THE EARLY EVOLUTION OF SUPERNOVA REMNANTS

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Abstract: The density distribution of the supernova ejecta and that of the surrounding medium are the most important parameters for the early evolution of supernova remnants. The distribution of the ejecta depends on the detailed hydrodynamics of the explosion, but the outer parts of a supernova can probably be represented by a steep power law density distribution with radius. Self-similar solutions are especially useful for modeling the interaction of a supernova with its surroundings. The supernova first interacts with mass loss from the progenitor star. Evidence for circumstellar interaction is present in a number of extragalactic supernovae, including SN1987a. The explosions of massive stars probably interact with circumstellar gas for a considerable time while Type Ia supernovae interact more directly with the interstellar medium. X-ray spectroscopy is a good diagnostic for the physical conditions in young supernova remnants and for the composition of the supernova gas.

1. Introduction: The early evolution of supernova remnants is determined by the nature of the supernova explosion and the properties of the ambient medium. The interaction between them involves shock waves and gas dynamical processes. This review will concentrate on developments since 1982, the time of I.A.U. Symposium No. 101 (Danziger and Gorenstein 1983). Energy input by a central pulsar will not be considered here. Section 2 discusses the expansion of supernovae, with an emphasis on the density and composition structure. Hydrodynamic features of the interaction are discussed in section 3; self-similar solutions are especially useful in this area. Interactions with circumstellar gas and with interstellar gas are presented in sections 4 and 5 respectively. The conclusions are in section 6.

2. Supernova Expansion: Supernovae are observationally divided into two major classes depending on whether hydrogen lines are absent (Type I) or present (Type II) in their spectra. It has recently been realized that there are two categories of Type I events. The Type Ia events are associated with an old stellar population and have strong Fe line emission in their late spectra while the Type Ib supernovae are associated with a young stellar population and have lines of O and other intermediate elements in their late spectra (Kirshner and Oke 1975; Gaskell et al. 1986; Filippenko and Sargent 1986).

The most successful theoretical model for Type Ia supernovae is the carbon deflagration of a white dwarf (Chevalier 1981; Sutherland and

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Wheeler 1984; Nomoto, Theilemann, and Yakoi 1984). This model can generally reproduce the light curves, early time spectra, and late time spectra (Axelrod 1980) of the supernovae. The models of Nomoto et al. (1984) are particularly detailed with regard to the composition and density structure and their model W7 has been used to model the observed spectra of Type Ia supernovae (Branch et al. 1985). The result of this work is that mixing of the intermediate element layers with velocities above 8000 km s^{-1} significantly improves the spectral fit. The density structure of the gas in the free expansion phase is complex because of the partial incineration of the gas. The process that mixes the gas may also smooth some of the dense features in density profile.

The mechanism that is responsible for the probable mixing is not known. However, the two-dimensional carbon burning calculations of Muller and Arnett (1986) are suggestive of the complex motions that can accompany the propagation of a burning front. They find that the burning creates hot bubbles that are Rayleigh-Taylor unstable and result in a corrugated burning front. It is not clear to what extent the numerical resolution plays a role in the calculated structure or whether the flow becomes fully turbulent.

The class of Type Ia supernovae is quite homogeneous and it has been difficult to definitively identify differences between specific events. Spectra of SN1986g have settled this question. The λ6355 line, identified with Si II, shows more rapid evolution in wavelength than did the same feature in spectra of SN1981b (Phillips et al. 1987). This is suggestive of a flatter density profile in SN1986g. Thus, Type Ia supernovae exploding in identical media are not expected to produce identical remnants.

The observed characteristics of Type Ib supernovae make an interpretation as the explosions of massive stars that have lost their hydrogen envelope attractive (Wheeler and Levreault 1985; Chevalier 1986). These are Wolf-Rayet stars. The deduction that SN1985f ejected at least 5 $M_\odot$ of oxygen (Begelman and Sarazin 1986) is particularly suggestive of this interpretation. Schaeffer, Casse, and Cahen (1987) have shown that the light curves of exploding Wolf-Rayet stars are roughly consistent with those of Type Ib supernovae. The hydrogen envelope can be lost either through massive single star evolution or through mass transfer in a close binary system. Blaauw (1985) has estimated that 18% of early B type stars are in close binaries. One-dimensional models of Wolf-Rayet star explosions show the ejection of layers of heavy elements (Ensman and Woosley 1987). However, the line profile of [OI]λ6300 in the spectrum of SN1985f implies the ejection of oxygen over a broad velocity range of 0 to > 3000 km s^{-1} (Filippenko and Sargent 1986; Fransson 1986a). The origin of this mixing is unknown, but it may be related to the inhomogeneous ejecta observed in the Cassiopeia A supernova remnant. There, some fast moving knots of heavy element gas are observed with heavier elements having higher velocities than lighter elements (Chevalier and Kirshner 1979). This gradient is opposite to that expected in the models.

The explosions of Wolf-Rayet stars are expected to have a range of progenitor masses. The uniformity of Type Ib supernovae, including the radio regime (Panagia, Sramek, and Weiler 1986), is thus a possible problem for the massive star model. The possibility that mass loss from massive stars drives the core toward a common structure is not anticipated in stellar evolution theory.

If a massive star explodes with its hydrogen envelope, the result is a Type II supernova. This is the least controversial of the various supernova models. The explosion is generally expected to occur in a red supergiant envelope, although the recent supernova 1987a shows the possibility of a blue supergiant progenitor. The available evidence points to the explosion of the B3 Ia star Sk-69 202 in this case (Kirshner et al. 1987; Woosley, Pinto, and Ensman 1987).

If the progenitor star has not undergone extensive mass loss, the heavy element mantle gas is effectively decelerated by the envelope. This process is expected to be Rayleigh-Taylor unstable and can lead to mixing of mantle and envelope gas. The spectroscopic study of Type II supernovae in their late phases should lead to information on the density and composition structure of the ejecta.

Numerical simulations of supernova explosions typically show that the outer part of the density profile can be approximated by a power law in radius. A recent example is Arnett's (1987) model for SN1987a which shows an outer profile of the form $\rho \propto r^{-n}$, where n is 8 to 9. Some insight into the production of power law profiles can be gained from self-similar flow theory. Sakurai (1960) found self-similar solutions for the propagation of a shock wave in a medium with $\rho = Ax^{\beta}$ where A and β are constants and x is the distance from the boundary of the star. The solutions are planar, but they should apply to the thin layers at the surface of a star. The solution can be continued into the regime where the gas expands into the vacuum. In the limit $t \to \infty$, the density profile asymptotically approaches a homologous free expansion. It is of the power law form $\rho \propto (-x)^{-(1+\lambda+\beta)/\lambda}$, where λ is an eigenvalue from the self-similar solution. For the adiabatic index $\gamma = 4/3$ and $\beta = \infty$, which is the limit of an initially exponential medium, we have $\rho \propto (-x)^{-6.67}$. Raizer (1964) had already noted that the planar expansion of a shock wave in an exponential medium asymptotically approaches a power law form. For $\beta < \infty$, the power law index is larger in magnitude (Chevalier and Jones 1987).

This solution can be expected to describe the propagation of a strong shock wave through the exponential atmosphere of a star if the density scale height is much less than the stellar radius and radiative losses are negligible. These assumptions should hold for the explosion of a star like Sk-69 202. The initially planar free expansion develops into a spherically symmetric expansion. Conservation of mass shows that this steepens the power law by two powers of radius, to $\rho \propto r^{-8.7}$. This result appears to agree with numerical computations and generally applies for the expansion of an initially exponential atmosphere.

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3. Hydrodynamic Evolution: The result of the supernova explosion is a radial flow in free expansion. The velocity field is given by $v = r/t$ where t is the age of the explosion and the density by $\rho = Bt^{-3}f(v)$ where B is a constant and f(v) is a function that depends on the initial hydrodynamic evolution. The pressure in the expanding gas is negligible because of adiabatic expansion. The pressure and velocity of the ambient medium can generally be neglected because of the high initial supernova velocities and only the density distribution is relevant. Because of these simplifications, self-similar solutions can be very useful in delineating the major features of the interaction. These solutions are calculated for one-dimensional flows. Although two-dimensional flows are expected to be self-similar when the ambient or supernova density can be separated into radial and angular functions, they are not easily calculated because partial differential, not ordinary differential, equations are involved. For spherically symmetric flows, the ambient medium is generally taken to be of the form $\rho \propto r^{-s}$, where s = 0 (interstellar medium) or 2 (circumstellar medium). This circumstellar medium results from a constant velocity wind with a constant mass loss rate.

The first case is a point explosion in a power law medium. Sedov (1959) obtained an analytic solution for this case and noted that the shock radius increases as $t^{2/(5-s)}$. For s=0, the shocked gas is concentrated at the shock front. For s = 2, the solution is particularly simple, with velocity $v \propto r$, density $\rho \propto r$, and pressure $p \propto r^3$. These solutions assume adiabatic postshock flow. In a young supernova remnant, heat conduction will tend to flatten the temperature profile if conduction is not impeded by magnetic fields. Korobeinikov (1956) and Solinger, Rappaport, and Buff (1975) discussed isothermal blast waves. The transport of heat into the shock reduces the shock compression ratio to 2.38 from 4. During the early phases, there is unlikely to be energy equipartition between ions and electrons. Electron heat conduction occurs on a faster timescale than proton conduction so that the electrons may be isothermal with the ions adiabatic. Cox and Edgar (1983) have investigated self-similar solutions in this case and for s = 0 find a shock compression of 3.24. They assume that ion-electron energy equilibrium is achieved in the collisionless shock front. Even if the magnetic field geometry is favorable for the action of heat conduction, it is quite possible that plasma instabilities reduce the mean free paths of the ions and electrons below the Coulomb interaction values. This has the effect of reducing heat conduction.

The other class of self-similar solutions for young remnants includes the shocked supernova ejecta gas as well as the shocked ambient medium. Chevalier (1982) and Nadyozhin (1985) found solutions for the interaction of a power law ejecta profile ($\rho \propto t^{-3}v^{-n}$) with a power law ambient medium. Dimensional analysis shows that the shock waves and contact discontinuity expand as $t^{(n-3)/(n-s)}$. For n = 5, the expansion law is the same as that for the Sedov solution, so for $n \leq 5$ the flow should approach that for a point explosion. For s=0, the density at the contact discontinuity drops to 0 for both the shocked supernova ejecta and the ambient medium while for s=2, the density at the contact

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discontinuity becomes infinite for both media. The density ratio between the shocked supernova gas and the shocked ambient medium increases for larger values of n.

Self-similar solutions with reverse shock waves and isothermal gas have not been found. Bedogni and d'Ercole (1987) have carried out numerical computations of the above case with heat conduction included and two-fluid flow. They find that the flow becomes complex with reverse shocks forming close to the contact discontinuity and thermal conduction driving a broad inner shocked region. Smooth self-similar flows may not exist in this case.

The reverse shock solutions do assume that the expanding supernova gas is smoothly distributed. Some remnants, like Cas A, indicate that the ejecta may be clumpy. Hamilton (1985) has investigated the interaction of clumpy ejecta with an ambient gas for cases similar to the reverse shock solutions discussed above. In order to preserve self-similar flow, certain assumptions, such as undecelerated clump motion, were necessary. Ablation of the clumps was allowed. If the clumps interacted strongly with the ambient medium, the solution for smooth flow was recovered. For weaker interaction, the clumps moved out ahead of the shock front in the ambient medium. This type of behavior is qualitatively expected.

The above reverse shock solutions assume a relatively steep power law density profile. Hamilton and Sarazin (1984a) have found self-similar solutions for the initial phases of a reverse shock in a medium with a flat density profile ($n < 1$). The solutions apply to the time when the distance between the reverse shock wave and the edge of the "freely expanding" ejecta is much less than the radius so that the flow is approximately planar. For uniform ejecta, the reverse shock propagates as $z \propto t^{(5-s)/2}$, where z is the distance to the edge of the ejecta if it continued in free expansion. As opposed to the steep power law case, the shocked supernova ejecta have a density peak at the contact discontinuity for both $s = 0$ and $s = 2$. The solutions for the shocked ambient medium resemble those for the steep power law case, although the flow is not exactly self-similar.

For the transition from the early reverse shock flow and for more general density distributions than power-laws in radius, numerical hydrodynamic calculations are needed. Because of the steep density profiles present in the early flows, many computational zones are needed in the one-dimensional calculations to reproduce the self-similar solutions (Jones and Smith 1983; Hamilton and Sarazin 1984a). A number of computations have been carried out on the ineraction with circumstellar matter (Fabian, Brinkmann, and Stewart 1983; Itoh and Fabian 1984; Dickel and Jones 1985). The general expectations for the expansion of a massive star are that it will first interact with the dense wind ejected in the red supergiant phase, it will then approach free expansion in the bubble created by the fast wind lost in the main sequence phase, and will finally interact with the swept up wind bubble shell.

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The interaction with the interstellar medium takes place in a late evolutionary phase. If Type Ib supernovae have Wolf-Rayet star progenitors, the dense wind does not occur close to the stellar surface, but may be present further out from an earlier evolutionary phase. Type Ia supernovae may interact more directly with the interstellar medium.

4. Circumstellar Interaction: There is excellent evidence for interaction with a dense circumstellar wind for the Type II supernovae SN1979c and SN1980k (see reviews by Chevalier 1984a and Fransson 1986b). The evidence includes radio emission from the interaction region for both supernovae (Weiler et al. 1986), infrared dust echoes for both supernovae (Dwek 1983), thermal X-ray emission from the interaction region in SN1980k (Canizares et al. 1982), and the ultraviolet line emission from highly ionized atoms in SN1979c (Fransson et al. 1984). The radio emission is a particularly good diagnostic because the early absorption of the radio emission can be interpreted as free-free absorption by the preshock gas and an estimate of the circumstellar density is obtained. Lundqvist and Fransson (1987) have made a detailed study of the temperature and ionization of the circumstellar gas in the radiation field of the supernova and have been able to reproduce detailed features of the radio light curves. They derive mass loss rates of 12×10^{-5} $M_{\odot}$ yr^{-1} and 3×10^{-5} $M_{\odot}$ yr^{-1} for a wind velocity v_w = 10 km s^{-1} for SN1979c and SN1980k respectively.

There are presently 5 radio supernovae with fairly extensive data, including the rising part of the radio light curve. They are SN1979c, SN1980k, SN1983n (Sramek, Panagia, and Weiler 1984), SN1986j (Rupen et al. 1987), and SN1987a (Turtle et al. 1987). Table 1 lists the supernova type, the time of optical depth at 20 cm, t_{20}, and the circumstellar density given in terms of the presupernova mass loss rate divided by the wind velocity. SN1986j was probably not observed near maximum light and the Type II designation given here is based solely on the presence of hydrogen line emission. Rupen et al. (1987) have suggested a Type V designation. Of the 5 supernovae, only SN1979c and SN1980k show clear evidence for circumstellar interaction outside of

Table 1
Radio Supernovae

Supernova	Type	t_{20} (days)	$\dot{M}/v_w$ ($M_{\odot}$ yr^{-1})/(km s^{-1})	
1979c	II	950	1×10^{-5}	a
1980k	II	190	3×10^{-6}	a
1983n	Ib	30	5×10^{-7}	b
1986j	II	1600	2×10^{-5}	c
1987a	II	2	1×10^{-8}	d

a. Lundqvist and Fransson, 1987
b. Chevalier 1984b; Sramek, Panagia, and Weiler 1984
c. Chevalier 1987
d. Chevalier and Fransson 1987

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radio wavelengths. For SN1983n and SN1987a this is attributable to the low circumstellar density and for SN1986j to the late discovery.

The results show that the winds around SN1979c, 1980k, and 1986j are consistent with the dense slow winds expected around red supergiant stars. The density around the Type Ib event SN1983n is considerably lower, but it roughly consistent with the value expected around a Wolf-Rayet star. A wind velocity of 1000 km s^{-1} and $\dot{M} = 10^{-4}$ $M_\odot$ yr^{-1} leads to a value of $\dot{M}/v_w$ that is a factor of 5 below the estimated value. SN1987a had an even earlier turn-on and was a faint radio supernova, but the estimated value of $\dot{M}/v_w$ is roughly consistent with the density expected around a B3 Ia star like the Sk-69 202 progenitor star (Chevalier and Fransson 1987). The observational estimate is again a factor of a few larger than the expected value. If there is clumping in the circumstellar wind, the observational estimates are reduced.

In the circumstellar interaction model for the radio emission, the radio luminosity at a given age should be correlated with the density of circumstellar material. This is observed. It appears that the circumstellar interaction does give information on the properties of the supernova progenitor.

An exciting development is the possibility of resolving radio supernovae with very long baseline interferometry (VLBI) techniques. The expansion of SN1979c has been measured (Bartel et al. 1985; Bartel 1986) and Bartel (private communication) has estimated that if the expansion follows $R \propto t^m$, then $m = 0.9 \pm 0.1$. The radius and the expansion law are consistent with circumstellar interaction. SN1986j which is currently the brightest radio supernova, has also been resolved by VLBI observations (Bartel, Rupen, and Shapiro 1987). Measurements of the expansion of the radio source should allow the age of the supernova to be estimated.

During the next phase of evolution the supernova may approach free expansion in a low density wind bubble. When SN1979c enters this phase, an accelerated rate of decline of the radio emission is expected. One way to identify supernova remnants in this evolutionary stage would be to search for pulsar nebulae which show little or no evidence for interaction with a surrounding medium. This may be the explanation for "Crabs without shells" which are about equal in number to the Crabs with shells (Becker and Helfand 1987). Of course the Crab Nebula itself is lacking a shell.

Of the young supernova remnants, Cassiopeia A is the most likely to be related to Type Ib supernovae. It has fast moving oxygen-rich gas and is interacting with dense nitrogen-rich circumstellar gas; Fesen, Becker, and Blair (1987) have suggested that the progenitor was a Wolf-Rayet WN star. The problems with the Type Ib identification are that Cas A has recently been found to have fast-moving hydrogen-rich gas (Fesen et al. 1987) and the supernova was probably too faint to be a typical Type Ib event, even if it was observed by Flamsteed in 1680 (Ashworth 1980). Although the presence of hydrogen would appear to rule

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out a Type I supernova, it is perhaps possible that the hydrogen would not have been detectable spectroscopically near maximum light.

An interesting recent suggestion is that Kepler's supernova remnant is the result of a Type Ib supernova. An analysis of the X-ray emission indicates that the initial stellar mass was $\gtrsim 7M_{\odot}$ (Hughes and Helfand 1985), although this is rather uncertain. Bandiera (1987) has argued that the progenitor star was a runaway Wolf-Rayet star from the galactic plane. Proper motion studies of the dense optical knots do imply a high space velocity (van den Bergh and Kamper 1977) and the asymmetry of the supernova remnant may be due to the interaction of presupernova mass loss with an ambient medium (Bandiera 1987).

5. Interstellar Interaction: The physical properties of young supernova remnants are probably best studied by X-ray spectroscopy and there have been a number of recent theoretical studies in this area. The first case to be examined in detail is the X-ray emission from a self-similar Sedov blast wave (Gronenschild and Mewe 1982; Hamilton, Sarazin, and Chevalier 1983). The properties of the emission are determined by two parameters, i.e. $n_o^2 E$ and t where n_o is the ambient density, E is the total energy, and t is the age. The most important property of the flow is that the gas is underionized compared to equilibrium values because ionization timescales can be longer than the hydrodynamic timescales. Since underionization can favor line emission, the X-ray luminosity from a nonequilibrium flow may be a factor of 10 higher than that from an equivalent flow assumed to be in ionization equilibrium.

It is unknown to what extent electrons are heated in collisionless shock fronts so that the amount of heating is often a parameter in theoretical studies (e.g. Hamilton, Sarazin, and Chevalier 1983). Even if collisionless heating does take place in the shock, electrons may be released by ionization in the postshock flow which have not been subject to this heating. Itoh (1984) noted that some fast shocks appear to be moving into a partially neutral medium and that the electrons released from the neutrals in the postshock flow are only subject to Coulomb heating. Hamilton and Sarazin (1984c) noted a similar process for the postshock ionization and heating of a heavy element gas. In either case, it is necessary to take into account two populations of electrons.

Hamilton and Sarazin (1984b) found that the X-ray emission from a variety of self-similar flows can be estimated without carrying out detailed calculations for each case. Two important parameters are an ionization time, τ, which is weighted by a Boltzmann factor and an emissivity parameter, ε, which is a function of radius. Two supernova remnants that have similar values of τ versus ε through the remnant belong to the same structural type. The two basic types are the Sedov type, which approaches a hot, low density medium in the postshock flow, and a type which approaches a cold, high density medium in the postshock flow. The interaction of a steep power law density profile with an $s = 0$ medium is of the first type. The interaction of a steep profile

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with an s = 2 medium and the reverse shock wave for uniform ejecta are of the second type. Two remnants of the same type that have similar values of average τ, average temperature, and total emissivity are expected to produce similar X-ray spectra. The fact that detailed spectra have been calculated for Sedov blast waves makes this method quite useful.

A more general way to calculate X-ray spectra is to solve the time dependent ionization equations along with a numerical hydrodynamic computation (Itoh and Fabian 1984; Nugent et al. 1984; Hughes and Helfand 1985). These calculations can be time consuming, but Hughes and Helfand (1985) have developed a useful matrix method that speeds up the calculation of the ionization equations.

As discussed in the previous section, the explosions of massive stars are likely to interact with circumstellar matter during their early phases. Direct interaction with the interstellar medium is most likely for Type Ia supernovae and Tycho's supernova (SN 1572) and SN1006 may belong to this class. Detailed modeling of the X-ray spectra of these remnants has been carried out by Hamilton, Sarazin, and Szymkowiak (1986a,b). They find that in both cases, the spectra are best fit by models of the second type discussed above, i.e. models with cool dense ejecta. A range of temperatures is needed to give an approximate power law continuum and to produce emission that approximates ionization equilibrium. Hamilton et al. concentrate on models in which constant density ejecta with a sharp edge expand into the interstellar medium. For both supernova remnants, the models can accommodate $\gtrsim 0.5\ M_{\odot}$ of Fe as expected in a Type Ia supernova because the Fe is either unshocked or is at low density. The presence of cold Fe in SN1006 appears to be confirmed by the presence of broad ultraviolet Fe absorption in the direction of the Schweizer-Middleditch star (Wu et al. 1983; Fesen et al. 1987).

The X-ray spectra of Tycho and of SN1006 are very different in that Tycho shows strong line emission while SN1006 does not. Hamilton et al. attribute this to a low density surrounding SN1006 so that its "ionization age" is less than that of Tycho and the ionization has not yet proceeded to the stage which gives X-ray line emission. Kirshner, Winkler, and Chevalier (1987) have recently confirmed this hypothesis by measuring the Balmer line emission from two remnants and using it to estimate shock velocities. SN1006 has a higher shock velocity even though it is an older remnant, which implies it is expanding into a low density medium.

The models of Hamilton et al. appear to be very promising, but they do not allow for the presence of a steep outer power law component to the density profile that is expected from supernova modeling (see section 2). A related problem may be that the expansion rates of the supernova remnants in the models are larger than is indicated by optical and radio observations. A power law region with n somewhat greater than 5 would lead to greater deceleration of the outer shock front. Possible resolutions of these problems are that there is an outer power law region but with a relatively small amount of mass or that clumping of the ejecta plays an important role.

6. Conclusions: Although it often seems as if a separate physical picture is needed for each supernova and supernova remnant, some general trends in the interpretation of these objects are becoming clear. For massive stars, mass loss plays a crucial role both for the supernova explosions and their remnants. Type Ib events may be closely related to Type II supernovae, but have lost their hydrogen envelopes in presupernova evolution. If the explosion of Sk-69 202 as a blue supergiant is related to presupernova mass loss, it may be an intermediate case (Woosley, Pinto, and Ensman 1987). Radio supernovae give good evidence for the expansion of massive explosions into the nearby circumstellar wind. The further evolution may be related to a wind bubble and its associated shell. Current observations of Type Ia supernovae are consistent with direct interaction with the interstellar medium. They are not observed as radio supernovae (Weiler et al. 1986) and the remnants of SN1572 and SN1006 appear to be interacting with the interstellar medium.

With regard to hydrodynamical modeling, spherically symmetric models for the interaction of a supernova with an ambient medium have now been calculated in considerable detail. However, there is the expectation of hydrodynamic instabilities and the observational data show evidence for clumpiness and mixing. It will eventually be important to clarify the three-dimensional evolution of supernovae and their remnants.

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