THE EARLY EVOLUTION OF SUPERNOVA REMNANTS

Claes Fransson
Stockholm Observatory
S-133 00 Saltsjöbaden, Sweden

1. INTRODUCTION

In his review in 1972 Woltjer [1] divided the evolution of supernova remnants into three different phases, the free expansion phase, the adiabatic Sedov phase and the radiative phase, when cooling of the gas becomes important. The first of these was only briefly discussed and little connection between the supernova explosion and the remnant phase was made. The reason for this is also easy to understand in view of the difficulty of determining the type of explosion even for well-known, young remnants like Cas A, Tycho, Kepler and the Crab remnant.

This situation has changed considerably during the last five years or so, mainly due to observations with new instruments like VLA, IUE and Einstein. With these, as well as large optical and infrared telescopes, the information about the supernova explosion and the early evolution of the supernova remnant has increased dramatically, and a more or less new picture of the explosion has emerged. Instead of a free expansion into a virtual vacuum, with few observational consequences, the supernova undergoes a complex interaction with its immediate surroundings, with a wealth of observational information. In this stage both the structure of the supernova ejecta and the circumstellar medium is crucial for the observational properties. Perhaps, the most interesting aspect of it is that we in this way can bridge the gap between the supernova explosion and the remnant stage.

It has also become increasingly clear that the ejecta dominates the emission for many of the 'classical' young remnants, which is in sharp contrast to the Sedov similarity case. These complications are, of course very welcome, since they permit us to extract much more information about the nature of the supernova.

Partly because of my own bias, but mainly because I think that these early stages will become increasingly important in the near future, with the advent of new instruments like the Space Telescope, ROSAT and the VLBA as well as new large optical telescopes, I will discuss these issues in more detail than would have been

https://doi.org/10.1017/S0252921100086061 Published online by Cambridge University Press

done ten years ago. The main emphasis will be on recent observational and theoretical developments in the field. For earlier reviews see [1-6].

2. PROGENITORS AND THE SUPERNOVA ENVIRONMENT

Observationally two types of supernovae can be distinguished. Here I just summarize the main characteristics of these, for a more detailed description see for example [5]. Type I supernovae are characterized by the absence of hydrogen lines, exponential light curves and their occurrence in both elliptical and spiral galaxies. Type II spectra on the other hand, are dominated by strong hydrogen lines, which become increasingly prominent with time, have light curves of less regular shape than Type I:s, often with a plateau lasting about two months and occur only in spiral galaxies. The presence of Type I:s in ellipticals indicate that at least these supernovae must originate from low mass stars ($< 2\ M_0$), while the prevalence of Type II:s to the inner spiral arms [7] indicate a mass larger than ~6 M_0 .

As discussed in the contribution by Woosley in this volume, detailed calculations of the structure and dynamics of supernova explosions have shown that the dividing line between Type I and II supernovae probably occur at 8-10 M_0. Later we will see that most of the observational properties of the interaction between the supernova and its environment depends on the structure of the envelope of the progenitor and the density of the surrounding medium. Evolutionary calculations with no mass loss imply that massive stars end their lives as red supergiants with low surface temperatures and very extended envelopes (10^{14} cm or more). Supergiants in our own Galaxy, however, in general have strong winds with mass loss rates $\dot{M}$, of the order of 10^{-6}-10^{-4} M_0 yr^{-1}, and velocities u, ~10 km s^{-1}. That this can have very strong influence on the properties of the envelope of the supernova progenitor has been found by several groups (see [8] for a review). For massive, luminous stars (more than 20-30 M_0) with high mass loss rates, the star can loose most of its outer hydrogen rich envelope before the carbon burning stage, so instead of ending its life as a red supergiant, it may collapse as a compact, hot Wolf-Rayet star with little hydrogen (radius less than 10^{12} cm). In this case the circumstellar medium is likely to be much more tenuous due to the high wind speed (2000-3000 km s^{-1}).

Direct evidence for a large amount of circumstellar matter around supernovae come from observations of a number of recent supernovae in radio with the VLA. Since the first observed radio supernova, the Type II SN 1979c [9], several others have been discovered [10]. The most interesting feature of these is that the peak of the radio emission occurred a considerable time after the optical maximum. For SN 1979c the delay was about one year at 6 cm and for SN 1980k about 45 days. The radio emission

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was first seen at short wavelengths and later at longer, indicating an optical depth effect.

Pacini and Salvati [11] proposed the exciting idea that the emission comes from the plerionic nebula powered by the pulsar, assumed to be the result of a Type II explosion. A severe problem for this model is, however, the very large optical depth to free-free absorption of the supernova ejecta at these wavelengths, making this interpretation rather unlikely.

A more plausible model was proposed by Chevalier [12], who found that the radio observations could be well explained if the radio emission arises close to the supernova shock wave, as it propagates out through the circumstellar gas around the supernova. The turn-on of the radio emission then occurs as a result of the decreasing free-free optical depth of the circumstellar gas, when the shock wave expands. The optical depth is given by $\tau_{ff} \propto (\dot{M}/u)^2 \; T_e^{-1.5} \; \lambda^2 \; R_s^{-3}$, where T_e is the temperature of the circumstellar gas, R_s the shock radius (estimated from the expansion velocity) and λ the wavelength. This form explains both the rapid turn-on of the emission, as well as its wavelength dependence. If the temperature of the wind is known, this model allows a determination of the quantity $\dot{M}/u$. For a temperature of 10^4 K and a wind velocity of 10 km s^{-1}, a mass loss rate of $5x10^{-5}$ M_0 yr^{-1} is obtained for SN 1979c and $1x10^{-5}$ M_0 yr^{-1} for SN 1980k. The temperature of the wind is, however, likely to be considerably higher due to heating by the shock (Sect. 4b), thereby increasing the derived mass loss rate by approximately a factor of two in these cases. These two supernovae and SN 1970g are the only which have been well-observed in radio, so judging from this small sample, strong mass loss from the supernova progenitor seems to be a general feature of Type II supernovae.

Of the 3 observed Type I:s, 2 have been detected. Although observed for two years, the apparently normal Type I SN 1981b was not detected. Scaling from the other cases, the mass loss rate must have been less than 10^{-7} M_0 yr^{-1} [13]. For the other two, a mass loss rate of $2x10^{-6}$ M_0 yr^{-1} (for a wind velocity of 10 km s^{-1}) was inferred for SN 1983n [14], and the flux of SN 1984l is also consistent with this value [15]. Panagia [13] has suggested that the radio bright Type I supernovae belong to a common class, with the designation Type I_{SL} (SL for subluminous), and could comprise as much as 25-50 % of all Type I:s. The characteristic feature of these is that they occur only in spiral galaxies, are subluminous by 1.5-2 magnitudes and lack the Si I feature at 6150 Å [16]. For this class of Type I:s the most likely origin of the circumstellar gas is not the supernova progenitor itself, but rather its companion star. Cameron and Iben [17] explains the circumstellar gas by mass lost from the binary system in the form of a common envelope surrounding the system.

For the Type II:s, the mass loss rates are at the high end of those observed from red supergiants in the Galaxy, but certainly compatible [18]. It should also be kept in mind that the determined mass loss rates for late type stars have large uncertainties (see discussion in [19]). There is also a number of stars in our Galaxy and in the Magellanic Clouds, which have very high mass loss rates, 10^{-4}-10^{-1} $M_0\ yr^{-1}$, so called super-winds [20]. Most of the stars with these abnormal mass loss rates are, however, very massive and therefore hardly typical for supernovae. Dopita et al [21] have suggested that the narrow component of the Hα line seen in the 1984 Type II supernova in NGC 3169 could have its origin in a wind of this type and estimate a mass loss rate of more than $10^{-4}\ M_0\ yr^{-1}$.

Although a wind is expected from the progenitor, more sporadic, shortlived mass ejections can not be ruled out. These may occur in the carbon burning phase or at later phases, due to shell flashes, similar to those suggested to be responsible for planetary nebulae.

Summarizing this discussion, circumstellar matter can thus be expected around both Type I and Type II supernovae. For Type I:s mainly due to mass loss from the binary system either in the form of a wind from the companion star or due to ejection of a common envelope, and for Type II:s due to a strong stellar wind or sporadic mass ejections in the red supergiant phase. Since the red supergiant stage was preceded by a blue supergiant phase, with a mass loss of approximately the same rate, but with a wind velocity of 2000-3000 km s^{-1}, the density is much smaller and a wind blown cavity in the interstellar medium may be formed outside the slow wind [22]. The interaction of the supernova with its surroundings is therefore likely to be quite complex.

3. OUTBREAK OF THE SHOCK

Since the spectra and light curves of Type I supernovae are discussed in the contributions by Drs. Harkness and Woosley, I will here concentrate on the Type II:s. After the hydrodynamic collapse and subsequent bounce (if this occurs), a strong shock wave is formed in the central region of the star. The exact details are yet controversial (see Woosley, this volume), but the main result for the subsequent evolution is that about 10^{51} ergs of thermal and kinetic energy is deposited outside the iron core. Since neutrino and nuclear dissociation losses will be negligible outside the core, and the streaming velocity of the photons is very small, the expansion of the hot bubble in the center will be essentially adiabatic, with an adiabatic index close to 4/3. The structure of the shock wave at this time has been studied in detail by Weaver [23], who finds that the shock is mediated by scattering of photons by the unshocked gas in front of the shock. The optical thickness, τ_s, of the shock transition is determined by the condition that the diffusion time scale, t_{diff}, over the shock thickness, Δ_s, is equal to the time it takes the shock to transverse this region. Thus we have $t_{diff} = (\Delta_s/\lambda_{mfp})^2\lambda_{mfp}/c = 3\Delta_s\tau_s/c = \Delta_s/V_s$, or $\tau_s = c/3V_s \sim 10\text{-}20$. Here V_s is the shock velocity and $\lambda_{mfp}=1/3\kappa\rho$ is the mean free path for the photons. Since the pressure is radiation dominated, the temperature behind the shock is given by $\sigma T^4 = 9/14\ \rho_0\ V_s^2$ or $T = 0.96\times10^8\ \rho_0^{1/4}V_9^{\frac{1}{2}}$ K, where ρ_0 is the density in front of the shock and V_{s9} the shock velocity in units of 10^4 km s^{-1}. Since the density of the envelope is $\sim10^{-8}$ g cm^{-3} the temperature behind the shock is $\sim10^6$ K. This is much less than that of a gas pressure dominated shock due to the large number of photons available compared to the number of ions. The density jump across the shock is $(\gamma+1)/(\gamma-1) = 7$. Belokon [24] has shown that as long as the ratio of radiation pressure to gas pressure is larger than 4.45, the transition is not a real discontinuity, but rather a continuous transition to the final state.

When the shock comes within a distance equal to τ_s from the photosphere of the star (as defined by the optical depth to electron scattering), the photons start to leak out on the diffusion time scale of the envelope. The subsequent evolution is governed by the recombination of hydrogen and the expansion of the remnant. The detailed form of the light curve closely reflects the density structure, and is therefore a valuable probe of the earlier hydrodynamic history. Here I will not go into any details of the light curve calculation, and just refer to the reviews by Chevalier [25] and Fransson [26], where these issues are discussed in more detail.

The structure of the shock wave close to the photosphere has been subject to some controversy. As the gas in front of the shock becomes transparent to the photons, the radiation will start to leak out and the pressure will gradually become dominated by the gas. As the radiation density decreases, the pre-acceleration of the gas by electron scattering will also decrease and a viscous shock, mediated by ion-ion collisions, may form. The extent to which pre-acceleration is important is, however, not clear and the two calculations, which have treated this situation have reached opposite conclusions. Lasher and Chan [27] found that the photon flux was sufficient to accelerate the gas and no viscous shock formed. This was, however, challenged by Chevalier and Klein [28], who included a more realistic treatment of the radiative transfer. While Lasher and Chan used a diffusion approximation also in the optically thin region, Chevalier and Klein employed a flux-limited treatment, which limits the streaming velocity of the radiation to that of the velocity of light . In their calculation they found that a viscous shock did indeed form, and consequently predicted a burst of hard (kT~10 keV) X-rays, in addition to the soft X-ray photons from the deeper regions. Unfortunately, they only included the flux-limiting in the momentum equation and not in the energy equation, where the

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Eddington approximation was used, although they state that experiments including flux-limiting also in this equation gave roughly the same results. This inconsistency has been criticized by Epstein [29], who argued that when scattering dominates the opacity, as is likely, the acceleration of the gas is governed by energy conservation and that the diffusion approximation should give the same results as a more accurate treatment. His conclusion was therefore that the calculation by Lasher and Chan was to be thrusted. Needless to say, more calculations with high resolution are needed to settle this question.

Independent of whether a viscous shock forms at this stage or not, a velocity gradient close to $v(r) \propto r^{-2}$ will be set up by the diverging beam in the optically thin, extended region due to electron scattering. Because of the negative velocity gradient and the absence of pressure forces, this will steepen into a shock wave at about twice the photospheric radius [30]. Since radiation pressure is then negligible, a viscous ion-collision dominated shock will form. The density of the gas will be large enough for collisions to mediate the shock, as well as to keep the ions and electrons at the same temperature. As the shock expands out into the surrounding gas of lower density, the electrons and ions will eventually not have time to reach equilibrium by collisions. Whether this will still be the case due to plasma instabilities is an open question (Sect. 6b).

4. INTERACTION WITH THE CIRCUMSTELLAR MEDIUM

With the arrival of the shock wave at the photosphere, the remnant phase starts. The evolution of the shock is now determined mainly by the interaction of the expanding supernova ejecta and the circumstellar and interstellar material. Before 1979 this was known as the free expansion phase and was thought to be observationally quite uninteresting, with the decaying continuum emission of the central regions of the supernova as the main characteristic. Both radio and X-ray emission were thought to be too weak to be observed.

With the appearance of SN 1979c in NGC 4321 (M 100), a new development was started, which is still in its infancy both observationally and theoretically. SN 1979c, followed by SN 1980k in NGC 6946 a year later, were close enough to be well observed, not only in radio as was discussed in Sect. 2, but also in the X-ray, UV, optical and infrared. Thus a large amount of observational data of high quality has become available, and in the next sections it will be shown how these can be combined into a fairly coherent picture. The main ingredient is the interaction of the supernova ejecta with the circumstellar medium around the supernova, and the resulting radiative processes. Because of our rudimentary understanding of the Type

I:s, I will mainly discuss the implications for the Type II:s. However, much of what will be said also applies to at least the radio bright Type I:s.

a. Hydrodynamics

The interaction of the rapidly expanding (V_s~10^4 km s^{-1}) supernova ejecta and the, for all practical purposes, static circumstellar medium, will result in a region of shocked gas separating these media, resembling a sandwich. A blast wave will expand out in the circumstellar medium, and the pressure of the shocked gas behind this will drive a reverse shock into the supernova ejecta. This must happen in order to slow down the freely expanding ejecta to the velocity of the decelerating blast wave. A schematic view of the structure is given in Fig. 1. The shocked ejecta and circumstellar gas will be separated by a contact discontinuity, where the velocity and pressure are continuous, but where the density and temperature may be discontinuous. The structure of this region is governed by the equations of mass conservation, momentum and energy together with the Rankine-Hugoniot relations at both shocks. To simplify the treatment, one can instead of the energy equation add an equation of state for the gas. As for shocks in general, there are two limiting cases: If the cooling time of the gas is short compared to the flow time, the gas can be considered to be isothermal in which case the shock is referred to as radiative, and in the opposite case of no cooling it will be adiabatic.

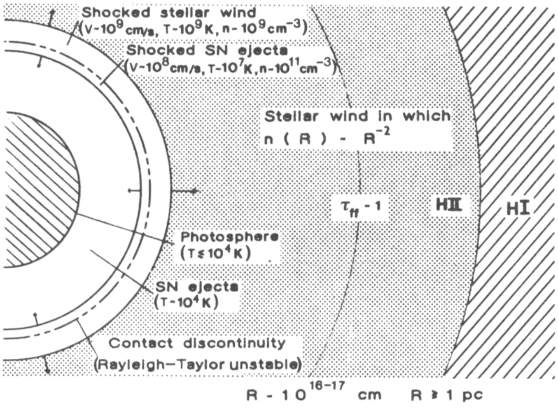

Fig. 1. Schematic structure of the shock region and the circumstellar medium (not to scale). Not shown is the dense, cool region behind the reverse shock and the contact surface. In reality this cool layer is broken up into blobs by the R-T instability. The X-ray flux comes from the reverse shock and the Comptonized UV from the shocked stellar wind.

In the case of both shocks being adiabatic, Chevalier [31] has found a very useful similarity solution under the assumption that the density of the outer layers of the supernova ejecta, into which the reverse shock propagates, can be described by a power law, $\rho(r)\propto r^{-n}$. If the velocity of the circumstellar medium is constant it will also be a power law, $\rho(r)=\dot{M}/(4\pi r^2 u)$, and a similarity solution can be found. Chevalier finds that the the shock radii scale as $R_s\propto t^{(n-2)/(n-3)}$. A simple

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argument, which explains this dependence is given in [26]. The temperature and density structure of the shocked gas is, of course, very sensitive to cooling, which is important, especially for the reverse shock, but also in the initial phases for the blast wave (see below). Also in these cases can similarity solutions describing the structure be found [12,32]. The basic time variation of the variables are, however, the same as for the adiabatic solution, since it is set by the density dependence of the circumstellar gas and supernova ejecta.

b. Radiative processes in the shock region

Starting with the blast wave, the temperature of the shocked gas is $T_s=1.36\times10^9 V_{s9}^2$ K. Most of the cooling of this shock is by Compton scattering of the soft ($h\nu\sim1$ eV) photons from the photosphere by the nearly relativistic electrons behind the shock [30,33]. For small electron scattering optical depths, τ_e, the cooling is proportional to the energy density of the photospheric radiation, but independent of the density, in contrast to cooling by binary collisions. Since the luminosity is decaying and the geometric dilution decreases the intensity, Compton cooling is important only during the first month, after which the shock is adiabatic.

Scattering of soft photons by very hot, thermal electrons is known as Comptonization of the photons, and is important for the spectra of active galactic nuclei and X-ray binaries. In each scattering the photons increase their energy by a factor $\sim 4kT_e/m_ec^2 \sim V_{s9}^2$. The probability of being scattered N times by the electrons is $\sim(\tau_e/2)^N$ (for $\dot{M}/u_1\sim10^{-4}$ and a radius of 10^{15} cm, $\tau_e\sim0.05$). Knowing the redistribution function and the scattering probability, one finds [30] that the Comptonized spectrum is a power law extension to the photospheric flux, $I_\nu \propto \nu^{-\gamma}$, where γ is given by $\gamma=-3/2+(9/4+m_ec^2/kT_e \ln(g(\tau_e)\tau_e/2))^{\frac{1}{2}}$ and $g(\tau_e)$ is of order unity. For typical values of τ_e and T_e, the value of γ is in the range 1.5 - 2.5. Fig. 2 shows the spectrum for $\dot{M}=4\times10^{-5}$ $M_\odot$ yr^{-1} and $V_s=1.25\times10^4$ km s^{-1}, 20 days after the explosion.

In the optical and near UV the photospheric contribution dominates, but in the far UV most of the flux comes from the Comptonized radiation. It is therefore interesting that both SN 1979c and SN 1980k had strong UV excesses shortward of 1500 Å [34,35], consistent with that predicted for the low energy part of the Comptonized radiation.

The most important effect of this component is for the C III-IV, N III-V and Si IV UV emission lines observed with IUE [34,36]. Since the photospheric flux falls rapidly above 13.6 eV, an additional strong source of ionizing photons is

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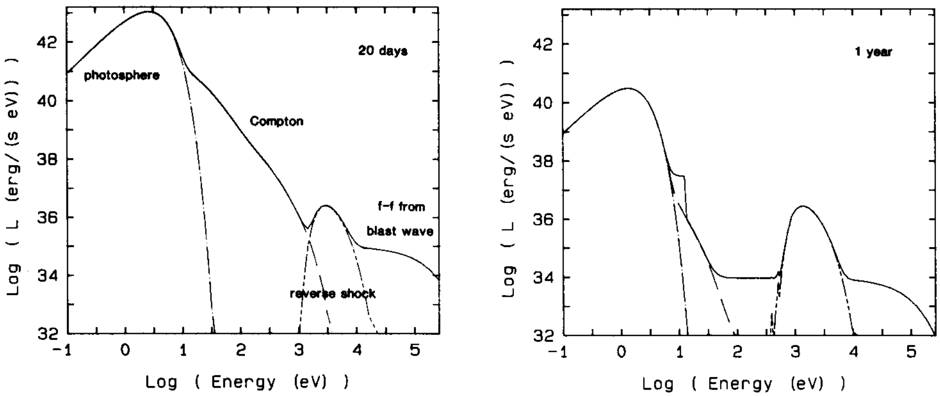

Fig. 2. Spectra from the supernova and the shock shortly after the explosion and one year after. Between 10 eV and 1 keV the Compton flux from the blast wave dominates initially, but decreases after a few months. Note the strong absorption of the X-ray flux from the reverse shock by the cool shell. At late times the ionizing radiation is dominated by this component.

needed to explain the presence of these ions, with ionization potentials of up to 77 eV. Detailed photoionization calculations [37] shows that the strengths of the different lines can be well explained as a result of the part of the Comptonized radiation that is absorbed by the supernova ejecta. In this relatively cool region ($T_e \sim 1.5 \times 10^4$ K), the ionizing radiation is re-emitted as UV line emission, in the same way as in QSO emission line regions. Also the observed time evolution of the luminosity of the emission lines is predicted by the model, since $L_{lines} \propto L_{Comp} \propto \tau_e R_{ph}^2 T_{eff}^{3+\gamma}$, where R_{ph} is the photospheric radius and T_{eff} the effective temperature of the supernova. Since all quantities in this formula can be obtained from the observations, a direct check on the model can be made, and it is found that a very good agreement between observations and theory is obtained.

Another important result, from the relative strengths of the carbon and nitrogen lines is, that N/C~7 [36]. This large overabundance of nitrogen indicates that the gas has undergone CNO processing and has been exposed at the surface due to convective mixing and mass loss, in a similar way as might have been the case for Cas A [38].

A small fraction of the energy of the blast wave is also going into the acceleration of the relativistic electrons responsible for the radio emission. The efficiency of this acceleration is of the same order as that in galactic supernova remnants (a few percent). The way this is done is not known, but both turbulent acceleration and first order Fermi acceleration across the shock are possible. It is worth noting that the spectral indices for the observed radio supernovae are not the

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same, ranging from 0.5 to 1.0. This may indicate that turbulent acceleration is more important, since a range of spectral indices are then expected.

Turning now to the reverse shock, both the hydrodynamic structure and the radiation processes are considerably more complicated due to the higher density and lower temperature. In terms of the stellar wind parameters and density power law index, n, of the supernova ejecta, the temperature and density behind the shock are given approximately by $T_e=1.36\times10^9 V_{s9}^2/(n-3)^2$ K and $n_e=0.5\times10^9(n-4)(n-3)\dot{M}_{-4}u_1^{-1}R_{s15}^{-2}$ cm^{-3} [12]. From this it is obvious that the conditions behind the reverse shock are sensitive to the density gradient in the supernova envelope. Hydrodynamic calculations of supernova explosions find that n~9-12 [39]. The density gradient can also be estimated from observations of the maximum width of the Hα line, if this emission arises in or near the shock region [37]. For SN 1979c a lower limit of n>12 is obtained.

For n=12, the temperature is $1.7\times10^7 V_{s9}^2$ K and density $3.6\times10^{10}\dot{M}_{-4}u_1^{-1}R_{s15}^{-2}$ cm^{-3} behind the shock. At this temperature free-free, bound-free and line emission of highly ionized metals are the most important coolants [40]. When comparing the cooling time with the flow time scale , it is found that for the observed supernovae the reverse shock is cooling for a time of a few months up to several years after the explosion, depending on the mass loss rate and value of n [32,37]. This means that all the energy swept up by the shock ($\sim10^{41}\dot{M}_{-4}u_1^{-1}V_{s9}^3$ erg s^{-1}) is radiated as soft X-rays (hν~2 keV) and EUV emission, and an isothermal shock with a density contrast of 10^3-10^4 is formed. Since the whole shell is decelerating, $V_s \propto t^{-1/(n-2)}$, the contact discontinuity between the shocked ejecta and circumstellar gas is, however, Rayleigh-Taylor unstable (see Fig. 1.). We can therefore expect dense blobs of cool supernova ejecta to be immersed in the hot, shocked circumstellar gas. Depending on the structure of the magnetic field, conduction may be important in evaporating the blobs [41].

Because of the large expected X-ray luminosity from the reverse shock ($\sim10^{4-5}$ times that of a typical galactic remnant), it is interesting to look a bit more in detail at the possibility of observing this [32]. Of the emitted flux half will propagate outwards and half will be absorbed by the ejecta. Since the column density of the cool gas behind the reverse shock is $\sim10^{23-24}$ cm^{-2}, most of the X-ray flux will, however, be absorbed by the cooling gas behind the shock and contact surface (Fig. 2). This situation closely resembles that of quasar emission line regions (see Mathews, this volume), and we expect that most of the X-ray flux will be converted to UV and optical emission, in a similar way to the radiation from the blast wave. Because of the high density ($\sim10^{11-12}$ cm^{-3}) and relatively low flux, most metals will be in their lowest ionization state. The dominant coolants will therefore be the Balmer lines and continuum (the Lyman lines and continuum are in detailed balance), Mg II λ 2800A, Ca II H and K and Fe II, i.e. the lines seen in Type II supernovae. It is thus possible that the shock may contribute an appreciable fraction to the line emission from Type II supernovae. This would be quite consistent with both the increase in strength with time and the nearly constant maximum velocity of the Hα line with time [37].

A different interpretation of the behaviour of the Hα line was proposed by Kirshner and Kwan [42], who explained it as a result of photoionization of the n=2 level of hydrogen by the Balmer continuum and subsequent recombination. It is, however, not clear if enough energy is available in the Balmer continuum at very late times. Another problem is to explain that the Hα line shows a very slow decrease in its width with time, making it necessary for the flux to originate in a shell close to the shock. The model, however, needs more detailed calculations.

An interesting consequence of the cooling of the shocked ejecta is that it may cool to temperatures less than ~2000 K, if the column density is high and the gas therefore shielded from the hard flux. The high density in the clumps will then be ideal for dust formation. An indication that this occurs comes from the profile of the Hα line, whose observed asymmetry may need an internal continuous absorption where the line is formed.

As was remarked above, most of the outgoing X-ray emission from the reverse shock is absorbed in the cool shell behind the shock. The optical depth of this gas decreases with time, since $\tau_X \propto R_s^{-1} \propto t^{-(n-3)/(n-2)}$, so the shell will become increasingly transparent (Fig. 2). The clumpiness of the cool gas, due to the Rayleigh-Taylor instability, may also decrease the absorption. Both SN 1979c and SN 1980k were observed with Einstein [43,44]. No X-ray emission was seen for SN 1979c, although at the time of the observation the X-ray flux should have been detectable. This indicates that the shell was opaque to the X-rays as expected. Also the dense stellar wind may absorb a substantial fraction of the X-rays [30]. SN 1980k was, however, detected with a luminosity of ~2×10^{39} erg s^{-1}, about 40 days after the explosion. This is in agreement with the fact that the expected mass loss rate of SN 1979c was a factor of ~5 larger than for SN 1980k and the absorption correspondingly smaller. The level of the X-ray flux is also close to that estimated theoretically. It should, however, be added that there are other models for the X-ray flux, like the inverse Compton model where the relativistic electrons responsible for the radio emission scatter the optical photons [44,45]. Chevalier [31], however, finds that the estimated luminosity is low by an order of magnitude for this process.

The hard flux from the shocks also influences the circumstellar gas around the supernova, and can have important consequences also for the ionization of the general interstellar medium. This is important to understand both for the mass loss determination, since the derived mass loss is proportional to $T_e^{3/4}$, and for the possibility of seeing UV absorption lines from highly ionized atoms, like C IV, N V and Si IV, in the wind. With the ionizing flux calculated as above, Lundqvist and Fransson [46] have modelled the structure of the circumstellar medium, using a time dependent photoionization code. This is necessary since the recombination and ionization time scales are comparable to or longer than the flow and flux decay time scales. When applied to the parameters of SN 1979c and SN 1980k, it is found that the temperature of the gas outside the blast wave in the initial stages is about 10^5 K and still after a year more than $2x10^4$ K. During the first months the Comptonized UV flux dominates the heating and ionization, but later the hard X-ray flux from the reverse shock takes over (Fig. 2). The high temperatures found means that the mass loss rates of these supernovae have been underestimated by a factor of 2-3, and the derived mass loss rates are $1.5x10^{-4}$ M_o yr^{-1} for SN 1979c and $2.x10^{-5}$ M_o yr^{-1} for SN 1980k (assuming u=10 km s^{-1}).

Another important result is that although the atoms in the wind are nearly completely stripped of electrons, there is even in the initial stages a fraction of 10^{-5}-10^{-3} of the lithium like ions C IV, N V and O VI. The corresponding column densities for a mass loss rate of 10^{-4} M_o yr^{-1} increase from 10^{14}-10^{15} cm^{-2} immediately after the explosion, to a maximum of 10^{17}-10^{18} cm^{-2} after 50-100 days and then slowly decline. Given that sufficient resolution is available, this should easily be observable. In the IUE spectra of SN 1979c there are indeed strong absorption lines due to C IV, Si IV and possibly N V [36], but unfortunately the resolution is not good enough to separate the different components from NGC 4321, the Galaxy and the circumstellar medium. A unique feature of the wind contribution is, however, that it should increase with time. This type of observations should be easy with the Space Telescope, and will provide an important diagnostic of both the radiation from the shock and the velocity and density of the wind. On still larger scales, the ionizing flux from the supernova will lead to the formation of a fossil H II region, which may be present around Cas A [47]. The size of this depends, however, rather sensitively on the assumptions about the flux during the first few days before the discovery, since the total number of emitted photons determines the radius. Also the total amount of mass lost is important.

5. FROM CIRCUMSTELLAR TO INTERSTELLAR INTERACTION

The subsequent dynamic evolution of the remnant depends on the duration and mass loss rate in the various evolutionary phases of the progenitor. In addition, the

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dynamics of the reverse shock is sensitive to the density structure of the supernova envelope. Berman and Kahn [48] have discussed the case of a reverse shock propagating into a uniform density envelope, and finds that cooling may still be important after several years. An interesting possibility is that as the shock propagates deeper and deeper into the ejecta, more metal rich matter is encountered, which increases the cooling, and a radiative shock may persist many years after the explosion. In the same way as was discussed in last section, this may be favourable for the production of dust in this metal rich environment.

The medium into which the remnant propagates can have a quite complicated structure with regions of highly different densities (Sect. 2), and the expansion of the supernova remnant will be correspondingly complex. Itoh and Fabian [49] have modelled this phase hydrodynamically, only taking the wind from the red supergiant into account. While in the wind region, the expansion follows that of Chevaliers similarity solution, but later when the shock reaches the interstellar medium, a second pair of shocks are formed as a result of the expansion into the low density medium. The main aim with their paper, except for studying the dynamics, was to understand the surprisingly high ionization state of iron found in Cas A. This is explained as a consequence of the high temperature and density behind the shock in the early phase. The ionization time scale then becomes small, and iron is essentially fully ionized. Because of the expansion, the gas has not time to recombine, and an over-ionized gas results. Due to numerical difficulties they did not include cooling, which probably modifies the structure of the reverse shock considerably, as argued earlier, but the general features are probably not very sensitive to this.

The duration of the interaction with the circumstellar medium scales with the time scale of the high mass loss phases and can range from a few years up to ~100 years. It is therefore quite likely that many of the young remnants seen in our and neighbouring galaxies are dominated by the interaction with their circumstellar medium, rather than by the general interstellar medium. Examples of this may be the very bright remnant in NGC 4449 and the large number of strong remnants seen in M 82 [50]. That both the radio and X-ray emission can be much stronger than 'standard' young galactic remnants of Cas A type is important to keep in mind, when modelling objects with rapid star formation, like star burst galaxies. Chevalier and Clegg [51] have studied the effects of the energy input from these supernovae on the global dynamics of star burst galaxies, and find that they may create winds and large scale mass transports of enriched material. The interaction of the wind and ambient medium may also result in X-ray emission and streaming motions out from the center.

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6. 'CLASSICAL' YOUNG SUPERNOVA REMNANTS

Most previous work on the structure of supernova remnants have been concerned with the properties at the time when the remnant interacts with the general interstellar medium, where the density is of the order of 1 particle cm^{-3}. Since the standard picture of supernova remnants can be found in many places (e.g. [1,2,52-54]), I will only mention some recent developments in the field.

a. Hydrodynamics.

As is well known, an adiabatic point explosion in the idealized case of a uniform gas is described by the Sedov similarity solution. The main assumption for this to apply, is that the mass of the swept up ambient medium should be much larger than that of the ejecta, so that the remnant has lost memory of the initial conditions. For young supernova remnants, like Tycho, Kepler, SN 1006 and Cas A, it has, however, become increasingly clear that the amount of swept up mass is close to or smaller than that of the ejecta [55,56]. The explosion has then not had time to relax to the Sedov solution and the structure of the ejecta and circumstellar medium will be important. In particular, the presence of a reverse shock propagating into the ejecta may dominate the observed X-ray flux. Although the ejecta structure is highly uncertain, with hydrodynamic instabilities complicating the situation, one can see many of the qualitative features from similarity solutions describing the interaction. This has been studied by Chevalier [57], to discuss the propagation of the blast wave and reverse shock in Type I supernova remnants. The outer parts of the ejecta were assumed to follow the r^{-7} density law found by Colgate and McKee [58] and inside this the density was constant. The size of the remnant is then given by a power law, $R_s \propto t^m$ where m depends on the density gradient of the external medium. Comparing with the observations, Chevalier finds that the expansion into a constant density medium describes the optical and radio observations of Tycho and SN 1006 better than into a gradient, typical of a circumstellar medium, contrary to some models of SN 1006 [59]. This conclusion depends however on the r^{-7} gradient, which probably applies only for a detonation, and may be quite different for a deflagration model [86]. Fabian et al. [60] found that for the case of a Type I explosion in a constant density medium, the reverse shock reached the center when the swept up mass was 19 times that of the ejecta, illustrating that even at late times the structure can differ considerably from the Sedov case. In the case of an explosion in an r^{-2} density gradient, the reverse shock never reached the center.

Another useful similarity solution was found by Hamilton and Sarazin [61], who discussed the interaction of a uniform density ejecta with an a power law, or constant density circumstellar medium. The solution is, however, only approximate,

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since it assumes that the region behind the reverse shock is infinitely thin. The same authors have applied this solution to model the X-ray spectra of SN 1006 and Tycho (Sect. 6d).

In reality the situation will be considerably more complicated, with both ejecta and the surrounding medium clumpy, as is seen in eg. Cas A [62]. The interstellar medium is also known to have an inhomogenous structure with a large range of densities. This may have important consequences, both for the dynamics and for the observed emission. As the blast wave overtakes the dense clouds, it will send a shock through the cloud to bring it into pressure equilibrium. Because of the high density, the shock velocity will, however, be smaller than the blast wave by a factor $(\rho_c/\rho_0)^{\frac{1}{2}}$, where ρ_c and ρ_0 are the cloud and ambient densities [63]. Since the shock velocity is low and the density high, this shock may be radiative and therefore emit strongly at optical wavelengths. In particular, Itoh [64] and Dopita et al. [65] have studied such shocks through clouds of pure metals, with application to the fast-moving knots in Cas A and the oxygen rich remnants in the LMC. Even if the column densities of the clouds are high enough to cool the gas, the cloud may evaporate either due to heat conduction [66,67] or due to hydrodynamic stripping [68].

b. Electron-ion equilibration in the shock.

A major uncertainty in the comparison between models and observations is the temperature of the radiating electrons behind the shock (see [4] for a good review). Depending on the density and velocity of the shock, the ions are heated either due to Coulumb collisions or due to some plasma instability. The need to consider collisionless processes between ions and electrons was realized already by Shklovsky [69]. The exact nature of the instability is unclear and depends on the strength and orientation of the magnetic field. The characteristic length scales for the shock transition are [4] the Coulumb collision scale, $\sim 8.4\times10^{18} V_8^4/n_e$ cm, the ion Larmor radius, $\sim 10^{10} V_8/B_{-6}$ cm, the Debye length, $\sim 6.9(T/n)^{\frac{1}{2}}$ cm, and the ion inertial length, $\sim 2.3\times10^7 n_e^{-\frac{1}{2}}$ cm (here V_8 is the shock velocity in 10^8 cm s^{-1} and B_{-6} the magnetic field in 10^{-6} Gauss). Thus, for a low density plasma the collisional length scale may easily become much larger than the system, and collisionless processes are likely to be important.

Since we observe the radiation from the electrons in the X-rays, either directly or indirectly by collisional excitation, it is the temperature of these, which is relevant for a comparison with the observations. On the other hand, it is the ions which are heated in the shock transition, so the transfer of energy between these two components is important. In the same way as for the ions alone, the exchange of

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energy between electrons and ions is governed by collisions or by various plasma instabilities . Because of the complicated nature of the problem, the electron temperature has mainly been treated in two limiting cases; a minimum temperature determined by ion-electron and electron-electron collisions, or complete equipartition between electrons and ions, $T_e = T_{ion}$. Itoh [71,72] has studied the temperature relaxation between ions and electrons under the assumption of no collisionless energy transfer between these components in the post shock gas, and for the case of an ionized and neutral medium. In the latter case a three fluid treatment is necessary, including plasma heated ions, hot collision heated electrons and cool, newly ionized electrons. In particular, Itoh suggests that the continuum of SN 1006 could be the result of several thermal components of different temperature. Evidence for collisionless energy exchange in supernova remnants come from observations of a hot component ($T_e > 3 \times 10^8$ K) of X-rays in Cas A and Tycho [70]. This temperature is much higher than the maximum due to Coulumb collisions only, $\sim 4 \times 10^6$ K for Cas A, illustrating the need for additional plasma heating.

For the blast wave in the circumstellar medium, the time scale for ion-electron collisions becomes long at a radius ~ $3 \times 10^{15} M_{-4} u_1^{-1}$ cm, and the temperature of the electrons and the shock thickness then depends on the importance of plasma instabilities [46]. Because of the larger density and lower velocity of the reverse shock, collisions are sufficiently rapid to mediate the transition and keep the electrons and ions in equilibrium throughout the evolution, in agreement with the calculation in [49].

c. Non-equilibrium ionization.

The simplest model for the spectrum of a hot adiabatic gas assumes that all processes have time to reach equilibrium, and as long as the gas is optically thin, the observed spectrum will then only be a function of the local temperature and abundances, with a very weak density dependence. The ionization equilibrium is determined by a simple balance between collisional ionization (including autoionization) and radiative plus dielectric recombination. With the abundances of the various ions known, it is then easy to determine the line emission (see eg. [73-75]).

The assumption of ionization equilibrium is, however, quite doubtful for supernova remnants, as has become clear from both observations and theoretical models. As an example, Becker et al. [76] had to use two very different temperature components to fit the X-ray continuum and lines of Tycho, resulting in strange abundances. Also the relative strengths of the forbidden, intercombination and resonance lines in several supernova remnants indicate that ionization equilibrium

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is a bad approximation [77]. From the theoretical point of view, Itoh [78,79] had already earlier reached this conclusion. The reason for the non-equilibrium is that the ionization time scale increases with increasing ionization potential of the ion, and for young supernova remnants the helium and hydrogen like ions have simply not had time to get ionized. As an example we can consider silicon at a temperature of $3x10^7$ K. An equilibrium model would predict that this element is essentially fully ionized and only ~3.7 % is in Si XIV or lower stages. The time scale for collisional ionization at this temperature are, however, ~ $85n_e^{-1}$ years for Si XII, ~$1.9x10^3n_e^{-1}$ years for Si XIII and ~$4.9x10^3n_e^{-1}$ years for Si XIV. Thus for typical densities and for ages less than ~10^3 years, the gas has not time to get ionized beyond Si XIII, which will be the most populated ion. Therefore, the He-like ions will be over-populated and the H-like and fully stripped ions under-populated, in contrast to the equilibrium case. Consequently, both the spectrum and the derived abundances can be affected by several orders of magnitude in some cases.

d. Self-consistent models of remnants.

From the earlier discussion it is obvious that a number of effects and complications have to be taken into account, before a meaningful comparison between observations and models of supernova remnants can be made. In the past a major problem has been the connection between the model properties of the remnants and the assumed properties of the exploding supernova. When models of young objects, like Cas A, Tycho, Kepler and SN 1006, have been calculated using the Sedov solution for the hydrodynamics, and with non-equilibrium effects properly taken into account, these problems have shown up in several ways. In particular, the remnants assumed to originate from Type I explosions have posed severe difficulties: The total mass of the remnants have been far in excess of 1.4 M_o, the mass of the white dwarf assumed to have caused the event [80,81], the abundance of iron has been close to solar (eg. [76]), instead of 25-50% of the total mass, as expected from the models, and there has in general not been any strong indications for nuclear processing.

The theoretical situation has now improved considerably in several of these respects. The main difference of these new models, compared to the earlier, is that the reverse shock propagating into the enriched ejecta is dominating the X-ray emission, instead of the blast wave interacting with the interstellar medium. Since the emissivity of the heavy element gas increases with the metal abundance and the density, this means that a much smaller total mass is required [82].

This interpretation has gained support by the HRI observations of the Tycho remnant by Seward et al. [56]. They identify three components of the X-ray emission, the swept up interstellar gas, a diffuse component of supernova ejecta heated by a

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reverse shock, and a clumped component from the same source. Using non-equilibrium calculations by Shull [83], they derive a mass of 2.2 $M_{\odot}$ for the swept up gas (for solar composition), and 1.9 $M_{\odot}$ for the shocked ejecta. The abundances of the ejecta were those found by Shull [83], enhanced in the Si group elements by a factor 3-8, compared to solar. Thus the mass of the ejecta is quite close to that expected from a Type I supernova. The mass calculated from equilibrium models and a simple Sedov solution is 7-15 $M_{\odot}$ [81], illustrating the sensitivity to the assumptions.

The same type of model has also been suggested by Fabian et al. [59] for SN 1006. This object is peculiar because it lacks appreciable line emission, with a continuum close to a power law, $F_{\nu} \propto \nu^{-1.2}$ up to ~30 keV, suggesting a non-thermal origin [84]. Fabian et al. gives a more conventional thermal interpretation of the spectrum, based on a superposition of free-free emission from a range of temperatures and densities behind the blast wave, giving the observed power law flux. To get the required density and temperature distribution, they suggest that the remnant is expanding into a medium with $\rho \propto r^{-2}$, due to the stellar wind of the progenitor. The low energy emission from the interior is explained by gas heated by the reverse shock to $\sim 10^{6}$ K. To decrease the interior mass, estimated to ~6 $M_{\odot}$ for cosmic abundances [80], they assume that the ejecta consists of ~1 $M_{\odot}$ of pure iron, consistent with a Type I detonation.

A self-consistent model for SN 1006 has recently been calculated by Hamilton et al. [85]. In contrast to Fabian et al., they consider the blast wave to be propagating into a uniform density medium, since a too flat continuum would otherwise result. For the dynamics they use the similarity solution [61], discussed earlier. Although the low energy emission below ~5 keV is due to metal enriched ejecta heated by the reverse shock, a major difference is that the ejecta primarily consist of ~0.3 $M_{\odot}$ shocked carbon instead of iron. This is needed in order to suppress the unwanted oxygen and iron line emission. The outer carbon layer is shocked at an early stage and dominates the emission because of its larger density at that epoch.For this to happen a fairly uniform density profile of the ejecta is required, quite different from the canonical r^{-7} law. Sutherland and Wheeler [86] have, however, found that partial burning of a white dwarf, as in the deflagration model, results in a piling up of unburned material and thus a more uniform density. The iron emission ($M_{Fe} \sim 0.8$ $M_{\odot}$) is largely absent due to the low density of the central regions when it is shocked. This shows that a large amount of iron can be hidden, if a stratified element distribution with iron in the center is assumed. A possible problem of the model is that carbon, rather than oxygen, is supposed to dominate the unburned ejecta, in contrast to most white dwarf models.

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This model has also been applied to the Tycho remnant [85], which differs from SN 1006 in having a rich emission line spectrum in soft X-rays. Also in this case a good fit to the spectrum can be obtained with a mass of 1.4 M_0, of which 0.65 M_0 is in the form of iron in the center. The main difference compared to the SN 1006 model, is the five times larger ambient density, resulting in stronger line emission.

The question of the iron supposed to be produced in Type I supernovae has received new input from a somewhat unexpected direction. Observations by Graham et al. [87] of SN 1983n approximately one year after the explosion, have revealed a strong emission line due to [Fe II] at 1.644 μm. They estimate the total amount of iron to ~0.3 M_0, but this is fairly uncertain both to the atomic data and to the fraction of iron in the form of Fe II, which has to be taken from model calculations. Also Wu et al. [88] claim to see broad absorption lines, due to unshocked Fe II in IUE observations of the SN 1006 remnant.

Taken together, I think that this shows that when all complications are taken into account, many of the earlier problems are solved. The picture also fits more natural into the assumed properties of the Type I explosion. This is, however, not the same as saying that all problems are solved, only that Nature has been more sophisticated than the most simplified models.

There are two well-studied Type II candidates among the young galactic remnants, the Crab and Cas A. Unfortunately, both of these seem to be somewhat peculiar, possibly indicating that this is the normal! Cas A because the explosion in ~1670 was at least five magnitudes fainter than a normal Type II. A likely explanation to this was proposed by Chevalier [89], based on the explosion of a compact Wolf-Rayet star, which had lost its envelope due to mass loss. The adiabatic losses in the explosion, as the ejecta expanded from ~10^{12} cm to 10^{15} cm, when the photon diffusion time scale becomes less than the dynamic, then resulted in a very faint event. The main argument for identifying Cas A with a massive star, is the mass of the remnant. From Einstein HRI-observations Fabian et al. [90] estimate that the mass is in the range 15-20 M_0. They also find that the two-shell structure and the dynamics suggests that it has not yet reached the Sedov phase, and that the outer shell is due to shocked circumstellar gas. Most of the X-ray flux comes from the reverse shock in the ejecta. As has already been discussed in Sect. 5, this picture is also consistent with the over-ionization of iron in Cas A. The very high oxygen abundance found in the fast-moving knots [91], presumably originating from processed core material, is also a strong indication for a massive progenitor.

For the Crab everything seems to be fine, except for one thing. The presence of a neutron star, the very high helium abundance (N(He)/N(H)>0.4 [92,93]), and the relatively low oxygen enrichment [94], all indicate a progenitor mass of 8-10 M_o [95,96]. The problem is, however, that the total mass of the visible nebula is only ~2 M_o [92], so taking into account the mass of the neutron star, ~5 M_o are missing! The question is how this can be reconciled with the observations. The first proposal [97], identifies the observed nebula with the He-rich mantle of the progenitor, including some mixing from the H-envelope, while most of the envelope is too tenous to be seen directly. Because of the large envelope mass, the mantle region is decelerated in the explosion. This leads to a reverse shock slowing down this region, which later forms the inner nebula, and most of the kinetic energy is transferred to the envelope. The expansion velocity of the unseen envelope should then be ~5000 km s^{-1}, the outer radius ~5 pc and the density ~0.3 cm^{-3}. The other possibility [95], is that the progenitor lost most of its envelope due to mass loss in the red supergiant phase. This requires, however, some fine-tuning since a reasonable fraction of the envelope must be left at the time of the explosion, in order to produce a bright event (cf. Cas A). Another possible problem is that the calculations by Maeder [98] show that only for masses larger than ~20 M_o does mass loss have an appreciable effect. This conclusion is, however, based on rather uncertain assumptions about the mass loss in the various phases, in particular during the last phases before the explosion.

Observationally, Murdin and Clark [99] claim to see an Hα halo around the inner nebula, with a flux consistent with that predicted by Chevalier. Whether this really comes from the envelope gas is , however, not clear since there is also the possibility that it may be due to scattered light from the inner nebula by surrounding dust. In X-rays there is some weak evidence for a halo [100], but also in this case it may be due to dust scattering. Radio observations by Wilson and Weiler [101] fail to give any evidence at all for a halo. A new possibility to settle this question, which should be free from the scattering problems, may be through observations in the UV resonance lines of C IV and N V [102]. Using a time dependent photoionization code to calculate the ionization history of the assumed halo, it is found that it should be observable as broad absorption throughs in these resonance lines. The Space Telescope should be a suitable instrument for this type of observation. Also for other young remnants it may be possible to probe the interior and surrounding regions in this way.

Acknowledgement: I am grateful to Roger Chevalier, Peter Lundqvist and Nino Panagia for interesting discussions on the various aspects of supernovae discussed in this paper.

https://doi.org/10.1017/S0252921100086061 Published online by Cambridge University Press

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DISCUSSION

WOOSLEY: 1. Is it possible to infer the time history of the mass loss from the observations you described. Specifically, is there evidence for or against it being episodic. 2. What is the terminal velocity of the dust forming layer. Will it stay in the Galaxy?

FRANSSON: 1. There are small amplitude fluctuations in the radio emission, which may be due to non-uniformities in the wind. Since the shock has traversed a distance corresponding to $V_{shock}/V_{wind}xt$ of the original wind, a time of 6 years corresponds to 6000 yrs, if the outflow velocity is 10 km s^{-1}. The ejections you found for a 10 $M_{\odot}$ model due to Ne shell flashes lasted too short time, but other instabilities may be possible in the late phases. There is some evidence for a decrease in the flux, compared to the model prediction for SN 1979c after about 5 years. 2. The gas to dust coupling is probably quite strong and should prevent the dust from escaping.

ÖGELMAN: Why have you dismissed the existence of circumstellar material around Type I SN:e. If we go along with the idea of a white dwarf in a binary system, there should exist ample circumstellar material.

FRANSSON: That is correct, and in addition the companion may have strong mass loss. In fact, the model by Chevalier explains the gas seen in the radio as originating from a companion red supergiant.

KLEIN: I would like to comment on the work of Klein & Chevalier concerning the hard burst of promt radiation due to an ion viscous shock. The work that we did showed both a soft X-ray burst, followed within a short period by a hard. The hard burst would have < 1% of the flux of the soft burst, making its direct detection difficult. I am re-doing the calculations with a highly accurate angle-dependent transport calculation, that does not make any flux-limited diffusion assumptions to settle the issue concerning the existence of the hard burst brought upon by the application of flux-limited diffusion into the momentum equation.

FRANSSON: Since the initial X-ray burst may be important for the ionization and heating of the circumstellar and interstellar gas, it is desirable to understand the initial stages as well as possible, and it is nice to hear that you are trying to settle this problem. I guess, however, that the exact structure of the envelope may also be very important for the resulting flux and temperature of the radiation in the initial stages, and the fact that the outer envelope is probably not hydrostatic has to be taken into account.

KLEIN: Concerning the instability in the expanding type II envelope, Chevalier and I have shown that a Rayleigh-Taylor instability sets into the envelope as the shock wave moves out of the envelope and a rarefaction wave moves back toward the center of the star. The rarefaction wave sets up an inverse pressure gradient to the density gradient and thus the conditions for the R-T instability are realized. Our 2-D calculations have demonstrated that the envelope begins to break up and an inhomogenous clumped shell gets ejected into the circumstellar medium.

FRANSSON: Whether or not the R-T instability sets in I think is fairly sensitive to the structure of the progenitor. Weaver and Woosley only found some local instabilities in their calculation. Even if the instability sets in I do not think that the basic features of the interaction will be very different, as long as the shell is not broken up into small fragments isolated from each other.

BANDIERA: I would like to point out that the nature of the instability is likely to be different from Klein's. From linear calculations one can in fact show that convection grows much faster than the R-T instability.

FISHER: How does the R-T instability effect the structure of the material behind the reverse shock? Can the instability effect the stability of the shock itself?

FRANSSON: As I mentioned in the talk, the instability in the cooling gas behind the reverse shock could give rise to filaments and blobs of cool gas mixed with the hot gas from the blast wave. Heat conduction may be important in evaporating the blobs.

ICKE: What happens to the fragments depend on their density and therefore their deceleration behaviour. If the shock decelerates faster, the fragments may break through. It is suspected that this may happen in Cas A, of which Dr. Perley will show us some pictures later.

FRANSSON: A similar case has recently been discussed by A. Hamilton in Ap. J.

STELLINGWERF: Can you say anything about the velocity structure across the shock/reverse shock region.

FRANSSON: The structure in the shock region depends on the importance of cooling in the gas. In the case of an adiabatic shock Chevaliers similarity solution gives the behaviour. In general, it should be a slowly decreasing function of the radius.

OPHER: What is the observational evidence of the state of the gas in front of the shock. Is it preheated and preaccelerated? Blueshifted absorption lines of highly excited atoms would give evidence of this.

FRANSSON: I have discussed these effects in an earlier paper and one finds that the temperature in front of the shock is about 10^5 K, which also agrees with the more accurate calculations together with P. Lundqvist. The extent to which the gas is pre-accelerated depends on the luminosity of the supernova, especially in the early phases. There is some evidence for pre-acceleration in the supernova seen in NGC 3169 by Dopita et al., but this may also be due to a fast stellar wind.

BEDOGNI: Could the thermal conduction from the inner to the outer shock play a crucial role on the dynamics of the shock.

FRANSSON: The general deceleration of the region is probably not affected, but the structure inside the region can be quite different. The importance depends of course on the topology of the magnetic field. Liang and Chevalier have done some calculations for an adiabatic flow, and finds that conduction can make both the density and temperature more uniform, as expected.

https://doi.org/10.1017/S0252921100086061 Published online by Cambridge University Press