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THE RADIO AND X-RAY EMISSION FROM TYPE II SUPERNOVAE

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ABSTRACT

The interaction of the outer parts of a supernova envelope with circumstellar matter gives rise to a high-energy density shell. The equation of motion of the shell is deduced based on the approximations that the shell is thin and that the supernova density profile is a power law in radius. The density structure in the shell is Rayleigh-Taylor unstable, and the energy density created by the instability can be a substantial fraction of the original thermal energy density. The instability can drive turbulent motions, and these may amplify the magnetic field and accelerate relativistic electrons. If the efficiency of these processes is comparable to that inferred for the Cassiopeia A supernova remnant, the observed radio luminosity from SN 1980k and SN 1979c can be reproduced. Several mechanisms are considered for the early low-frequency absorption of the radio emission. Free-free absorption by circumstellar matter is the most likely mechanism because of the steep time dependence of the radio emission and the magnitude of the absorption effect. If the circumstellar matter is smoothly distributed, it is inferred that the presupernova star of SN 1980k had a mass loss rate of about $10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ and that of SN 1979c about $5 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$. Clumping of the matter would reduce the estimated mass loss rates. It is also inferred that SN 1979c had more high velocity matter than did SN 1980k.

Thermal X-ray emission is expected from both the shocked circumstellar medium and the shocked supernova matter. The shocked supernova matter dominates the emission in the band observed with the *Einstein* Observatory, and it can produce the X-ray flux observed from SN 1980k. Inverse Compton emission is another possibility for the observed X-ray emission, but it is less likely because it would decrease the number of radio-emitting electrons.

Subject headings: nebulae: supernova remnants — radiation mechanisms — radio sources: general — X-rays: sources

I. INTRODUCTION

Radio emission has now been detected from three Type II supernovae: SN 1970g (Allen *et al.* 1976), SN 1979c (Weiler *et al.* 1981), and SN 1980k (Sramek, van der Hulst, and Weiler 1980). While the emission has been attributed to synchrotron radiation, the origin of the required magnetic field and relativistic electrons is not known. Marscher and Brown (1978) proposed a model for the SN 1970g source in which the emission is from the outer parts of the supernova envelope; the magnetic field is provided by a central pulsar, and energy for the relativistic electrons is provided by the kinetic energy of the supernova. However, it is not clear how the pulsar magnetic field can penetrate the bulk of the expanding envelope or how electrons are accelerated in a cool uniformly expanding medium.

Pacini and Salvati (1981) suggested that the SN 1979c emission is from a bubble of magnetic field and relativistic particles around a central pulsar, and that the expanding supernova material has no effect on the radio emission. This requires that the supernova shell be filamentary in order to avoid free-free absorption of the radio waves. The constraints on a pulsar model are especially strong for SN 1980k, which was observed at 6 cm on 1980 December 4, only 36 days after optical maximum light. Models for Type II supernovae (e.g., Chevalier 1976) indicate that maximum light occurs about 15 days after the time of the explosion, so the radio emission was observed about 51 days after the explosion. From observations of other Type II supernovae, it is known that the photospheric temperature is about 6000 K 36 days after maximum light, and the models show that the gas temperature in most of the envelope interior is about 1.6×10^4 K at this time. If 5 $M_{\odot}$ were ejected in a smooth envelope at 5000 km s^{-1}, the free-free optical depth at 6 cm is about 2×10^9 at this time. While a pulsar model requires filamentation of the envelope, it is not clear how it is accomplished. The Crab Nebula is an example of a pulsar bubble with filamentary ejecta, but in a model for the nebula by Chevalier (1977), the filaments formed at least 10 years and perhaps hundreds of years after the explosion. The pulsar must generate an energy comparable to the kinetic energy of the expanding gas in order to create filaments. In the case of SN 1980k, about 10^{51} ergs must be generated in 51 days, or 2×10^{44} ergs s^{-1}. This energy input is approximately that of a maximally rotating pulsar and is orders of magnitude larger than the initial luminosity deduced for observed pulsars. Even if such a large energy input occurred, the filamentary nature of the ejecta would mean that existing hydrodynamic models for Type II supernovae (Chevalier 1976; Falk and Arnett 1977; Weaver and Woosley 1980) are incorrect. Yet these models have been successful in reproducing the observed characteristics of Type II supernovae. Thermal instability cannot give the required filamentation because the thermal energy of the ejecta is much less than the kinetic energy when the material becomes optically thin. The energies would have to be comparable if the thermal pressure were to drive the ejecta into a small number of filaments.

Another possible problem with a pulsar model is inverse Compton losses of the electrons. As noted above, the interior radiation temperature must be about 1.6×10^4 K in order to produce the observed optical radiation. In a model like that of Pacini and Salvati (1981), the electrons have $\gamma \geq 10$, and their inverse Compton lifetime is about 6000 s. If the relativistic particles are created close to the pulsar, they can move at most 2×10^{14} cm from the pulsar before losing their energy, and the volume they fill is too small to give the observed radiation. Particle acceleration throughout the pulsar bubble is necessary.

These considerations suggest that the radio emission from Type II supernovae is not related to a central pulsar, but is from a region outside the bulk of the supernova envelope. Chevalier (1981*a*, hereafter Paper I) identified this region as the high-energy density shell created by the interaction of the rapidly moving envelope material with circumstellar material. In the present paper, a model for the interaction of the outer supernova envelope with the circumstellar matter is described in § II. The radio emission from supernovae is discussed in the context of this model in § III.

The supernova SN 1980k has been observed not only at radio wavelengths, but also at X-ray wavelengths (Canizares, Kriss, and Feigelson 1982). Two possible sources for the X-ray emission are discussed in § IV and it is found that the emission can be accounted for in the present model. Some implications of the model are discussed in § V.

II. HYDRODYNAMIC INTERACTION

As discussed in Paper I, the progenitors of Type II supernova are expected to be surrounded by a density distribution given by

$$n_{\rm H} = 2.2 \times 10^7 \dot{M}_{-5} r_{15}{}^{-2} v_1{}^{-1} \text{ H atoms cm}^{-3} , \quad (1)$$

where $\dot{M}_{-5}$ is the mass loss rate from the presupernova red supergiant in units of 10^{-5} $M_\odot$ yr^{-1}, v_1 is the presupernova wind velocity in units of 10 km s^{-1}, and r_{15} is the radius in units of 10^{15} cm. In Paper I, it was argued that the initial interaction of the supernova with the circumstellar medium can be viewed as a constant velocity piston moving into the surrounding medium. A dense shell with mass about 10^{30} g is expected to form by radiative effects when the shock wave emerges from the star. However, in the present paper it is shown that the presupernova mass loss rate may be closer to 10^{-5} $M_\odot$ yr^{-1} than to the 10^{-6} $M_\odot$ yr^{-1} used in Paper I. Under these circumstances, the dense shell is expected to be decelerated by its interaction with the surrounding medium by the time of maximum light. Another factor is that Rayleigh-Taylor instabilities may smooth out the dense shell at very early times (Falk and Arnett 1977).

If the shell is not important, the gas density in the outer parts of the supernova is expected to decrease with radius and may be described by a power law distribution, r^{-n}. Branch *et al.* (1981) calculated line profiles assuming a power-law density distribution to compare with observations of SN 1979c near maximum light and found that profiles calculated with $n = 7$ give an adequate fit. However, Branch *et al.* did not attempt to find a preferred value for n, although they do note that $n > 4$ is required to fit the profiles. Branch *et al.* presumably used $n = 7$ because it was found by Colgate and McKee (1969) in their supernova models. The Colgate and McKee models involve the explosion of a polytropic star with polytropic index 3. A red supergiant is not described by such a stellar model and the outer density distribution of the exploded star may be different from an $n = 7$ power law. In a supernova model described by Chevalier (1976) which gave velocities in excess of 10^4 km s^{-1}, the outer density distribution was approximately an $n = 12$ power law. Jones, Smith, and Straka (1981) modeled an explosion of the 15 $M_\odot$ stellar model of Weaver, Zimmerman, and Woosley (1978) by depositing 10^{51} ergs of energy at the center. In the free expansion phase, the outer density profile was described by an $n = 12.5$ power law.

While in free expansion, the outer power law density distribution is given by

$$\rho_{\rm sn} = t^{-3}\left(\frac{r}{tU_c}\right)^{-n} , \quad (2)$$

where U_c is a constant. This distribution applies out to some initial maximum velocity $u_{\rm max}$. The circumstellar density distribution is given by

$$\rho_{\rm cs} = qr^{-2} , \quad (3)$$

where q is a constant. This profile applies from the circumstellar region to a radius R_0, which is close to the radius of the presupernova star. These two density distributions interact in a shell which has two components. The first component, to be denoted by a subscript 1, contains shocked circumstellar matter, and the other component, to be denoted by subscript 2, contains shocked matter from the supernova envelope.

I now assume that the thickness of the interaction shell is small compared to its radius, so that its position can be denoted by a radial value R. The shell decelerates as it interacts with the surrounding medium. The deceleration is determined by the pressure differential across the shell, or

$$(M_1 + M_2)\frac{d^2R}{dt^2} = 4\pi R^2(P_2 - P_1) , \quad (4)$$

where M is the mass of each shell component, P_2 is the total pressure at the inner shock wave, and P_1 is the pressure at the outer shock wave. In terms of the density distributions given above, we have

$$M_1 = 4\pi q(R - R_0)\,, \tag{5}$$

$$M_2 = 4\pi[R^{3-n} - (u_{\max} t)^{3-n}]t^{n-3}U_c^n/(n-3)\,, \tag{6}$$

$$P_1 = \frac{q}{R^2}\left(\frac{dR}{dt}\right)^2\,, \tag{7}$$

and

$$P_2 = t^{-3}\left(\frac{R}{tU_c}\right)^{-n}\left(\frac{R}{t} - \frac{dR}{dt}\right)^2\,. \tag{8}$$

At maximum light and thereafter, it is expected that $R \gg R_0$, so that the neglect of R_0 in equation (5) is justified. Also, the value of $u_{\max}$ is not known, but it is likely that $R^{3-n} \gg (u_{\max} t)^{3-n}$, considering that $n \geq 7$. Thus, I drop the $(u_{\max} t)^{3-n}$ term in equation (6). With these approximations, the terms in equation (4) become independent of the initial conditions of the problem. Also, both the supernova and the circumstellar density distributions are scale free, so that the solution $R(t)$ should also be scale free, i.e., a power law $R = Kt^m$, where K is a constant. The solution of equation (4) is

$$R = \left[\frac{2U_c^n}{(n-4)(n-3)q}\right]^{1/(n-2)} t^{(n-3)/(n-2)}\,. \tag{9}$$

The evolution of the shell radius should tend toward this solution.

With this solution, it is possible to find ratios of the physical quantities in the two shell components. The mass ratio is

$$\frac{M_1}{M_2} = \frac{2}{n-4}\,. \tag{10}$$

Ratios of the quantities at the two shock waves are

$$\frac{P_1}{P_2} = \frac{2(n-3)}{n-4}\,, \tag{11}$$

$$\frac{\rho_1}{\rho_2} = \frac{2}{(n-4)(n-3)}\,, \tag{12}$$

and

$$\frac{T_1}{T_2} = (n-3)^2\,. \tag{13}$$

For $n = 7$, we have $M_2/M_1 = 1.5$, $P_2/P_1 = 0.37$, $\rho_2/\rho_1 = 6.0$, and $T_2/T_1 = 0.062$. For Type II supernovae, $n = 12$ appears to be more likely, and we have $M_2/M_1 = 4.0$, $P_2/P_1 = 0.44$, $\rho_2/\rho_1 = 36$, and $T_2/T_1 = 0.012$.

Existing models for Type II supernovae do not reliably give values of the constant U_c. Constraints on the value of U_c can be obtained from supernova observations. From observed line profiles in the spectra of Type II supernovae near maximum light, Kirshner *et al.* (1973) deduced the presence of material moving at 15,000 km s^{-1}. This requires $R/t \gtrsim 1.5 \times 10^9$ cm s^{-1}. Taking $n = 12$, $t = 20$ days, and $\dot{M} = 10^{-5}\ M_\odot$ yr^{-1}, we have $U_c \gtrsim 2.7 \times 10^9$. The model of Chevalier (1976) discussed above had $n = 12$, $U_c = 1.77 \times 10^9$. At a given velocity, the density is too small by a factor of $190\dot{M}_{-5} v_1^{-1}$. However, in the case of SN 1979c, the maximum observed velocity was 10,500 km s^{-1} (Panagia *et al.* 1980; Branch *et al.* 1981). If this was the maximum velocity present, the required value of U_c is 2.0×10^9, and the model density is small by a factor of $5.4\dot{M}_{-5} v_1^{-1}$. The model discussed by Jones, Smith, and Straka (1981) had $n = 12.5$ and $U_c = 3.88 \times 10^8$, which is much too small to explain the observations. In order to produce a velocity of 15,000 km s^{-1} near maximum light, the density must be increased by a factor of $3 \times 10^{10}\ \dot{M}_{-5} v_1^{-1}$.

The thickness of the interaction shell depends on whether cooling is important for the postshock gas. For the values of $\dot{M}$ used in Paper I, Compton cooling dominated radiative cooling. Compton cooling was estimated to be marginally important near maximum light. At earlier times it should cause the material to collapse to a dense shell with a gas temperature similar to that of the radiation, and at later times it should have a negligible effect on the hydrodynamic evolution. The Compton cooling time is independent of the gas density. The cooling time for bremsstrahlung emission is

$$t_{\rm br} \approx 6.0 \times 10^7\ T_9^{1/2}\alpha^{-1}\dot{M}_{-5}^{-1}v_1^{1}r_{15}^{2}\ {\rm s}\,, \tag{14}$$

where T_9 is the electron temperature in units of 10^9 K and α is the ratio of the gas density to the density immediately behind the outer shock wave. For $n = 12$, we have $\rho_2/\rho_1 = 36$, and the radiative cooling is important at the inner shock wave at early times. However, by maximum light when $r_{15} \gtrsim 2$, the bremsstrahlung cooling is no longer significant. Radiative cooling may be enhanced if the gas is out of ionization equilibrium so that line emission dominates bremsstrahlung emission. The ionization time scale is approximately 10^3 n^{-1} yr. In the present case, the ionization time scale is

$$t_{\rm ion} = 4.3 \times 10^2\ \alpha^{-1}\dot{M}_{-5}^{-1}v_1 r_{15}^{2}\ {\rm s}. \tag{15}$$

In the inner shock region, where cooling is the most important, nonequilibrium effects appear to be negligible.

Under these conditions, the flow can be treated as being adiabatic. The situation in region 1 of the hot shell is the same as for a piston moving with radial time dependence proportional to t^m into a medium with $\rho \propto r^{-2}$. Parker (1963) has calculated similarity solutions for the postshock flow in this case. Solutions are only available for $m \geq 2/3$; this critical value of m corresponds to shock wave propagation with instantaneous energy input. That is, the shock wave would move at least as rapidly as $t^{2/3}$ even if the piston stopped. For the models discussed above, we have $m = 0.9$ corresponding to $n = 12$, and $m = 0.8$ corresponding to $n = 7$. For m in this range, the thickness of the hot region is about 20% of the shock radius. If ρ_1 and ρ_2 are taken to be characteristic densities of regions 1 and 2, the ratio of the thickness of the inner region to that of the outer region is

$$\frac{\Delta R_2}{\Delta R_1} = \frac{1}{n-3}\,. \tag{16}$$

For plausible values of n, the region 2 is considerably thinner than region 1.

An important aspect of the flow is that the hot shell decelerates and that the inner parts of the shell have higher density than the outer parts. This situation is subject to the Rayleigh-Taylor instability. Dense blobs of gas are expected to move out into the lower density gas, probably creating turbulence in the shell. I analyze this situation in a manner similar to Kahn's (1975) analysis of the expansion of a uniform supernova envelope into a uniform medium. The growth time for the Rayleigh-Taylor instability, $t_{\rm R-T}$, is approximately $(g_{\rm eff}/l)^{-1/2}$, where $g_{\rm eff}$ is the effective gravity and l is the unstable length scale. We have $g_{\rm eff} = -d^2R/dt^2 = m(1-m)R/t^2$ and define β_1 by $l = 0.2\,\beta_1 R$. The number of growth times is then

$$\frac{t}{t_{\rm R-T}} = \left[\frac{m(1-m)}{0.2\beta_1}\right]^{1/2} = \left[\frac{5(n-3)}{(n-2)^2\beta_1}\right]^{1/2} . \quad (17)$$

For $n = 12$, there are $0.7\beta_1^{-1/2}$ growth times so that the instability can be expected to grow into the nonlinear regime on a scale that is small compared to the shell thickness. The instability can be viewed as mass from region 2 moving into and mixing with mass from region 1. Assuming that the mass moves a distance $\beta_2\,\Delta R$ within the shell, the energy liberated by this process is approximately $M_2\,g_{\rm eff}\,\beta_2\,\Delta R$. This energy is probably deposited as turbulent energy. The ratio of the turbulent energy density to the thermal energy density in the outer postshock region is

$$\frac{u_{\rm tu}}{u_{\rm th}} = \frac{\beta_2 M_2 g_{\rm eff}}{4\pi R^2}\frac{2}{3P_1} \quad (18)$$

$$= \frac{2}{3}\frac{\beta_2 M_2}{(M_1+M_2)}\frac{(P_1-P_2)}{P_1}$$

$$= \frac{1}{3}\frac{(n-4)}{(n-3)}\beta_2 .$$

For $n = 12$, $u_{\rm tu}/u_{\rm th} = 0.30\ \beta_2$; the turbulent energy density can be a large fraction of the thermal energy density if the instability covers a large part of the shell.

III. RADIO EMISSION

I assume that the supernova envelope in SN 1980k interacted with circumstellar material as described in § II. The supernova was observed at 6 cm near maximum light, approximately 51 days after the explosion (see § I). If the maximum material velocity is taken to be 15,000 km s^{-1}, the shell has expanded to 6.6×10^{15} cm at the time of the radio emission. The observed 6 cm flux from the supernova on 1980 December 4 was 0.7 mJy (Sramek, van der Hulst, and Weiler 1980), but the flux subsequently rose to about 2.6 mJy over the next 80 days (Weiler *et al.* 1982). The low-frequency turnover in the spectrum (Weiler *et al.* 1982) implies that the reduced emission on December 4 is probably due to an absorption effect. On the assumptions that the unabsorbed flux on December 4 was 2.6 mJy, that the distance to the supernova is 10 Mpc (Sandage and Tammann 1974), that the optically thin spectral index is $\alpha = 0.5$ (where α is defined by flux proportional to $\nu^{-\alpha}$), and that the maximum radio frequency is 10^{11} Hz, the radio luminosity is 7×10^{36} ergs s^{-1}. While there are some unsupported assumptions in this estimate, the deduced luminosity is not much larger than the minimum plausible luminosity. In the present model, the radio emission is taken to be from the hot shell, and the emitting region is assumed to cover a radial region $0.2\,\beta_3 R$ in the shell, where β_3 is approximately the fraction of the shell that is occupied by the emitting region. The radio photons from the shell which move in toward the center of the explosion are absorbed by free-free processes, so that only a fraction ϕ of the total luminosity can be observed. If the emitting region extends from R_2 out to R_1 and if the absorbing material extends to R_2, we have

$$\phi = \frac{1}{2} + \frac{(1 - R_2^2/R_1^2)^{3/2}}{2(1 - R_2^3/R_1^3)} . \quad (19)$$

Taking $R_2/R_1 = 0.8$, $\phi = 0.72$. Under these circumstances, the equipartition magnetic field in the shell is $0.21\ \beta_3^{-2/7}(R/6.6 \times 10^{15}\ {\rm cm})^{-6/7}$ gauss, if there is no protron acceleration. The energy density in the magnetic field, u_B, is then $1.7 \times 10^{-3}\,\beta_3^{-4/7}(R/6.6 \times 10^{15}\ {\rm cm})^{-12/7}$ ergs cm^{-3}, and the relativistic electron energy density, u_e, is 4/3 times as large. This can be compared with the postshock thermal energy density for a 15,000 km s^{-1} shock wave, $3.0\ \dot{M}_{-5}\,v_1^{-1}(R/6.6 \times 10^{15}\ {\rm cm})^{-2}$ ergs cm^{-3}. Although it depends on the presupernova mass loss rate, the equipartition field and particle energy densities are likely to be less than 1% of the thermal energy density.

If a similar analysis is applied to the radio shell in the Cas A remnant and if the thermal energy density is taken from X-ray observations of the remnant (Fabian *et al.* 1980), a similar result is obtained: the equipartition energy density is about 1% of the thermal energy density. In Cas A, the field amplification and particle acceleration can plausibly be attributed to turbulent motions generated by the Rayleigh-Taylor instability created by the deceleration of the supernova ejecta by the surrounding medium (Gull 1973*a*, *b*). I have shown in § II that a similar situation occurs with the interaction of the outer supernova envelope with circumstellar matter. There are differences between the two situations which may affect the particle acceleration. The density in the supernova case is higher by about 10^6, which enhances nonthermal particle losses by ionization (Cerenkov emission) and free-free processes. However, these losses are not expected to be important for electrons.

The expected time dependence of the supernova radio luminosity can be deduced on the assumption that the ratio of the magnetic energy density and the relativistic electron density to the thermal energy density remains constant. It is straightforward to show that the radio luminosity evolves as $R^3 t^{-(\gamma+5)/2}$, where R is the shell radius and γ is the electron spectral index. Taking the time dependence of the shell radius to be a power law as in § II, the luminosity evolves at $t^{-(\gamma+5-6m)/2}$, where m is in the range of 0.8 to 0.9. This evolution applies when the emission is optically thin and while the shell is still within a circumstellar region in which the presupernova mass loss rate has been approximately constant.

Radio luminosity curves have been obtained for both SN 1979c and SN 1980k (Weiler *et al.* 1982), and they clearly show that there was low-frequency absorption of the radio emission. The increasing transparency is perhaps best shown by the rise in the 20 cm flux from SN 1980k; if a power law is fitted to the data, it is as steep as $F_\nu \propto t^7$. The data indicate that optical depth unity at 20 cm occurred about 180 days after the explosion. Four possible mechanisms for the low frequency turnover are (*a*) synchrotron self-absorption, (*b*) free-free absorption in the emitting shell, (*c*) free-free absorption in the cool circumstellar matter, and (*d*) the Razin-Tsytovich effect, which tends to suppress synchrotron radiation because the index of refraction of the plasma is not equal to unity. In examining these possibilities, I assume that the energy densities of the field and relativistic particles evolve as described above.

Synchrotron self-absorption can be ruled out as the absorption mechanism for two reasons. First, the absorption depth is too small. The optical depth, τ_{syn}, is proportional to $u_e u_B^{(\gamma+2)/4}\beta_3\,\Delta R$ for a line of sight passing radially through the shell. Using the model described above for the emission and taking $m = 0.9$ and $\gamma = 2$, τ_{syn} is 0.03 $\beta_3^{-1/7}$ at 20 cm 180 days after the explosion. The model does assume equipartition, which may not apply, but τ_{syn} can also be written as proportional to $Lu_B^{1/4}R^{-2}$, where L is the luminosity. For τ_{syn} to be of order unity, the magnetic energy density would have to be larger than the thermal energy density, which is not allowed in this model. Another argument against synchrotron self-absorption is the increase of flux with time. In the optically thick limit, the flux varies as

$$F_\nu \propto I_\nu R^2 \propto B^{-1/2}\nu^{5/2}R^2 \propto \nu^{5/2}R^2 t^{1/2}\,, \tag{20}$$

where I_ν is the intensity of the radiation. The radius R increases at most as proportional to t, so the observed rapid rate of increase cannot be reproduced.

Free-free absorption within the shell can also be ruled out for two reasons. First, as noted in Paper I, the absorption is likely to be less than the circumstellar absorption because of the higher temperature in the shell. The only reason to alter this conclusion would be if the radio emission is from a denser inner region of the hot shell (e.g., region 2 of the shell). An estimate of the absorption in the shell shows that the density would have to be 500 times greater than the postshock density for the internal absorption to be greater than the circumstellar absorption, if all the shell mass were at the high density. The fraction of the mass at this density is probably so small that the effect is negligible. The second argument against the internal absorption is again the steep rise in flux with time. In the optically thick limit, the flux is

$$F_\nu \propto I_\nu R^2 \propto \frac{u_e B^{(\gamma+1)/2}R^2}{n^2 T_{\text{sh}}^{-3/2}} \propto t^{(18m-\gamma-11)/2}\,, \tag{21}$$

where it has been assumed that the shell radius increases as t^m. Taking $\gamma = 2$, the time dependence is no more extreme than $F_\nu \propto t^{5/2}$, which is contrary to the observations. Marscher and Brown (1978), in a similar calculation, obtained $F_\nu \propto t^{9/2}$ for internal free-free absorption. The reason is that they assumed that the emission was from an expanding sphere rather than an expanding shell, so that $n \propto R^{-3}$ in their case.

In the case of absorption by the external circumstellar matter, there is no problem with the steep turn on: an exponential rise is expected. In fact, the 20 cm rise of SN 1980k can be approximately fitted by an exponential rise. As in Paper I, the free-free optical depth in this case can be written as

$$\tau_{\nu\text{ff}} = 4\,\dot{M}_{-5}{}^2 v_1{}^{-2} u_4{}^{-3} t_7{}^{-3}\left(\frac{\nu}{1.4\text{ GHz}}\right)^{-2}\,, \tag{22}$$

where u_4 is the maximum material velocity in units of 10^4 km s^{-1} and t_7 is the time since the explosion in units of 10^7 s. In order to give $\tau = 1$ at 20 cm at $t = 180$ days, $\dot{M}_{-5}v_1{}^{-1}u_4{}^{-3/2}$ must be 1.0. This implies a presupernova mass loss rate of order $10^{-5}\,M_\odot$ yr^{-1}, which is in the observed range (Zuckerman 1980). The mass loss estimate would be reduced by a factor $\bar{n}/\langle n^2\rangle^{1/2}$, where $\bar{n}$ is the average density, if the circumstellar gas were clumpy.

The Razin-Tsytovich effect is also capable of giving the observed rapid flux rise because the spectrum decreases exponentially at low frequency (e.g., Simon 1969). However, for the model for SN 1980k on day 180, the density in the radiating region would have to be at least 50 times greater than the postshock density for the Razin-Tsytovich effect to dominate circumstellar absorption. This density is greater than that expected in most of the hot shell. Even if there are regions of high density, there is no reason to expect the radio emission to be correlated with these regions. In the present model, the radio emission is associated with turbulence in the gas which fills most of the shell volume. Thus, it is unlikely that the Razin-Tsytovich effect is important, although it cannot be completely ruled out.

The above analysis ruled out two possibilities for the low-frequency turnover, but it leaves two: the circumstellar free-free absorption, and possibly the Razin-Tsytovich effect. Another check on the possibilities is provided by the relative time of turn-on at the two well observed frequencies. From equation (22), the time to achieve a fixed optical depth to free-free absorption is

$$t_{\text{ff}} \propto \dot{M}^{2/3}v^{-2/3}u^{-1}\nu^{-2/3}\,, \tag{23}$$

while for the Razin-Tsytovich effect, the critical time is

$$t_R \propto \dot{M}^{1/2}v^{-1/2}u^{-2}\nu^{-1}\,. \tag{24}$$

The radio data for SN 1980k indicate that $\tau = 1$ at 20 cm on day 180; the 6 cm flux curve is less well defined, but it appears that $\tau = 1$ was achieved on about day 63. Assuming that the mass loss rate and velocity are constant, the ratio of the shell velocity on the two days can be found. For the free-free absorption, $u_{180}/u_{63} \approx 0.78$

and for the Razin-Tsytovich effect, $u_{180}/u_{63} = 1.1$. The free-free absorption requires deceleration of the shell (e.g., from 15,000 km s^{-1} to 12,000 km s^{-1}), while the Razin-Tsytovich effect is consistent with no deceleration. If the shell expands as t^m, the deceleration required in the free-free absorption case corresponds to $m = 0.76$, which is slightly below the range of m (0.8 to 0.9) discussed in § II. Considering the uncertainties in the model, either mechanism for the low-frequency turnover is consistent with the data.

A further influence on the spectrum is the inverse Compton losses of the relativistic electrons to the photospheric photons. While adiabatic expansion losses are the dominant particle energy loss, an electron spectrum injected with a power law index γ maintains its spectral index. However, if inverse Compton (or synchrotron) losses dominate the adiabatic losses, the spectrum is steepened to a slope $\gamma + 1$ (e.g., Pacholczyk 1970). I now consider SN 1980k on day 51 when the supernova was observed at 6 cm. For adiabatic expansion, the energy of an individual particle varies as $n^{1/3}$ or as $R^{-2/3}$ in the present model. The adiabatic expansion loss time, t_a, is thus approximately 1.5 times the age, or 6.6×10^6 s. The inverse Compton losses depend on the radiation energy density, u_r, which is $WaT_{\text{eff}}{}^4$, where W is the dilution factor, a is the radiation constant, and T_{eff} is the effective photospheric temperature. For a Type II supernova about a month after maximum light, 6000 K is a good estimate for T_{eff}. The dilution factor is $r_{\text{ph}}{}^2/(4R^2)$ where r_{ph} is the photospheric radius, and taking $v_{\text{ph}} = 8000$ km s^{-1} and $u = 15{,}000$ km s^{-1} implies $W = 0.07$. Then $u_r = 0.70$ ergs cm^{-3}. The Compton loss time for relativistic electrons is

$$t_c = \frac{1}{3.97 \times 10^{-2}\, u_r E}, \tag{25}$$

where E is the electron energy and cgs units are used. Setting t_c equal to t_a gives the electron energy above which inverse Compton losses are important. This energy is $\gamma_e = 7$, where γ_e is the relativistic factor of the electrons. Assuming equipartition, the electrons giving the 6 cm flux have $\gamma_e \approx 76\,\beta_3{}^{1/7}$, indicating that these electrons are reduced in number by a factor of 10 compared to their number in the absence of inverse Compton losses. If the magnetic field in the emitting region is larger, this factor is reduced. As time passes, inverse Compton losses should become unimportant, which could give an increase in the emitted flux. Part of the early rise at 6 cm could be due to this effect rather than free-free absorption or the Razin-Tsytovich effect.

Radio emission has now been detected from three Type II supernovae; they are listed in Table 1. The distances to the parent galaxies are from Sandage and Tammann (1974, 1976) and the radio data is from Allen *et al.* (1976) on SN 1970g and from Weiler *et al.* (1982) on SN 1979c and SN 1980k. The 6 cm fluxes are chosen to represent the fluxes when they have approximately leveled out. The time t_t is the time when the 20 cm is rising sharply. It is not accurately known for SN 1970g. SN 1979c became thin at 20 cm considerably later than SN 1980k. If the absorption is free-free absorption in the circumstellar envelope, the difference between the two supernovae can be found in the context of the model described in § II. At a given frequency, we have

$$\begin{aligned} L_\nu &\propto R^3(m^2\dot{M}v^{-1}t^{-2})^{(5+\gamma)/4}\nu^{-(\gamma-1)/2} \\ &\propto (U_c{}^n)^{3(1-m)}(\dot{M}/v)^{(\gamma-7+12m)/4}m^{(5+\gamma)/2} \\ &\quad \times t^{-[(\gamma+5-6m)/2]}\nu^{-(\gamma-1)/2}, \end{aligned} \tag{26}$$

where equation (9) has been used to substitute for R. The quantity $U_c{}^n$ has been kept in the expression because it is proportional to the supernova density at a given material velocity. The optical depth is

$$\begin{aligned} \tau_\nu &\propto (\dot{M}/v)^2 R^{-3}\nu^{-2} \\ &\propto (U_c{}^n)^{-3(1-m)}(\dot{M}/v)^{5-3m}t^{-3m}\nu^{-2} \end{aligned} \tag{27}$$

so that the time to reach a given optical depth is

$$t_t \propto (U_c{}^n)^{-[(1-m)/m]}(\dot{M}/v)^{(5-3m)/3m}\nu^{-2/3m}. \tag{28}$$

SN 1979c has L_ν larger than that of SN 1980k by a factor of about 17, and t_t is larger by a factor of about 3.4. These differences cannot be explained by changes in $U_c{}^n$ alone because this would change L_ν and t_t in opposite directions. Combining equations (26) and (28) and taking $\gamma = 2$, we have

$$U_c{}^n \propto L_\nu{}^{[4(5-3m)]/[45(1-m)]}t_t{}^{-[m(12m-5)]/[15(1-m)]} \tag{29}$$

and

$$\dot{M}/v \propto L_\nu{}^{4/15}t_t{}^{4m/15}. \tag{30}$$

The differences between SN 1979c and SN 1980k can be attributed to SN 1979c having $U_c{}^n$ larger by a factor of 4.5 and $\dot{M}/v$ larger by 5.2 compared to SN 1980k for $m = 0.9$, or $U_c{}^n$ larger by 4.6 and $\dot{M}/v$ larger by 4.7 for $m = 0.8$. There is some independent observational

TABLE 1

Radio Supernovae

Parameter	SN 1970g, NGC 5457	SN 1979c, NGC 4321	SN 1980k, NGC 6946
Distance (Mpc)	6.5	22	10
F_ν (6 cm) (mJy)	~5	7	2
Relative L_ν (6 cm)	1	17	1
t_t (20 cm) (days)	$160 < t_t < 560$	550	160

evidence for more high velocity gas in SN 1979c than in SN 1980k. The Hα line was found to be considerably broader in the spectrum of SN 1979c than in that of 1980k (Kirshner 1981).

An additional constraint on models for the radio emission is that the linear polarization of the 6 cm flux from SN 1979c was observed to be less than 1% (Weiler *et al.* 1982). In the present model, the mechanism for the radio emission is analogous to that in Cas A. The average degree of polarization around the rim of Cas A at 6 cm is about 5%, and there are regions where it reaches 10% (Rosenberg 1970). However, the integrated polarization of the remnant is only 1.4 ± 0.5% (Rosenberg 1970), because of the approximate circular symmetry of the remnant. A polarized fraction of this approximate magnitude would be expected for the supernova emission if internal Faraday dispersion were negligible. For SN 1979c at an age of one year, we have $n_e \Delta R \approx 3 \times 10^{21}$ cm^{-2} and a magnetic field of about 0.02 gauss in the emitting shell. Under these circumstances, the polarization fraction at 6 cm can be reduced by a factor of about 5×10^4 as a result of internal Faraday dispersion (Burn 1966). The polarized fraction is predicted to be very small.

IV. X-RAY EMISSION

Einstein Observatory observations of SN 1980k have provided the first X-ray detection of a supernova soon after maximum light (Canizares, Kriss, and Feigelson 1982). On the assumption of a distance of 10 Mpc, the 4.0 keV luminosity was 2×10^{39} ergs s^{-1} on 1980 December 11 (day 58 for the supernova in the present paper) and was about 1×10^{39} ergs s^{-1} on 1980 January 27 (day 105). Thermal emission, inverse Compton scattering of photospheric photons, and reverberation of an initial X-ray burst were considered as possible sources of the X-rays by Canizares, Kriss, and Feigelson (1982) and by Chevalier (1981*b*). Canizares, Kriss, and Feigelson also briefly considered synchrotron emission, "self-Compton" scattering, pulsar emission, and degradation of γ-rays. They favor inverse Compton scattering of photospheric photons, although thermal emission is another possibility. Synchrotron radiation is a more remote possibility. The problem of inverse Compton losses decreasing the number of radiating electrons discussed in § III is greater for the high energy electrons emitting X-ray synchrotron radiation. Here I discuss the most promising X-ray emission mechanisms: thermal emission and inverse Compton emission.

In the context of the hydrodynamic model described in § II, there are two components to the thermal emission: emission from the shocked circumstellar medium and emission from the shocked supernova gas. The bremsstrahlung luminosity of the shocked circumstellar gas is estimated to be (Paper I):

$$L_1 \approx 1.6 \times 10^{39} \dot{M}_{-5}{}^2 v_1{}^{-2} r_{15}{}^{-1} T_9{}^{1/2} \text{ ergs s}^{-1} , \quad (31)$$

where T_9 is the postshock electron temperature in units of 10^9 K. For the case of SN 1980k, $\dot{M}_{-5} v_1{}^{-1} = 1$ and $r_{15} = 6.6$ yield a luminosity of 2.4×10^{38} ergs s^{-1}. Because of the high postshock temperature, most of this luminosity would be radiated at a photon energy close to 100 keV and the energy in the 0.2–4 keV band would be about 3×10^{37} ergs s^{-1}. It is unlikely that the shocked circumstellar medium contributed significantly to the observed emission from SN 1980k. The luminosity of the shocked supernova gas, L_2, can be estimated using the model of § II. We have

$$\frac{L_2}{L_1} \approx \frac{\rho_2 M_2 \Lambda(T_2)}{\rho_1 M_1 \Lambda(T_1)} = \frac{(n-3)(n-4)^2}{4} \frac{\Lambda(T_2)}{\Lambda(T_1)} , \quad (32)$$

where Λ is the optically thin cooling function in units of ergs cm^3 s^{-1}, so that

$$\frac{L_2}{L_1} \approx \begin{cases} 9.0 \dfrac{\Lambda(0.062 T_1)}{\Lambda(T_1)} & \text{for} \quad n = 7 \\ 140 \dfrac{\Lambda(0.012 T_1)}{\Lambda(T_1)} & \text{for} \quad n = 12 . \end{cases} \quad (33)$$

While bremsstrahlung is the dominant emission process, Λ is proportional to $T^{1/2}$, but as the temperature approaches 10^7 K, emission in lines dominates. The emissivity at 10^7 K is about a factor 1.5 smaller than the emissivity at 10^9 K (Raymond, Cox, and Smith 1976). Not only is the luminosity from the shocked supernova gas much larger than that of the shocked circumstellar gas, but also most of the luminosity appears in the 0.2–4 keV energy range because of the lower gas temperature. The situation is similar to that thought to occur in young supernova remnants (McKee 1974). I have neglected occultation of the X-rays, but the reduction is less than a factor of 2, which is small compared to other uncertainties in the problem. It is clear that the shocked supernova gas can produce X-ray emission at the observed level; in fact, the $n = 12$ model may overproduce X-rays. The situation would be modified if electron-ion energy equipartition is not achieved in the shock waves or if electron conduction is important. As more detailed observations become available, it will be necessary to consider these effects.

I now estimate the inverse Compton X-ray emission using parameters from the model for the radio emission discussed in § III. Beall (1979) first noted that a supernova which radiates synchrotron radio emission could emit a substantial inverse Compton X-ray flux. I take the unabsorbed radio flux from SN 1980k to have been 2.6 mJy on 1980 December 4 and assume that the electron spectral index was 2. The inverse Compton flux at 1 keV is then

$$F_\nu = 0.003 \left(\frac{T_{\text{eff}}}{6000 \text{ K}}\right)^{3.5} \left(\frac{W}{0.07}\right) \left(\frac{B}{B_{\text{eq}}}\right)^{-3/2} \beta_3{}^{3/7} \times \left(\frac{R}{6.6 \times 10^{15} \text{ cm}}\right)^{9/7} \mu\text{Jy} , \quad (34)$$

where B_{eq} is the equipartition magnetic field. This is to be compared with an observed flux of 0.04 μJy on 1980 December 11 (Canizares, Kriss, and Feigelson 1982). Occultation effects can reduce the predicted X-ray flux. Unlike the thermal emission, the inverse Compton emission is anisotropic. The emissivity is proportional to $(1 - \cos\theta)^{\alpha+1}$, where θ is the angle between the electron direction of motion and the photon direction of motion and α is the spectral index (Jones, O'Dell, and Stein 1974; Reynolds 1982). I consider the case where the supernova photosphere (the photon source) is at a much smaller radius than that of the shell containing the relativistic electrons. Then photons move out radially from the center of expansion and photons from inverse Compton interactions with a large angle θ (close to 180°) are absorbed. The emissivity is the largest for these angles. If the radiating shell is at R and the occulting region extends to R_0, the luminosity is reduced by a factor

$$f = \{\tfrac{1}{2} + \tfrac{1}{2}[1 - (R_0/R)^2]^{1/2}\}^{2+\alpha} . \qquad (35)$$

For $R_0 = R$ and $\alpha = 0.5$, the luminosity is reduced by 0.18. This is an extreme case, and for likely values of R_0/R the luminosity change is less than a factor of 2.

The inverse Compton flux calculated in equation (34) is more than an order of magnitude below the observed flux, but there is considerable uncertainty in the model parameters. However, changing the parameters to increase the inverse Compton flux aggravates the problem discussed in § III that the density of radio-emitting electrons is decreased by inverse Compton losses. The fact that a substantial radio flux was observed on 1980 December 4 argues against the importance of these losses. While the inverse Compton mechanism for the X-rays cannot be ruled out, it appears to be less likely than thermal emission.

X-ray observations of SN 1979c were undertaken with the *Einstein Observatory* 63, 73, and 239 days after optical maximum light, but it was not detected (Palumbo *et al.* 1981). At a distance of 22 Mpc, the upper limits on days 63 and 73 are about 2×10^{40} ergs s^{-1}. These times are between the times (relative to maximum light) of the X-ray observations of SN 1980k. The corresponding luminosity of SN 1980k would be somewhat greater than 1×10^{39} ergs s^{-1}. The model for the radio emission in § III indicated that both $U_c{}^n$ and $\dot{M}v^{-1}$ were higher in SN 1979c than in SN 1980k by factors of about 4.7. Since the ratio of $U_c{}^n$ to $\dot{M}v^{-1}$ is the same in both supernovae, the shell radius and velocity should be the same at the same time (assuming that the same value of n applies to both supernovae). The thermal emission from SN 1979c should be higher than that from SN 1980k by a factor $4.7^2 = 22$. If the observed X-ray emission from SN 1980k was thermal, the predicted luminosity for SN 1979c is between 2×10^{40} and 3×10^{40} ergs s^{-1}, which is marginally in conflict with the upper limits. If an explanation is required for this slight discrepancy, one possibility is that the two supernovae were characterized by different values of n.

The circumstellar matter that appears to be responsible for the absorption of the radio emission might also be expected to absorb the X-ray emission. If oxygen is not completely ionized, the dominant X-ray absorption process at 1 keV is K shell ionization of oxygen. The photoionization cross section at 1 keV is about 1.2×10^{-19} cm^2 for a range of ionization stages of oxygen (Daltabuit and Cox 1972). Taking $n_0/n_H = 6 \times 10^{-4}$, the optical depth through the circumstellar matter is

$$\tau_{1\,\mathrm{keV}} = 18\,\dot{M}_{-5}\,v_1{}^{-1}u_4{}^{-1}(t/1\ \mathrm{day})^{-1} . \qquad (36)$$

This is an upper limit to the optical depth; it is reduced if oxygen is completely ionized or is in the form of O VIII. Taking $\dot{M}_{-5}v_1{}^{-1} = 1$ for SN 1980k and $L_x = 2 \times 10^{39}$ ergs s^{-1} on 1980 December 11, $\xi = L_x/nr^2$ is characterized by $\log \xi \approx 2$. At earlier times it is expected to be larger. Although they treat only a bremsstrahlung X-ray source, the calculations of Tarter, Tucker, and Salpeter (1969) indicate that oxygen is completely ionized at early times if the gas is optically thin. Optical depth effects are expected to be important, and a complete radiative transfer calculation is required to accurately determine the absorption of X-rays. However, equation (36) shows that absorption is important only at very early times, perhaps before maximum optical light. A measurement of the X-ray absorption would be valuable because it would give a measure of $\int n dr$, while the radio absorption gives $\int n^2 dr$ in the circumstellar medium.

V. DISCUSSION

If the model described in this paper is correct, radio and X-ray observations give information on a region of the supernova which is distinct from the optical photosphere. Interpretation of these observations leads to estimates of the presupernova mass loss rate and to the density structure of the outer parts of the expanding supernova. Ultraviolet observations of SN 1979c appear to give independent evidence on circumstellar gas because spectral lines imply the presence of gas with a velocity range smaller than that of the supernova photosphere (Panagia *et al.* 1980). One theory for these features is that they are formed in a preshock region which is accelerated by radiation pressure in ultraviolet lines (Paper I). The theory assumed a presupernova mass loss rate of $10^{-6}\ M_\odot$ yr^{-1}, but the present work indicates a mass loss rate of about $5 \times 10^{-5}\ M_\odot$ for SN 1979c based on the radio free-free absorption. This high rate of mass loss would not allow sufficient radiative acceleration in ultraviolet lines. The two mass loss estimates may be reconciled if the low estimate is correct and the circumstellar gas is clumped, with much of the gas in regions with a density 2500 times the average density. The proper amount of absorption occurs because it depends on the density squared. The present models also indicate a larger supernova X-ray luminosity than was estimated in Paper I. This results in ionization of the low density gas ahead of the shock wave to ionization stages beyond those observed. However, optical depth effects would be important for the ionizing photons and a region containing Si IV and C IV would be expected at some distance from the shock front (e.g., Fransson 1982). Acceleration may still occur in this region. Finally, the low mass loss rate would yield a smaller postshock thermal energy density. However, the equipartition magnetic field and relativistic electron energy densities would still be less than 5% of the thermal energy density.

Another possibility is that some other mechanism is responsible for the preshock acceleration. In the model for the ultraviolet lines of Fransson (1982), the presupernova mass loss rate is about $10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$, and the preshock acceleration is by electron scattering. One difficulty with this theory is that the required radiated energy is more than an order of magnitude larger than the observed radiated energy (Branch *et al.* 1981). This emission would have to occur between the time of the explosion and the time of discovery of the supernova. In the absence of light curve models which fit the light curve of SN 1979c, it is not known whether this is plausible. The mass loss rate from the SN 1979c progenitor implied by the theory of Fransson (1982) for the ultraviolet lines and by the present study of the radio emission is much larger than that assumed in Paper I. With the large mass loss rate, the circumstellar emission theory for the infrared radiation becomes viable (Paper I; Bode and Evans 1980). This is especially true if the large radiated energy implied by the theory of radiative acceleration by electron scattering was emitted.

The discovery of X-ray emission from Type II supernovae can have implications for emission at other wavelengths, e.g., optical, because on the order of half of the X-ray luminosity may be absorbed by the expanding supernova envelope. The reradiation of this emission is currently under investigation.

The models described here apply only to Type II supernovae. If Type I supernovae are exploding white dwarf stars, they are not expected to have extended circumstellar envelopes and the phenomena described in this paper do not occur. This is consistent with the fact that radio emission from Type I supernovae has not yet been detected.

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