THE INTERACTION OF SUPERNOVA EJECTA WITH AN AMBIENT MEDIUM

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ABSTRACT

Plausible environments for supernovae are the interstellar medium with constant density or a circumstellar medium built up by mass loss with $\rho \propto r^{-2}$. Self-similar solutions for the interaction region between the expanding supernova gas and the ambient gas exist provided that the expanding gas has $\rho \propto r^{-n}$ with $n > 5$. The circumstellar medium case is likely to be important for the early evolution of Type II supernovae because their progenitor stars are probably red supergiants. The radio and X-ray emission observed from extragalactic supernovae may be from this interaction region. The early self-similar solutions can also be applied to the young galactic remnants.

1. SUPERNOVAE AND THEIR SURROUNDINGS

Models for the explosions of Type II supernovae and for their light curves have shown that these events are likely to be the explosions of massive stars (Chevalier 1976a; Falk and Arnett 1977; Weaver and Woosley 1980). The mass range of the progenitor stars is not well known but is likely to be in some range above about 7 $M_\odot$. These massive stars are expected to undergo different phases of mass loss. While they are on and near the main sequence, they are observed to have stellar winds with velocities of about 2000 km s^{-1} and mass loss rates of about 10^{-6} $M_\odot$ yr^{-1}. Over the lifetime of the star, this wind can create a low density bubble around the star with a radius of about 20 pc (Weaver et al. 1977). When the star becomes a red supergiant (for the last 10% of its life), it continues to lose mass but the wind properties change. The wind has a velocity of about 10 km s^{-1} and a mass loss rate of 10^{-6} to 10^{-4} $M_\odot$ yr^{-1} (e.g. Zuckerman 1980). This slow wind can create a relatively high density region around the star with a radius of $1(v_w/10 \text{ km s}^{-1})(\tau_{rg}/10^5 \text{ yr})$ pc, where v_w is the wind velocity and τ_{rg} is the lifetime of the red supergiant phase. It is at the end of this phase that the star explodes as a supernova.

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The density structure of the expanding gas in a Type II supernova depends on the structure of the progenitor star. If the stellar envelope has a flat density distribution, a shell is ejected (Chevalier 1976a). On the other hand, Weaver and Woosley (1980) calculated an envelope structure with decreasing density ($\rho \propto r^{-1.5}$, see Jones, Smith, and Straka 1981) and most of the ejected envelope had constant density. Outside of the envelope is a region with a steep density gradient. This region has generally been calculated with poor resolution, although Jones, Smith, and Straka (1981) have begun to remedy this situation. They calculated the explosion of the stellar model of Weaver, Zimmerman, and Woosley (1978) and included moderately fine zoning in the outer parts of the star. After the explosion, this region had a steep density gradient ($\rho \propto r^{-12}$). However, computations with better resolution gave a flatter density profile ($\rho \propto r^{-9}$) (Jones 1981). The calculations do not take into account the effect of mass loss on the outer parts of the star; this effect could be substantial.

The question of the progenitors of Type I supernovae is still controversial, although the explosion of a white dwarf in a binary system appears to be favored. In this model, radioactive energy input is responsible for the supernova radiation and several 0.1's - 1 $M_{\odot}$ of Fe are ejected (see papers in Wheeler 1980). During the evolution of the binary system, there may be mass loss but it is not known what form this mass loss takes. Another suggestion for the progenitors of Type I supernovae is that they are single stars with masses in the range 4-6.5 $M_{\odot}$ (Tinsley 1979). In this case, the nature of the star at the end of its life and the nature of the explosion are similar to the properties of Type II supernovae.

The density distribution of expanding gas in the exploding white dwarf model for Type I supernovae is different from that expected for Type II supernovae. In the Type II supernovae, all the energy is released by the core collapse at the center of the star. In an exploding white dwarf, the energy is released as a detonation or deflagration wave propagates through the star. Thus the central matter is accelerated by a relatively weak wave and does not achieve a high final velocity. The result is that a shell is not ejected, but a density profile with the highest density towards the center. Colgate and McKee (1969) found that the density profile could be approximated by a constant density for the inner 4/7 of the mass and by $\rho \propto r^{-7}$ for the outer 3/7 of the mass. This density profile is in accord with Type I supernova light curves near maximum light (Chevalier 1981).

2. THEORY OF THE INTERACTION

From the preceding discussion, the expansion of the supernova ejecta into two types of media is of interest: the interstellar medium and a circumstellar medium built up by mass loss. The interstellar medium is assumed to have constant density because the sizes of young supernova remnants are smaller than the typical distances between clouds. If the circumstellar medium is created by a stellar wind, $\rho \propto r^{-2}$ is expected.

Circumstellar gas may also be in the form of ejected shells.

Initial work on the interaction of supernova ejecta with a constant density interstellar medium used numerical, finite-difference hydrodynamic methods. Gull (1975), Itoh (1977), and White and Long (1982) presented detailed results for the interaction of constant density, uniformly expanding ejecta with a uniform medium. Their calculations assumed that the ejecta had expanded to a certain radius and had density ρ_i when the interaction with the ambient medium of density ρ_a began. The interaction created a reverse shock wave in the ejecta (e.g. McKee 1974) which initially gave a density $4\rho_i$ at the contact discontinuity. The density at the reverse shock front decreased with time because of the uniform expansion of the ejecta and the density at the contact discontinuity decreased because of adiabatic expansion. A dense region of shocked ejecta formed at the contact discontinuity. The high density was accompanied by a low temperature so that this region was very important for the emission of soft X-rays (Itoh 1977). However, the properties of this region were dependent on the choice of initial conditions for the calculations through the value of ρ_i/ρ_a.

A more appropriate choice of initial conditions would be to include the steep density profile expected at the outer part of the expanding supernova. Jones, Smith, and Straka (1981) have carried out such a numerical calculation by computing the explosion of the star as well as the interaction with the uniform ambient medium. This calculation did not show a region of very high ejecta density as had been found in the previous calculations.

A more complete understanding of the interaction of the steep outer density profile with the ambient medium was provided by the realization that this phase could be described by a self-similar solution if the density profile of the expanding gas is a power law in radius (Chevalier 1982a; Nadyozhin 1982). If the ambient density is given by $\rho = A_1 r^{-s}$ and the ejecta density is given by $\rho = A_2 t^{-3} (r/t)^{-n}$, then the motion of the contact discontinuity between the two shock waves can be expressed as

$$R_c = \left(B \frac{A_2}{A_1}\right)^{\frac{1}{n-s}} t^{\frac{n-3}{n-s}}$$

where B is a constant which depends only on n and s. The self-similar solutions exist for $s < 3$ and $n > 5$. For $n = 5$, the outer shock wave expands as $t^{2/(5-s)}$, the expansion law for a point explosion (Sedov 1959). The most notable difference between the solutions for $s = 0$ and $s = 2$ is that for $s = 0$, $\rho \to 0$ and $T \to \infty$ at R_c while for $s = 2$, $\rho \to \infty$ and $T \to 0$ at R_c.

All of the self-similar solutions contain density gradients that are subject to the Rayleigh-Taylor. The ultimate outcome of the instability is not known, but some mixing between the ejecta and the ambient medium may occur. The only attempted calculation of the Rayleigh-Taylor instability in supernova remnant evolution is that of Gull (1973). His treatment was one-dimensional and was analogous to turbulent convection. However, it is not clear whether the motion is fully turbulent or whether a particular mode dominates the gas motions. The effects of the instability need further investigation.

The self-similar solutions show that while the reverse shock wave is in the part of the density profile with n substantially greater than 5, the thickness of the interaction region is small compared to its radius. Once it is in the part with $n < 5$, the reverse shock wave propagates toward the center and the outer shock wave tends toward the blast wave expansion law. Chevalier (1982c) examined the interaction of a Type I supernova with an ambient medium with $s = 0$ or 2 on the assumption that the expanding gas has a region of constant density inside of a region with $\rho \propto r^{-7}$ (see section 1). If $s = 0$, the transition time between $n > 5$ evolution and $n < 5$ evolution is $t_c = 0.362\ (M^5/E^3\rho_a^2)^{1/6}$, where M is the total ejected mass and E is the total energy. The approximate transition time between the early self-similar expansion law and the blast wave expansion law for the outer shock wave is $t_s = 4.58\ t_c$. For $t < t_s$, $R_1 \propto t^{4/7}$ and for $t > t_s$, $R_1 \propto t^{0.4}$. The time at which the reverse shock wave reaches $r = 0$ is $t_r = 3.4\ t_c$.

The evolution for $s = 2$ can also be examined. Now $R_1 \propto t^{0.8}$ for $t < t_s$ and $R_1 \propto t^{2/3}$ for $t > t_s$. The reverse shock wave proceeds slowly toward $r = 0$ because the pressure drops to 0 at the center of the blast wave solution. A general difference between $s = 0$ and the $s = 2$ density profiles is that the density is more strongly peaked at the outer shock wave for $s = 0$.

3. TYPE II SUPERNOVAE

The discussion of section 1 indicates that the early evolution of Type II supernovae should involve the interaction of the supernova ejecta with circumstellar gas built up by the slow wind from a red supergiant star. Chevalier (1982b) suggested that the radio emission observed from extragalactic Type II supernovae (Weiler et al. 1982,1983) is a result of this interaction. The observed radio flux can be produced if the ratio of relativistic electron energy density and magnetic energy density to thermal density is comparable to that required to produce the radio emission from the Cas A supernova remnant. The Rayleigh-Taylor instability may play a role in the production of these energy densities (e.g. Gull 1973). In SN 1979c and SN 1980k, the radio emission was observed to have a delayed turn-on and the delay was longer at low frequencies (Weiler et al. 1982,1983). This delay can be attributed to free-free absorption by the unshocked circumstellar gas. In that case, the mass loss rates from the progenitors of SN 1980k and SN 1979c were about $10^{-5}\ M_\odot\ yr^{-1}$ and $5 \times 10^{-5}\ M_\odot\ yr^{-1}$ respectively, if the velocity of the winds was 10 km s^{-1}.

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The interaction of the expanding supernova gas with the circumstellar medium can create hot gas that radiates at X-ray wavelengths. In fact, SN 1980k was observed as an X-ray source (Canizares, Kriss, and Feigelson 1982). The solutions described in section 2 with $s = 2$ can be applied to this situation and the observed X-ray flux is close to that expected (Chevalier 1982b). The thermal emission is dominated by that from the region of shocked ejecta which has a higher density and lower temperature than does the region of shocked circumstellar gas. Another possible source for the X-ray emission is the inverse Compton mechanism. X-ray spectroscopy is needed to distinguish between these two mechanisms.

The circumstellar gas responsible for the radio and X-ray emission may also be responsible for infrared emission at late times (about one year after maximum light) through radiation of the supernova light by dust (e.g. Bode and Evans 1980). In fact, the late infrared emission from SN 1979c and SN 1980k may be consistent with the presupernova mass loss rates deduced from the radio observations (Dwek 1982). If this interpretation is correct, the high rates of presupernova mass loss apply out to about 10^{18} cm from the star. Under these circumstances, the radio emission should decline slowly over a period of about 30 years and should not show a sudden decline in the near future. The ratio of the timescale for the radio emission to that for the infrared emission is approximately equal to the ratio of the speed of light to the supernova shock velocity. By combined observations of Type II supernovae at various wavelengths (including the ultraviolet), it should be possible to deduce a detailed model for the interaction with circumstellar matter and to determine whether the other emission mechanisms, like a pulsar (Pacini and Salvati 1981; Shklovsky 1981), are important.

The observed radio supernovae have a range of luminosities, which can be attributed to a range of presupernova mass loss rates. Stellar observations do indicate a large range of mass loss rates and the occasional star with a very high mass loss rate might be expected to yield a very luminous supernova. The radio source 41.9 + 58 in M82 may be such an object; its properties have been reviewed by Kronberg, Biermann, and Schwab (1981). The source was observed for over a decade and was found to be decreasing in flux with an e-folding time of 12 years. Its spectrum had a low-frequency turnover at about 1 GHz. These properties can be approximately reproduced by the circumstellar interaction model if the supernova was about 10 years old when it was first observed and the presupernova mass loss rate was 4×10^{-4} $M_\odot$ yr^{-1}. Scaling from the observed radio luminosities of SN 1979c and SN 1980k gives about the correct radio luminosity for 41.9 + 58. One possible problem is with VLBI observations of the source. Geldzahler et al. (1977) found a source size of $\sim 0\farcs0015$, which is too small to be compatible with the supernova model. However, Shaffer and Marscher (1979) found a size ten times larger at a lower frequency. If this size applies to the source and is not the result of scattering, it is compatible with the supernova model. Further VLBI observations should provide the best test of the model. It would be particularly valuable to measure the expansion of the source.

Griffiths (1979) has found that 41.9 + 58 is an X-ray source with a luminosity of $\sim 10^{39}$ ergs s^{-1}. The model of section 2 would give a substantially greater X-ray luminosity from the shocked ejecta. However, in this case the supernova would have interacted with several $M_{\odot}$ of circumstellar gas and the reverse shock may no longer be in the steep part of the supernova density profile. This could reduce the thermal X-ray luminosity to an acceptable level.

After an expanding Type II supernova has swept up the circumstellar matter from the red supergiant wind, it may expand into a low density region created by the earlier, fast stellar wind. If SN 1054 was a Type II supernova, its remnant may be in this phase. This would explain te absence of thermal X-ray emission (Schattenburg et al. 1980) and radio emission (Wilson and Weiler 1982) in a shell and the presence of a fast optical shell (Murdin and Clark 1981; Henry, MacAlpine, and Kirshner 1982). The X-ray and radio emission require interaction with an ambient medium, while the optical emission can be the result of photoionizing radiation from the central Crab Nebula.

4. TYPE I SUPERNOVAE

The three historical galactic supernovae SN 1006, SN 1572, and SN 1604 can plausibly be classified as Type I events, although the evidence is weak for SN 1006 (e.g. Clark and Stephenson 1977). All of these supernovae created remnants which are fairly strong X-ray emitters (Pye et al. 1981; Reid, Becker, and Long 1982; White and Long 1982), which implies that they are interacting with moderately dense gas. Although there are uncertainties due to non-equilibrium ionization and heavy element overabundances, White and Long deduce an ambient hydrogen density $n_o > 0.1$ cm^{-3} for the SN 1604 remnant. This density is higher than might be expected for the ambient interstellar medium, especially because the remnants are some distance from the galactic plane. This has led to the suggestion that the remnants are interacting with circumstellar mass loss (White and Long 1982; see also Fabian, Stewart, and Brinkmann 1982). The required amount of mass loss would be similar to that believed to occur in the progenitors of Type II supernovae (although somewhat more extended) and would be consistent with the moderately massive single star hypothesis for the progenitors of Type I supernovae.

Chevalier (1982c) checked on the circumstellar versus the interstellar model for the Type I remnants using the theory described in section 2. A powerful discriminant between the models is the exponent m in the expansion law $R_1 \propto t^m$. For s = 0, m is expected to be between 0.4 and 0.57, and for s = 2, m is expected to be between 0.67 and 0.8. For the incomplete optical shell of the SN 1572 remnant, m is observed to be 0.38 ± 0.01 (Kamper and van den Bergh 1978) and for the complete radio shell, m is 0.47 ± 0.05 (Strom, Goss, and Shaver 1982). The optical emission is likely to be from the outer shock front and the radio shell expands in the same way as the optical shell where they overlap. The optical filament in the remnant of SN 1006 expands with m = 0.47 ± 0.07 (Hesser and

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van den Bergh 1981). In both cases, evolution in a medium with $s = 0$ is implied. Further evidence for this type of evolution comes from the fact that some of the radio and X-ray emission is concentrated toward the outer shock wave in all three elements.

If the progenitor of Type I supernovae do have dense winds, extragalactic Type I events may be observable as radio sources. Radio observations of SN 1981b have been attempted for a year now and it has not been detected (Weiler et al. 1983). Current observations are consistent with interaction with the interstellar medium and imply that an interstellar density $n_o \geqslant 0.1\ cm^{-3}$ is fairly pervasive. If $n_o = 0.1$, then the remnants of SN 1572 and SN 1604 are in an early evolutionary stage. The reverse shock wave should be close to the dividing point between the steep and the flat supernova density gradient and much of the ejecta may not yet have been shocked. This situation provides a possible explanation for the lack of strong X-ray Fe line emission from the Type I remnants (Becker et al. 1980; Arnett 1980).

5. DISCUSSION

The properties of young supernova remnants are generally consistent with the properties of the initial supernova events. Type II supernovae probably initially interact with circumstellar gas from presupernova mass loss and Type I supernovae probably interact directly with the interstellar medium. There may be other stellar explosions in which the entire envelope is lost in presupernova mass loss and the result is neither a Type I nor a Type II supernova. The Cassiopeia A explosion may have been such an event (Chevalier 1976b). There are now several remnants with similar properties to Cas A; a particularly remarkable one is the source in NGC 4449 (Blair et al. 1983).

The interaction with circumstellar material implies that the young remnants of massive star explosions can be quite luminous at radio and X-ray wavelengths. The VLA (Very Large Array) is well suited to detect these objects. Its high spatial resolution allows it to pick out compact, high brightness temperature sources. Studies of regions of star formation, such as that of Sramek (1982), are expected to reveal young remnants. Once radio positions are known, further studies at X-ray and optical wavelengths will be valuable.

High resolution radio and X-ray studies of the galactic remnants make possible not only analyses of the current structure of the remnants, but also allow the measurement of structural changes in time. As discussed in section 4, these studies are crucial for determining the type of evolution that the remnant is undergoing. Finally, it is clear that X-ray spectroscopy with high spatial resolution will play an important role in distinguishing the shocked ejecta from the shocked interstellar medium.

With regard to the theory of the interaction of ejecta with an ambient, most features of the one-dimensional evolution are now clear. The largest uncertainty in the dynamical evolution is the role of the Rayleigh-Taylor instability, which may be responsible for a widening of the shell of ejecta, for the creation of clumps, and for mixing of the ejecta with the ambient medium. At present, the theory of the Rayleigh-Taylor instability in the nonlinear regime is in a rudimentary state. Further progress will probably require the use of two-dimensional numerical hydrodynamic calculations with high resolution.

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DISCUSSION

MATHEWSON: If the circumstellar gas lies in a plane, how much does this affect your model?

CHEVALIER: My model does assume spherical symmetry. If the gas is concentrated toward a plane, the shock wave would be retarded in the plane. Two-dimensional hydrodynamic models would be required for the dynamics. The mass loss rate deduced from the radio absorption would not be correct and the observed properties of a supernova would depend on the viewing angle.

WEILER: Two comments: (1) From IR results you predicted that Type II radio supernovae may be visible for up to 30 years. However, from observations the Type II SN 1980k is already decreasing strongly in the radio at age 2 years and there is very strong evidence from observations that no extragalactic SN remains as strong as Cas A for more than 5-10 years. (2) You suggested that Type I supernovae may also be radio sources. Our present limit on Type I SN 1981b is ~ 60 μJy (1σ) and no detection.

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CHEVALIER: (1) My model does predict a slow decrease in radio flux. The recent radio data should be compared with the model to see if there is a contradiction. If so, the interpretation of either the radio or the infrared data will need to be modified. The source 41.9 + 58 in M82 may be in the intermediate age range. (2) The lack of radio emission is consistent with the lack of a dense circumstellar medium around Type I supernovae.

HEIDMANN: With respect to possible future observations of compact sources with the VLA, Dave Heeschen and I just observed at 6 cm a non-nuclear variable source in the clumpy galaxy Mkn 297. It increased by a factor of 3 in 27 months and is now 20 times stronger than SN 1979c in M100. In addition to being possibly related to very powerful SN events, it is the first example of a non-nuclear compact variable very strong radio source.

CHEVALIER: I believe that Type II supernovae can have a wide range of radio luminosities. However, a slow increase in flux is not characteristic of supernovae.

MCKEE: In the case of SN 1006, you suggested that the reverse shock has propagated farther than in the case of SN 1572 and SN 1604. Where is the X-ray emission from the reverse shocked gas in SN 1006?

CHEVALIER: The greater evolution of SN 1006 is based on the assumption that all the young Type I remnants are expanding into a medium of the same density. This is not necessarily the case. Recent ultraviolet observations of a star that may be behind the SN 1006 remnant show evidence for cool rapidly expanding Fe.

TUFFS: Just a short point of information: The ratio of the shock velocity deduced from radio proper motion observations to the average velocity of expansion of the remnant is 0.44. This would place Cas A nearer the s = 0 than the s = 2 density law for its circumstellar medium.

DENNEFELD: You conclude that Type I SN are essentially interacting with the interstellar medium rather than circumstellar one, based on SN 1006, 1572 and 1604. I thought that there was evidence in Kepler of the contrary (high density and nitrogen overabundance in the shocked material)?

CHEVALIER: Kepler's supernova is evidently interacting with small clouds but I believe that they have a small volume filling factor and that the overall dynamics is probably determined by the interaction with the interstellar medium.

FEDORENKO: All the observed SNR are produced by the SN explosion into ISM or into the region of stellar wind. The density is $n \gtrsim 0.1\ cm^{-1}$. But it is well known that most of the volume of our Galaxy consists of a hot ($T \sim 10^6\ {}^oK$), dilute ($n \sim 3 \times 10^{-3}\ cm^{-3}$) plasma. What will be the result of explosion of SN into such a coronal ISM?

CHEVALIER: The expansion of a remnant into the hot medium should be faint at radio and X-ray wavelengths until the remnant begins to interact with clouds. However, the question of whether the hot medium occupies most of the volume of the Galaxy is still controversial.

COX: Why do we not see the several young remnants which "should have" been generated in the last few hundred years, using either radio or X-ray techniques?

CHEVALIER: If remnants are interacting with a low density medium, as could be created by a fast presupernova wind, they may be faint at radio and X-ray wavelengths.

SHAPIRO: Comment concerning the chances of "seeing" in radio or X-rays of a new supernova remnant in our Galaxy: This is a reasonable question, especially in the light of G. Tammann's extimate of the supernova frequency in our Galaxy. To within a factor of two, he puts this frequency at ≈ 8 per century. Given the obscuration by dust of most supernova events in the Galaxy in the optical channel, should we nevertheless have detected such an event in radio or X-rays? It seems to me not surprising that we haven't if we consider that the effective history of radio astronomy is only 3 or 4 decades, and that of X-ray astronomy is hardly 2 decades.

MURDIN: If you just look at the Poisson statistics of events occurring a few times per century and then put in light travel times from the events across our Galaxy, then gaps of three hundred years are not uncommon. Supernova bunch together and long gaps occur between bunches. Unseen young SNR may be unseen simply because none have happened recently.