THE EVOLUTION OF SUPERNOVAE IN CIRCUMSTELLAR WIND BUBBLES. II.
CASE OF A WOLF-RAYET STAR

Vikram V. Dwarkadas
Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637; vikram@oddjob.uchicago.edu

Received 2006 September 3; accepted 2007 May 31

ABSTRACT

Mass loss from massive stars leads to the formation of circumstellar wind-blown bubbles surrounding the star, bordered by a dense shell. When the star ends its life in a supernova (SN) explosion, the resulting shock wave expands within this modified medium. Following up on an introductory paper (Dwarkadas), herein we study the evolution of a SN in the bubble formed by a 35 $M_{\odot}$ star that evolves through the phases O star, red supergiant, and Wolf-Rayet star. We model the evolution of the circumstellar medium, and the expansion of the SN shock wave within this medium. Our multidimensional simulations clearly reveal density and pressure fluctuations within the surrounding medium, the presence of hydrodynamic instabilities, the growth of vorticity, and the onset of turbulence. The SN shock interaction with this medium, and then with the dense shell, gives rise to transmitted and reflected shocks. Their effect on the X-ray emission is examined. In this particular case the shock wave is trapped in the dense shell for several doubling times. The turbulent interior, coupled with the density and pressure fluctuations, lead to a corrugated SN shock that impacts the dense shell. The impact occurs in a piecemeal fashion, with some parts of the shock wave interacting with the shell before others. As each interaction is accompanied by an increase in the X-ray and optical emission, different parts of the shell will “light up” at different times. The situation is reminiscent of the scenario in SN 1987A. The reflected shock formed upon shell impact comprises several smaller shocks with different velocities, which are not necessarily moving radially inward. The spherical symmetry of the initial shock wave is completely destroyed.

Subject headings: hydrodynamics — instabilities — shock waves — stars: winds, outflows — supernova remnants — supernovae: general

1. INTRODUCTION

Core-collapse supernovae (SNe), those generally classified as Type Ib/c and Type II, arise from massive stars ($M > 8 M_{\odot}$). These stars lose a considerable amount of mass prior to their explosion as SNe. Mass loss from the star will modify the medium surrounding it, giving rise to wind-blown cavities surrounded by expanding shells of gas. When the SN explodes, the resulting blast wave will eventually interact with this modified circumstellar medium (CSM) rather than the interstellar medium (ISM) into which the star was born.

In the past decades several pieces of evidence have suggested that many SNe arise within circumstellar (CS) bubbles. The most famous example is the exceptionally well-studied SN 1987A, which is thought to have exploded within a bipolar CS bubble (Sugerman et al. 2005a, 2005b). This bubble is due to the interaction of the wind from the blue supergiant progenitor with the mass loss from a prior red supergiant (RSG) stage (Luo & McCray 1991; Blondin & Lundqvist 1993). Other well-known SNe that have been interpreted as arising within a wind-blown bubble include Cas A (Borkowski et al. 1996), G292+0.8 (Park et al. 2002), RCW 86 (Vink et al. 1997), and the Cygnus Loop (Levenson et al. 1997). CS interaction models have been proposed for N132D (Hughes 1987) and Kepler’s supernova remnant (SNR; Bandiera 1987).

The formation of wind-blown bubbles around stars has been studied in detail, both analytically (Weaver et al. 1977; Koo & McKee 1992a, 1992b) and numerically (Frank & Mellema 1994; Mellema & Frank 1995; Dwarkadas et al. 1996). Such models usually assume an ad hoc prescription for the wind properties. Some attempts have been made to take the evolution of the wind into account in the case of planetary nebulae (Mellema 1995; Dwarkadas & Balick 1998) and Wolf-Rayet (WR) bubbles (Garcia-Segura & Maclow 1995; Brighenti & D’Ercole 1997).

The evolution of SNe in different media has also been studied, especially in a constant density medium, and in a medium whose density decreases as a power law with radius. Self-similar solutions for the interaction of SNe with a power-law density profile have been derived by Chevalier (1982). Ostriker & McKee (1988) present a compilation of solutions for the evolution of astrophysical blast waves in various media.

The density structure within a CS bubble, however, is quite different from that in the constant density ISM. Thus, the evolution of the SNR within the preexisting wind-blown bubble differs considerably from its counterpart evolving in the pristine ISM. The evolution of SNe in wind-blown bubbles has not received quite as much attention as it deserves. Ciotti & D’Ercole (1989) did some preliminary work, and Chevalier & Liang (1989) studied the evolution analytically. A series of papers by Tenorio-Tagle and his colleagues (Tenorio-Tagle et al. 1990, 1991; Rozyczka et al. 1993) studied the numerical evolution in further detail. A CS evolution model for Cas A was computed by Borkowski et al. (1996).

In Dwarkadas (2005, hereafter Paper I) we introduced the various aspects of the problem, and carried out one-dimensional (1D) calculations that illustrated the various parameters involved. The results are summarized in § 2. These calculations assumed idealized winds with constant properties, appropriate for studying the various factors that affect SN evolution. More realistic models, however, require a prescription of the mass-loss history of the star as its ascends the H-R diagram, coupling the evolution of the CS gas to that of the star itself.

An important step forward in this process was the computation of detailed stellar evolution models of 35 and 60 $M_{\odot}$ stars by Norbert Langer (Langer et al. 1994). These models, which provided the required mass-loss history with time, were used by Garcia-Segura et al. (1996a, 1996b [hereafter GLM96]) to compute the dynamical evolution of the surrounding gas. As they
show in their work, taking the complete stellar mass-loss history into account results in a much more complicated CS structure. The presence of a variety of small-scale structures, various dynamical instabilities, and multiple shock fronts presents a complex morphology that compares well with observations. These calculations, however, did not compute the full evolution of the CS bubble in multidimensions, nor the final SN phase of the star and the resulting interaction with the surrounding medium.

In this paper we take a more detailed look at a specific case, that of the 35 $M_\odot$ star. Using the 35 $M_\odot$ star model, courtesy of Norbert Langer, we first study the formation of the medium around the star as it evolves along the H-R diagram. We then assume that the star explodes as a SN, leaving behind a compact remnant, and study the evolution of the SN shock wave within this medium. Initially we compute spherically symmetric 1D calculations that illustrate the various shock structures and the dynamics involved. This is followed by two-dimensional (2D) computations that take multidimensional factors such as deviations from symmetry, the onset of turbulence, and the presence of hydrodynamic instabilities into account.

Our aim in this paper is to show the impact of a single massive star on the surrounding medium throughout its lifetime. Although we concentrate on a specific case, our goal is to illustrate general properties of the interaction that are more globally applicable, and to identify the various features that distinguish this from the interaction of a SN shock with the ISM. Preliminary results from this work were outlined by Dwarkadas (2007). This work expands considerably on the results outlined therein, describes in detail the spherically symmetric calculations that are necessary to understand the shock dynamics and structures, computes X-ray luminosity and surface brightness, and elaborates on the intricacies of the multidimensional calculations. In a companion paper (V. V. Dwarkadas 2007, in preparation) we also provide a more general analytic discussion for the properties of wind-blown bubbles around massive stars.

The rest of this paper proceeds as follows. In §2 we give a brief overview of SN explosions within wind-blown cavities. In §3 we present 1D simulations that illustrate the evolution of the bubble density and pressure with time, and describe the various evolutionary phases. This is followed by a 1D simulation of the SN-bubble interaction, which captures the essence of the hydrodynamics. Section 4 follows up with 2D simulations that show the formation of various dynamical instabilities and other higher dimensional effects. Section 5 summarizes the paper, provides a general discussion of the results and their applications, and outlines follow-up work.

2. OVERVIEW OF SNR–WIND BUBBLE INTERACTION

Tenorio-Tagle et al. (1990) and Paper I showed that the interaction of the SN ejecta with a wind-blown shell can be divided into various regimes, depending on the ratio of the mass of the shell to the mass of the ejected material, a quantity that we label as $\Lambda$. If this ratio is small ($\Lambda \ll 1$), then the presence of the shell merely acts as a perturbation to the flow. Indications of the interaction are visible in the density, velocity, and temperature profiles of the ejecta. However, once the shock has swept up an amount of material exceeding a few times the shell mass, the ejecta “forget” about the existence of the dense shell. The ejecta density profile reverts back to the profile that would have existed in the absence of the shell. The expansion parameter “$\delta$” (where $R_{SN} \propto t^\delta$), which had dropped considerably at the point of shell interaction, increases gradually until it reaches the value it would have had in the absence of the shell. In about 10–20 doubling times, the SN will completely forget about the shell and continue to evolve as if the shell had never existed. The density profile changes to reflect this. Since the emission from the remnant after a few months is mainly due to CS interaction, the changing density profile will be reflected in a change in the emission from the remnant, such as the optical and X-ray emission. Paper I showed the change in the X-ray surface brightness profile due to changes in the density profile.

As the ratio $\Lambda$ increases, the energy imparted by the remnant to the shell is larger, and the evolution begins to change. The interaction of the remnant with the shell drives a shock front into the shell. The high pressure behind the shock-shell interface sends a reflected shock back through the ejecta. Thermalization of the ejecta is achieved in a much shorter time as compared to thermalization by the SN reverse shock. The ejecta after reaching the center bounce back, sending a weaker shock wave that will collide again with the shell. In time a series of shock waves and rarefaction waves are seen to be traversing the ejecta. Each time a shock wave collides with the dense shell a corresponding (but successively weaker) rise in the X-ray emission from the remnant is seen.

The presence of the dense shell results in a deceleration of the shock wave, transfer of ejecta energy to the shell, as well as conversion of kinetic to thermal energy, which in the case of a very dense shell may be effectively radiated away. These effects tend to speed up the evolution of the nebula. The “Sedov stage” may be reached later than for evolution in a constant density medium (due to the lower interior density) and may last for a shorter time (due to the dense shell). In some cases when the value of $\Lambda \gg 1$ the Sedov stage may be completely bypassed. In such a situation the shock wave will merge with the wind driven shell. The velocity of the blast wave is sufficiently decreased that the flow time becomes comparable to the age of the remnant. Radiative cooling begins to dominate, and the remnant may enter the radiative stage much earlier on in its lifetime.

Herein we have outlined the basics of SN shock wave interaction with dense shells. Further details can be found in Paper I and references therein.

3. EVOLUTION OF THE CSM AROUND A 35 SOLAR MASS STAR

3.1. One-Dimensional Calculations

In this section we outline the evolution of the WR bubble around a 35 $M_\odot$ star, and describe the eventual SN-shell interaction. Although this has been previously carried out by GLM96, we chose to redo the entire calculation. It is necessary for us to run the calculation in order to be able to remap it onto the grid, and set up the initial conditions for the SNR to interact with this medium. In the process of carrying out this simulation we found several differences between our work and that of GLM96, especially in the 2D case. Our use of a lower ambient density (more characteristic of the ISM) allowed the bubble to expand to a much larger size. The differences in our simulations are mainly due to us being able to compute the evolution over all the stages in two dimensions as a result of the considerable increase in computational power. This is reflected in a change in the character of the medium into which the SNR evolves. Given the size and morphology variations in our computations as compared to those of GLM96 and the necessity in describing accurately the medium into which the SN shock wave is evolving, we have chosen to present herein a rather detailed description of the evolution of the bubble.

The simulations were carried out using the VH-1 code, a 2D finite-difference hydrodynamic code based on the piecewise parabolic method (Colella & Woodward 1984). The code employs
an expanding grid, which tracks the outer shock front and expands along with it. This trick is very useful in cases where the dimensions of the grid expand by many orders of magnitude over the course of a run. The 1D simulations presented here were carried out on a grid of 2000 zones. 2D simulations were carried out on a grid of 600 x 600 zones. Radiative cooling was implemented in the form of a cooling function, adopted from the function given in Sutherland & Dopita (1993), and modified to extend to lower temperatures. The effect of the lower temperature is mainly to make the shells thinner.

In the course of its evolution the star evolves through three phases. The wind properties in each phase are computed generally from parameterizations derived from fits to the observed data (Kudritzki et al. 1989; Langer 1989; Nieuwenhuijzen & de Jager 1990). The first and longest lasting is the main-sequence (MS) stage, which lasts for about 4.56 Myr. In this stage the star, which starts its life as an O star, loses mass in the form of a wind with a mass-loss rate of order $10^{-7}$ to $10^{-6}$ $M\odot$ yr$^{-1}$, and a wind velocity that starts close to 4000 km s$^{-1}$ and gradually decreases with time. The wind velocity of the star over its evolution is shown in Figure 1, and the mass-loss rate is depicted in Figure 2. At the end of the MS phase the star swells up immensely in size to become a RSG. In this phase mass is lost in the form of a very slow, dense wind. The velocity in this simulation decreases down to about 75 km s$^{-1}$, although in reality we would expect RSG winds to be even slower, of order 10-20 km s$^{-1}$. The mass-loss rate increases to close to $10^{-4}$ $M\odot$ yr$^{-1}$. Since the RSG phase lasts for about 250,000 yr, the total mass lost in this stage is very large, about 19.6 $M\odot$. At the end of the RSG phase, the star sheds its H envelope and becomes a WR star. Stars in this stage lose mass in the form of radiatively driven winds, with a mass-loss rate that is a factor of a few smaller than their RSG predecessors, but a velocity that is 2 orders of magnitude higher. As can be surmised, the recurrent changes in the wind properties can lead to continuous changes in the structure of the surrounding medium into which the stellar wind is expanding.

In order to accurately compute the surroundings we assume that the star was born in a medium with constant density $2.34 \times 10^{-24}$ g cm$^{-3}$, a number density of about 1 particle cm$^{-3}$ for a medium with 90% H and 10% He. This density is lower than that assumed by GLM96, who used an artificially high density to avoid large computational domains. Our use of an expanding grid partially circumvents the latter problem, since we do not need to start from a grid extending out to about 100 pc. Our initial grid extends out to about $10^{15}$ cm. The lower external density results in a bubble about twice the radius obtained by GLM96.

It is not clear what the density of the medium around the star is over its lifetime. On one hand, many observations suggest that the mean surface density of a massive star-forming region is around 1 g cm$^{-2}$ (see review in McKee 2004), which would indicate a very high volume density. But OB stars have high velocities that may cause them to drift away from their birthplace (Mdzinarishvili & Chargeishvili 2005). The presence of GRBs occurring several hundred parsecs away from massive star-forming regions (Hammer et al. 2006) shows that some massive stars do end their lives in low-density regions, irrespective of where they were born. Observations of isolated H II regions that are far removed from their host galaxies (Ryan-Webber et al. 2004) also indicate that sometimes massive star formation can occur in very low density regions. Taking all these factors into account, we have assumed a density of 1 particle cm$^{-3}$ as an average ISM density over the stellar lifetime. We note that if the density is higher, many of the results will scale appropriately.

The interaction of the MS wind with the surrounding medium leads to the formation of a double-shocked structure, consisting of an outer shock expanding into the ISM and a reverse shock, often referred to as a “wind termination shock.” The termination shock separates the free-streaming wind from the shocked wind region and moves inward in a Lagrangian sense, i.e., the entire structure expands outward, but the termination shock eventually moves toward the center with respect to the outer shock. Most of the volume is occupied by the shocked wind region, forming a hot, tenuous region that may emit in soft X-rays. The formation of wind-blown bubbles is further described in Paper I and references therein. The density and pressure structure at various time steps during the evolution of the bubble in this stage are shown in Figure 3. The title of each plot gives the evolution time in years. The two numbers in the top right-hand corner denote the wind velocity in kilometers per second (top) and the mass-loss rate in solar masses per year (bottom). The initial wind velocity is close to 4000 km s$^{-1}$ and decreases slowly with time, accompanied by a corresponding increase in its mass-loss rate. This happens in such a manner that the mechanical luminosity (0.5$M\odot$/c$^2$) is almost constant. Weaver et al. (1977) calculated an analytic solution that describes the evolution of the outer shock with time under such circumstances. The radius $R$ of the shell increases as $R \propto t^{0.6}$, which confirms reasonably well with the simulations throughout.
most of the MS stage, and the structure of the bubble is reasonably consistent with our expectations based on this paper. As mentioned, the MS stage in this model lasts for about $4.5 \times 10^6$ yr. The total amount of mass lost in this stage is of order $2.5 \, M_\odot$.

Toward the end of the MS stage there is an abrupt drop in wind velocity as the star swells up considerably in size and enters the RSG stage. The large drop in velocity, and corresponding rise in mass-loss rate, leads to a much higher density for the RSG wind and a change in the wind ram pressure. A new system of pressure equilibrium is established in the bubble interior, and the position of the termination shock adjusts accordingly (Fig. 4, top two panels). It is not clear that a pressure equilibrium can always be established. If the wind velocity is very low, then the pressure at the base of the RSG wind will never be equal to that in the MS shell. In this case, where the wind velocity is set (in an ad hoc fashion) to a minimum of about 70 km s$^{-1}$, the ram pressure is sufficient to establish a new equilibrium (Fig. 4; at time $T \sim 4.75 \times 10^6$ yr). Once the pressure equilibrium reaches steady state a region of freely expanding RSG wind is seen, separated from the surrounding medium by a shock. The RSG wind is abruptly decelerated at this shock and piles up against it, forming a thin RSG shell. Note that the RSG wind velocity is much smaller than that of the material into which it is expanding. Thus, the expansion of the RSG wind into the MS wind does not result in a wind-blown bubble. Even though the duration of the RSG stage is small (only about 230,000 yr), the mass-loss rate is 2 orders of magnitude higher than in the previous stage. Thus, the total amount of mass lost is estimated by GLM96 to be about $18.6 \, M_\odot$.

At the end of the RSG phase the star enters the WR phase. The wind velocity increases by over 2 orders of magnitude, to a value of around $2000$ km s$^{-1}$, while the mass-loss rate drops by a factor of a few. The fast, low-density wind from the WR star collides with the free-streaming RSG wind, creating a thin shell of swept-up material, and forming an inner shock that separates the unshocked and shocked winds (Fig. 5, top left). Given the high velocity of the WR wind and the fact that the mass loss is
lower only by a factor of a few, the momentum of the WR shell considerably exceeds that of the RSG shell. The WR shell collides with the RSG shell in about 10,000 yr (Fig. 5; at time $T \sim 4.79$ Myr). The collision leads to a reflected shock that moves back into the unshocked WR wind, and a transmitted shock that enters the thin shell. The emergent shock wave drags the RSG shell along with it as it enters the low-density MS bubble. Eventually this structure will collide with the MS shell (Fig. 5; at time $T \sim 4.88$ Myr). We note that this whole phase, which has extremely important implications for the bubble and SN evolution, was not modeled by Garcia-Segura et al. (1996a). The energy transferred to the MS shell is not significant and does not cause appreciable motion of the latter. The collision results in an increase in pressure and a rise in the X-ray emission from the shell. The pressure behind the compressed shell is sufficient to send a reflected shock expanding back into the wind material, which ends up compressing the already shocked material. The wrinkles seen in the density profile are due to small-scale changes in the wind properties. This is partially due to the fact that the boundary conditions are calculated in a discontinuous fashion. It may be possible to interpolate over the terminal wind velocity and mass-loss rate as a function of time and store them as continuous functions; however, we have not attempted to do so. Note that at the very end of the star’s lifetime the wind speed rises to about 3000 km s$^{-1}$, whereas the mass-loss rate decreases gently, resulting in a drop in the wind density. The reverse shock, which is moving back into a high-density medium, suddenly finds itself plowing through a much lower density environment. The situation finally reaches an equilibrium when the dynamic pressure of the freely expanding wind equals the pressure behind the reverse shock.

The X-ray luminosity of the bubble over the evolution is shown in Figure 7. Our aim is to obtain a reasonable approximation to the X-ray luminosity without carrying out complex calculations, which is not the intention of this paper. We have therefore used the approximate fit to the Raymond et al. (1976) cooling curve, as suggested by Chevalier & Fransson (1994): the cooling function $\Lambda = 2.5 \times 10^{-27} T^{-0.2} \text{ergs cm}^3 \text{s}^{-1}$ for temperature $T > 4 \times 10^7$ K, and $\Lambda = 6.2 \times 10^{-19} T^{-0.6} \text{ergs cm}^3 \text{s}^{-1}$ for temperatures $10^6 \text{K} < T < 4 \times 10^7$ K. This cooling function accounts for

Fig. 4.—Density and pressure profiles at various time steps in the evolution of the wind-blown nebula, during the RSG stage. Other details are the same as in Fig. 3.
thermal bremsstrahlung at the higher temperatures, and line emission in the lower range. We see that throughout the early evolution of the bubble, the luminosity of the bubble is quite low, a few times $10^{32}$ ergs s$^{-1}$. The variations are not as important as the average luminosity indicated. Using the calculators on the Chandra Web site we find that a bubble with this luminosity in our Galaxy at a distance of a few kiloparsecs would not be observable by the Chandra X-ray satellite, as the background count rate would exceed that from the source. The luminosity increases after the appearance of the WR wind, and especially after the collision of the WR wind with the RSG wind. The reason is that the density of the RSG wind, into which the WR wind is expanding, is much higher than the density of the surrounding bubble. Thus, the emission measure is much larger for the X-ray emission from the WR wind, than for that from the earlier phases. As expected, the emission decreases once the WR wind passes the RSG wind and

![Fig. 5.—Density and pressure profiles at various time steps in the evolution of the wind-blown nebula, during the WR stage. Other details are the same as in Fig. 3.](image-url)
encounters the low-density MS interior. However, it rises again once the expanding shock wave collides with the dense MS shell.

We note that the X-ray luminosity is in general quite low. The Weaver et al. (1977) picture suggests a very hot interior temperature and observable diffuse X-ray emission. However, several authors have pointed out the paucity of WR bubbles with diffuse X-ray emission (Chu et al. 2003, 2006; Wrigge et al. 2005). Furthermore, even the bubbles seen in a number of lower temperature than expected from the models. Our results suggest that the emission measure from these bubbles is low enough that diffuse emission may not be seen, and this may account for some of the discrepancy. However, the temperatures in our models, although lower than those suggested in the analytic models of Weaver et al. (1977) due to the mixing and turbulence in the interior, are still around a few times $10^6-10^7$ K, much higher than those actually observed. Perhaps this is partly due to the fact that much of the observed X-ray emission may be coming from high-density, lower temperature clumps in the unstable, turbulent interior. We will investigate this suggestion more carefully in future, using our multidimensional simulations.

According to GLM96, the star at this point is in the transition phase from a WN to a WC star. The model calculations terminate at this point, and the density and pressure profiles at the end of its evolution are shown in Figure 6. Note that the overall structure is quite similar to what one would expect from a two-wind interaction, although there are considerable fluctuations in the density profile in the bubble interior. In particular, there is one region in the bubble interior where there is an increase in density by almost 2 orders of magnitude compared to the surroundings. This will be somewhat smoothed out by instabilities in multidimensions.

It must be kept in mind that the evolution described above is only 1D. In two dimensions, as we will show below (§ 4.1), strong instabilities may develop in the shells, the interior of any surrounding bubble will not be isobaric, and the structure of the CSM is not as clear-cut as in the ID models. It is, however, clear from this picture (Fig. 6) that in general the medium surrounding a massive star is a low-density medium, surrounded by a high-density thin shell. This is similar to what was assumed in the calculations carried out in Paper I. It is significant also that the shell size is essentially set by the MS stage, while the composition of the bubble consists mostly of material emitted in the RSG phase. This material would not have gone too far, however, were it not for the high-momentum WR wind, which mixes all the material out to the radius of the dense shell. Thus, what we refer to as a “WR bubble” is the cumulative consequence of the previous stages of evolution.

3.2. Interaction of the SN Shock with the Surrounding Medium

The 35 $M_\odot$ model presented here ends its evolution as a 9.15 $M_\odot$ star. In order to study the further evolution, we assume that the star subsequently explodes as a SN of energy $10^{51}$ ergs. The outer layers are expelled in the explosion, leaving behind a remnant neutron star of mass 1.4 $M_\odot$. Thus, the amount of mass ejected in the explosion is about 7.75 $M_\odot$. Given the mass and energy, one more parameter, the exact form of the ejecta density profile, is needed in order to model the SN explosion. As described in Paper I, we have assumed that the ejecta are well described by a power-law profile in the outer parts, with a power-law index of 7, and a constant density profile in the interior (Chevalier & Fransson 1994). The choice of power-law index is necessarily arbitrary and meant to be illustrative, although it is useful to remember that less steep power laws are thought to be more appropriate to describe the ejecta of SNRs arising from compact stars (Borkowski et al. 1996).

The initial interaction of the SN shock with the free wind was carried out separately on an expanding grid. The wind parameters used were those existing at the end of the star’s WR stage. The shock structure was then interpolated and mapped back onto the first few (typically 75–100) zones of the grid containing the final stages of the WR star. Inflow boundary conditions are used.

The innermost wind termination shock of the WR bubble is at a radius of about 11.2 pc. The SN shock takes about 880 yr to reach this point. Note that this time is shorter than that predicted by the self-similar solution (Chevalier 1982; Chevalier & Fransson 1994). The reason is that the self-similar solution assumes the external medium has a negligible velocity, whereas in this case the ambient velocity (due to the WR wind) is a finite (and non-negligible) fraction of the SN shock velocity. The collision of the SN shock with the inner wind termination shock results in a reflected shock moving back into the SN ejecta and a transmitted shock advancing into the low-density bubble. The reflected shock can be seen (Fig. 8; 3743 yr) climbing the steep power-law part of the ejecta profile.

The SN shock wave at the start of the simulation was moving close to 13,000 km s$^{-1}$ (see Fig. 12). The collision with the termination shock reduces the velocity considerably, and the transmitted shock emerges into the interior cavity of the MS bubble.
with a velocity close to 5000 km s\(^{-1}\). The shock continues to sweep up more of the surrounding material, but the low density implies that the swept-up mass is quite small, and therefore its velocity does not change appreciably. As shown in Figure 8, a high-density perturbation exists about 41 pc from the center, with a maximum density of about 0.01 particles cm\(^{-3}\) about 47 pc from the center. The collision of the transmitted shock with this region results in a corresponding drop in velocity, and a weak reflected shock whose presence is mainly discernible as a slight perturbation in the pressure profile, but that tends to otherwise blend into the density structure (Fig. 8; 9299 yr). When the shock hits the highest density part of this region (at about 47 pc) another reflected shock is seen that is slightly stronger (labeled \(r_1\) in Fig. 8). The collision compresses the dense region, increasing its density (Fig. 8; 12,531 yr), and results in a transient increase in the X-ray emission (Fig. 13).

The transmitted shock that emerges from this collision has a velocity that is closer to 2000 km s\(^{-1}\). Note that this is lower than the velocity the shock would have if it were expanding in a medium with a constant, low density equal to the bubble interior density. It is the frequent collisions with the higher density fluctuations that tend to slow it down. The forward shock moves roughly at constant velocity until it collides with the MS shell, at about 22,000 yr (Fig. 9). The mass of the shell far exceeds the mass of the shocked material colliding with it, so this collision falls in the regime where \(\Lambda \gg 1\) (see Paper I). The shock front merges with the shell, and its velocity drops almost to zero. Since the shock has essentially merged with the shell, it is very difficult to track the shock and note its actual radius, and hence velocity, resulting in the velocity fluctuations seen after about 23,000 yr in Figure 12. Meanwhile, a strong reflected shock resulting from the collision with the dense shell moves back into the already shocked material. This reflected shock collides with the remains of the previously shocked high-density perturbation, resulting in a weaker forward shock that expands outward and subsequently impacts the MS shell (Fig. 9; around 30,000 yr). The result of all these frequent collisions is a plethora of shock waves crisscrossing the region of the remnant in the vicinity of the MS shell. A high-pressure region

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**Fig. 8.**—Density and pressure profiles at various time steps in the evolution of the SNR during the bubble.
is formed there, and some weaker shocks are later seen to expand outward and subsequently collide with the MS shell (Figs. 10 and 11).

In the meanwhile, the reflected shock $r_1$ from the earlier collisions has reached the flat part of the density profile. This reflected shock moves toward the center at a rapidly increasing velocity, with maximum velocities approaching 6000 km s$^{-1}$. On reaching the center, and given our inflow boundary conditions, the shock bounces back. This much weaker re-reflected shock will expand outward and eventually collide with the MS shell in about another 30,000 yr, and the cycle tends to repeat itself (Figs. 10 and 11). However, the SN density at the origin (center) is decreasing as $t^{-3}$. The density in the interior increases when the ejecta are shocked, although it will then again decline with time. In general then, the shocks are continuously interacting with material of lower density, and therefore any radiation signatures from the interaction, such as increasing X-ray emission, are continually diminished. In fact, the subsequent reverse shock interactions with the shell hardly result in an increase in the X-ray luminosity of the remnant, although the interaction of the re-reflected shock with the dense MS shell certainly leads to a noticeable increase.

A few salient points of the interaction are noticeable in Figures 8–11:

1. At several times during the evolution, a variety of reflected, transmitted, and re-reflected shocks are visible in the SN density, and especially pressure profile (e.g., at time 89,485 and 100,187 yr). The pressure and density profiles are very different from those assumed for a SN interacting with a constant density medium or a wind, and therefore the emission computed from these will vary.

2. In the 1D calculations the high-density fluctuation that is initially present is visible almost throughout the simulation. In multidimensions this will probably be somewhat flattened due to the presence of instabilities. But fluctuations in density will exist in multidimensions, and the simulations reasonably depict the behavior in such cases.
3. Once the SNR shock impacts the dense shell the evolution is more or less restricted to the WR bubble for 5–6 doubling times, and the motion of the shell is negligible. Thus, the size of the remnant in this period is confined to that of the WR bubble, and the remnant will appear to have stalled.

4. Changes in the radiation signatures during this time are almost entirely due to the effects of the reflected and other shocks within the bubble, and the forward shock has very little role to play.

5. The complex surrounding structure results in a variety of shock waves traversing the bubble at any given time. A large range of gas velocities will be observed over the interior of the remnant. When the SNR shock is heading toward the dense shell, gas velocities ranging from $-2000$ to $+2000$ km s$^{-1}$ are seen in the interior. Once the shock hits the shell the forward shock velocity is considerably reduced, but the gas velocity behind the reverse shock can increase to $5000$ km s$^{-1}$ as the shock expands in a continually lower density medium. Thus, line emission or absorption spectra from different parts of the remnant will show vastly different velocities, sometimes differing by thousands of km s$^{-1}$. If a spectrum is taken that shows lines arising from different parts of the remnant, it will reveal a very confusing and complicated velocity structure.

6. By the end of the calculation the transmitted shock can be seen expanding outward, pushing the dense shell with it. It will take considerably more time before this shock separates from the shell and is visible as a separate entity (see Paper I).

The evolution of the SNR is thus very different from that seen if it had expanded in the pure ISM. The shock wave entering the MS shell causes the shell to expand. As shown in Paper I, the shock more or less merges with the shell in this case, and the transmitted shock does not seem to appreciably separate from the shell. Over time the density of the shell decreases, but its thickness appears to increase as the forward shock expands without effectively separating from the shell. Even as late as 150,000 yr, or over six doubling times, the outer shock is seen at a distance of about 84 pc, which means that is has moved just 3 pc in about 125,000 yr. A large fraction of the kinetic energy has been converted to thermal energy and emitted as radiation. The ejecta are completely thermalized even before reaching the so-called Sedov

Fig. 10.—Density and pressure profiles at various time steps in the evolution of the SNR during the bubble.
stage. In fact, the remnant at this stage does not fit anywhere in the classical evolutionary pattern of free expansion, Sedov, radiative stage, and eventual dispersal into the ISM. It comes closest to being somewhere in between the Sedov and radiative stages, much closer to the latter.

An important point to note is that most of the gas within the bubble is shocked, and is at temperatures $10^6$ K or higher. Occasionally a passing shock will raise the temperature at some point to greater than $10^7$ K. The entire remnant will appear luminous in X-rays, although the emission from the outer parts dominates through much of the evolution. The inner regions may brighten up when the reflected shocks collide with them. As the X-ray surface brightness depends on the square of the density, we have computed this value at various different times (Fig. 14; for details, see Paper I). The quantity plotted in the various frames is the square of the particle density, integrated along the line of sight, at all points where the temperature exceeds $10^6$ K, and normalized to the maximum value. This quantity shows approximately the surface brightness of the remnant in X-rays. As can be seen, in most

Fig. 11.—Density and pressure profiles at various time steps in the evolution of the SNR during the bubble.

Fig. 12.—Velocity of the forward shock with time over the expansion of the remnant.
cases the outer regions appear to dominate the surface brightness. It is noteworthy that in the last few plots in Figure 14, the emission appears to arise from the entire remnant, but the emission measure at this point is so low that it would likely not be observable.

The total X-ray luminosity from the remnant varies considerably with time, depending strongly on the behavior of the various shock waves crisscrossing the remnant. While an exact computation of the X-ray emission, which would involve taking non-equilibrium processes into account during the early evolution, is far beyond the scope of this paper, Figure 13 illustrates the evolution of the X-ray emission over the first 150,000 yr of the remnant, in a similar manner to Figure 7. The X-ray luminosity is on average about $10^{34}$ erg s$^{-1}$, with occasional periods when it increases by a few orders of magnitude. A large extended source with this average luminosity at a distance of 10 kpc would hardly be visible with the Chandra satellite above the Galactic background. Thus, the presence of the low-density CSM considerably reduces the emission from the remnant. However, the periodic brightening would increase the visibility considerably. The initial increase in luminosity is due to the collision of the shock wave with the MS shell, while the secondary maximum at about 89,000 yr is due to a combination of the re-reflected shock hitting the MS shell and various reflected shocks moving back into the ejecta. This shows that even older remnants may experience some brightening in X-rays if the SN explodes within a preexisting cavity, rendering them visible even at late times.

The above description illustrates the differences between the evolution of SNRs in a constant density medium as compared to more realistic structured environments sculpted by the pre-SN progenitor star. In this section we have shown 1D calculations that accurately track the expansion of the SN shock wave through the surrounding medium. The 1D simulations can capture the dynamics of the multitude of shocks that appear to crisscross the remnant at various times, and enable us to understand the complicated hydrodynamics and kinematics. However, in order to obtain a complete picture, one needs to carry out multidimensional simulations that can capture effects such as the formation of hydrodynamic instabilities and deviations from spherical symmetry that cannot be seen in 1D simulations. To this effect we have also carried out 2D simulations, as described below.

4. TWO-DIMENSIONAL COMPUTATIONS

4.1. Evolution of the Surrounding Medium

Unlike GLM96, we have chosen to carry out 2D simulations from the start of the MS stage. While computationally this is extremely time-consuming, since the simulation runs for over a million time steps, we feel that a thorough treatment of the problem requires 2D modeling of the entire evolution from the beginning of the star’s life. As we will show below, the MS bubble in two dimensions shows a much more complicated structure, with a nonisobaric interior that shows considerable density and pressure fluctuations. In our simulations, the RSG and WR shells also become unstable. Only the instability of the WR shell was noted by GLM96. Our simulations show differences from theirs right from the start. Besides, they did not model the interaction of the WR wind with the MS shell and its consequences, which are important to us to define the pre-SN stage.

The 2D simulations were carried out on a spherical ($r$-$\theta$) grid. The simulations described used 600 zones in both the radial and azimuthal directions. In order to accurately compute the inner boundary conditions, i.e., the velocity, the density from the mass-loss rate and wind velocity, and the temperature, the simulation runs for about 1.79 million time steps, one good reason why it was not carried out in full two dimensions by GLM96.

In Figure 15 we show density images of the evolution of the MS bubble at various time steps. The radius scale is in parsecs. In the top right corner of each figure we show the current wind parameters—the velocity in km s$^{-1}$ and the mass-loss rate in $M_\odot$ yr$^{-1}$—as well as the time in years. The color scale shows the logarithm of the gas density, calibrated in g cm$^{-3}$.

The evolution of the MS bubble in two dimensions starts off as in the 1D case. A thin shell of swept-up material is formed, bounded on the outside by a highly radiative shock and on the inside by a contact discontinuity. The outer shock sweeps up the surrounding ISM into a thin shell. The expansion of the bubble closely resembles that shown in the previous sections and in Weaver et al. (1977), with the radius increasing approximately as $t^{0.6}$. The interior is initially isobaric. However, after about 75,000 yr minor perturbations in density and pressure seem to appear within the interior. Perturbations appear to start close in to the inner shock, and somewhat later just inside of the contact discontinuity. We have not added any perturbations to the initial conditions. The origin of the perturbations can be traced to irregularities that arise at the inner shock, and we suggest that it is the response of the inner shock to the changing wind parameters that gives rise to the fluctuations. As the wind parameters vary, the shock position varies correspondingly at every time step. The variation in the position of the inner shock causes variations in the pressure around the shock, and since the shock position is continuously varying, and the interior is subsonic with respect to the reverse shock, the pressure waves do not have enough time to isotropize within the interior. This leads to further variations and density inhomogeneities, which result in the development of turbulence in the interior, visible in Figure 15.

The fluctuations in the position of the shock front, and the shear associated with it, result in a considerable amount of vorticity being deposited into the shocked wind. As the shocked wind is expanding outward, the deposited vorticity is carried out with the wind, and does not dissipate to smaller scales. Pressure variations due to the deposition of vorticity near the inner shock lead to density variations within the region, as regions at different temperatures cool differently. The net result is the formation of higher density regions within the interior. The stellar wind is forced to flow around these obstacles, leading to slower moving regions within the radial flow. The buildup of vorticity in these regions is clearly demonstrated in Figure 15. The cumulative effect is the growth of turbulence within the interior.

At the same time, we find that the dense, thin shell also shows some signs of shear instabilities. Although we do not include any
Fig. 14.—X-ray surface brightness profiles during the SN evolution.
initial perturbations in our calculation, small perturbations can be initiated within the shell due to the shear flow between the contact discontinuity and the cavity just interior to it, due to the difference in the flow velocities. Such perturbations can already be seen in the top right panel in Figure 15. These instabilities tend to persist throughout the growth of the bubble, but their effect is minor, and does not lead to any significant distortion of the spherical shell. This is clearly seen in the last panel (bottom right), which shows the structure of the bubble toward the end of the MS stage. This complicated turbulent structure is the medium into which the RSG wind will expand.

We note here that in previous low-resolution simulations (Dwarkadas 2001, 2002, 2004), we have reported the presence of an unstable thin shell in the MS phase, which we attributed to a Vishniac-type thin shell instability (Vishniac 1983; Vishniac & Ryu 1989). This was seen in simulations with grid resolutions from $200 \times 200$ to $400 \times 400$. However, this instability disappeared when we ran simulations with the even higher resolution reported herein. We feel that the higher resolution simulations are far more believable, although we have been unable to understand the reasons for triggering of the instability at lower resolutions. However, the presence of this instability (or lack of it) does not
affect the subsequent evolution of the bubble or the SN shock, which is our main concern for this paper. The remaining behavior is seen as expected at both lower and higher resolutions, with the higher resolutions providing increasingly sharper clarity to view the Rayleigh-Taylor (RT) instabilities and turbulence within the interior. It is curious, though, that we have noted similar behavior when carrying out simulations of a 40 $M_\odot$ star from a stellar model provided by Georges Meynet. The MS shell instability was seen at a resolution of 400×400 zones, but not at a higher resolution of 600×600 zones. The current situation should be unstable to the Vishniac ram pressure instability (Vishniac 1983), but the appearance of this would differ from the finger-like perturbations that we had written about earlier. Thus, the presence (or absence) of an instability in the MS shell is still a puzzle that remains to be solved.

The interior of the cavity thus differs considerably from the isotropic spherical bubble assumed by GLM96. At the end of about 4.5 Myr, with the MS shell at a radius close to 75 pc from the star, the wind velocity begins to decrease rapidly as the star enters the RSG stage. As mentioned earlier, the higher mass-loss rate and lower velocity of the RSG wind causes the pressure equilibrium within the bubble to change, and a termination shock is formed where the ram pressure of the RSG wind is equal to the thermal pressure in the interior. The RSG shell is also found to be unstable, as shown in Figure 16. GLM96 suggest that the shell is stable to RT instabilities, but this would be strictly true only if the wind velocity was constant or monotonic. In this case the RSG wind velocity varies from about 95 to about 70 km s$^{-1}$ over the evolution, and the pressure equilibrium also varies. The RSG shell is found to be decelerating as it expands outward. The high density behind the shock decelerated by the high pressure of the wind-blown cavity within the MS bubble provides the right conditions for the RT instability, and we see clearly the growth of RT fingers in our simulations. As the dense shell is being decelerated the fingers tend to expand outward. Figure 17 zooms in on the RSG region toward the end of the RSG stage, showing vividly the expanding RT filaments, with slightly bulbous heads due to the formation of Kelvin-Helmholtz instabilities at the tip of the fingers, resulting from the shear flow between the fingers and the surrounding material. The filaments grow in length over the evolution of the shell.

At the end of the RSG stage the surface temperature of the star begins to increase: it sheds its outer envelope and enters the WR phase. The WR wind expanding into the RSG wind will form a miniature version of the MS bubble, complete with an inner shock, a contact discontinuity, and a thin shell. The WR shell is also found to be unstable, and filamentary structure can be seen at the inner edge of the shell. We attribute the growth of these structures also to the development of the RT instability.

In the ideal course of the collision of two winds with constant wind properties, the wind-blown shell would expand with a constant velocity, and the conditions would not allow for the development of the RT instability. However, in this particular case, although the WR wind is expanding within the RSG wind, there

Fig. 16.—Evolution of the wind-blown bubble in the red supergiant (top panels) and WR (bottom panels) phases. The legend is the same as for Fig. 15.
are some important differences. First, the wind parameters are not constant, either in the WR or the RSG stage. Second, the WR bubble is so highly supersonic that it does not cool efficiently, and therefore the outer shock is not highly radiative, and the shell that forms is not thin. The formation of a thin, dense, cool shell may have led to the development of thin-shell instabilities. Instead, due to the variation in parameters we find that the WR shell is accelerating down the ramp of the RSG wind. The pressure inside the dense shell (in the interior cavity of the WR bubble) is much larger than the pressure outside (in the RSG wind). The high pressure pushing on the high-density shell provides the appropriate conditions for the RT instability to develop. In this case, however, as opposed to the RSG case, the fingers expand inward, from the high-density shell into the bubble, rather than outward, as is expected from the physical conditions. The structure at this stage is shown in Figure 16, and magnified in the top right panel in Figure 17.

It is interesting to note that, although the formation of the RT instability is seen in both the RSG and WR cases, the structure looks quite different. One reason is that in the RSG case the shell is
decelerating outward, whereas in the WR case the shell is acceler-
ating outward. Another reason is that the density contrast, or the
Atwood number, is very different between the two cases. The time
that the instability can develop is very short in the WR case, as
the WR wind quickly advances in the RSG wind before colliding
with the shell. For these reasons the appearance of the RT fingers
is different in the two cases, as is apparent in Figure 17. In our
simulation we do not have enough resolution in the radial direc-
tion to study the instability in the WR wind in great detail.

The extremely large velocity of the WR wind (of order 3300 km s$^{-1}$),
coupled with a mass-loss rate that is only a factor of a
few smaller than that of the RSG, means that the ram pressure of
the WR wind far exceeds that of the RSG wind. The WR wind
slams into the RSG shell, causing it to fragment completely, and is
seen to break out of the shell at many different points (Fig. 17),
primarily along the axis (although this may be a numerical effect).
The formation of the funnel-like feature close to the axis is
certainly a numerical effect, due to the presence of very narrow
zones along the axis. However, the simulation clearly reveals
the breakup of the RSG shell, with the fragments being dispersed
throughout the interior of the WR bubble. The momentum of the
WR wind carries some of the RSG material along with it toward
the MS shell (Fig. 16). The WR gas collides with the MS shell and
bounces back, in the process distributing the RSG material
throughout the interior of the nebula. Thus, although the RSG wind
itself was not able to penetrate even a fifth of the MS radius,
much of the mass in the interior of the nebula will be comprised
of material dredged up from the RSG stage. This material is then
shocked by the WR wind, perhaps leading to an overabundance of
N and/or C in the nebular material. The collision of the WR wind
with the MS shell results in a shock being driven into the shell and
a reflected shock back into the unshocked wind. This reflected
shock penetrates as far back as it can toward the center, before
its advance is arrested by the ram pressure of the outflowing
WR wind, and an inward facing wind termination shock forms.

Figure 17 (bottom right), shows a combined contour and vector
plot of the structure of the bubble at the end of the simulation. The
complex nature of the velocity field is due to the various evo-
duional phases, although the imprint of the WR phase is un-
mistakable in the inward flow near the axis and the complicated
behavior in the equatorial regions. The intersection of the ram
pressure of the radially outward flow and the thermal pressure
behind the reflected shock leads to the formation of the WR wind
termination shock. It is of consequence to note that the wind
termination shock is not spherical but slightly elongated toward
the equatorial latitudes. This is due to a combination of factors.
The unstable WR wind pushes out on the unstable RSG wind,
fragmenting the RSG shell. The material is not carried out in a
spherically symmetrical manner. This asphericity is enhanced
when it travels through the cavity due to the pressure and density
fluctuations, and again on this material colliding with the shell.
Therefore, when the reflected shock’s progress toward the center
is finally halted, the equilibrium between the isotropic pressure
of the WR wind and the varying thermal pressure behind the
reflected shock leads to an aspherical wind termination shock.
This has important consequences for the subsequent evolution
of the SN shock wave.

Qualitatively a radial cut through the nebula resembles the
1D profile. However, there is considerably more structure in
the 2D profile. Also, since the 2D resolution is about a third of
the 1D case, the structure is more smeared out, and the sharp shock
fronts of the 1D model are spread out over a larger distance in 2D.

We note that our final picture of the WR bubble agrees well
with observations, including the large size and the complicated
internal structure (Cappa et al. 2003). The size of the bubble of
course is a direct consequence of the external density that we have
assumed. A much higher density would lead to a smaller size. This
would, however, just compress the entire picture into a small
radius, and therefore increase the density in the bubble interior,
but it would not appreciably change the dynamics and kine-
matics that we see.

4.2. Evolution of the SN Shock Wave

In the next stage the star was assumed to undergo a SN ex-
losion, as outlined in § 3.2. The SN profile was interpolated
onto the CSM grid. The SN profile occupies 63 zones, and the
interpolation results in a smearing out of the shock front and other
features. The simulation was then run to study the evolution of
the SN shock wave into the surrounding medium. In this discus-
sion we will concentrate on describing the main multidimensional
effects and departures from the spherically symmetric case dis-
cussed in § 3.2.

The overall evolution of the SN shock wave proceeds as in
the 1D case, but with one major difference—the SN shock does
not remain spherical. We elaborate on this aspect, and its con-
sequences, below.

The evolution of the SN shock wave in the freely expanding
wind proceeds as expected, and in a fashion similar to the 1D case,
up until the time that the shock reaches the wind termination
shock. Note that due to the aspherical nature of the wind termi-
nation shock, the interaction first takes place in the region of the
symmetry axis. This is shown in Figure 18 (at 2597 yr), which
shows snapshots of the pressure at various times during the evo-
lution. The pressure is chosen as a quantity to highlight the shocked
interaction region between the forward and reverse SN shocks.
As explained in § 3.2, the interaction results in a transmitted and
a reflected shock wave. The transmitted shock wave has been
decelerated by the interaction with the wind shock, and is there-
fore slower than the rest of the shock, which is still undecelerated,
as it has not yet encountered the wind shock. Thus, this portion
lags slightly behind the rest of the shock wave. As the next part of
the shock wave hits the wind shock, it also gets decelerated. Since
the velocity of the SN shock is decreasing as it moves outward,
each subsequent impact of some part of the SN shock with the
wind shock happens at a lower velocity. The net result of this
impact is that different parts of the transmitted (and reflected)
shocks travel outward at slightly different velocities. Both shock
waves assume the shape of the aspherical wind shock to a certain
degree.

The effect is further accentuated by the fact that the interior
cavity is not isotropic, but shows considerable variation in pres-
sure and density, with several regions that are higher density than
the surroundings. Furthermore, as shown in Figure 17 (bottom
right), the interior also contains several vortices with velocities
as high as 1000 km s$^{-1}$. The interaction of the SN shock wave
with this highly turbulent material, and the fact that the average
pressure behind the shock wave is not significantly higher than
the pressure of the interior, causes further corrugations in the
shock wave. The result is a highly wrinkled shock wave, with
various bumps and wiggles, by the time it reaches the outer
dense shell.

Figure 19 illustrates how the spherical shock slowly becomes
a wrinkled and corrugated structure. In order to display this
effect vividly, we plot the density profile of the shock wave at
various time steps as it expands toward the wind-blown shell.
Although the outer and inner shock are not very well resolved in
the density color scale, it is easy to spot their location, especially
using Figure 18. In Figure 19 at time 4932 yr, the shock wave is
encountering a density fluctuation within the bubble. The shock appears slightly depressed in that region, and a reverse shock (purple in color) can be seen reflecting off the perturbation. At later times this event is repeated, adding to the asymmetry of the shock wave each time, until finally the shock wave becomes extremely distorted just before it is about to collide with the shell, at about 20,000 yr.

Since the shock is not spherical, the expansion is not completely radial. The bumps in the shock wave, and the crinkled nature of the shock, result in just one or two extended sections of the shock hitting the dense shell at about 22,000 yr, as opposed to the entire shock wave in the 1D case. Each collision will result in a rise in the X-ray and optical emission, as we have seen before (see Paper I). However, in this case, since the shock collides with the shell in a piecemeal fashion, different parts of the shell will brighten up in the X-ray and optical at different times. Therefore, instead of seeing a glowing shell, what will be seen are different sections of the shell “lighting up” at different times. Eventually, in this case over a timescale of about 15,000 yr, the entire shell will brighten up as the entire extent of the shock has collided with the shell.

Another effect of this piecemeal collision is that instead of having one reflected shock bouncing off the shell, we will have several small “shocklets,” with velocity vectors pointing in different directions. This results in an even more aspherical reverse shock, as is shown in Figure 18 after about 35,000 yr. Different parts of the reverse shock will then move at different velocities toward the center. Since the velocities are not all radial, some portions will advance preferentially toward the symmetry axis or the equatorial axis, and collide with it. In the last panel in Figure 17, just after 45,000 yr, one part of the reflected shock can be clearly seen to have collided with the axis of symmetry, and a re-reflected shock is just starting to move back. Note that this shock is directed almost perpendicular to the axis. In part this is due to an axis effect, as has often been discussed for 2D axisymmetric simulations. Therefore, we caution into reading too much into the specific behavior of the shock outlined in this case, emphasizing more the existence of an overall global asymmetry, and reflected shocks that are not moving radially inward.

Due to this piecewise interaction the reflected shock takes a longer time to reach the center in multidimensions. In the 1D case the reflected shock takes about 31,000 yr or so to reach the center and bounce back. In the 2D case, only a very small fraction of the reverse shock has reached the center in almost 45,000 yr. This is not surprising, considering that the entire forward shock itself has barely just finished colliding with the dense shell, and that the reverse shocklets that are formed have a significant azimuthal component rather than just a radial, centrally directed component.

The SN shock wave gets essentially trapped in the dense shell in this case, as outlined in § 3.2. A transmitted shock eventually emerges, as shown in the 1D case. However, in this case the transmitted shock takes an even longer time to emerge as compared
to the 1D case, for the same reasons that we have outlined above, mainly the slower motion of the SN shock wave and the larger time taken for the entire shock wave to collide with the shell. This will thus introduce an even larger degree of asymmetry in the transmitted shock wave, as different parts of the shock emerge from the shell at different times. The appearance will be of a very aspherical remnant. Unfortunately, due to computational time constraints we have not carried out the simulations further. In future we plan to use a parallel adaptive mesh code to carry out this simulation in three dimensions, thus removing any axis of symmetry.

The final panel in Figure 19, at about 42,000 yr, displays the density profile long after shock-shell interaction. The filamentary nature of the resulting remnant is very clearly evident in this picture, resulting from dense shell material expanding into the low-density cavity after the shock-shell interaction, suggestive of Richtmeyer-Meshkov and RT instabilities. The final morphology is a combination of the various asymmetries and the piecemeal collision, together with the various pieces of reverse shock that also interact with each other. The result is a spaghetti-like mesh of filaments emanating from the inner walls of the nebula. The color scale gives the logarithm of the density. It can be seen that the filaments are about 2 orders of magnitude higher in density.

It is clear from the description that both the transmitted and reflected shocks may be considerably aspherical. Furthermore, the radial symmetry of the remnant is gradually lost over increasing interactions. In our case we started with the SN shock evolving in a highly turbulent, but still spherical bubble, yet ended up with a structure with a very aspherical shock wave and reflected shock. In a case where the CS bubble around the remnant is itself not spherical but bipolar, such as the very well observed SN 1987A, this effect will be even more pronounced. Thus, many of our simplistic notions of radially expanding outgoing and incoming shock waves in SNRs need to be reevaluated.

5. SUMMARY AND DISCUSSION

Continuing our series of papers on the evolution of SNe in structured wind environments, we have herein explored the case of a $35 M_\odot$ Wolf-Rayet (WR) star via numerical simulations. The star starts its life on the main sequence as an O star, evolved through the red supergiant (RSG) phase, and then becomes a WR star. As it evolves, it loses mass via winds, whose properties change dramatically over the entire evolution. The mass loss leads to the formation of a structured wind-blown bubble around the star. A MS bubble with a dense shell is formed initially. The slow and dense RSG wind does not expand very far inside this shell, and its low velocity does not result in the formation of a wind-blown bubble, but a termination shock is formed and the wind piles up against it. The high momentum of the WR wind pushes the RSG material outward, until it collides with the MS shell and rebounds back. Finally, a WR wind termination shock is formed at the radius where the ram pressure of the freely expanding wind and the thermal pressure behind the shock are equal.
This is the basic description of the evolution. Multidimensional calculations add further details to the overall picture. The constantly fluctuating position of the reverse shock in the MS phase results in the buildup of pressure fluctuations and the deposition of vorticity into the shocked wind. The vorticity is carried out with the shocked expanding flow. These effects result in the formation of eddies and the onset of turbulence within the shocked medium.

The RSG wind and the WR wind shell are also found to be unstable to RT instability. The high-momentum WR wind pushes out on the RSG material, causing it to fragment, and carrying the material far beyond it would have otherwise traveled. This is important for the formation of WR bubbles—they may be composed in some cases mainly of RSG material, perhaps material that has been dredged up. The WR wind is instrumental in dispersing this material over an area of tens of parsecs, which the RSG wind by itself, with its low velocity, could not accomplish.

The global structure of the bubble in multidimensions is not very different from that predicted in one dimension, but with considerable fluctuations in the density and pressure of the interior. The various instabilities and turbulence result in a WR wind termination shock that is not spherical, but slightly elongated toward equatorial latitudes. This has implications for the subsequent evolution of the SN shock wave within this medium.

We note here that in some cases, such as the one presented here, the WR wind termination shock is not formed by the direct interaction of the WR wind with the surrounding medium, or even with the wind from a preexisting stage. Rather, it results from the WR wind interaction with the MS shell, and a reflected shock bouncing back until pressure equilibration with the ram pressure of the freely expanding wind is achieved. This means that it is not possible to predict the radius of this shock a priori from wind-wind interaction, as is sometimes done nowadays for calculations of the structure around gamma-ray bursts. This could lead to an erroneous answer. In calculating the radius of the WR wind termination shock, one must take into account the previous evolution of the CSM.

Our results have important implications for the surrounding environments, and the environment in which SNe, and possibly gamma-ray bursts, evolve. We do point out that in our calculations we have not considered the effects of the ionizing radiation from the star. These were briefly detailed in Paper I. It is possible that the ionization front sweeping through the star may have a dynamical effect that needs to be taken into account. We are now working on a code that includes the effects of the ionization from the star. These simulations will be detailed in forthcoming papers.

During the writing of this paper we have realized that the ionizing effects in a similar case have recently been considered in simulations by Freyer et al. (2006). Unfortunately, they do not provide details of the shock structures in a 1D model, which would have been very useful to compare the direct effects of the ionization front. And even though their highest resolution was larger than what we use here, the fuzziness of their published figures precludes a detailed comparison with this work. They see the formation of an ionization front instability in the dense shell in the MS stage, but they do not see in their simulations the RT instabilities that are mentioned herein in the RSG and WR stages. Conversely, they note the formation of an RT instability when the WR wind passes over the boundary between the RSG and MS wind. We do see the formation of filamentary structure in this case (Fig. 17, bottom left panel), but it is not clear that this is just due to the existing instabilities that we have noted, the formation of a new RT instability, or even a combination of the two. Since they started with a surrounding medium different from that used here, the size of the bubble and its properties would differ correspondingly, so it is difficult to get a good read on how much the parameters such as density, pressure, and velocity are affected by the ionizing radiation. The ionization front will raise the temperature, and therefore the pressure, of the ionized region, which will affect the evolution of the wind bubble in that region. One point of direct comparison is the X-ray luminosity of the bubble over time, which can be directly compared to Figure 19 of their paper. The variations in the luminosity are much larger in our plot, possibly due to our more approximate method. The luminosity calculated by us is slightly larger, by a factor of a few, compared to their plot. This is partly because we include all emission larger than 10^6 K, whereas they include only emission from 0.1 to 2.4 keV. However, the overall similarity in the plots, especially the large rise in luminosity during the WR phase, is striking. This also attests to the validity of our simpler method of calculation. In the final analysis, and without access to their data, we conclude from their Figure 15 that while the formation of an H II region plays a role, the pre-SN state of the gas at the end of their calculation is not significantly different from that found herein, and this is the main quantity that we are interested in.

Our most interesting results deal with the expansion of the SN shock wave within this medium, which is the main goal of this paper. We find several interesting effects. The evolution of the SN shock wave is confined within this bubble for a substantial large part of time of several doubling periods after the SN shock wave interacts with the dense shell. This will often be the case for SNe that arise from WR stars (Type Ic SNe). The overall level of the emission from the remnant is significantly reduced due to the lower density within the cavity. Due to the fluctuations in density and pressure within the bubble, there are several shocks and rarefaction waves seen crisscrossing the remnant. A large range of velocities will be seen at any given time throughout the remnant. The interior is almost completely thermalized and heated to high, X-ray-emitting temperatures throughout. Thus, as suggested in Paper I, SN shock waves in shells could be one explanation for remnants that show centrally peaked emission. However, it must be pointed out that, at least in this particular case, the density within the remnant is so low that the emission measure in the interior is very small, and most X-ray emission will be seen to arise only from the edge of the remnant.

The spherical SN shock wave interacting with an aspherical wind termination shock results in an aspherical, and considerably wrinkled, transmitted shock. The corrugated nature of the shock wave results in the interaction of the shock with the dense shell taking place in a bit-by-bit fashion, with different parts of the shock wave interacting with the dense shell at different times. As pointed out in § 3.2, the interaction of the shock wave with the shell leads to a brightening up of the shell due to an increase in X-ray and optical emission. In this case, as different parts of the shock wave collide with the shell at different times, the shell will brighten up in different places at different times, almost like blinking Christmas lights.

This effect is reminiscent of the situation in SN 1987A. Optical observations have shown the presence of very bright “hot spots” on the equatorial ring surrounding the SN. The first spot was seen around 1997, and gradually over the next few years many more have been visible. The latest Hubble Space Telescope pictures show spots almost all the way around the ring. The ring itself is known to be the equatorial waist of a CS bipolar nebula surrounding the progenitor star, and the spots can be interpreted as the interaction of a wrinkled shock wave with the ring. This could be one example of the kind of situation outlined in the previous paragraph. We caution that our simulations are not meant to represent the situation in SN 1987A, which is considerably
more complex, and whose progenitor was probably a much lower mass B3 Ia star. Furthermore, in the case of SN 1987A we know that the ionization from the star is important in creating an $\text{H II}$ region interior to the dense shell (Chevalier & Dwarkadas 1995), and that perhaps there are fingers (instabilities) pushing inward from the ring with which the shock is interacting. But nevertheless, the similarities are intriguing. Even though this particular simulation may not be representative of SN 1987A, it shows that it is possible for the SN shell interaction within a bubble to occur in a discontinuous fashion due to a wrinkled shock wave. SN 1987A may be the rare case in which it is possible to investigate these effects.

Our results provide useful pointers for investigating SNRs in wind-blown cavities. A case in point is the oxygen-rich remnant RCW 86. For several reasons, including the low $n_{e}t$ values, the faint emission, and the X-ray profiles, it has been suggested (Vink et al. 1997) that the remnant was formed in a wind-blown cavity. Our simulations could be useful in testing some of these theories and predicting the future evolution. Another remnant that may have been formed in a wind-blown cavity is G292.0+1.8. This remnant shows the interesting presence of instabilities, identified by some authors as RT instabilities that arise from the initial explosion (Ghavamian et al. 2005). We note that in our simulations, such filamentary structures are also formed after the shock-shell interaction, while the reverse shock is headed back into the remnant and the transmitted shock is trapped in the dense shell. This may provide an alternative explanation for the presence of such structures. In future papers we hope to study individual remnants in much further detail.

Our simulations illustrate that it is possible to start with a spherical shock wave from a SN and still end up with a highly aspherical remnant due to the complexity of the surrounding medium. And as noted we have not even taken global asymmetries in the surrounding medium into account, as in the case of SN 1987A. Although we caution against reading too much into the specific details of a single calculation, it serves to illustrate the basic point that SN evolution in wind-blown cavities differs considerably from that in a wind or a constant density medium, and that the structure and evolution of the remnant, its dynamics and kinematics, may all change as a result. Furthermore, the X-ray emission from the remnant evolving in the low-density cavity may be considerably reduced, with occasional periods of increased luminosity. It is therefore necessary to investigate SN shock waves while taking an accurate picture of the ambient medium into which it expands. This, however, is only possible if stellar evolution calculations including the parameters of the mass loss from massive stars for every time step during its evolution are readily available. Fortunately, the situation is consistently improving, and more and more such calculations are now being published.

In future papers we will investigate further the evolution of SN shock waves in environments created by the pre-SN star. We will look at the effects of more massive stars, and especially rotating stars, where strong rotation leads to the formation of a wind that is faster and denser at the poles of the star as compared to the equator (Maeder & DesJacques 2001; Dwarkadas & Owocki 2002). These environments can have considerable effect on the evolution of the shock wave.

V. V. D.’s research is supported by award AST 03-19261 from the National Science Foundation, and by NASA through grant HST-AR-10649, awarded by the Space Science Telescope Institute. We would like to acknowledge several very constructive discussions with Roger Chevalier, especially in identifying the various instabilities that have been seen. Comments and suggestions from John Blondin, Thierry Foglizzo, and Robin Williams have proved extremely useful. We would like to thank the anonymous referee for some very useful comments and suggestions.

REFERENCES

Bandiera, R. 1987, ApJ, 319, 885
Blondin, J. M., & Lundqvist, P. 1993, ApJ, 405, 337
Borkowski, K., Szymkowiak, A. E., Blondin, J. M., & Sarazin, C. L. 1996, ApJ, 466, 866
Brighten, F., & D’Ercol, A. 1997, MNRS, 285, 387
Cappa, C. E., Arnal, E. M., Cichowolski, S., Goss, W. M., & Pineault, S. 2003, in IAU Symp. 212, A Massive Star Odyssey: From Main Sequence to Supernova, ed. K. A. van der Hucht, A. Herrero, & C. Esteban (San Francisco: ASP), 596
Chevalier, R. A. 1982, ApJ, 258, 790
Chevalier, R. A., & Dwarkadas, V. V. 1995, ApJ, 452, L45
Chevalier, R. A., & Fransson, C. 1994, ApJ, 402, 268
Chevalier, R. A., & Liang, E. P. 1989, ApJ, 344, 332
Chu, Y.-H., Gruendl, R. A., & Guerrero, M. A. 2006, in Proc. of The X-ray Universe 2005, ed. A. Wilson (ESA SP-604; Noordwijk: ESA), 363
Chu, Y.-H., Guerrero, M. A., Gruendl, R. A., Garcia-Segura, G., & Wendker, H. L. 2003, ApJ, 599, 1189
Ciotti, L., & D’Ercol, A. 1989, A&A, 215, 347
Colella, P., & Woodward, P. R. 1984, J. Comput. Phys., 54, 174
Dwarkadas, V. V. 2001, J. Korean Astron. Soc., 34, 243
———. 2005b, ApJS, 159, 60
Dwarkadas, V. V., & Pauldrach, A., Puls, J., & Abbott, D. C. 1989, A&A, 219, 205
Langer, N. 1989, A&A, 220, 135
Langer, N., Hamann, W.-R., Lennon, M., Najarro, F., Pauldrach, A. W. A., & Puls, J. 1994, A&A, 290, 819
Levenson, N. A., et al. 1997, ApJ, 484, 304
Luo, D., & McCray, R. 1991, ApJ, 379, 659
Maeder, A., & DesJacques, V. 2001, A&A, 372, L9
McKee, C. F. 2004, in ASP Conf. Ser. 323, Star Formation in the Interstellar Medium: In Honor of David Hollenbach, Chris McKee, and Frank Shu, ed. D. Johnstone et al. (San Francisco: ASP), 21
Melnitzariskii, T. G., & Chargeishvili, K. B. 2005, A&A, 431, L1
Mellena, G. 1995, MNRS, 277, 173
Mellena, G., & Frank, A. 1995, MNRS, 273, 401
Nieuwenhuijzen, H., & de Jager, O. 1990, A&A, 231, 134
Ostriker, J. P., & McKee, C. F. 1988, Rev. Mod. Phys., 60, 1
Park, S., et al. 2002, ApJ, 564, L39
Raymond, J. C., Cox, D. P., & Smith, B. W. 1976, ApJ, 204, 290
Rozyczka, M., Tenorio-Tagle, G., Franco, J., & Bodenheimer, P. 1993, MNRS, 261, 674
Sugerman, B. E. K., Crotts, A. P. S., Kunkel, W. E., Heathcote, S. R., & Lawrence, S. S. 2005a, ApJ, 627, 888
———. 2005b, ApJS, 159, 60
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Tenorio-Tagle, G., Bodenheimer, P., Franco, J., & Rozyczka, M. 1990, MNRAS, 244, 563
Tenorio-Tagle, G., Rozyczka, M., Franco, J., & Bodenheimer, P. 1991, MNRAS, 251, 318

Vink, J., Kaastra, J. S., & Bleeker, J. A. M. 1997, A&A, 328, 628
Vishniac, E. T. 1983, ApJ, 274, 152
Vishniac, E. T., & Ryu, D. 1989, ApJ, 337, 917
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377
Wrigge, M., Chu, Y-H., Magnier, E. A., & Wendker, H. J. 2005, ApJ, 633, 248