Forming a Clumpy Circumstellar Material in Energetic Pre-supernova Activity postprint

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Abstract

We demonstrate by three-dimensional hydrodynamical simulations of energy deposition into the envelope of a red supergiant model the inflation of a Rayleigh–Taylor unstable envelope that forms a compact clumpy circumstellar material (CSM). Our simulations mimic vigorous core activity years to months before a core-collapse supernova (CCSN) explosion that deposits energy to the outer envelope. The fierce core nuclear activity in the pre-CCSN explosion phase might excite waves that propagate to the envelope. The wave energy is dissipated where envelope convection cannot carry the energy. We deposit this energy into a shell in the outer envelope with a power of Lwave = 2.6 × 106L or Lwave = 5.2 × 105L for 0.32 yr. The energy-deposition shell expands while its pressure is higher than its surroundings, but its density is lower. Therefore, this expansion is Rayleigh–Taylor unstable and develops instability fingers. Most of the inflated envelope does not reach the escape velocity in the year of simulation but forms a compact and clumpy CSM. The high density of the inflated envelope implies that if a companion is present in that zone, it will accrete mass at a very high rate and power a pre-explosion outburst.

Full Text

Preamble

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Forming a Clumpy Circumstellar Material in Energetic Pre-supernova Activity

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Abstract

We demonstrate through three-dimensional hydrodynamical simulations of energy deposition into the envelope of a red supergiant model that a Rayleigh-Taylor unstable envelope inflates and forms a compact clumpy circumstellar material (CSM). Our simulations mimic vigorous core activity years to months before a core-collapse supernova (CCSN) explosion that deposits energy in the outer envelope. This fierce core nuclear activity in the pre-CCSN explosion phase might excite waves that propagate outward, with wave energy dissipating where envelope convection cannot carry the energy. We deposit this energy into a shell in the outer envelope with a power of Lwave = 2.6 × 10 L or Lwave = 5.2 × 10 L for 0.32 yr. The energy-deposition shell expands while its pressure exceeds that of its surroundings, but its density becomes lower. This expansion is therefore Rayleigh–Taylor unstable and develops instability fingers. Most of the inflated envelope does not reach escape velocity during the year of simulation but forms a compact and clumpy CSM. The high density of the inflated envelope implies that if a companion is present in that zone, it will accrete mass at a very high rate and power a pre-explosion outburst.

Key words: stars: massive -stars: mass-loss -(stars:) supernovae: general

1. Introduction

The early light curve and spectroscopy of many core-collapse supernovae (CCSNe) indicate the presence of compact circumstellar material (CSM), which refers to CSM that interacts with explosion ejecta within several days after the CCSN explosion. Two prominent examples are the relatively close and recent CCSNe SN 2023ixf (e.g., Berger et al. 2023; Bostroem et al. 2023, 2024; Grefenstette et al. 2023; Kilpatrick et al. 2023; Teja et al. 2023; Hu et al. 2025; Kumar et al. 2025; Van Dyk et al. 2024) and SN 2024ggi (e.g., Chen et al. 2025, 2024b; Jacobson-Galán et al. 2024; Pessi et al. 2024; Xiang et al. 2024; Zhang et al. 2024). In these two CCSNe, there are no indications of pre-explosion outbursts within tens of years before the explosion (e.g., Jencson et al. 2023; Soraisam et al. 2023; Neustadt et al. 2024; Shrestha et al. 2024).

An enhanced mass loss rate that begins years to weeks before the explosion—possibly, but not necessarily, accompanied by a pre-explosion outburst—might form a compact CSM (e.g., Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2010; Margutti et al. 2014; Ofek et al. 2014; Svirski & Nakar 2014; Tartaglia et al. 2016; Yaron et al. 2017; Morozova et al. 2018; Wang et al. 2019; Prentice et al. 2020; Bruch et al. 2021; Jacobson-Galán et al. 2022). Alternatively, there might exist a long-lived dense CSM around the CCSN progenitor (e.g., Dessart et al. 2017), either as an extended, accelerated zone of the wind (e.g., Moriya et al. 2017, 2018; Moriya & Singh 2024) or as a long-lived circumstellar zone of gas parcels that rise and fall above the stellar photosphere (e.g., Soker 2021, 2023, 2024; Fuller & Tsuna 2024; see further discussion by Fuller & Tsuna 2024).

The energy source that triggers enhanced pre-explosion stellar activity must be in the core, as only the core evolves rapidly on timescales of years to days before the explosion. This energy source can be the excitation of waves by vigorous core convection (e.g., Quataert & Shiode 2012; Shiode & Quataert 2014; Ro & Matzner 2017; Wu & Fuller 2021, 2022) or convection-powered enhanced magnetic activity in the core (e.g., Soker & Gilkis 2017; Cohen & Soker 2024). Energy deposition might lead to substantial envelope expansion that enhances the mass loss rate and even leads to some mass ejection and weak to mild outbursts (e.g., Fuller 2017; Ouchi & Maeda 2019, 2021), but cannot by itself trigger an energetic outburst that mimics a weak supernova (e.g., Mcley & Soker 2014). A close companion that accretes mass from the inflated envelope and launches jets might power an energetic pre-explosion outburst (e.g., Soker 2013; Danieli & Soker 2019).

In some cases, observations indicate that the CSM does not cover the entire sphere, e.g., SN 2023ixf (e.g., Vasylyev et al. 2023). For the CSM of SN 2023ixf, Smith et al. (2023) consider equatorial mass concentration, while Singh et al. (2024) and Bostroem et al. (2024) mention a clumpy CSM, as expected in the effervescent model (e.g., Soker 2023, 2024) and the similar boil-off model studied by Fuller & Tsuna (2024).

In this study, we show that depositing large amounts of energy in the envelope results in Rayleigh–Taylor instability (RTI) that leads to the formation of a clumpy CSM. "Large amounts" refers to possible pre-explosion core activity that deposits energy at a power much larger than the regular stellar luminosity. Fuller (2017) performed one-dimensional (1D) simulations and noticed that energy deposition forms a high-pressure, low-density zone prone to RTI, as Leung & Fuller (2020) confirmed with two-dimensional (2D) simulations. Fuller mentioned that RTI can smooth the density radial gradient and mix envelope zones. The present study explores some properties of the three-dimensional (3D) RTI modes.

Section 2 describes the 3D hydrodynamical code and its settings and lists our assumptions. Our results are presented in Section 3, and we summarize this study in Section 4.

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2. Numerical Setup

2.1. Numerical Code and Stellar Model

Our numerical setup follows our previous papers (e.g., Hillel et al. 2023; Schreier et al. 2025). We built a red supergiant (RSG) stellar model from a zero-age-main-sequence star of metallicity Z = 0.02 and mass M ,ZAMS = 15 M , evolving it with the 1D stellar evolution code MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019). We map this 1D RSG stellar model, with a mass of M = 12.5 M and a radius of RRSG = 881 R , onto the 3D grid of the hydrodynamical code FLASH (Fryxell et al. 2000). To save computational time, we treat the inner sphere with radius Rinert = 0.2 RRSG = 176 R as inert; we do not evolve its structure. We include the gravity of the RSG star at its initial value when we start the 3D simulations, including the gravity of the inner sphere.

We use a Cartesian grid with outflow boundary conditions and treat the gas as an ideal gas with an adiabatic index of = 5/3, including radiation pressure. The center of the RSG is at the origin. The cell size in most simulations is Δc = LG/256 = 9.766 × 10^{11} cm, for LG = 250 × 10^{12} cm. For comparison, we also run one case with lower resolution of Δc,low = LG/128 = 1.953 × 10^{12} cm.

2.2. Energy Deposition

We consider the pre-explosion process of energy transport from the core to the envelope, e.g., by waves (Quataert & Shiode 2012; Shiode & Quataert 2014), as described in Section 1. We consider wave energy dissipation to occur around the radius where convection at the sound speed is insufficient to carry the wave power Lwave, i.e., where the convective flux is less than the wave flux. In Figure 1 [Figure 1: see original paper], we plot the maximum power that convection can carry according to the stellar structure as a function of radius, from r = 10^{13} cm to the edge of the convection zone at R = 6.1 × 10^{13} cm. The vertical line marks the outer radius of the inner inert core, and the horizontal lines mark our two simulation powers, extending over the energy-deposition shell (see Table 1).

We simulate mainly two wave powers: Lwave = 1 × 10 erg s ¹ = 2.6 × 10 L and Lwave = 2 × 10^3 erg s ¹ = 5.2 × 10 L (for comparison, we also simulated two other powers, as described in Section 3.2). Some 1D studies use similar powers. Mcley & Soker (2014) considered core oxygen burning in a non-rotating Mzams = 15 M stellar model from Shiode & Quataert (2014) and adopted wave power, duration, and total energy of Lwave,n = 3.2 × 10 L , twave,n = 2.3 yr, and Ewave,n = 8.9 × 10 erg, respectively. Oxygen core burning is shorter than 2.3 yr and somewhat less than a year (e.g., Fuller 2017). Ouchi & Maeda (2019), in their 1D simulations, deposited energy with four different powers ranging from Lwave = 10^3 erg s ¹ to Lwave = 10 erg s ¹, starting three years before core collapse. Ouchi & Maeda (2021) studied the type IIP SN 2009kf and deposited energy with a power of Lwave = 3 × 10^3 erg s ¹ for three years before core collapse. Leung & Fuller (2020), in their benchmark 2D simulation, used Lwave

= 3 × 10 L for twave,n = 0.33 yr. We therefore deposit energy for twave   10 s = 0.32 yr.

We inject energy in two ways. In uniform injection, the power per unit mass is uniform in the shell and zero outside, creating a sharp jump at the inner and outer boundaries. In the continuously varying injection profile (C-profile), the energy deposition power per unit mass increases linearly from zero at the inner boundary to its maximum at the shell center, then decreases linearly to zero at the outer boundary.

2.3. Simulations

We summarize the simulations in Table 1 . The first column gives the run number, the second column lists the inner and outer radii of the energy injection shell, and the third column lists the power of the energy source. The letter C in the second column indicates continuous variation of the energy deposition power per unit mass with radius (C-profile; Section 2.2); otherwise, the energy deposition has uniform power per unit mass in the injection shell, sharply decreasing to zero outside.

Energy injection increases the shell pressure, causing the shell to expand and accelerate the overlying layers. Due to this expansion, the shell density becomes lower than that of the overlying material while its pressure remains higher. This flow is prone to Rayleigh–Taylor instabilities (RTIs; e.g., Leung & Fuller 2020). Specifically, if the angle between the density and pressure gradients exceeds 90°, the typical growth time of the RTI is short. To map stable and unstable zones, we plot the quantity fst, which acts as a frequency in stable zones (hence the subscript “st”). In unstable zones fst < 0, and -1/fst approximates the RTI growth time, assuming the perturbation wavelength is about the density scale height. In stable zones, fst approximates the Brunt-Väisälä frequency, valid when the density gradient is much steeper than the pressure gradient, as in our case where low-density zones are much hotter.

3. Results

3.1. Run 1

Figure 2 [Figure 2: see original paper] presents density maps (left column) and fst maps (right column) in the z = 0 plane at three times for Run 1. The deep blue zones in the RTI maps have a growth time of about 1/8 yr, much shorter than the simulation time of nearly a year. The two late density maps show the development of RTI modes into the nonlinear regime. The RTI forms clumps in the outer envelope and ejecta.

Qualitatively, our simulation results are similar to the benchmark case of Leung & Fuller (2020) who used Lwave = 3 × 10 L for twave,n = 0.33 yr, similar to our Run 1, though they employed a different energy deposition scheme and their 2D simulation had lower resolution than our 3D simulations. Like Leung &

Fuller (2020), we find the RTI enters the nonlinear regime after a year, with RTI fingers and mushrooms inside the expanding photosphere. A smooth inflated envelope layer lies above the highly nonlinear instability clumps.

The flow resulting from RTI fingers penetrating between dense and low-density regions forms vortices. Figure 3 [Figure 3: see original paper] shows the vorticity in the z = 0 plane at the two late times defined in Figure 2. Areas showing large RTI mushrooms (lower-left panel of Figure 2) coincide with regions of high vorticity (lower panel of Figure 3). The typical circularization timescale of the strongest vortices is much shorter than the simulation time, and the vortices, like the RTI mushrooms, are well-developed after about a year.

We further emphasize the RTI mushrooms in Figure 4 [Figure 4: see original paper]. The upper panel shows the tracer map of the energy-deposition shell. The tracer is a numerical quantity that follows the flow of a designated volume; here, gas in the shell $35 \times 10^{12} < r < 45 \times 10^{12}$ cm is given an initial tracer value of 1. With time, the tracer value in each cell shows the fraction of mass that originated in the shell, ranging from 0 to 1. Comparison of the upper panel of Figure 4 with the lower-left panel of Figure 2 shows that the original shell material occupies low-density volumes. The lower panel of Figure 4 depicts the ratio of the local velocity magnitude to the escape velocity, with three density contours overlaid. At the grid edge $r = 125 \times 10^{12}$ cm = 1800 R , the escape velocity is 52 km s ^{1}.

The ejecta have not reached escape velocity, similar to Leung & Fuller (2020) who found that at most a small mass in the outer layer reaches escape velocity in their benchmark simulation. In any case, the explosion is expected to occur within the year we simulate, or shortly thereafter, before much mass is ejected (Leung & Fuller 2020).

Within about a year from the beginning of energy deposition (the core oxygen burning phase), we expect the star to explode. A close companion might accrete mass from the expanding ejecta and launch jets that power a much brighter event months to weeks before explosion. Indeed, the ejecta density remains high to a distance of 2000 R , more than twice the initial RSG radius. Figure 5 [Figure 5: see original paper] shows the density profile of the outer envelope and ejecta. In addition to the initial profile (black line), we show the density along a diagonal with no dense RTI clumps (red line) and along a direction containing RTI clumps that is denser (blue line). If a companion exists within the ejecta, it can accrete at a very high rate, launch jets, and power a pre-explosion outburst. Because the ejecta are optically thick, this binary interaction resembles common envelope evolution. For a density of $= 10^{1}$ g cm ^{3}, the Bondi-Hoyle-Lyttleton accretion rate for a 1.4 M companion orbiting at 1600 R is high. A main-sequence star of this mass would release accretion gravitational energy at 10 L , while a neutron star would release 10^{1} L . Due to the negative jet feedback mechanism (e.g., Grichener et al. 2021; Hillel et al. 2022), these powers will be lower by more than an order of magnitude; in particular, neutron star jets will be weaker by two to three orders of magnitude (Hillel et al. 2022). The powering of pre-explosion outbursts by accreting companions is the subject of future study.

3.2. Other Cases

We describe results from our other simulations as density maps in the z = 0 plane at t = 0.95 yr, except for Run 7. Run 1 is detailed in Section 3.1. Run 1L has the same physical parameters as Run 1 but lower numerical resolution (grid cell size twice as large). As expected, the RTI fingers and mushrooms are larger but reach the same level of nonlinearity, similar to the low-resolution 2D simulations of Leung & Fuller (2020).

The seven other simulations have different physical parameters. Run 2 differs from Run 1 by using a C-profile where energy power per unit mass increases linearly from zero at the inner shell boundary to a maximum at the shell center, then decreases linearly to zero at the outer edge, eliminating sharp jumps at the boundaries. The total jet power is the same as in Run 1. This C-profile is also used in Runs 4 and 6. The shock front reaches the same radius in Runs 1 and 2, but RTI develops more slowly in Run 2. Clear RTI fingers appear at t = 0.95 yr, though well-developed mushrooms are not yet present. Given their lower resolution, comparison with Leung & Fuller (2020) is difficult, but their energy deposition scheme appears to yield RTI development intermediate between our Run 1 and Run 2. We therefore suggest the real situation lies between these cases—between sharp-jump and C-profile deposition.

Run 3 differs from Run 1 by having an energy deposition shell twice as wide in radius. Its outer edge reaches much closer to the photosphere in mass coordinate, leaving little mass above the deposition shell. RTI fingers break into the low-density outer envelope forming columns rather than mushrooms. Run 4 is like Run 3 but uses a C-profile, showing RTI fingers only at the beginning of their nonlinear phase with densities about twice that of their surroundings.

Runs 5 and 6 represent low-energy outbursts with energy deposition in the outer envelope (see Table 1). Although the power is 20% of that in Runs 1-4, the involved mass is much smaller and RTI fingers still reach the nonlinear regime. In Run 5 with sharp boundaries, RTI develops much larger fingers similar to Run 3. In Run 6 with the C-profile, fingers are at an earlier evolutionary phase at t = 0.95 yr.

We close with Run 7, which is three times more powerful than Run 1, and Run 8, which has one-third the power of Run 1 (Table 1). The RTI of Run 7 develops much faster than in Run 1 and the envelope expands so rapidly that by t = 0.95 yr the RTI fingers and mushrooms have left the numerical grid. We therefore present its density map at t = 0.4 yr, where clear RTI fingers and mushrooms are already present. As expected, Run 8 expands slower than Run 1 due to its lower energy, yet RTI fingers and mushrooms are well-developed at t = 0.95 yr.

All simulations show development of RTI fingers and mushrooms in the expanding envelope, forming a clumpy and inhomogeneous CSM.

4. Summary

We conducted 3D hydrodynamical simulations of large energy deposition into an RSG envelope to mimic energy release from fierce nuclear burning in the core years to months before explosion (Section 1). We focused on two energy deposition powers (Figure 1) and added two extra powers for comparison (Table 1; Figure 6 [Figure 6: see original paper]), varying the deposition shell and profile. The energy deposition inflates the envelope (Figures 2 and 6). Most mass does not reach escape velocity in our simulations (e.g., lower panel of Figure 4), though a fraction might escape. Some mass approaches escape velocity and will rise to large distances. We did not follow the ejecta beyond twice the initial stellar radius of RRSG = 881 R .

Our results are similar to the 2D simulations of Leung & Fuller (2020), but our 3D simulations resolve RTI development much better. We also explore additional parameters beyond their study, though Run 1 has similar physical parameters to their benchmark case.

Our main result is that large energy deposition into the outer envelope creates a prominent inflated envelope and ejected mass that forms a clumpy CSM due to RTI, as all figures show (right column of Figure 2). Observations of some CCSNe interacting with compact CSM also suggest clumpiness, e.g., SN 2023ixf (e.g., Bostroem et al. 2024; Singh et al. 2024). However, this does not necessarily imply that SN 2023ixf' s compact CSM formed via energy deposition, as there are no indications of pre-explosion outbursts for SN 2023ixf (e.g., Jencson et al. 2023; Soraisam et al. 2023; Neustadt et al. 2024). An alternative is that large-amplitude pulsation and vigorous convection in the RSG progenitor lift bound material to several or even tens of stellar radii, as in the effervescent model (e.g., Soker 2023, 2024) and the similar boil-off model (Fuller & Tsuna 2024). Freytag et al. (2024) find in their AGB star simulations that pulsation and convection lead to episodic levitation of dense gas clumps due to RTI without extra energy deposition.

We conclude that the compact CSM of CCSNe is expected to be highly clumpy, whether formed by stellar pulsation and convection or by core energy deposition into the outer envelope. Our simulations show that energy deposition does not accelerate much mass to escape velocities but forms a compact, dense, extended envelope (Figure 5). A companion accreting from this extended envelope/CSM —whether a main-sequence star, neutron star, or black hole—can release gravitational energy (Section 3.1), mainly via jets, that can eject mass and power a bright pre-explosion outburst (theory: e.g., Soker 2013; Danieli & Soker 2019; observation: e.g., Pastorello et al. 2025). This interaction introduces large-scale departure from spherical symmetry. One goal of CCSN observations shortly after explosion should be searching for departures from sphericity due to clumps (short scale) and binary interaction (large scale). Note that because the companion accretes clumpy material, the angular momentum of the accreted gas might vary, causing the jets to have varying directions–so-called wobbling jets (e.g., Dori et al. 2023), as suggested for multi-polar planetary nebulae (Avitan & Soker 2025).

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