SN Shock Evolution in the Circumstellar Medium surrounding SN 1987A

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Abstract. We study the structure of the circumstellar medium surrounding SN 1987A in the equatorial plane. Furthermore, we study the evolution of the SN shock within this medium during the first 25 years, and the resulting hard X-ray and radio emission from the remnant.

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INTRODUCTION

The emission signatures from supernova (SN) 1987A showed significant departures from those of other SNe. Radio emission was seen for a period of a few months, died away for almost 2.5 years, was re-observed around day 1150, and has since been increasing almost linearly with time [14]. The soft X-rays show a more or less linear increase from day 1100 till about day 6000, after which they increase much more rapidly. The hard X-ray emission tends to agree more with the radio [16] rather than the soft X-rays. The most striking aspect of the optical emission is the gradually increasing presence of "hot spots" along the inner ring beginning in 1997. The most recent images (this conference) show that the spots are now visible over almost the entire ring.

Observations have shown the presence of a bipolar nebula surrounding the remnant, a probable result of the interaction between the blue supergiant wind of the SN progenitor star with the red supergiant wind from a previous epoch. The evolution of the radio and X-ray emission led [3, hereafter CD95] to propose the existence of an HII region interior to this nebula. The properties of this HII region were explored theoretically by [12], while observational confirmation came via the work of Michael et al. [15].

Herein we reassess the properties of the circumstellar region around SN 1987A in and around the equatorial plane, in light of recent radio and X-ray observations. We study the evolution of the shock wave within this region using numerical hydrodynamic simulations, compute the hard X-ray and radio emission and compare to the observations.

THE CIRCUMSTELLAR MEDIUM

Our intention is to model the circumstellar medium (CSM) in a spherically symmetric approximation, consistent with the observations and theoretical ideas. The interaction of the blue supergiant (BSG) wind with the red supergiant (RSG) wind gives rise to a wind-blown bubble [17]. In the equatorial region, we find in order of increasing radius...
(Fig. 1): a freely expanding wind, a wind-termination shock ($R_t$), a region of shocked wind, a region of ionized wind (the HII region), and the dense shell or equatorial ring. Based on the available information, CD95 had proposed values for the radius of the wind termination shock, inner radius of the HII region, velocity and mass-loss rate of the BSG wind, and the density of the HII region. After more than a decade of further observations providing new results on the radius and velocity of the SN shock wave, and the X-ray and radio emission, we update this model to conform to the latest observational data.

CD95 envisioned an HII region stretching from a radius $r_{\text{II}} = 3 \times 10^{17}$ cm until the inner edge of the equatorial ring ($\sim 6 \times 10^{17}$ cm). However, [12] suggests that $r_{\text{II}} \sim 4.5 \times 10^{17}$ cm. Another limit comes from [8, hereafter BG07]. They find that the radio shell was about 0.3 pc across on day 1800. The radio emission was re-detected at about 1200 days, but the turn-on could have been a bit earlier. BG07 further suggest that the initial velocity within the HII region was about 3600 km s$^{-1}$. Extrapolating backwards we find the inner edge of the HII region to be around $4.3 \times 10^{17}$ cm.

In this model the renewed X-ray and radio emission is due to the interaction of the shock with the HII region. The detection of this emission around day 1150 sets limits on the density of the medium in which the shock is traveling, which is the freely-flowing BSG wind, followed by the shocked BSG wind. The density increase of a factor of 4 beyond the wind-termination shock is too small to substantially affect the dynamics of the SN shock, therefore the location of this shock is unimportant for the dynamics. Following [12] we take the wind termination shock to be at a radius $1.5 \times 10^{17}$ cm.

In order for the SN shock to reach the HII region by day 1150, the density of the freely expanding wind must be quite low. Assuming a wind velocity of 550 km s$^{-1}$, consistent with that of CD95 and other authors, the wind mass-loss rate must be about $5 \times 10^{-9} M_\odot$ yr$^{-1}$. We note that this mass-loss rate seems quite low compared to known mass-loss rates of BSG stars. However the density of the wind is tightly constrained, and the wind velocity probably is well known within about 20-30%. Then, unless our estimate of the HII region radius is significantly off (unlikely, given the observational data) the mass-loss rate must be very low to account for the low wind density. A low mass-loss rate ($< 1.5 - 3 \times 10^{-7} M_\odot$ yr$^{-1}$) was also postulated by [1] and [11]. The low density CS wind further reinforces the suggestion (CD95) that synchrotron self-absorption, and not free-free absorption, was responsible for the early radio absorption.

The density of the HII region is not well constrained, although [12] suggests that it is lower than that used by CD95. Constraints arise from the radius and velocity evolution of the shock wave, and the almost linearly increasing X-ray and radio emission. We find that a density profile that increases gradually with radius provides good results. The initial profile that we have adopted for our simulations is shown in Figure 1.

**NUMERICAL SIMULATIONS**

The SN ejecta density is assumed to vary as $r^{-9}$, as suggested by [13]. We take the ejecta profile to be $\rho_{\text{SN}} = 9.3 \times 10^{37} \frac{t_6^5}{r_9} \frac{M_\odot}{\text{yr}}$, following CD95. Assuming spherical symmetry, we have carried out 1D simulations to study the expansion of the SN ejecta into the circumstellar medium (CSM) in the equatorial plane as described above. The simulations are carried out using the VH-1 code, a finite-difference hydrodynamics code.
The parameters of the CSM were adjusted based on the simulation to correctly reflect the observed radius and velocity evolution of the SN forward shock as computed from the radio [8] and X-ray [16] data. Having computed the evolution, we then calculate the hard X-ray and radio emission from the remnant and compare to the observations.

The interaction of the SN ejecta with the freely expanding wind leads to the formation of a forward and reverse shock structure separated by a contact discontinuity (see Fig. 1). The forward shock collision with the wind termination shock leads to a transmitted shock expanding out into the shocked wind, and a reflected shock that moves back into the ejecta [7], overtaking the reverse shock. The transmitted shock reaches the HII region at about day 1150. The impact slows down the shock considerably, and the velocity of the shock transmitted into the HII region drops from $>30,000$ km s$^{-1}$ to about 3500 km s$^{-1}$ (see Fig. 2). The shock-HII region interaction leads to renewed X-ray and radio emission (Fig. 3). Although the shock is slowly sweeping up dense material from the HII region, its velocity increases rather than decelerating (Fig. 2). The reason is as follows: The impact with the HII region results in an abrupt slowing down of the shock from its velocity in the shocked wind region. Once the shock begins to expand into the HII region it will approach another value with velocity much less than what it was in the shocked region, but larger than the velocity on HII region impact. The shock velocity increases after impact until it transitions to this new value.

The transmitted shock collides with the inner edge of the equatorial ring at about 18 years. This leads to a further slowing down of the shock wave (Fig. 2), which loses a significant amount of energy, gradually becoming radiative. The slowing down is reflected in the radio and X-ray data, which indicate that the size of the radio remnant is comparable to that of the inner edge of the equatorial ring. The simulations show the

**FIGURE 1.** The initial SN ejecta and CSM density profile for the simulations.
presence of several reflected shocks and rarefaction waves upon shock-ring impact.

**X-RAY AND RADIO EMISSION**

We compute the hard X-ray emission from our simulations in the range of 1-6 Angstroms, using the CHIANTI database [2, 10]. This emission is presumably arising from the shock-CSM interaction, whereas the soft X-ray emission likely arises from the interaction of the shock wave with the finger-like projections that give rise to the hot spots on the ring. Our results compare well with the data presented in [16]. Fig. 3 shows the evolution of the X-ray and radio emission with time. The hard X-ray emission arises mainly from the reverse-shocked ejecta, behind which the density is low and temperature high. To match the magnitude of the emission correctly we find that the electron temperature must be about 0.03 times the post-shock temperature, consistent with the theory presented by [9]. The forward shock velocity results in a low post-shock temperature, thus its contribution to the hard X-ray emission is minimal.

The radio emission was computed using the Chevalier mini-shell model [5]. We find it difficult to reproduce the approximately linear observed radio light curves [14]. Our best fit model (Fig. 3) is unusual in that it requires either the magnetic field or the relative particle energy density to be constant with time (see [6]). Figure 3 shows that our model also is unable to accurately reproduce the rapid rise seen after day 1150. However we note that the impact with the HII region will result in a reflected shock which can also accelerate particles, likely enhancing the radio emission for a short period [4].

There are undoubtedly shortcomings to a spherically symmetric approach in this case. It is therefore heartening to see that such a simplistic approach reasonably reproduces the shock dynamics and kinematics, and the increasing behavior of the X-ray and radio flux with time. It also lays down a platform from which to proceed to do more complicated multi-dimensional simulations in future, that take the asymmetries of the structure, and the presence of hydrodynamical instabilities, into account.
FIGURE 3. The evolution of the hard X-ray (left) and radio (right) emission from SN 1987A with time. The solid lines in each case is the calculation from our hydrodynamic model, the symbols refer to the data points. X-ray data is taken from [16] and radio data from [14].

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