In this paper, we explore the emission from cosmic strings, a remnant of the early universe. Using a specific model that incorporates the peer pressure, we derive the expression for the radio emission from these strings. We find that this emission can be significant, particularly in the high-frequency range. The results are consistent with previous studies and provide a new perspective on the detection of cosmic strings. The implications of this work are discussed, emphasizing the need for further observations to confirm our findings.
by the synchrotron self-absorption interpretation of the radio spectrum of SN1998bw and discuss the origin of the field. In §4 I mention possible mechanisms for achieving electron-ion and particle-field equipartition. In §5 I ask if the radio spectrum may in fact be the result of inverse bremsstrahlung by a thermal gas; although possible, this does not lead to drastically lower estimates of the field than those presented in §3. §6 questions the association of SN1998bw with GRB980425. §7 contains a summary discussion and predictions.

2. Compton Electrons

Iwamoto, et al., 1998 inferred, on the basis of its visible light curve, that SN1998bw contained about 0.7$M_\odot$ of $^{56}$Ni, or $N_{56} = 1.5 \times 10^{55}$ atoms. The 6.10 d half-life of $^{56}$Ni (an $\alpha$-folding decay time of 8.8 d) is comparable to the duration of the first peak of radio intensity found by Kulkarni, et al. 1998. The daughter nucleus $^{56}$Co decays with a half-life of 77 d (an $\alpha$-folding decay time of 111 d), comparable to the rise and decay time scale of the second, lower frequency, peak of radio emission in SN1998bw.

The two characteristic time scales of radio emission and the double-peaked intensity observed at some wavelengths suggest two distinct, but analogous, processes. In addition, the observation of expansion with Lorentz factor $\Gamma$ in the approximate range 1.6–2 calls for explanation. Is there a natural explanation of the observation of mildly relativistic expansion with this particular value of $\Gamma$?

The decay of $^{56}$Ni (which is by electron capture) produces gamma-rays of 0.788 MeV, 0.812 MeV and 1.56 MeV, which are emitted in 48%, 85% and 14% of the decays, respectively (Lederer, Hollander & Perlman 1967). The decay of $^{56}$Co, 80% by electron capture, produces gamma-rays of several energies, of which the most important are 0.847 MeV (100%), 1.04 MeV (15%), 1.24 MeV (66%), 1.76 MeV (15%), 2.02 MeV (11%), 2.60 MeV (17%) and 3.26 MeV (13%); 20% of its decays are by $\gamma$ emission, with an energy distribution extending up to 1.5 MeV. This copious production of gamma-rays offers a possible explanation of the existence and expansion speed of the radio source and perhaps of its magnetic field.

It is necessary to assume that the $^{56}$Ni is mixed to the surface of the debris; perhaps a jet or plume of $^{56}$Ni-rich material penetrates any envelope and is expelled. The absence of H or He in the spectrum of SN1998bw establishes the absence at least of a massive envelope cloaking the high-Z material. After 10$^5$ s at the observed photospheric velocity of $6 \times 10^3$ cm/s this matter is in a shell of column density $\approx 3$ gm/cm$^2$. If mixed with an equal quantity of other material, to make up a Chandrasekhar mass of debris, the total column density is $\approx 6$ gm/cm$^2$, which is transparent (optical depth $\approx 0.5$) to 0.812 MeV gamma-rays, the most important emission of $^{56}$Ni.

After the gamma-rays emerge from the supernova debris they enter any surrounding medium, moving outward at the speed of light. Their source gradually becomes transparent to them as it expands, and their emergent intensity increases with a rise time of a few days, until the competition between increasing transparency and radioactive decay leads to a peak at $\approx 10$ d, corresponding to the first peak in radio intensity. Averaging over the Klein-Nishina cross-section, the mean electron produced by Compton scattering of a 0.812 MeV gamma-ray has $\gamma = 1.65$ and the most energetic has $\gamma = 2.12$. The stopping column density of a $\gamma = 1.65$ (kinetic energy $E_C = 330$ KeV) electron in dilute ($n_e \sim 10^4$ cm$^{-3}$; the dependence on $n_e$ is only through the Coulomb logarithm and is very weak) ionized plasma is $\tau_s \approx 8 \times 10^{21}$ cm$^{-2}$ (Lang 1980). Comparing this to the Klein-Nishina cross-section $\sigma_{KN} \approx 2.6 \times 10^{-25}$ cm$^{-2}$ yields an estimated efficiency of conversion of gamma-rays to Compton electrons $\epsilon = \tau_s \sigma_{KN} \approx 2 \times 10^{-2}$; the remaining energy appears as thermal heating of the plasma by Compton electrons which stop within it.
If there is less than a stopping length of low-Z medium surrounding the $^{56}$Ni then the efficiency will be reduced, because in traversing the high-Z debris the Compton electrons suffer Coulomb scattering by the nuclei as well as energy losses to the electrons; the scattering length in pure $^{56}$Ni is only $\approx 10^{19}$ cm$^2$ (Spitzer 1962). A hydrogen-rich shell of column density $10^{20}$ cm$^{-2}$ (requiring only $4 \times 10^{-3} M_\odot$ at a radius of $6 \times 10^{15}$ cm, the distance traveled by the massive debris in $10^6$ s) would be sufficient to regenerate the full flux of Compton electrons and to restore the efficiency to the value of the preceding paragraph. As discussed above, supernovae are expected to be surrounded by the remains of the winds of their progenitors.

These Compton electrons move outward with a mean speed $v_e \approx 0.8c$ and current density $j_{Compt}$. Once they have expanded to a radius $> 2$ times that at which they were born they move essentially radially outward, which may be shown either by considering them as an adiabatically expanding gas (non-relativistic components of motion are, in effect, random thermal velocities, soon converted to ordered outward motion) or as individual ballistic particles. This free expansion requires a denser ambient medium in order to provide a return (counter-) current density $\vec{j}_c$ to maintain electrical neutrality. The free-streaming density of Compton electrons

$$n_{Ce} = \frac{\nu_{56}^{N_{56}} \exp(-\nu_{56} \Delta t)}{4\pi r^2 v_e},$$

(1)

where $\nu_{56}$ is the radioactive decay rate ($1.3 \times 10^{-6}$ s$^{-1}$ for $^{56}$Ni) and $\Delta t$ the time between creation of the $^{56}$Ni and the decays whose Compton-scattered electrons are observed; the nonrelativistic motion of the $^{56}$Ni and the gamma rays' path between production and Compton scattering are neglected. Adopting $\Delta t = 7$ d and $r = 3 \times 10^{16}$ cm yields $n_{Ce} \approx 3 \times 10^{3}$ cm$^{-3}$, corresponding to $\approx 3 \times 10^{-5} M_\odot$ of hydrogen, similar to values estimated elsewhere in this paper. A medium even slightly denser than this, such as plausibly produced by loss of the progenitor’s envelope over $\sim 10^3$ y, would supply the countercurrent required by charge neutrality with only a small cost in energy to the Compton electrons (the potential required to drive the countercurrent retards the Compton electrons, but only slightly if the countercurrent density is significantly larger and velocity significantly less).

After the $^{56}$Ni decays, $^{56}$Co produces its own gamma-rays, Compton electrons and positrons. The combination of positrons and Compton electrons permits a neutral mildly relativistic wind even in the absence of a background plasma to provide a countercurrent, should there be none. In other respects, the effects of $^{56}$Co decays are similar to those of $^{56}$Ni decays, although the $^{56}$Co gamma-rays and Compton electrons are more energetic (the abundant 1.24 MeV gamma-ray produces a mean Compton $\gamma_e = 2.14$ and the gamma-ray spectrum extends up to 3.26 MeV). This new wave of Compton electrons will eventually outshine the $^{56}$Ni Compton electrons and produce a second peak of radio emission, as observed.

3. Magnetic Field

3.1. Self-Absorbed Spectrum

Inspection of the radio spectrum of SN1998bw (Kulkarni, et al. 1998) shows evidence of self-absorption. The characteristic self-absorption frequency is $\approx 5$ GHz 10 d after the supernova, declines to $\approx 2$ GHz after 30 d, and continues to decline as the source fades thereafter. This agrees with expectations for an expanding self-absorbed synchrotron source. The low frequency (self-absorbed) flux first rises as the radiating area expands. The higher frequency flux declines as a consequence of declining magnetic field or electron energies. It is possible to fit simple models to the data, but the observed (Kulkarni, et al. 1998) double-peaked time dependence of the flux at most frequencies implies that simple models will not be
satisfactory.

The brightness temperature $T_B'$ in the emitting frame may be obtained directly from the observed intensity, if the size of the radiating region is known, and Kulkarni, et al. 1998 used such brightness temperatures, combined with energetic arguments, to infer the rate of expansion of the self-absorbed source:

$$kT_B' (\nu') = \frac{S_\nu d^2}{2 \pi b' c^2 e^2 D},$$

where $k$ is Boltzmann’s constant, $S_\nu$ is the observed flux density, $d = 38$ Mpc is the distance (assuming a Hubble constant of 65 km/s/Mpc), $\nu'$ is the frequency of observation, $t$ is the elapsed time since expansion began, $bc$ is the apparent velocity of expansion ($b = \Gamma \beta$ where $\Gamma$ and $\beta c$ are the Lorentz factor and expansion speed), $D = \left[ \Gamma (1 - \beta \cos \theta) \right]^{-1} \Gamma$ and $\nu' = \nu / D$ where $\nu$ is the observed frequency and $\nu'$ the frequency in the comoving frame.

The brightness temperature of a self-absorbed source will generally approximate the energy of the radiating particles (in thermal equilibrium it equals the particle temperature). Hence the radiating electrons have a Lorentz factor in the co-moving frame

$$\gamma'_e \approx \frac{S_\nu d^2}{2 \pi b' c^2 e^2 \nu^2 D}$$

(3)

### 3.2. Required Field

The co-moving magnetic field $B'$ may be estimated from (3) using the synchrotron radiation relation $B' \approx 2 \pi m_e c \nu' / e \gamma'^2$:

$$B' = \frac{8 \pi^3 m_e^3 \nu^5 B^4 t^4 D^2}{\gamma'^4}.$$ 

(4)

The values of $B$ inferred for SN1998bw are remarkably high. For mildly relativistic motion approximate $D \approx 1$, $b \approx \beta$ and $B \approx B'$. The numerical values (Kulkarni, et al. 1998) $\nu = 2.49$ GHz (nominally $\lambda = 13$ cm), $t = 1.01 \times 10^6$ s (11.7 d), $S_\nu = 19.7$ mJy and $d = 38$ Mpc yield

$$B \approx 0.13 \beta^4 \text{ gauss}.$$ 

(5)

These large inferred fields are a consequence of the low $T_B$ (and $T_B$) implied by a rapidly expanding source of large linear size. The low brightness temperature combined with the interpretation of self-absorption implies radiation by electrons of comparatively low energy, and hence a high magnetic field is required to produce radiation of the observed frequency.

Waxman & Loeb 1998 suggest $\beta \approx 0.5$. This would imply a substantially lower value of $B$ than for mildly relativistic motion (their numerical estimates are somewhat larger than that of (5) because of differences in various details). Kulkarni, et al. 1998 dispute such low values of $\beta$, and this paper does not attempt to resolve this issue.

Is the magnetic field (5) plausible, extended over a region of size $r \approx \Gamma \beta t \approx 3 \times 10^{16} \beta^2$ cm? The implied magnetic energy is

$$\mathcal{E}_B = \frac{D^3 B^2 r^3}{6} \approx 8 \times 10^{44} \beta^{11} \Gamma^{11} D^4 \text{ ergs}.$$ 

(6)

This is modest if the expansion is not relativistic ($\Gamma \approx D \approx 1$). In that case Waxman & Loeb 1998 point out that $\mathcal{E}_B$ is several orders of magnitude less than the kinetic energy of SN1998bw and the energy of the radiating electrons. Only if $\Gamma$ exceeds 2 does $\mathcal{E}_B$ approach the kinetic energy of the supernova debris.
3.3. Sources of Field

3.3.1. Flux

Energy is not the only relevant criterion. If a magnetic field’s dependence on distance can be described by a power law $B \propto r^{-\alpha}$, three simple models may be considered. A static dipole field has $\alpha = 3$; this is clearly inadequate. If the field is frozen into a conducting outflow either from the progenitor or from the SN itself, then flux is conserved and $\alpha = 2$. In this case the apparent inferred flux

$$\Phi_m \approx 10^{32} \beta^6 \text{ gauss cm}^2;$$

(7)

this flux is only apparent because it is $\int |\vec{B}| dS$ rather than $\int \vec{B} \cdot d\vec{S}$. For comparison, the flux of a typical pulsar is $\sim 10^{34}$ gauss cm$^2$, that of a (perhaps-hypothetical) “magnetar” is $\sim 10^{27}$ gauss cm$^2$ and that of the Sun is $\sim 10^{23}$ gauss cm$^2$. The magnetic fields of SN progenitors are not directly measured but it is clear that the estimate (7) is excessive, and that such a flux cannot be produced by a flux-conserving flow. If this model is to be salvaged there must be another source of field.

3.3.2. Hydrodynamic Dynamo Fields

When supernova debris runs into a surrounding medium the contact discontinuity between the two shocked fluids is generally hydrodynamically unstable and may amplify pre-existing fields by a turbulent dynamo mechanism; but this is not readily quantified. Such a medium and shocks are not necessary parts of a supernova model, but will occur if the supernova is surrounded by the remains of a wind produced by its progenitor (Benetti et al. 1999), as is assumed elsewhere in this paper. This is the only mechanism in which the field is powered by the hydrodynamic energy of the supernova, although only a small fraction of this energy is available unless the surrounding medium is as massive as the fast debris.

3.3.3. Radiation Fields

Another possibility is the field of a propagating electromagnetic wave, for which $\alpha = 1$. Because the field alternates in direction with a short wavelength the actual flux is not large, even though the field and apparent flux may be large. The magnetic field at a distance $r \gg c/\omega$ from a source of rotational frequency $\omega$ and dipole moment $\mu$ is

$$B \sim \frac{\mu\omega^2}{c^2 r}.$$

(8)

For a magnetic neutron star ($\mu \sim 10^{33}$ gauss cm$^3$) rotating at breakup ($\omega \sim 1.5 \times 10^4$ s$^{-1}$) $B \sim 10$ gauss at $r = 3 \times 10^{16}$ cm. This is certainly more than sufficient, and allows for smaller $\omega$ or $\mu$. An electromagnetic wind from a neutron star (or magnetized accretion disc) would be required to emerge through the dense debris implied by the visible light curve of the supernova. This is in contrast to a GRB in which the presence of relativistic outflow implies the absence of dense debris, at least in directions in which gamma-rays are observed. If the supernova debris is confined to dense filaments then the electromagnetic wind may penetrate between these filaments, as in the much older Crab Nebula.

If the magnetic field has its origin in the radiation of a new pulsar, then (8) determines $\mu\omega^2$. The spindown power is

$$P = \frac{2}{3} \frac{(\mu\omega^2)^2}{c^3} \sim \frac{2}{3} B^2 r^2 c \sim 10^{48} \text{ erg/s}.$$

(9)
In principle, such a pulsar may be observed once the nonrelativistic debris becomes transparent.

Eq. (8) may be applied to other astronomical objects. For example, a similar estimate has been used to explain the field of the Crab nebula, in which there is a pulsar of known properties, and no dense gas intervening between it and the synchrotron emitting nebula. Accretion discs around black holes in AGN and extragalactic double radio sources are another application; the rotating magnetized disc implies an oscillating magnetic dipole moment and radiation. If the radiation is beamed into an angle $\Omega$ then (8) should be replaced by

$$B \sim \frac{\mu \omega^2}{e^2 r} \left( \frac{4\pi}{\Omega} \right)^{1/2} \sim \left( \frac{B_d}{10^4 \text{gauss}} \right) \left( \frac{M}{10^8 M_\odot} \right) \left( \frac{r}{300 \text{ Kpc}} \right)^{-1} \left( \frac{\Omega}{10^{-2} \text{sterad}} \right)^{-1/2} 3 \mu\text{gauss} \quad (1)$$

$$\sim \left( \frac{L}{10^{46} \text{erg/s}} \right)^{1/2} \left( \frac{r}{300 \text{ Kpc}} \right)^{-1} \left( \frac{\Omega}{10^{-2} \text{sterad}} \right)^{-1/2} 3 \mu\text{gauss}, \quad (2)$$

where $B_d$ is the disc field and the last relation is obtained assuming only that the disc viscosity is magnetic (Katz 1991) and $L$ is the accretional power. In double radio sources equipartition is also suggested if the pressure of the relativistic wind is balanced by that of the electrons accelerated as its fields reconnect.

3.3.4. Compton Current Fields

Electrostatic neutrality requires $\vec{\nabla} \cdot \vec{j}_{\text{comp}} = -\vec{\nabla} \cdot \vec{j}_{ec}$ to high accuracy. It does not require $\vec{j}_{\text{comp}} = -\vec{j}_{ec}$, and if the flow is not spherically symmetric the latter equality is not likely to hold. As a result, the Compton electrons may create closed loops of net current, with resulting magnetic fields. One characteristic value of the field is obtained from Ampère’s Law: $B \sim \epsilon N_{55} \nu_{55} \exp \left( -\nu_{55} \Delta t / r_c \right) \sim 10^{18}$ gauss! It is evident on energetic grounds that fields of this magnitude cannot be created; magnetic forces will induce counter-currents which will cancel the divergence-free part of the Compton current (as well as its divergence) to high accuracy. However, this cancellation will not be exact. Just as electrostatically-driven counter-currents leave a net potential (which drives them) of some fraction of the Compton electron energy, magnetic counter-currents may leave a net current sufficient to produce a field whose energy approaches equipartition with that of the Compton electrons. This energy is $\sim \epsilon N_{55} \nu_{55} \exp \left( -\nu_{55} \Delta t \right) E_c \sim 10^{46}$ ergs, corresponding to $B \sim 0.04$ gauss for $r \sim 3 \times 10^{16}$ cm. This is comparable to that suggested by the synchrotron self-absorption argument, and offers a possible explanation of the apparent deviation of the magnetic energy from energetic equipartition—equipartition is, in fact, achieved, but with the Compton electrons’ energy rather than with the bulk hydrodynamic energy.

3.3.5. Plasma Instability Fields

A related hypothesis attributes the magnetic field to electromagnetic plasma instabilities resulting form the interpenetration of Compton- and counter-currents. In this case the field is chaotic on fine scales rather than ordered, but the possible field energy is again comparable to (but somewhat less than) the energy of the Compton electrons.

4. Equipartition?
4.1. Particle-field Equipartition

Kulkarni, et al. 1998 assume equipartition between magnetic and particle energies in their theoretical argument for mildly relativistic expansion. There are two classical arguments for this assumption. The first is based on attempts to calculate the generation of magnetic fields by dynamo mechanisms. This argument comes in as many forms as there are theories of dynamos, but it generally concludes (or assumes) that when the magnetic energy density becomes a significant fraction of the kinetic energy density its back-reaction on the motion will suppress further dynamo activity. If the particle energy density is similarly limited by the hydrodynamic energy density (Katz 1991) then rough particle-magnetic equipartition will be achieved. Clearly, without detailed understanding of the dynamo and acceleration processes in any particular configuration this argument is very approximate, or perhaps only suggestive, but it does appear to be crudely correct for the interstellar medium and (excluding the energetic particles) for the Solar convective motion.

The second classical argument for particle-field equipartition notes that for a given total energy the synchrotron power radiated will be maximized if equipartition obtains. Astronomical surveys are generally flux-limited, implying that most detected sources will be fairly close to equipartition, if it can be achieved.

It is unclear if either of these arguments applies to SN1998bw. There may be opportunity for Rayleigh-Taylor instability at the contact discontinuity between the forward and reverse shocks when the debris encounters the surrounding medium (likely a wind ejected by the SN progenitor; cf. Benetti, et al. 1999), but this depends on the details of the hydrodynamics. Departures from spherical symmetry may lead to Kelvin-Helmholtz instability. It is unknown if, or how effectively, these processes may produce dynamo field amplification. The radio counterpart of SN1998bw was detected by a search targeted on this unusual visible and gamma-ray object, and was radio flux-limited only in the implicit sense that its detection was limited by the radio sensitivity.

4.2. Electron-ion Equipartition

Electron-ion equipartition presents a question entirely distinct from that of particle-magnetic field equipartition. All GRB models require at least an approximation to electron-ion equipartition in order to couple the ion kinetic energy to the electrons which radiate. Waxman & Loeb 1998 require this too, and in fact their assumed velocity fairly approximates that required (assuming a composition of helium or heavier elements) to produce their estimated electron energies if equipartition occurs. The mechanism of electron-ion equipartition in a collisionless shock, relativistic or non-relativistic may be as simple as an electrostatic double-layer with a potential sufficient to slow the ions as implied by the shock jump condition (Katz 1994).

If cold electron and ion streams penetrate an orthogonal magnetic field their differing gyroradii would lead to a charge separation which can only be avoided by the presence of a potential sufficient to equalize the gyroradii, which (in the relativistic limit) equally divides the kinetic energy between electrons and ions (in the nonrelativistic limit the electron kinetic energy exceeds that of the ions by the ion/electron mass ratio). This is an oversimplification because it assumes the magnetic stress greatly exceeds the hydrodynamic stress, but the qualitative justification for equating gyroradii (and energies, in the relativistic regime)—that only if the gyroradii are equal will electrostatic neutrality be maintained when shocks occur in magnetic fields—may be valid. If the gyroradii are unequal an electrostatic potential will develop which will equalize them.
5. Inverse Bremsstrahlung?

The interpretation of the low-frequency turnover in the radio spectrum of SN1998bw as synchrotron self-absorption led to the inference of a magnetic field too large to be easily explained. An alternative explanation for this turnover is absorption by inverse bremsstrahlung, as suggested by Chevalier 1982. Inverse bremsstrahlung absorption will not, in general, produce the quantitative \( F \propto \nu^2 \) or \( F \propto \nu^{5/2} \) spectra of synchrotron self-absorption, but when the low frequency turnover is only defined by two spectral points of moderate accuracy, as was the case for SN1998bw (Kulkarni, et al. 1998) it is impossible to distinguish between these two explanations on spectral grounds alone.

If the low frequency turnover is the result of inverse bremsstrahlung absorption then the observed brightness temperature is only a lower bound on the brightness temperature in the (optically thin) emitting region. This, in turn, is only a lower bound on the energy of the emitting electrons. Hence the magnetic field is only bounded from above, and may be as small as required by a theory of field generation. The actual field value depends on the electron energy (or vice versa); in the absence of a detailed theory of particle acceleration it is generally impossible to reject an inferred value of the electron energy. High electron energies need not, however, imply excessive brightness temperatures because the source is optically thin. Hence, as argued by Kulkarni, et al. 1998, the synchrotron self-Compton catastrophe may be avoided if the source is expanding relativistically, which reduces the inferred brightness temperature, as first pointed out by Wolter 1966.

If the magnetic field is too small then the ratio of inverse Compton luminosity \( L_{IC} \) to synchrotron \( L_S \) becomes excessive. The value of \( L_{IC} \) permitted by the observations depends on its (unknown) frequency, but it probably safe to require it to be less than the visible luminosity \( L_V \sim 10^{43} \) erg/s, roughly \( 5 \times 10^4 \) times the radio power at \( 10^8 \) s (Kulkarni, et al. 1998). This sets a lower bound on \( B \):

\[
B \approx \left( \frac{2 L_V L_S}{\pi c L_{IC}} \right)^{1/3} > 0.04 \text{ gauss},
\]

where the numerical value has assumed only mildly relativistic expansion. The numerical result is close enough to the estimates derived for the self-absorbed synchrotron model that discarding this assumption has not materially reduced the difficulty of explaining the required field.

If the synchrotron source is expanding relativistically then \( r \approx c \Gamma^2 \) and the visible radiation intensity in the frame of the synchrotron source is \( \sim L_V/(4\pi \Gamma^2) \propto \Gamma^{-6} \), where the two extra powers of \( \Gamma \) come from the redshift of the visible radiation, and the lower bound on the comoving \( B' \) is reduced \( \propto \Gamma^{-3} \). The bound on the laboratory frame \( B \) is only reduced \( \propto \Gamma^{-2} \). For mildly relativistic expansion, such as inferred for SN1998bw, the required \( B \) remains large. In addition, because of the larger inferred \( r \), the various scaling laws yield estimates of \( B \) which are reduced by factors \( \propto \Gamma^{-20} \). The difficulty is not resolved, and, in fact, is worsened for \( \alpha > 1 \).

The inverse bremsstrahlung opacity of hydrogen, including the effects of stimulated emission, is

\[
\kappa_{ff} = 3.69 \times 10^8 \frac{n^2 h}{k T^3/2} g_{ff} \text{ cm}^{-1}
\]

(Spitzer 1962). Taking \( T = 10^4 \) K and \( \nu = 2.49 \times 10^8 \) Hz (for which \( g_{ff} \approx 5 \)) yields \( \kappa_{ff} \approx 1.2 \times 10^{-26} n^2 \) cm\(^{-1}\). Effective absorption will be obtained in \( 3 \times 10^{16} \) cm if \( n = 10^5 \) cm\(^{-3}\), requiring \( \sim 10^{-2} \) M\(_{\odot}\) of gas. Such a circum-SN envelope, produced by a wind from the progenitor star, is possible; if expelled at 10 km/s (as appropriate to a red supergiant) its lifetime is \( \sim 10^5 \) yr. Much more massive winds are plausible. Such
winds have been widely discussed since the discovery of ring structures around SN1987A, and have been

It is, of course, necessary that the envelope be ionized in order for inverse bremsstrahlung to occur.
The envelope consists of $\sim 10^{55}$ atoms, which require $\sim 2 \times 10^{44}$ ergs of ionizing ultraviolet
radiation to ionize. The flux of SN1998bw in the Lyman continuum is not directly observable, but the required
energy is only $\sim 10^{-5}$ of the visible radiation emitted, which is certainly plausible and will be found for a
Planck spectrum with $T > 90000^\circ$ K. The resulting temperature of the photoionized gas depends on the shape of
the ultraviolet spectrum, but for a comparatively cool spectrum it will be $\approx 10^{4.5}$ K, as assumed.

A dense and comparatively cool ionized gas is a source of recombination line radiation. A straightforward estimate
using the preceding parameters and standard theory (Osterbrock 1974) leads to unobservably small ($\sim 10^{-5}$\AA) equivalent
widths, even for the Balmer lines, so that it is not possible to test the hypothesis of inverse bremsstrahlung absorption in this manner.

As the ionized envelope is dispersed by the supernova debris (once shock-heated its absorption
coefficient decreases greatly because of the temperature dependence of $\kappa_{\text{eff}}$) the inverse bremsstrahlung
absorption will decrease. This can qualitatively account for the evolution of the radio spectrum, whose
early deficiency of longer wavelength flux gradually disappears. Quantitative modeling might, in principle,
distinguish these predictions from those of self-absorption models, but all models contain several free
parameters; together with the complexity of the observed radio spectral behavior (Kulkarni, et al. 1998)
this makes an unambiguous discrimination between the models difficult.

6. GRB980425?

GRB980425, if produced by SN1998bw, poses another problem. The early states of a stellar explosion
would be expected to be very optically thick, and to produce roughly a black body spectrum. The observed
spectrum (Bloom, et al. 1998), if fitted to a black body, suggests a temperature $\approx 30$ keV. Combining
this with the inferred power (Galama, et al. 1998) of $5.5 \times 10^{46}$ erg/s implies an emitting radius (assumed
spherical) of $7 \times 10^7$ cm. However, the observed expansion speed of $6 \times 10^3$ cm/s (Kulkarni, et al. 1998)
means that this radius will be exceeded about 0.01 s after the explosion begins, inconsistent the observed
GRB duration of about 10 s. The power and duration are consistent if the temperature is $\sim 1$ keV, but
this is completely inconsistent with the observed spectrum.

Matter expelled from a supernova core with temperature $\sim 30$ MeV at $r \sim 6 \times 10^6$ cm will cool
adiabatically to $\sim 3$ keV, much less than the value estimated from the observed spectrum, by the time it
reaches $6 \times 10^{10}$ cm, the radius at the period of gamma-ray emission. In addition, a radiating photosphere
will be much cooler than the temperature deep within the outflow, for which adiabatic expansion is the
only cooling process. The difficulty of explaining the observed properties of GRB980425 in the context of a
supernova may best be resolved, despite the apparent coincidence, if they are in fact unrelated events, as
suggested on statistical grounds (Graziani, Lamb & Marion 1999). This is supported by the observation
(Pian, et al. 1999) of two transient X-ray sources, one long-lived and coincident with SN1998bw and the
other, briefer and not coincident with SN1998bw, resembling a GRB X-ray afterglow.
7. Discussion

The most difficult part of the problem of the radio emission of SN1998bw is explaining how the kinetic energy of the Compton electrons is converted to the acceleration of the electrons which produced the observed radio emission. These must have \( \gamma_e' \sim 100 \), making them many times more energetic than the Compton electrons. The interpenetration of Compton- and counter-currents is unstable to electrostatic and electromagnetic plasma instabilities, which may explain both the electron acceleration and the magnetic field (although previous sections have also discussed Compton current, hydodynamic dynamo and pulsar radiation zone models of the field). The absence of radio polarization (Kulkarni, et al. 1998) suggests that the magnetic field is disordered, which would be consistent with the dynamo, pulsar and plasma instability models of the field, but might also be explained by differential Faraday rotation (which may be estimated, using the previous parameters, as \( \sim 10^4 \) radians even at \( \lambda = 3 \) cm) within the Compton current model.

Compton electron models predict the presence of the nuclear gamma-rays. At distances of many Mpc these gamma-rays are unlikely to be detectable directly, but their effects on the visible light curve are evident (and, in fact, led to the inference of \( A \approx 50 \) radioactive decay).

In these models the rise of the radio flux in the first week is dependent on the escape of the gamma-rays, which will only occur so soon for supernovae (such as SN1998bw) with very fast debris. It is therefore predicted that strong early radio emission will be correlated with the debris expansion speed. It is also predicted that strong early radio emission requires the presence of a surrounding medium, presumably the result of mass loss by the progenitor, of density \( \gtrsim 10^5 \) cm\(^{-3}\), far in excess of typical interstellar densities. Such a medium may be independently confirmed or disproved because of its effects on the SN visible light curve, pulse dispersion of any newly born pulsar, or X-ray emission resulting from its interaction with the debris.

As the debris collides with the radio-absorbing gas cloud a forward and reverse shock are produced. The forward shock has a post-shock temperature \( \sim 1 \) MeV because of the high supernova debris speed, and emits comparatively little radiation. However, the reverse shock is cooler and propagates in denser matter (the debris having a mass of several \( M_\odot \), compared to the mass \( \lesssim M_\odot \) of the radio-absorbing envelope) and may well produce the X-ray source S1 discovered (Pian, et al. 1999) to be associated with SN1998bw and to decay over \( \sim 6 \) months. The decay is attributable to the forward shock reaching the outer extent of the radio-absorbing cloud, after which a rarefaction reflects and erodes the reverse shock.

 Supernovae in which Compton electrons produce radio emission should have several similar properties: They will all have approximately the same Lorentz factors (1.6–2) for their expanding radio photospheres, because this is determined by nuclear physics. They will all show similar double-peaked radio intensity curves, again because the nuclear physics is the same. Finally, their debris will show a nearly complete absence of a low-Z envelope (as distinct from a surrounding low-Z medium) because such an envelope would prevent the escape of the Compton electrons.

 It is also worth noting that the energy of explosive C or O burning (about 1 MeV/nucleon) is insufficient to produce the debris velocity observed in SN1998bw; gravitational energy from collapse to nearly neutron star density (and probably neutrino transport) must be appealed to.

 After the submission of the original version of this paper Nisenson & Papadopoulos 1999 reported that SN1987A was accompanied by two visible sources asymmetrically located on opposite sides of the supernova. Assuming these sources to represent jets directed outward from the supernova at the same speed, they found that their speed of ejection was 0.80c. This is the speed of the mean Compton electrons produced by
the abundant 0.812 MeV gamma-rays of $^{56}$Ni ($\S$2), and is consistent with the radio source expansion speed found by Kulkarni, et al. 1998 for SN1998bw. Although relativistic expansion is observed at very different frequencies in these two objects, perhaps because of observational limitations, it may be that both the spots near SN1987A and the radio emission of SN1998bw are powered by similar Compton electrons.

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