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CIRCUMSTELLAR BUBBLE CREATED BY TWO MASSIVE STARS

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Abstract. The massive stars are formed in clusters then numerical models of wind-blown bubble should evolve bubble created by several stars. Aims. We develop a two-dimensional (2D) model of the circumstellar bubble created by two massive stars, a 40 M_{odot} star and a 25 M_{odot} star, and follow its evolution with MPI-AMRVAC hydrodynamics code until the end of the stellar evolution and he supernova explosion of each star. The stars are separated by approximately 16 pc and surrounded by a cold medium with a density of 20 particles per cm3. The simulations showed that the evolution of a wind-blown bubble created by two stars deviates from that of the bubbles around single stars. In particular, once one of the stars has exploded, the bubble is too large for the wind of the remaining star to maintain and the outer shell starts to disintegrate. The lack of thermal pressure inside the bubble also changes the behavior of circumstellar features close to the remaining star. The supernovae are contained inside the bubble, which reflects part of the energy back into the circumstellar medium.

Keywords: hydrodynamics, circumstellar matter, stars, winds, outflows, supernovae remnants, bubbles

1 Introduction

The winds of massive stars create large-scale (10 pc) bubbles around their progenitors. Weaver et al. (1977) did the analytical study of these bubbles. The time-dependent nature of stellar winds were incorporate in numerical model by (Garca-Segura et al. 1996b), (van Marle et al. 2005), (Dwarkadas 2007) and (Toalá & Arthur 2011). However, these models only considered the evolution of a bubble blown by a single star. However, since massive stars are typically formed in star clusters, it is unlikely that any single star could form a bubble on a scale of tens of parsecs, without encountering other massive stars. The expanding bubble should instead collide with other, similar bubbles and merge as in the case of WN8-WN9h (Mauerhan et al. 2010). A good example of the resulting bubble can be found in the Rosetta nebula around cluster NGC 2244 (Li & Smith 2005).

Because of the numerical problems associated with modeling the bubbles of multiple stars, attempts to account for the influence of multiple stars on the evolution of the bubble have been limited to the details of the colliding winds of binary stars (e.g. Folini & Walder (2000); Pittard & Parkin (2010); van Marle et al. (2011)), or dealt with only part of the stellar evolution.

In this proceeding, we present the result of a two-dimensional (2D) numerical simulation that models the evolution of a bubble, blown by the winds of two massive stars by following all evolution phases of the stars.

2 Setup

We use the MPI-AMRVAC hydrodynamics code (Meliani et al. 2012; Keppens et al. 2012), which solves the conservation equations for mass, momentum, and energy on an adaptive mesh grid. The effect of radiative cooling is included (van Marle & Keppens 2011), using a cooling curve for solar-metallicity gas generated with the CLOUDY code. We set a minimum temperature of 100 K throughout the simulation, which limits the amount of compression due to radiative cooling, preventing numerical problems. Here we neglect the effect of photoionization, which would increase the gas temperature within the Strmgren radius to about 10000 K.

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We set up our simulation as a 2D cylindrically symmetric grid in the r,z-plane. The grid has a basic resolution of 120 240 gridpoints over 100 200 pc. The adaptive mesh has four layers, allowing for an effective resolution of 960 1920 gridpoints. At the start of the simulation, this grid is filled with gas with a constant density of $10^{-22.5}$ g cm^{-3} and solar metallicity. The stars are defined as small spheres (R = 1.5 pc), placed 16.2 pc apart that are filled, at the beginning of each timestep, with material according to the wind parameters given in Table 1. The duration of the evolutionary phases and the mass-loss rates are based on the parameters for a 25 M_{odot} star and a 40 M_{odot} star used by (van Marle et al. 2005), respectively. Wind velocities reflect those typically found in observations ((Lamers & Cassinelli 1999), and references therein). For the 40 M_{odot} star, the mass-loss rate in the final phase (the Wolf-Rayet phase) has been reduced to reflect the values obtained by (Vink & de Koter 2005).

When a star reaches the end of its evolution, we fill a sphere (R = 0.75 pc) with a constant density and thermal energy according to the supernova values given in Table 1. The masses reflect the final masses of the stars as well the as values calculated by, e.g., Eldridge & Tout (2004). For simplicity, we use a supernova energy of 10^{51} erg, which is typical of core-collapse supernovae (e.g. (van Marle et al. 2010), and references therein).

Table 1. Wind and supernova parameters.

Phase	$t_{\rm end}$ [Myr]	$\dot{m}$ [$M_\odot$ yr^{-1}]	$v_{\rm w}$[km s^{-1}]	M [$M_\odot$]	E (10^{47} [erg])
40 $M_\odot$					
MS	4.3	1.0×10^{-6}	2000	4.3	1710
RSG	4.5	5.0×10^{-5}	15	10	0.224
WR	4.77	1.0×10^{-5}	2000	3.0	1190
SN					10 000
hline 25 $M_\odot$					
MS	6.5	2.0×10^{-7}	1500	1.3	170
RSG	7	1.0×10^{-5}	15	5.0	0.112
SN					10 000

3 Result

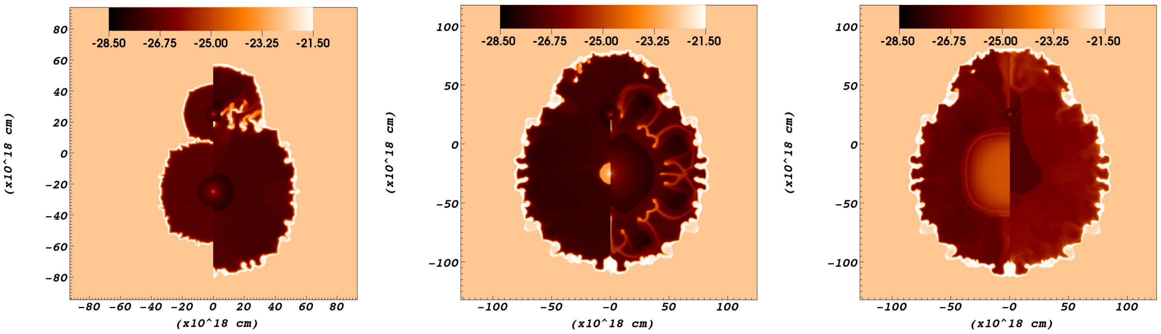

Fig. 1. Logarithm of the density of the circumstellar medium in g/cm3 after 1.17 and 2.35 Myr (left panel), after 4.42 and 4.58 Myr (center panel), and after 4.774 and 4.783 Myr (right panel). On the left, the shells of the two bubbles encounter each other (left panel, left side) and are destroyed in the process. The remnants are pushed toward the lightest of the stars (left panel, right side). On the right, the 40 M star (at Y = 2.5 2019 cm) goes through the RSG phase, which forms a thin shell at the wind termination shock (center panel, left side) and then the WR phase. The WR wind sweeps up the RSG wind and the RSG shell is destroyed in the collision. The debris of the collision moves outward into the hot shocked gas (central panel, right side). Finally, the 40 M star explodes as a supernova, which expands into the circumstellar bubble (right panel, left). Once it has hit the outer shell, the supernova bounces back and starts flowing inward (right panel, right).

Each star initially creates its own circumstellar bubble. These bubbles follow the pattern predicted by Weaver et al. (1977): the wind expands freely until it hits the termination shock. The kinetic energy of the wind is then turned into thermal energy creating a volume filled with very hot (T 107 108 K) shocked wind material. The high thermal pressure of the shocked wind material causes it to expand, sweeping up a shell of shocked ISM, which moves outward. Eventually, the swept-up shells of the two bubbles encounter each other and both are fractured during the collision (left panel of Fig. 2). The remnants are pushed into the bubble with the lowest thermal pressure (resulting from the weakest wind, and therefore, typically, the lightest star). Once the shells have been fractured, the two bubbles merge, creating a single, aspherical bubble in which the thermal pressure is equalized as the shocked gas of the two stellar winds mixes. The thin outer shell is unstable and shows both linear thin-shell (Vishniac 1983) and Rayleigh-Taylor instabilities.

The 40 M star, which has the shortest lifespan, leaves the main sequence and goes through the RSG and WR phases (central panel of Fig. 2). The RSG wind forms a thin shell at the termination shock, which is destroyed by the WR wind. Finally, the star explodes as a supernova. At this time, the bubble is still quite aspherical, despite the outer shell being driven by the thermal pressure in the shocked wind. It has a maximum length (along the axis connecting the stars) of 57 pc. At the position of the 40 M star, it is 52 pc wide, whereas at the position of the 25 M star the width is only 39 pc. The shape of the outer shell still indicates that it is the merger of two spherical bubbles.

The supernova quickly expands into the low density bubble that has been created by the stellar winds, but stops when it reaches the contact discontinuity separating the shocked wind from the shocked ISM (right panel of Fig. 2). The injection of energy from the supernova (approximately three times the total energy injected so far by the stellar winds) causes the bubble to expand more rapidly (left panel of Fig. 3). Because the supernova has injected a lot of energy, but (relatively) little mass, the density inside the bubble decreases quickly during the expansion and the Rayleigh-Taylor instabilities in the outer shell grow quickly. The bubble is left with only one source of energy, the wind from the 25 M star, which is insufficient to maintain the expansion of the bubble. As a result, the thermal pressure inside the wind bubble decreases leading to a loss of compression at the outer shell, which starts to expand because of its own internal pressure (left panel of Fig. 3). During this phase, the asymmetrical shape of the bubble starts to disappear as the isotropic pressure in the shocked wind bubble pushes the shell outward equally in all directions.

Eventually, the 25 M star reaches the RSG phase, which further reduces the energy being added to the bubble. A thin shell forms at the wind termination shock (central panel of Fig. 3). This initially happens close to the star because of the low ram pressure of the slow RSG wind. However, owing to the relatively low pressure in the bubble, this shell can move farther away from the star than would have been possible if the 25 M star had been alone (R 6.5 pc, rather than R 4.8 pc when comparing the right side of the center panel of Fig. 3 with Fig. 1).

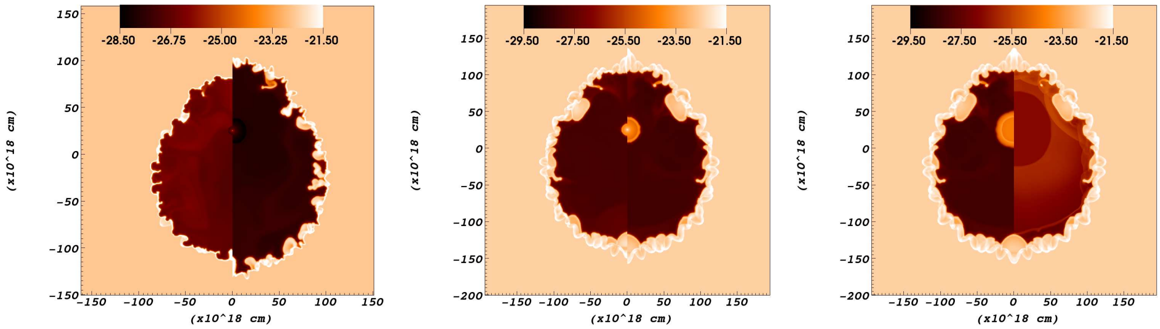

Fig. 2. Logarithm of the density of the circumstellar medium in g/cm3 after 4.86 and 5.60 Myr (left panel), after 6.58 and 7.0 Myr (center panel), and after 7.01 and 7.07 Myr (right panel). On the left, the mass, ejected by the first supernova has spread throughout the bubble, which, due to the injection of energy, expands rapidly. The density inside the bubble decreases and the Rayleigh-Taylor instabilities in the outer shell become more pronounced. In the central panel, the 25 M star has reached the RSG phase and forms a shell at the wind termination shock that moves away from the star as the thermal pressure in the bubble decreases over time. Finally, on the right, the 25 M star explodes as a supernova, which sweeps up the RSG shell and fills the bubble.

Finally, the 25 M star reaches the end of its evolution and explodes (right panel of Fig. 3), sweeping up the surrounding RSG wind as well as the RSG shell. The bubble has lost most of its asymmetry; it has a length of 105 pc and a maximum width of 104 pc. The outer edge of the shell has an almost spherical shape. As in the case of the first star, the supernova quickly expands into the low density shocked wind bubble until it reaches the outer shell, then falls back inward. From this moment on, the bubble has no energy source. While energy continues to be lost from the bubble by thermal conduction, turbulent mixing, and radiative cooling, the outer shell starts to push inward owing to is own internal pressure, which is considerable because of its relatively high density. Assuming a typical speed for gas in the shell of 1...2 km s-1 (the sound speed for gas at a 102103 K), the gas in the outer shell would take a minimum of 2.5 × 107 years to reach the center, though in practice it would take longer owing to the continuing resistance of the hot bubble.

4 Conclusions

The presence of multiple stars inside the circumstellar bubble influences the evolution of the bubble in several ways.

The most obvious is in terms of the outer shape of the bubble, which is strongly aspherical during the early phase of its evolution. This effect is clearly visible until after the supernova explosion of the first star. In addition, remnants of the collision between the two outer shells of the individual bubbles remain visible within the shocked wind bubble until after the supernova explosion of the 40 M star.

The collapse of the outer shell, which is caused by a decrease in the internal pressure of the bubble, is unique to the multi-star scenario. It can only occur when the bubble persists for an extended period of time (105 106 yr) with a significantly diminished energy source (the wind of the remaining star). The effective result is that the outer shell resembles the single-star shell of the star with a stronger wind. As long as the 40 M star exists, the shell looks like a shell created by a single 40 M star. Afterwards, it starts to resemble the circumstellar shell of a 25 M star as it becomes relatively thick. However, it is far more instable as a result of the instabilities created in the initial evolution. This lack of internal pressure also affects the medium close to the 25 M star: the RSG shell can move further away from its progenitor than would have been the case for a single-star bubble.

The supernovae are contained by the outer shell and do not break out of the bubble. This is surprising, considering the amount of energy in the supernova. However, the mass of the outer shell is very high. A bubble with R = 30 pc and an ambient medium density of $10^{-22.5}$ g cm-3 has a 5.3 104 M outer shell that forms a very effective barrier against a supernova, which is high in energy, but low in mass.

We neglected the effect of photoionization, which would give the gas a minimum temperature of about 10000 K during the main sequence and WR phases. During these phases, the shells would become thicker owing to their higher thermal pressure. This increase in pressure within the outer shell would also hasten its expansion after the first supernova.

We conclude that simulating the bubbles around more than one star improves our understanding of the evolution of the circumstellar bubbles of massive stars. Self-evident truisms, self-fulfilling prophecies and the like.

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