rate given by the upper stability line.



Acknowledgments

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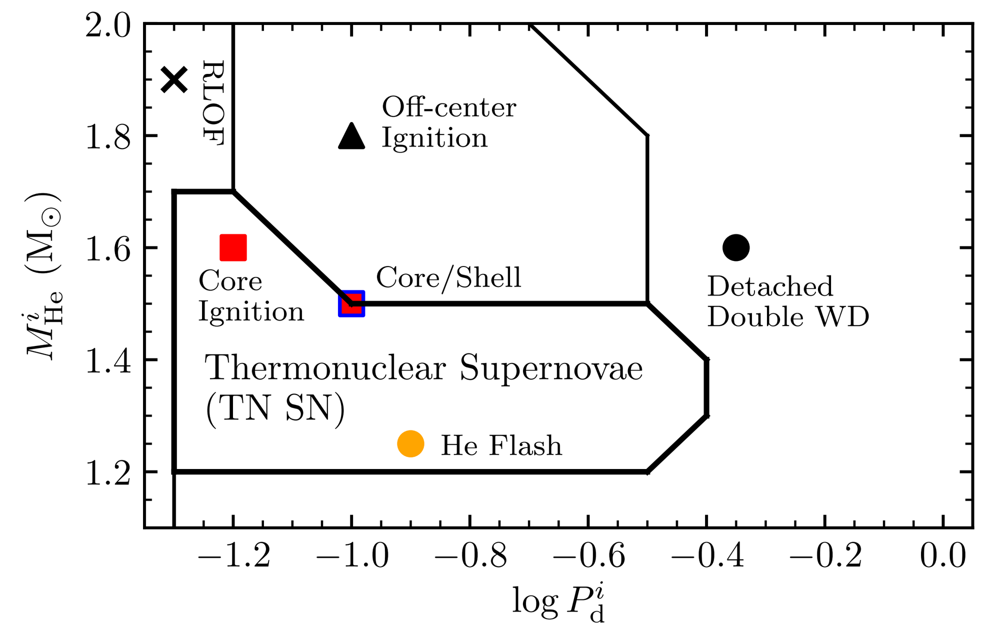
Final fate of the WDs

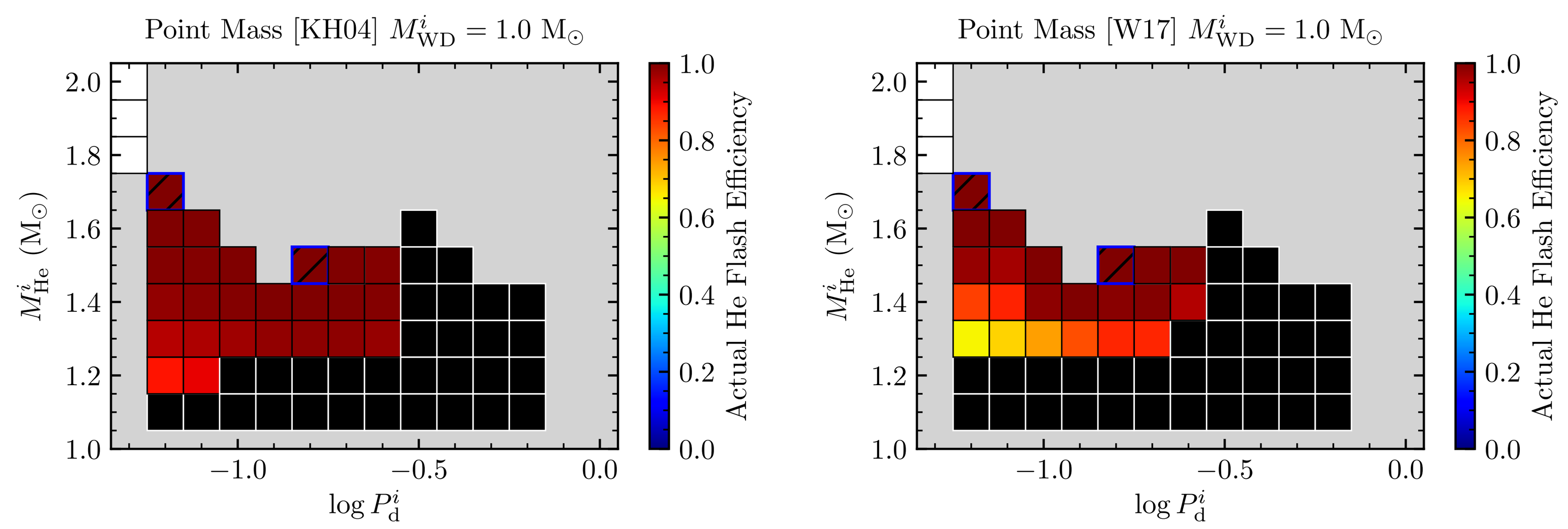
The mass transfer history and hence binary parameters determine the final outcome. We explored different assumptions about the specific angular momentum carried by mass lost from the system, but found this did not have a strong effect.



These outcomes are in general agreement with past work (Wang et al. 2009, 2017). Because our binary models include WDs with resolved interior structures (i.e., non-point-mass) they are able to self-consistently identify the occurrence of off-center ignitions.

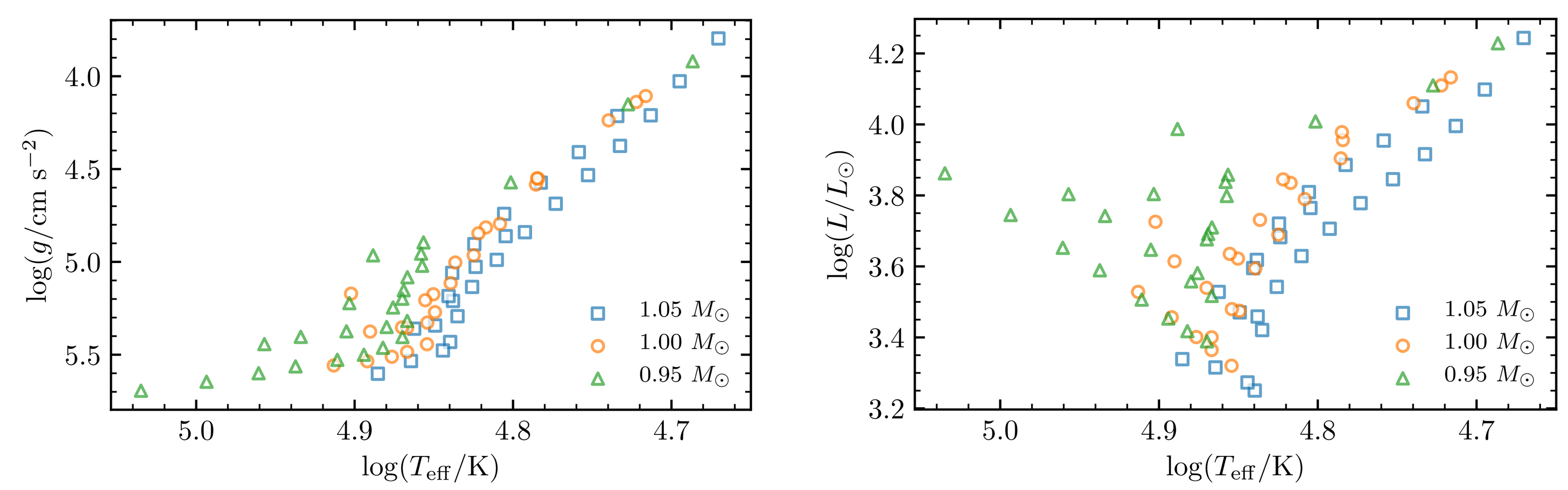
Re-simulation of He-flashing systems

While resolving the structure of the WD is an advantage for detecting off-center carbon ignition, it is a disadvantage once He novae begin to occur. Computational constraints prevented our original models from following systems that entered the region of thermally-unstable He burning through their many He flashes. Therefore, we re-simulated a subset of systems, using two different prescriptions for the He retention fraction: Kato & Hachisu (2004) and Wu et al. (2017). Longer period and lower He star mass systems do not retain enough to reach the Chandrasekhar mass.



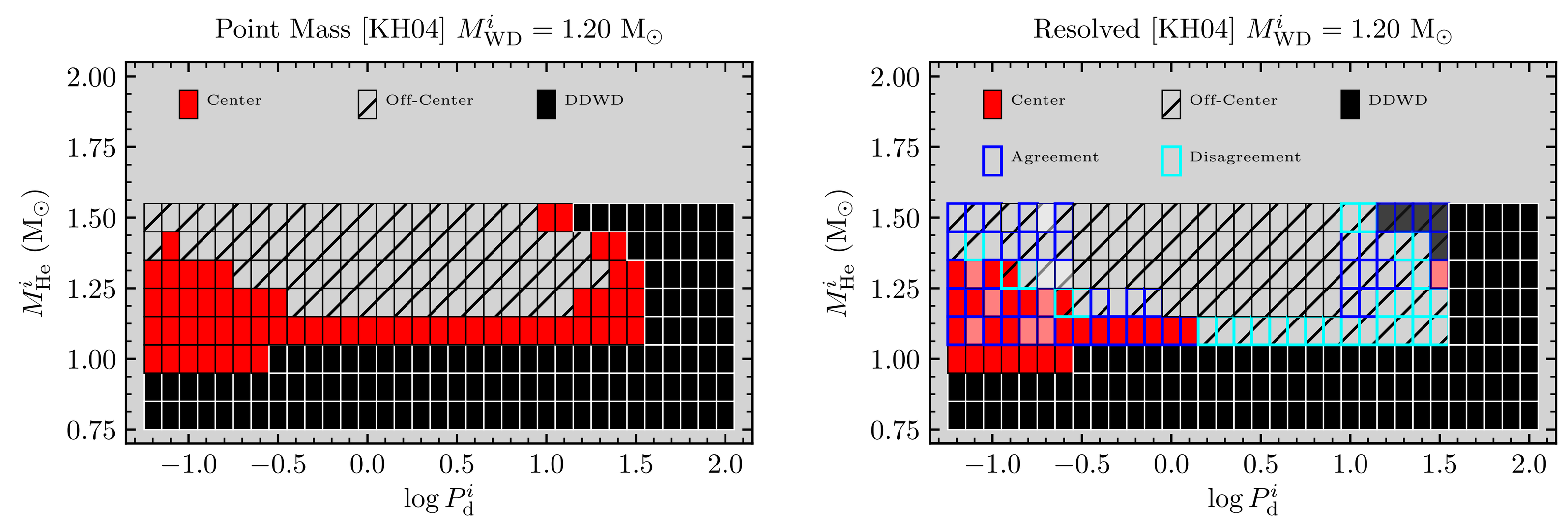
Pre-explosion properties of the He stars

At the time the WD reaches the Chandrasekhar mass, we record the properties of the He star donor. These stars have been further stripped; at this time they typically have masses $\approx 0.9\,M_\odot$ with a $\approx 0.2\,M_\odot$ He envelope.



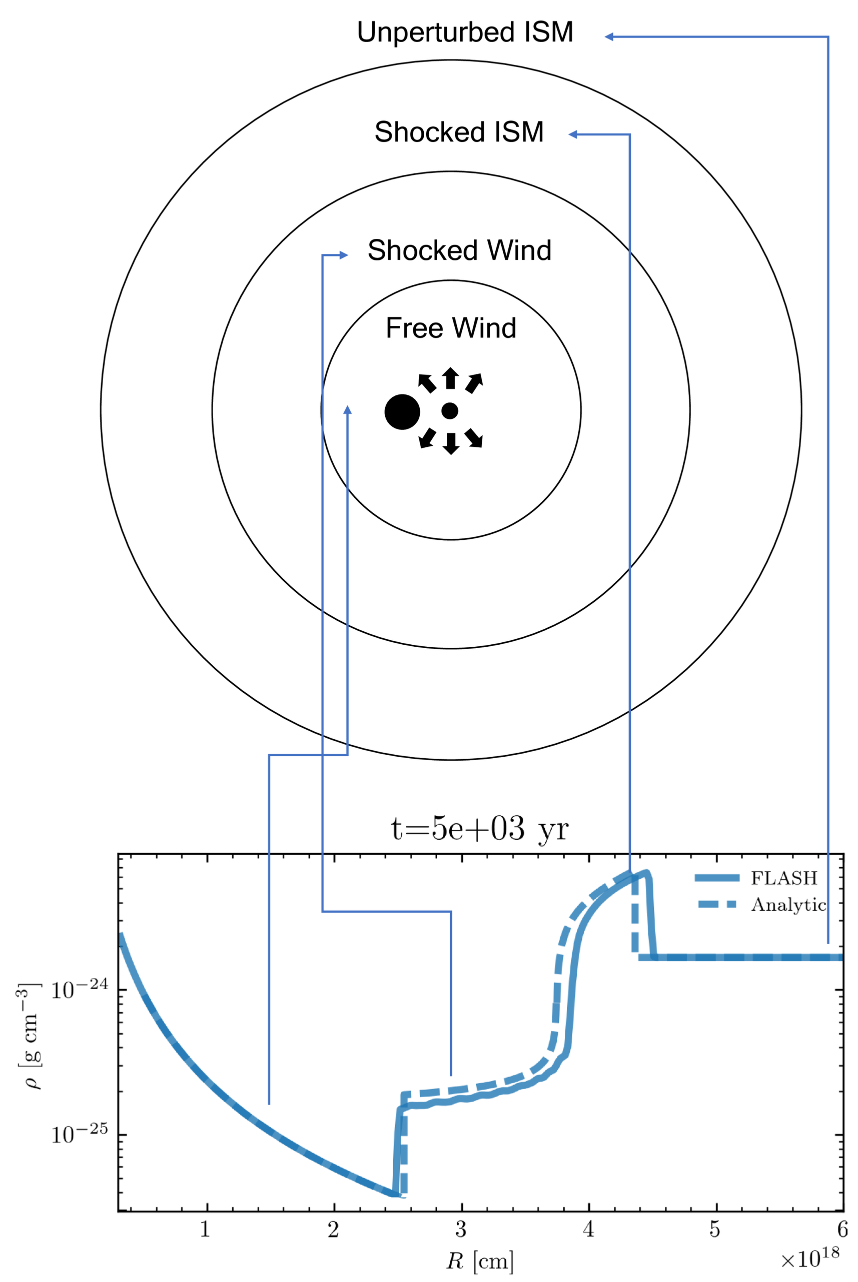
Extension to more massive WDs

The type Iax supernova 2012Z has a pre-explosion detection of a luminous, blue progenitor system (McCully et al. 2014). Reproducing this source with a He star requires a longer-period system (Liu et al. 2015), in order to allow the Roche-lobe-filling photosphere to be cool enough to emit mostly in the optical. Longer periods also lead to increasingly more non-conservative mass transfer, thus requiring an initially more massive WD in order to reach the Chandrasekhar mass.



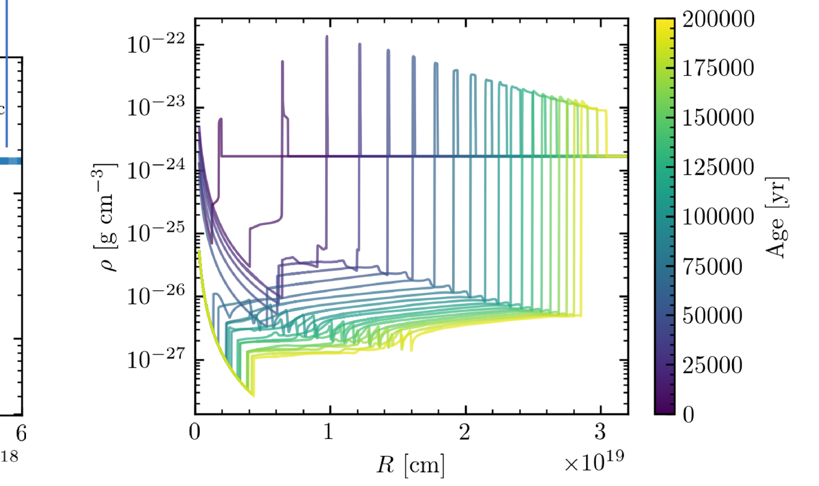
We performed a set of calculations using massive CO WDs where we modeled them as point masses (left) and where we resolve their structure (right). All the resolved models with periods longer than about a day experienced off-center carbon ignitions, rather than the central ignitions needed to produce a thermonuclear supernova.

Ongoing: Understanding the circumstellar environment and its effects



Given that these binary systems underwent a phase of non-conservative mass transfer (as well as experienced He novae) before their explosion, they have modified their circumstellar environments.

With hydrodynamics simulations that include cooling and use time-dependent winds motivated by the mass-transfer histories of our binary calculations, we are exploring the structure of the surrounding wind-blown bubbles.



We find that a wind bubble with a radius of 5 − 10 pc is carved out by the time of the supernova explosion. Both the accreting WD and the He star can emit copious amounts of ionizing photons, which can photoionize the surrounding ISM. Our rough estimate shows that the photoionization due to the binary should extend out to beyond the wind cavity (about 20 pc). We are currently performing photoionization calculations in order to predict the observational signatures of these systems, especially when they are spatially unresolved.

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