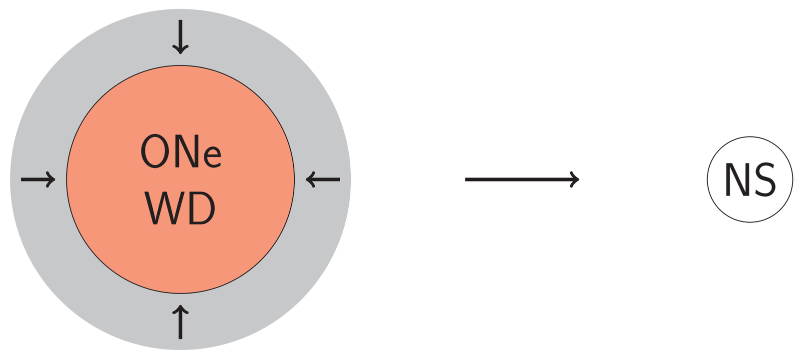
Accretion-Induced Collapse and its Progenitors

Josiah Schwab[*], Lars Bildsten, Jared Brooks, Eliot Quataert

Overview

If an oxygen-neon white dwarf (WD) grows to near the Chandrasekhar mass, electron-capture reactions can trigger a collapse to form a neutron star (NS).



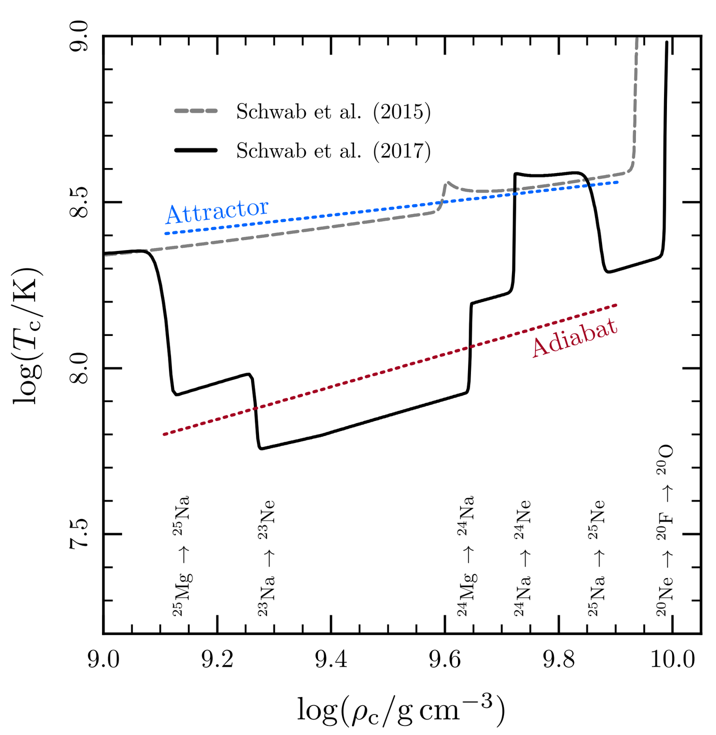
Such a situation can arise in a binary system with a massive ONe white dwarf accreting from a non-degenerate companion (e.g., Nomoto & Kondo 1991). Alternatively, this can occur in the remnant of a super-Chandrasekhar (total mass) WD-WD merger, where the compression is caused by the cooling of the outer layers (e.g., Saio & Nomoto 1985). Electron-capture supernovae from super asymptotic giant branch stars are a closely related phenomenon; there, a degenerate ONe core is formed and then compressed by the deposition of material from exterior shell-burning (e.g., Miyaji & Nomoto 1987),

Accreting ONe WDs: The approach to collapse

The thermal and compositional evolution of accreting ONe WDs is largely driven by weak reactions. We have updated the MESA stellar evolution code with an accurate treatment of electron-capture and beta-decay reaction rates in electron-degenerate conditions and applied these capabilities to studies of accreting WDs.

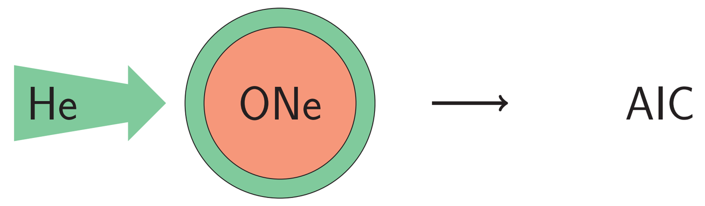
Our MESA models confirm previous work showing the role that ^{24}Mg and ^{20}Ne play in reducing the electron fraction and heating the core. We demonstrate the presence of a thermal runaway in the core that launches an oxygen deflagration wave from the center of the star. The ability of MESA to perform fine spatial zoning allows the models to reach length-scales that, for the first time, directly connect full-star simulations to studies of oxygen deflagrations performed using micro-zoned hydrodynamics codes (e.g., Timmes & Woosley 1992). We also demonstrate that the carbon-burning products ^{23}Na and ^{25}Mg lead to substantial cooling of the WD via the Urca process. We derive an analytic formula for the peak Urca-process cooling rate and obtain a simple expressions for the temperature to which the Urca process cools the WD. We also demonstrate and explain the novel result that models with lower temperatures at the onset of the ^{24}Mg electron captures develop convectively unstable regions, even when using the Ledoux criterion. If these convectively unstable regions grow, they may strongly influence the subsequent evolution and collapse.

These are important steps in producing progenitor models with more realistic temperature and composition profiles that are needed for the evolution of the subsequent oxygen deflagration and hence for studies of the signature of AIC.

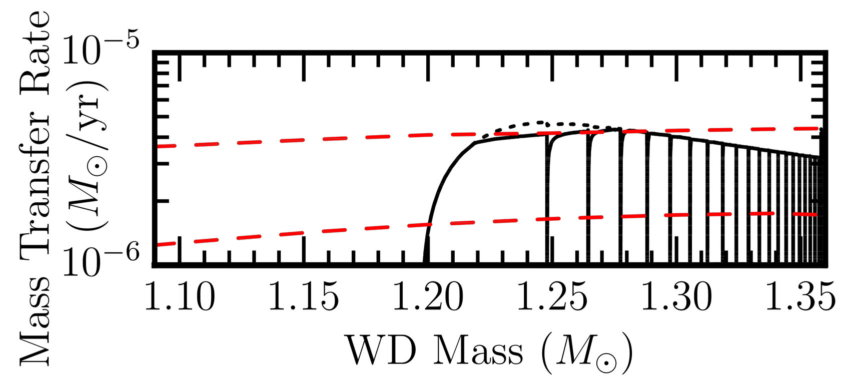


The evolution of the central temperature and density of an accreting ONe WD. The 2015 line (dashed gray) considers only ^{16}O, ^{20}Ne, and ^{24}Mg; the 2017 line (solid black) adds ^{23}Na and ^{25}Mg. The labeled dotted lines show the attractor solution (where neutrino cooling balances compressional heating) and a sample adiabat. The accurate inclusion of key weak reactions, which are indicated at the densities where they occur, is essential for understanding the evolution of these objects.

Single Degenerate Progenitors: He Star + ONe WD

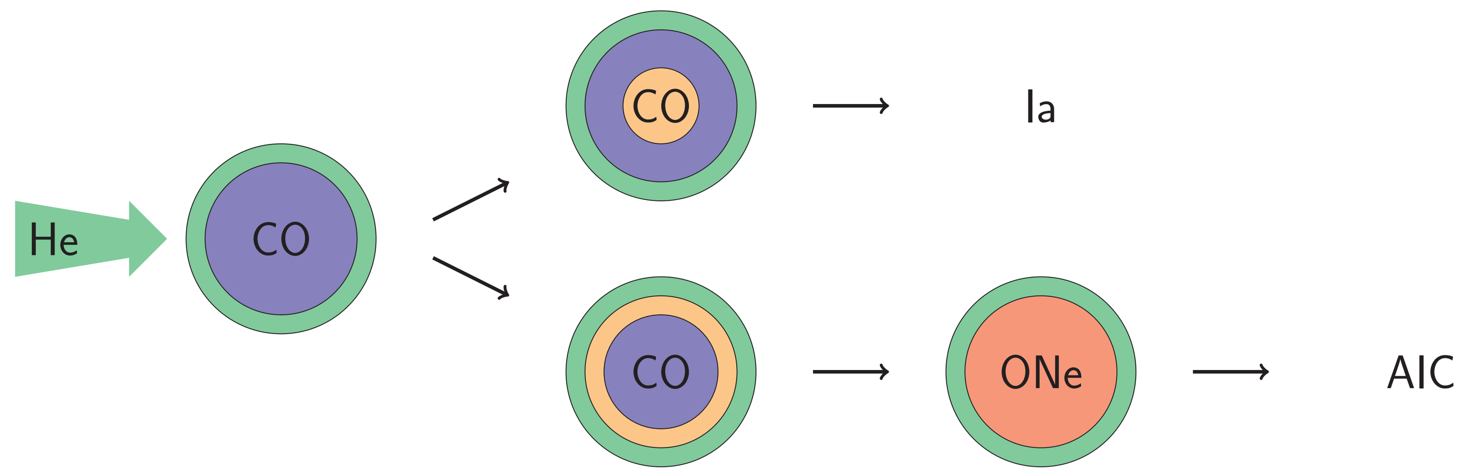


Thermal-timescale mass transfer in He star-WD binaries gives $\dot{M}$ in the regime for stable He burning on the WD (Yoon & Langer 2003). We use MESA to evolve both stars plus their orbit. Our models show stable He burning, plus unstable carbon flashes, but the WD grows to near-Chandrasekhar and reaches the conditions for the onset of AIC.



Mass transfer history for a 1.2 $M_\odot$ ONe WD in a binary system with a 1.5 $M_\odot$ He star at an initial orbital period of 3 hours. The mass transfer is punctuated by brief mass loss episodes caused by carbon shell flashes in the He-burning ashes. The stable He burning boundaries are shown by the dashed red lines.

Single Degenerate Progenitors: He Star + CO WD



For mass transfer from a He star onto a CO WD, there is a race to ignition between the CO in the core and the CO ashes of the He burning. In the case that off-center ignition occurs first, it leads to an inward-going carbon flame and the CO WD core is quiescently converted to an ONe WD. The WD then continues to accrete and can reach AIC conditions. This latter channel may be important for understanding the rates of AIC since CO WD accretors are likely more numerous than ONe ones.

Work covered by this poster (2015-2017)

Thermal runaway during the evolution of ONeMg cores towards accretion-induced collapse
J. Schwab, E. Quataert, and L. Bildsten
MNRAS, 453, pp. 1910–1927

The importance of Urca-process cooling in accreting ONe white dwarfs
J. Schwab, L. Bildsten, and E. Quataert
MNRAS, 472, pp. 3390–3406

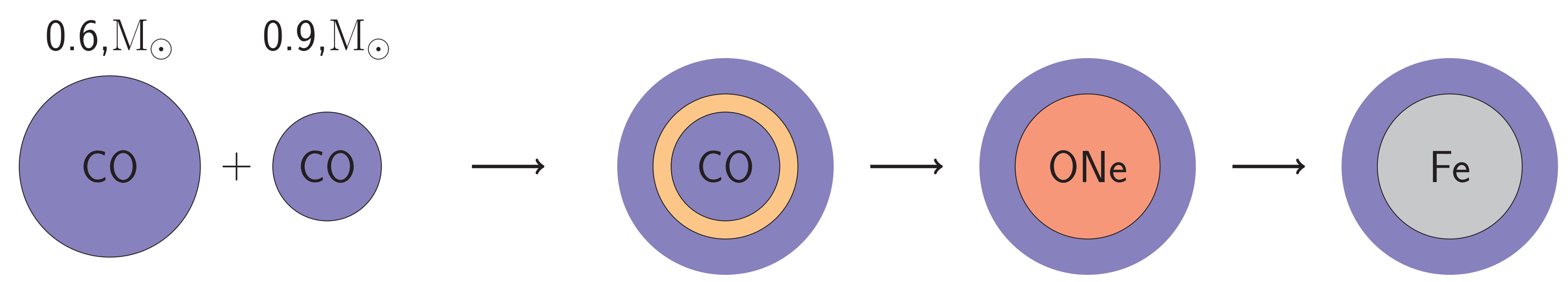
Carbon Shell or Core Ignitions in White Dwarfs Accreting from Helium Stars
J. Brooks, L. Bildsten, J. Schwab, and B. Paxton
ApJ, 821, p. 28

Accretion-induced Collapse from Helium Star + White Dwarf Binaries
J. Brooks, J. Schwab, L. Bildsten, E. Quataert, and B. Paxton
ApJ, 843, p. 151

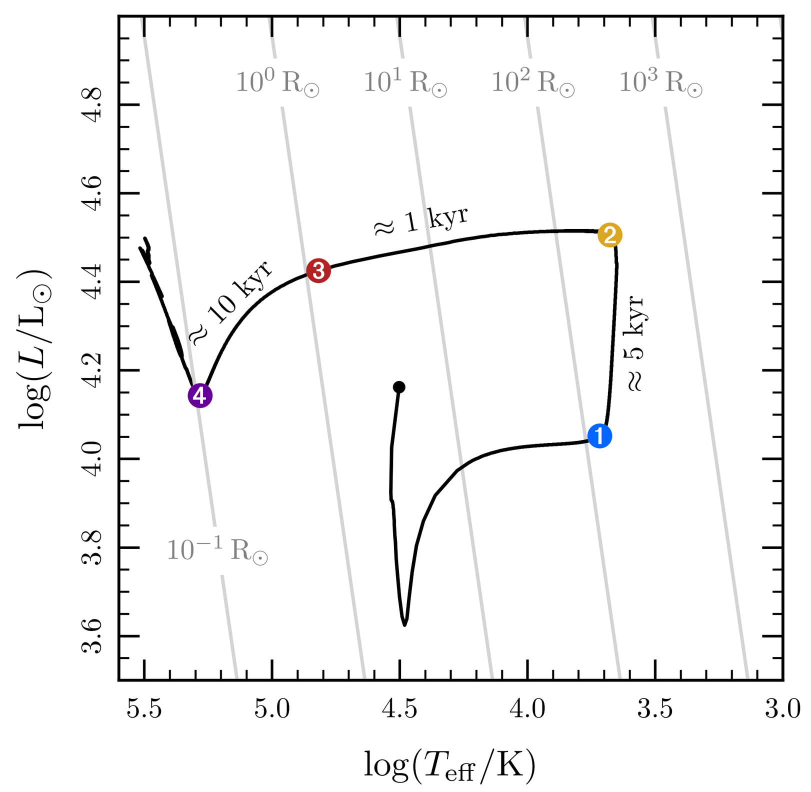
The evolution and fate of super-Chandrasekhar mass white dwarf merger remnants
J. Schwab, E. Quataert, and D. Kasen
MNRAS, 463, pp. 3461–3475

Fast and Luminous Transients from the Explosions of Long-lived Massive White Dwarf Merger Remnants
J. Brooks, J. Schwab, L. Bildsten, E. Quataert, B. Paxton, S. Blinnikov, and E. Sorokina
ApJ, 850, p. 127

Double Degenerate Progenitors: CO WD + CO WD

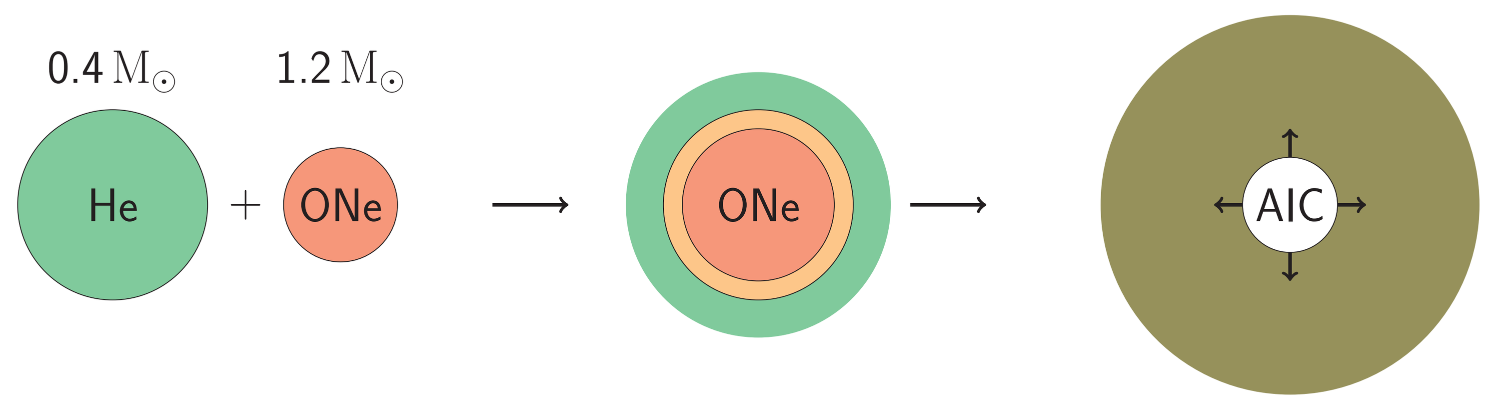


The merger of two CO WDs with a total mass in excess of the Chandrasekhar mass has long been proposed to lead to the formation of an NS (Nomoto & Iben 1985; Saio & Nomoto 1985). Instead of triggering a core ignition, the merger leads to off-center carbon ignition and then an inward-going carbon flame that converts the core to ONe. We have taken results from double WD merger simulations and mapped them into MESA. Our calculations evolve the remnant for longer than previous work and find that because the degenerate core is massive, it subsequently also experiences off-center ONe ignition. If the inward-going neon-oxygen flame reaches the center, this prevents the electron-capture-triggered collapse that occurs in a cold ONe core. Instead, the process likely leads to collapse to a NS reminiscent of that in low-mass Fe core collapse SNe.



Evolution of WD merger model in the HR diagram. The inward-going carbon flame is ignited around at circle 1 and reaches the center at circle 4. The approximate elapsed time between adjacent circles is indicated. The total duration of evolution is $\approx$ 25 kyr, which implies $\sim$ 10 such merger remnants should exist in the Milky Way and M31 at any time. Given the pure metal composition, the presence of a dusty wind around these objects may modify their appearance.

Double Degenerate Progenitors: He WD + ONe WD



The merger of a He and ONe WD with a total mass in excess of the Chandrasekhar mass is a relatively unexplored AIC channel. The merger sets up a He burning shell and leads to a structure with a giant envelope. At the time the core reaches AIC conditions and NS formation injects $\approx 10^{50}$ erg, there is still an envelope with $\approx 0.1\,M_\odot$ and a radius of $\approx 400\,R_\odot$. Using the STELLA radiative transfer code, we predict the resulting optical light curves from these exploded envelopes. Reaching absolute magnitudes of $M_V \approx -17$, these transients are bright for about one week, and have many features of the class of luminous, rapidly evolving transients studied by Drout and collaborators.

Acknowledgements

Support for this work was provided by NASA through Hubble Fellowship grant # HST-HF2-51382.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555.

[*]Hubble Fellow, Department of Astronomy & Astrophysics, UC Santa Cruz