SUPERNOVAE AND STELLAR MASS LOSS

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ABSTRACT. Type I supernovae can be modeled as the carbon deflagration of white dwarfs and Type II supernovae as the explosions of massive stars with hydrogen envelopes. The massive stars at the ends of their lives are expected to be red supergiants, which are observed to have slow, dense winds. The interaction of the supernova kinetic energy and radiation with the circumstellar gas gives rise to observational phenomena at a range of wavelengths. Additional phenomena, such as a scattered light echo, are predicted. While the light from a Type II supernova near maximum light is probably from energy deposited in the initial explosion, there is now good evidence that the radioactive decay of ^{56}Co powers the emission at late times. It was been noted that the explosions of massive stars without hydrogen envelopes would be quite unlike normal Type II supernovae. There is now good evidence for such explosions - SN1985f and the class of peculiar Type I supernovae. It is suggested that these supernovae be called Type III with the spectroscopic definition of a) no H lines and b) broad [OI] lines at late times. That not all very massive star explosions are of this type is indicated by SN1961v, which was probably a very massive explosion, but in which hydrogen was present.

1. INTRODUCTION

Over the past ten years, a consensus has arisen on the nature of Type I and Type II supernovae. Type II supernovae (SNII) are thought to be the explosions of massive stars ($M \gtrsim 8M_{\odot}$) with hydrogen envelopes at the ends of their lives and Type I supernovae (SNI) are thought to be the carbon deflagration of a white dwarf with mass close to 1.4 $M_{\odot}$. The white dwarf may arrive at this state from mass accretion in a binary system. The basic evidence for these models is summarized in Table 1, where a + sign indicates compatibility with the model and a question mark indicates uncertainty. The column on Type III supernovae will be discussed in Section 3. The supporting evidence on SNI and SNII is discussed in Chevalier (1981a, b) and Wheeler (1982). Type I supernovae are taken here to be of the standard kind (like SN1972e) and peculiar

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Table 1. Evidence for Supernova Models

	Type I as C deflagration of white dwarf	Type II as explosion of massive star with H envelope	Type III as explosion of massive star without H envelope
Positions in galaxies	+	+	+
Rate	?	+	+
Abundances	+	+	+
Light curves	+	+	?

Type I's are not included. A possible problem with the model for Type I events is the rate of events. Iben and Tutukov (1984) analyzed the ways in which a white dwarf in a binary system could lead to an explosion and concluded that catacysmic variables, which had been proposed as possible progenitors, did not lead to explosions at a sufficiently high rate. Double white dwarf systems seemed more promising with regard to rate, but it has yet to be shown that their evolution can lead to a C deflagration supernova. Nomoto (1985) finds that double white dwarf systems are not promising, but that white dwarfs accreting 10^{-8} - 10^{-6} $M_\odot$ yr^{-1} from subgiants undergoing Roche lobe overflow or red giants undergoing wind-type mass loss are possibilities. Another possible problem with the model for SNI is that Fe may be overproduced in the galaxy. However, the models for late Fe emission lines from SN1972e do provide evidence for the ejection of 0.5 - $1M_\odot$ of Fe (Meyerott 1980; Axelrod 1980).

Some implications of the supernova models are given in Table 2. SNIII will be discussed in Section 3. It is of interest that SNI and SNII have similar absolute magnitudes at maximum, but involve very different physical mechanisms.

2. TYPE II SUPERNOVAE

2.1 Circumstellar Interaction

Observations of the Type II supernovae SN1979c and SN1980k have given excellent evidence for the interaction of the supernovae with a pre-supernova wind (for reviews, see Chevalier 1984a and Fransson 1985). Such a wind is expected from the red supergiant progenitor for a SNII. The best evidence for the circumstellar interaction is the consistency of the results obtained from the interpretation of observations at a variety of wavelengths (see Table 3). In each case, the observations depend on the density of the wind, or $\dot{M}/v_w$ where $\dot{M}$ is the mass loss rate and v_w is the wind velocity. The observed phenomena are due either to the interaction of the supernova shock wave with the circumstellar matter (radio, x-ray, ultraviolet) or to the interaction of

Table 2. Implications of Supernova Models

	Type I	Type II	Type III
Progenitor	White dwarf in binary	Massive star with H envelope	Massive star without H envelope
Explosion	Thermonuclear (C burning)	Core collapse	Core collapse or thermonuclear (O burning)
Total energy release (ergs)	$\sim 10^{51}$	$\sim 10^{51}$	$\gtrsim 10^{51}$
Energy for radiation a) near maximum	Radioactivity	Heating in initial explosion	Recombination and radioactivity
b) late times ($t \gtrsim 200$ days)	Radioactivity	Radioactivity	Radioactivity
Radiated energy (ergs)	$\sim 4 \times 10^{49}$	$\sim 2 \times 10^{49}$	$\lesssim 8 \times 10^{48}$
Neutron star remnant?	No	Probably	Probably (core collapse) No (thermonuclear)

the supernova radiation with the circumstellar matter (infrared). This, along with the time of the observations, accounts for the range of radii which characterize the interaction.

In the circumstellar interaction model, the radio emission is synchrotron radiation from the high energy density region between the expanding supernova and the circumstellar gas. The particle acceleration probably involves the shock waves and/or turbulent motions in the interaction region, but the details of the acceleration process and the resultant particle energy spectrum are not understood. However, an efficiency of production of relativistic electrons and magnetic fields comparable to that found in extended nonthermal sources like supernova remnants can reproduce the observed radio luminosities. The sharp turn-on of the radio emission, which is increasingly delayed at lower frequencies (see Weiler et al. 1986) is well explained by free-free absorption by ionized circumstellar gas external to the shock front. It is from the time of the radio turn-on that the mass-loss estimate is obtained.

The infrared emission from these supernovae is attributed to emission from circumstellar dust which is radiatively heated by the supernova light (Dwek 1983). It is an echo effect. The mass loss

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Table 3. Circumstellar Interaction in SNII

	$\dot{M}/v_w$ ($M_{\odot}yr^{-1}$/km s^{-1}) SN 1979c	SN 1980k	Extent (cm)
Radio	$0.5\text{-}1.5\times10^{-5}$	$1\text{-}3\times10^{-6}$	$10^{16}\text{-}10^{17}$
Infrared	$0.4\text{-}2\times10^{-5}$	$0.5\text{-}2\times10^{-6}$	10^{18}
Ultraviolet	$\sim0.5\times10^{-5}$		3×10^{15}
X-ray	-	1×10^{-6}	10^{16}
$\dot{M}$($M_{\odot}yr^{-1}$) for v_w = 10 km s^{-1}	$\sim1\times10^{-4}$	$\sim2\times10^{-5}$	

estimate is related to the fraction of the supernova light that is absorbed and reradiated in the infrared. There is some uncertainty in the results that they are dependent on the dust properties and the gas-to-dust mass ratio.

The ultraviolet emission lines observed from SN1979c at early times (Fransson et al. 1984) require a source of relatively energetic photons. This source is likely to be photospheric photons which are Compton scattered in the hot circumstellar interaction region (Fransson 1984). The required Compton optical depth is about 0.02, which gives consistency with the mass loss estimate. The x-ray emission for SN1980k (Canizares, Kriss, and Feigelson 1982) is interpreted as thermal emission from the shocked supernova gas. The observed flux is directly related to the mass loss rate, although some assumption about the density distribution of the freely expanding supernova gas is needed (Chevalier 1982).

These are the current observational techniques which can be used to determine mass loss rates. In the future, it may be possible to observe ultraviolet absorption lines due to the circumstellar gas (Lundqvist and Fransson 1985). Such observations would give another measurement of the wind density. Another observation is suggested by the interpretation of the infrared radiation. If the circumstellar dust grains are able to absorb the supernova radiation, they should also be able to scatter it. Chevalier (1985) investigated the properties of the scattered light echo for plausible assumptions about the grain albedo and degree of forward scattering. The lack of evidence for such an echo from SN1979c indicates that the circumstellar grains do not have properties like those of interstellar grains. An exciting future observation is the possible spatial resolution of the light echo from a nearby supernova.

At radio wavelengths, spatial resolution of the emission has already been achieved using VLBI techniques. Bartel et al. (1985) have measured both the angular diameter and the expansion of the radio emitting region associated with SN1979c. The results are compatible with the circumstellar interaction model. At present it is not possible to map the emission, but with the future availability of more complete telescope arrays, this may become possible and a wealth of information on the circumstellar interaction will become available. It will be particularly important to check on the degree of symmetry of the emission; spherical symmetry is an assumption in the current models.

2.2 Late Optical Emission

While it has been known for some time that SNII light curves extend over several 100 days, it has only recently become clear that the late flux decline is exponential with a decay constant roughly equal to that for ^{56}Co decay. Barbon, Cappellaro, and Turatto (1984) compiled B-band photometry on the Type II supernovae SN1962m, SN19691, SN1979c, and SN1980k and concluded that they decline exponentially in the age range 200 to 400 days with a half-life of 92.6 $\pm$ 2.3 days. The half-life for ^{56}Co decay is 77 days. Uomoto and Kirshner (1985) have presented spectrophotometry of SN1980k up to an age of nearly 700 days. They found that the Hα line intensity decays exponentially with a decay time very close to that expected for ^{56}Co decays. The Hα line dominates the spectrum beginning at an age of about 200 days and at these late times, continuous emission is not clearly present. While there may be a blue continuum, this emission may be the superposition of broad emission lines. The minimum mass of ^{56}Co needed to power the Hα by γ-ray energy input is approximately 0.001 $M_\odot$.

Weaver and Woosley (1980) had proposed that about 0.1–0.4 $M_\odot$ of ^{56}Ni might be synthesized in a SNII, and that the late emission observed from these events might be powered by the radioactive decays. In their model the γ-rays are absorbed in slow moving mantle gas that has been decelerated by the interaction with the envelope. The energy is thermalized and the radiation takes the form of photospheric blackbody radiation. However, the dominant radiation from SN1980k is in a broad Hα line. While continuous emission is not clearly present, it may be present at the level needed to ionize the hydrogen in the n=2 level by Balmer continuum emission (Kirshner and Kwan 1975). Another possibility is that slow moving gas is not present and γ-rays ionize the fast-moving hydrogen directly. The optical depth to the γ-rays for a uniformly, expanding sphere of hydrogen with mass M_H is

$$\tau \simeq 15 \left(\frac{M_H}{5M_\odot}\right) \left(\frac{v_e}{6000\ \mathrm{km\ s^{-1}}}\right)^{-2} \left(\frac{t}{100\ \mathrm{days}}\right)^{-2}$$

where v_e is the velocity at the edge of the sphere. Over the time of observation of the Hα line, τ varies by a factor of 10 so that either the line would be very narrow at early times or the intensity decline would be more rapid than that of the exponential radioactive decay. These are not observed. One possibility is that the expanding gas is in optically thick clumps which have only a small covering factor. This would lead to a line of constant profile with the correct decay.

One expectation of this model is structure within the line profile. The spectra of SN1980k are not of sufficiently high signal-to-noise to check this, but late spectra of SN1979c do show structure in the Hα line profile (Branch et al. 1981; Kirshner and Chevalier, unpublished).

3. MASSIVE STARS WITHOUT HYDROGEN ENVELOPES

The presence of a hydrogen envelope plays a crucial role in the properties of SNII. However, there is a class of massive stars which have lost their hydrogen envelopes; the massive Wolf-Rayet stars are in this class. The loss of the envelope may occur either through mass loss in a single star or through mass transfer and loss in a close binary system. Without the envelope, the star is relatively compact compared with a red supergiant. The core evolution proceeds as in the case of the envelope being present and explosions are expected. Chevalier (1976) noted that these explosions would appear quite unlike normal SNII not only because the H lines would be absent but also because the supernova would be faint owing to adiabatic expansion losses. I suggested that Cas A is the remnant of such a supernova. The fact that it was not observed in the late 1600's implies that it was a faint explosion.

Maeder and Lequeux (1982) estimated the rate at which massive stars without H envelopes explode to be 1/7 to 1/3 of the normal supernova rate. The rate was obtained by taking the observed number of Wolf-Rayet stars in the galaxy and dividing by their expected lifetime. Another similar estimate was obtained from the birthrate of stars with initial masses, $M_i \gtrsim 23 M_\odot$. Observations indicate that stars with these high masses lose their envelopes in a stellar wind.

Stars in this high mass range can explode by either of two mechanisms. Ones with $M_i \lesssim 100\ M_\odot$ are expected to undergo Fe core collapse, as do SNII. For $M_i > 100\ M_\odot$, the core is subject to the pair formation instability (Bond, Arnett, and Carr 1984 and references therein). This initiates collapse which leads to O burning and complete disruption of the star. Cahen, Schaeffer, and Cassé (1986) have investigated light curve models for the explosions of cores with masses $M_i = 8 M_\odot$ and $68\ M_\odot$; these cores are from stars with initial masses $M_i = 40$ and $100\ M_\odot$ respectively. The first is in the Fe core collapse range, while the second undergoes the pair instability. In both cases, the predicted luminosities are below those of normal supernovae, but are higher than the luminosity of Chevalier's (1976) model because of the inclusion of energy input from recombination of oxygen and from radioactivity. It is assumed that $0.02\ M_\odot$ of ^{56}N is synthesized in the explosion.

Direct observational evidence for this type of supernova has recently become available. Observations of a new exploding star, SN1985f in NGC4618, by Filippenko and Sargent (1985) showed it to be unlike either SNI or SNII. Strong lines in the optical region (4300 - 7500 Å) were MgI]λ4571, NaIλ5893, [OI]$\lambda\lambda$6300 and 6364, and [CaII]λ7308. While other fainter lines were also present, the hydrogen lines were absent. Continuous emission was also definitely present. The explosion was very close to an HII region. The strength of the O lines imply a mass of O > $5M_{\odot}$ (Filippenko, private communication). Begelman and Sarazin (1985) suggest that the supernova mass is about 50 $M_{\odot}$, implying that the explosion was of the pair instability type.

Another set of supernova observations also seem to provide evidence for Wolf-Rayet star explosions. The objects are the SNI pec which have spectra near maximum that have similarities to the spectra of normal SNI, but the λ6115 absorption feature is absent. They are subluminous compared to normal SNI by > 1 mag. The supernovae which fall into this calss are SN1962l, SN1964l, SN1983i, SN1983n, and SN1984l (Uomoto and Kirshner 1985 and references therein; Wheeler and Levreault 1985; Kirshner, private communication). These supernovae can also be clearly distinguished from normal SNI by their infrared light curves (Elias et al. 1985). Elias et al. refer to these supernovae as SNIb.

The infrared light curves of SN1983i, SN1983n, and SN1984l show considerable uniformity (Elias et al. 1985), although SN1983i may be fainter than the other two by ~ 1 mag in absolute magnitude. SN1983n and SN1984l were both detected as radio sources and had similar radio properties (Sramek, Panagia, and Weiler 1984; Panagia, Sramek, and Weiler 1985). Spectra of SN1984l at an age of about 400 days (Kirshner, private communication) show the same strong lines as observed in spectra of SN1985f in NGC4618 (identified as lines of MgI], NaI, [OI], and [CaII]). These spectra provide a link between the Filippenko and Sargent supernova and the SNI pec and suggest that both are the explosions of Wolf-Rayet-type stars (see also Wheeler and Levreault 1985). However, it is unlikely that SN1985f was exactly like a SNI pec near maximum light. When SN1985f was first observed (Feb. 1985), its magnitude corresponded to that of a SNI pec somewhat older than 100 days. At this age, a SNI pec like SN1983n or 1984l would have been detectable as a radio source, but SN1985f was not detected (Sramek 1985, quoted in Filippenko and Sargent 1985). Also, the rate of SNI pec is too high for them to have very massive progenitors, as has been suggested for SN1985f. One way to estimate the rate of SNI pec is from the list of supernovae identified by their spectra that is given by Oke and Searle (1974). Of 8 SNI which occurred in Sc galaxies, 2 (SN1962l and SN1964l) are of the pec subclass. All of the observed SNI pec have been in Sc galaxies and most have been closely associated with HII regions. In Sc galaxies the SNII rate is about equal to the SNI rate. The observed rate of SNI pec may be affected by the facts that they are subluminous and are associated with HII regions; however, it appears that their rate is roughly consistent with the rate deduced by Maeder and Lequeux (1982) for Wolf-Rayet star deaths.

Unlike normal SNI, Fe lines do not dominate the spectrum of late times for SNI pec. However, it is likely the decay of ^{56}Co again provides the energy for the luminosity. The early observations of SN1983n imply that it was a compact star at the time of the explosion. (Panagia 1985). To provide the radiative energy near maximum light, approximately 0.1-0.2 $M_{\odot}$ of ^{56}Ni must be synthesized in the explosion (Wheeler and Levreault 1985). As Wheeler and Levreault point out, the energy release from the nucleosynthesis is probably insufficient to completely disrupt a white dwarf progenitor. This points to core collapse, which is expected in the core of a massive star. Graham et al. (1985) inferred about 0.2 $M_\odot$ of Fe in SN1983n from emission in an infrared line. An interesting difference with normal SNI is that the Fe line is narrower, 2000 km s^{-1} vs 4000 km s^{-1} for a normal SNI. In a SNI pec, the Fe may be confined to the very central region outside of which is a massive O region. The γ-rays from radioactivity are then primarily absorbed by the O-rich gas instead of the Fe-rich gas.

The radio emission from SN1983n and SN1984l can be adequately modeled as the result of the interaction of the supernova with circumstellar gas (Chevalier 1984b; Panagia, Sramek, and Weiler 1985). For SN1983n, the turn-on of the radio emission provides an estimate of the mass loss rate from the progenitor star. Chevalier (1984b) assumed that the exploding star was a normal SNI and may have overestimated $\dot{M}/v_w$. A value of $\dot{M}/v_w$ in the range 2-5 x 10^{-7} ($M_\odot$ yr^{-1})/(km s^{-1}) is indicated. Wolf-Rayet stars are observed to have $\dot{M} \simeq 2 \times 10^{-5}$ $M_\odot$ yr^{-1} and $v_w \simeq 2000$ km s^{-1} (Abbott et al. 1985), or $\dot{M}/v_w \simeq 10^{-8}$($M_\odot$ yr^{-1})/(km s^{-1}). The large density derived for the supernova could be in error (e.g. due to clumping of the wind gas) or Wolf-Rayet stars may have stronger winds at the ends of their lives. The gas which causes free-free absorption in the model for SN1983n is lost within a year of the explosion.

The available evidence makes the identification of SN1985f and and the SNI pec with the explosions of massive Wolf-Rayet stars very attractive. They have been classed as SNI because they lack H lines, but it appears that they come from a different stellar population and involve different physical meçhanisms from normal SNI. Their association with massive stars causes confusion with SNII; the explosion which gave rise to Cas A has often been called a Type II event (e.g. Shklovsky 1968). In view of this, a new type designation seems to be in order. I once suggested that these supernovae be called Type VI since Zwicky (1965) had assigned Types I through V (Chevalier 1981a). However, Types III and IV have only one example each and it now generally agreed that these examples can be classified as Type II (Oke and Searle 1974). If the Type III designation is thus left open, it seems appropriate to use it for the explosions of massive stars which have lost their envelopes. The suggested spectroscopic definitions of the types are I: H lines absent, Fe lines dominate at late times ($t > 200$ days), II: H lines present, and III: H lines absent, broad [OI]$\lambda\lambda$6300, 6364 lines dominate at late times. A possible problem with these definitions is that Minkowski (1939) observed narrow ($\Delta\lambda$ < 40 Å) [OI] lines in spectra of SN1937c in the range 180-339 days after maximum. SN1937c was a normal SNI, but SN1972e, which was also of this type, did not show [OI] emission at late times (Kirshner and Oke 1975). There is no theoretical explanation for the presence of [OI] lines with velocities less than those in Fe lines. Further late spectra of SNI are needed to resolve this point.

Table 1 lists some of the basic evidence for this interpretation of SNIII. Their close association with HII regions and Sc galaxies indicates an even younger (and more massive) progenitor population than that of SNII, as expected. Light curve models have not yet been compared with observations of SNIII, so this point is still open. However, Wheeler and Levreault (1985) note that the width of the light curves and the observed velocities in SNI pec are similar to those for SNI, so that the ejected masses are similar if the opacity is the same. It is likely that the compositions of the bulk of the mass are different in the two cases so that differences in opacity might be expected. It appears that recombination of oxygen reduces the opacity in the models of Cahen et al. (1985). Differences in density distributions may also allow differences in ejected mass. It is expected that explosions of massive Wolf-Rayet stars involve more than 1.4 $M_\odot$, which is the mass generally believed to be involved in the explosions of SNI.

Another possible problem with this interpretation of SNI pec is the uniformity of their infrared light curves and radio properties. Wolf-Rayet stars are expected to span a wide range of initial masses and core masses. The observations may indicate that mass loss drives different cores to structures with similar properties.

Table 2 lists some basic observational properties and physical interpretation of SNIII. The class include both Fe core collapse (M_i < 100 $M_\odot$) and pair instability (M_i > 100 $M_\odot$) supernovae. The latter type of supernova may have energies of order 10^{52} ergs (Bond, Arnett, and Carr 1984).

4. EXPLOSIONS OF VERY MASSIVE STARS

The above discussion suggests that SNII come from stars in the approximate mass range 8-23 $M_\odot$ that are not in close binaries and SNIII come from stars with mass > 23 $M_\odot$ and less massive stars that are in close binaries. A complication is indicated by the example of a Type V supernova - SN1961v in NGC1058 (Zwicky 1965). Spectra of this supernova did show H lines, which would imply a SNII, but the light curve was more extended and showed more structure than that of any SNII. Also, the gas velocities were only 2000 km s^{-1}, several times less than those in SNII and He lines were strong, unlike SNII. Of particular interest is that the star was observed for 24 years prior to the outburst. The implication is that a stable star existed over this period and, using the luminosity estimate of Branch and Greenstein (1971), I suggested that the stellar mass was $\gtrsim$ 500 $M_\odot$ based on the Eddington limit (Chevalier 1981a). This estimate assumes (1) a distance to NGC1058 of 5.7 Mpc, (2) a bolometric correction of 2 mag, (3) A_V = 0.9 mag to the supernova. Uncertainties in these assumptions could easily give a significant error. For example, Sandage and Tammann (1974) estimate the distance to NGC1058 to be approximately 19.6 Mpc, which would increase the luminosity (and mass) by an order to magnitude. The case for the very massive star (M_i > 100 $M_\odot$) appears to be excellent. Utrobin (1984) recently modeled the explosion as that of a 2000 $M_\odot$ star. It is noteworthy that in this case mass loss did not completely remove the H envelope by the time of the explosion so the supernova was not of Type III.

The mass of the progenitor of SN1961v is of considerable importance not only because of the evidence for a very massive star, but also because stars with M_i > 300 $M_\odot$ are theoretically expected to collapse to black holes instead of explode (Bond, Arnett, and Carr 1984 and references therein). The reason is that the gravitational binding energy rises more rapidly with mass than does the energy available from thermonuclear burning. Utrobin (1984) hypothesized that a non-homologous initial collapse would allow complete disruption or central black hole formation with an outer explosion even for a 2000 $M_\odot$ star. Since explosions of very massive stars are expected to be rare, further modeling and observational studies of SN1961v are warranted. The supernova has been recently detected as a radio source (Branch and Cowan 1985) and Fesen (1985) has found an emission line knot which appears to be coincident with the site of the supernova. The observations suggest that interaction with circumstellar gas is taking place.

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