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Mixing in classical nova outbursts

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Classical novae are stellar explosions in close binary systems, driven by mass transfer episodes. The material piles up under degenerate conditions, and a thermonuclear runaway (TNR) reaching $T_{\rm peak} \sim (1-4) \times 10^8$ K ensues. In the explosion, about $10^{-4} - 10^{-5}\,M_{\odot}$ are ejected into the interstellar medium, containing large amounts of ^{13}C, ^{15}N, and ^{17}O. To account for the energetics of the explosion as well as for the inferred abundance pattern, mixing at the core-envelope interface has been invoked. Over 40 years, theoreticians have been exploring different mixing mechanisms that could lead to the observed metallicity enhancement in the ejecta. In this study we show that Kelvin-Helmholtz instabilities can naturally dredge up carbon and oxygen from the outer layers of the with dwarf core, leading to a final envelope metallicity above 0.20.

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1. Introduction

In classical nova explosions, material from a low mass, main sequence star flows through the inner Lagrangian point (L_1) of a stellar binary system, building up an accretion disk around the white dwarf component. A fraction of this solar-like matter spirals in and piles up on top of the white dwarf surface. Due to compression, the envelope is heated up, and thermonuclear reactions ensue. Because of partial degeneracy, the envelope undergoes a thermonuclear runaway. 1-D simulations of nova outbursts have been extensively performed for over 40 years. They succesfully reproduced the main observational properties of these explosions, such as the shape of the light curve, the peak luminosites, or the chemical abundance pattern of the ejecta [1, 2, 3]. However, it was soon realized that the high metallicity of the ejecta cannot be explained by nuclear processing of the solar-like accreted material [1, 4, 5, 6, 7], favoring instead a mixing process operating at the core-envelope interface. An additional problem faced by these simulations is the adopted geometry: indeed, spherical symmetry excludes the expected multidimensional effects that likely show up in the course of the evolution (such as convection).

A few multidimensional nova simulations have been performed in the last years, with somewhat contradictory results. The first studies were performed in 2-D [8, 9, 10] using the code VULCAN (an arbitrarily Lagrangian and Eulerian code). The study showed that Kelvin-Helmholtz instabilities are a very effective mixing mechanism during the course of the TNR, leading to an overall metallicity enhancement of ~ 0.30. The second study was performed in 2-D [11] and 3-D [12], respectively, in the framework of the Eulearian code PROMETHEUS. In contrast with the results found in previous works, these studies suggested that mixing by Kelvin-Helmholtz instabilities at late stages of the TNR is very limited, resulting in very mild TNRs, with low peak temperatures and fluid velocities. Instead, it was concluded [12] that mixing should take place at much earlier stages. The differences found between both studies were later interpreted as due to the specific choice of the outer boundary conditions [13]. But clearly, an independent study to shed light into this problem was mandatory.

2. Input physics and numerical methods

The present study has been performed with FLASH, an Eulerian code based on the piecewise parabolic method and with an adaptive mesh refinement. Our simulations include thermal diffusion, which is added explicitly (including conductive and radiative opacities) [14] and an equation of state suitable for degenerate matter [15]. The simulation relies on the same initial model used previously [9, 11]. It consists of a $1 M_{\odot}$ carbon-oxygen white dwarf which accretes solar-like material ($Z = 0.02$) onto its surface at a rate of $5 \times 10^{-9} M_{\odot}$ yr^{-1}. The total accreted envelope mass is $2 \times 10^{-5}\ M_{\odot}$. When the temperature at the innermost envelope layers reaches $\approx 10^8$ K, the model is mapped onto a 2-D cartesian grid. We set periodic boundary conditions at both vertical sides, and hydrostatic conditions at the horizontal edges, but we also set the velocity to outflow at the top and to reflect at the bottom [16]. Our 2-D computational domain has a size of 800×800 km and our adopted resolution is 1.56×1.56 km. To reproduce the energetics of the explosion, we have adopted a reduced nuclear reaction network, consisting of 18 nuclear processes and the following 13 isotopes: ^{1}H, ^{4}He, ^{12,13}C, ^{13,14,15}N, ^{14,15,16,17}O and ^{17,18}F.

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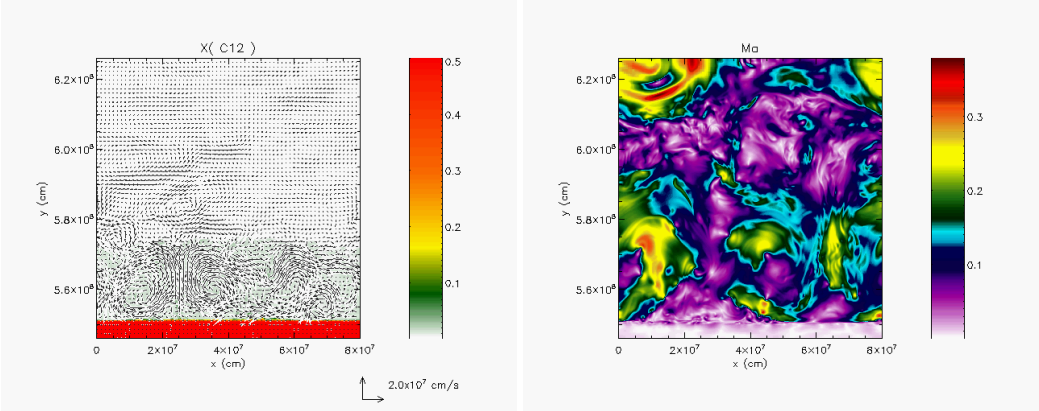

Figure 1: Left panel: velocity field superimposed on the ^{12}C abundance at $t = 325$ s. Right panel: Mach Number at $t = 475$ s.

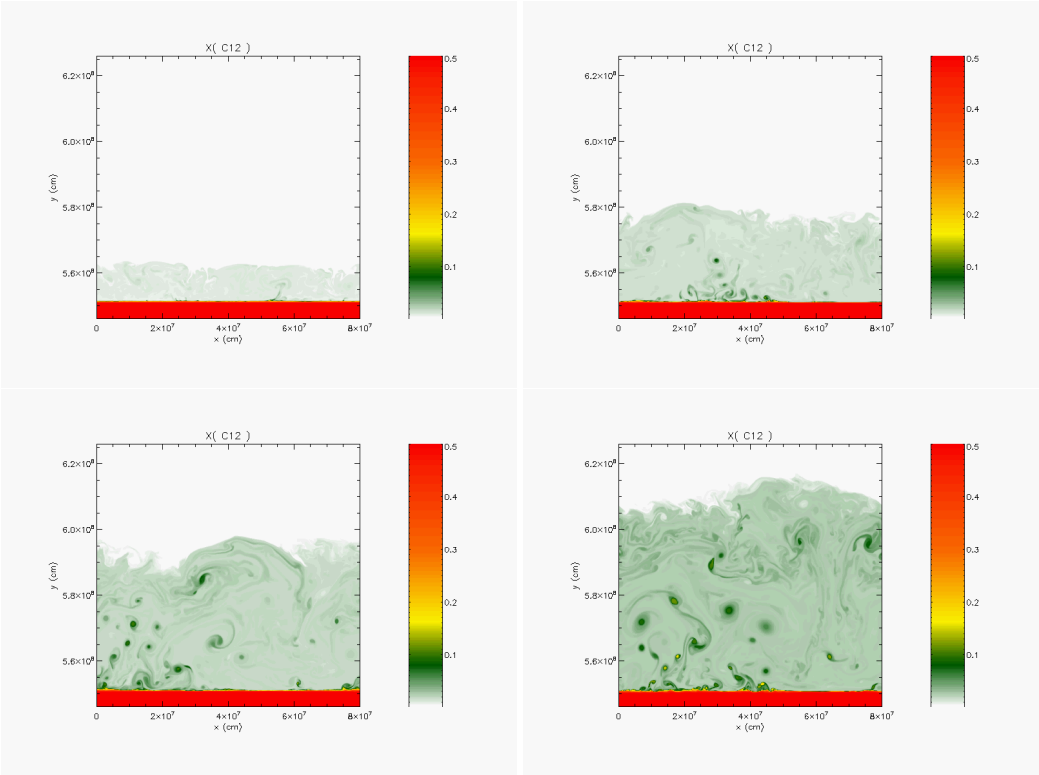

Figure 2: Snapshots of the development of convection at $t = 250$ s (upper left panel), 350 s (upper right), 425 s (lower left), and 475 s (lower right), shown in terms of the ^{12}C mass fraction (in logarithmic scale). Shear mixing drives the formation of Kelvin-Helmholtz instabilities, which cause mixing at the core-envelope interface. The mean metallicity in the envelope at the end of the simulation is above 0.20.

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3. Results

Once the 1-D model is mapped into a 2-D domain, and relaxed to guarantee hydrostatic equilibrium, we apply an initial temperature perturbation of 5% at the core-envelope interface (during one time step, 10^{-10} s). The size of the perturbation is 2×2 km (very small, if compared with the size of the computational domain). The perturbation causes fluctuations that move along the interface and spread through the envelope, breaking the initial equilibrium. Between 150 and 200 seconds since the beginning of the simulation, several temperature fluctuations arise at the core-envelope interface. An effective shear powers the formation of Kelvin-Helmholtz instabilities that grab fresh ^{12}C and ^{16}O from the core into the envelope. As soon as material is brought to the envelope, small convective cells show up (Fig. 1, left panel). As time goes on, the convective cells grow in size and eventually merge, occupying almost the whole computational domain, and driving the fluid motion to become more and more violent. The initial convective turnover time drops from 10 s, at the early stages of the simulation, to 5 s, at the very end. At this stage, the nuclear energy generation rate reaches 10^{15} erg g^{-1} s^{-1} and the velocities of the fluid exceed 10^7 cm s^{-1}. It is worth noting that the motion remains subsonic at all times, with a Mach number always below 1 (Fig. 1, right panel). The convection front progressively advances and when it reaches the top, material will start flowing off of the grid (fig. 2). At that time, we stop the simulation. Meanwhile, the envelope metallicity increases from an approximately solar value to above 0.20, matching the values inferred from observations of novae hosting CO white dwarfs [3]. Additional details of this study can be found elsewhere [17].

4. Conclusions

We have shown that Kelvin-Helmholtz instabilities are an efficient mixing mechanism that operates at the core-envelope interface, dredging up material from the white dwarf core into the accreted envelope. At late stages of the TNR, this mechanism can account for the observationally inferred envelope metallicity enhancements over 20%. It is worth noting, however, that in 2-D simulations, the fluid motion cannot be reproduced consistently because of the restrictions imposed by the adopted geometry, forcing the convective cells to recombine and merge into large cells [18, 19]. Nevertheless, we have performed a 3-D simulation (which is currently under analysis) and our results do not differ quantitatively from those found in 2-D simulations.

Acknowledgments

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