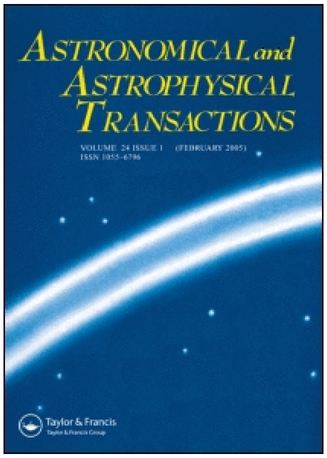

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Radio supernovae and particle acceleration

V. I. Slysh [a]
[a] Astro Space Center, Lebedev Physical Institute, Moscow, U.S.S.R.

Online Publication Date: 01 February 1992
To cite this Article: Slysh, V. I. (1992) 'Radio supernovae and particle acceleration', Astronomical & Astrophysical Transactions, 1:3, 171 - 193
To link to this article: DOI: 10.1080/10556799208260465
URL: http://dx.doi.org/10.1080/10556799208260465

Astronomical and Astrophysical Transactions, 1992,
Vol. 1, pp. 171–193
Reprints available directly from the publisher.
Photocopying permitted by license only

RADIO SUPERNOVAE AND PARTICLE ACCELERATION

V. I. SLYSH

Astro Space Center, Lebedev Physical Institute, Moscow, U.S.S.R.

(18 February 1991)

The radio emission from supernovae is observed in the first days or years after the explosion. It has a power law spectrum with a low-frequency cut-off moving with time to lower frequencies. The size of radio emitting region increases with time at a rate consistent with the rate of supernova envelope expansion. This kind of spectrum evolution was described by the free-free absorption in the circumstellar matter accumulated by the stellar wind of the pre-supernova or by the synchrotron self-absorption.

The synchrotron emission of supernovae is produced by relativistic electrons which are most likely accelerated by the shock associated with the expanding envelope. Three different mechanisms of the shock acceleration were discussed. The first-order Fermi, or diffusive shock acceleration can provide observed flux density of all detected supernovae, but requires very high mass-loss rate and magnetic field. Of the two quasi-perpendicular mechanisms the acceleration by lower-hybrid waves seems to be not efficient enough to produce relativistic electrons, while the shock drift acceleration is capable to accelerate a sufficient number of electrons to relativistic energies. This conclusion was derived from scaling of the Earth's bow shock electron energy density to the supernova shock parameters. The shock drift acceleration can supply sufficient number of relativistic electrons for the equipartion with the magnetic field.

KEY WORDS Supernovae, radio emission, particle acceleration

1. INTRODUCTION

Compared to supernova remnants (SNR), the radio emission that accompanies explosions of supernovae at early phases (several years after outburst) was discovered quite recently (Gottesman *et al.* 1972). This is a completely new phenomenon and its properties cannot be found by a simple extrapolation back from SNR's. The secular variation of the SNR radio flux density predicted by I. S. Shklovsky (1960) and confirmed by subsequent observations of Cassiopea A, is caused by the SNR envelope expansion. If the process were reversed, and the Cassiopea A were compressed to a size which the supernova 1979c had at the age of 2.3 years that is to 8×10^{16} cm, its radio luminosity would be by 3 to 7 order of magnitude higher than that of the supernova 1979c, depending on, either the energy of relativistic electrons is decreasing due to the expansion adiabatically, or the decrease is compensated by some further acceleration. This means that the radio emission of an SNR cannot be regarded as an emission of the highly expanded envelope of the supernova. There must be a greater distinction between SNR's and supernovae: during the process of evolution from the supernova phase to the phase of SNR, the rate of the decrease of radio luminosity changes to larger values.

Another distinction between supernovae and SNR's may be caused by a neutron star activity in type II supernovae. At the supernova phase the envelope is dense enough to completely block any emission from the neutron star. As the envelope is expanded it becomes transparent, not only to a radiation of the rotating neutron star (a pulsar) but also to relativistic particles accelerated in its magnetosphere. A supply to the radio emitting region of the SNR of relativistic particles becomes possible. Thus, a manifestation of the neutron star activity is more probable at a later time during the SNR phase.

Young SNR's as a rule have a rather regular circular shape, which means the existence of a high spherical symmetry (not counting Crab nebula and similar SNR's powered by pulsars). The spherical symmetry of SNR's is a result of the independence of the expansion on initial conditions in self-similar (Sedov) explosions. It was I. S. Shklovsky who had applied the self-similar solution to SNR's (1962). The situation is quite different during the supernova phase when the envelope is not yet decelerated and is in a free flight. The free flight may be asymmetric due to many reasons, for example, due to asymmetry of the explosion when the envelope is moving in one direction and the neutron star in another direction (Shklovsky, 1980). The first VLBI radio image of a supernova shows a lack of the symmetry in SN1986j (Bartel, 1990). Thus, there are several important differences between radio supernovae and radio SNR's. In one of his last papers, Shklovsky (1985) discussed radio emission from a type Ib supernova SN 1983n and came to a conclusion that the radio envelope of the supernova was expanding with the velocity of about 60,000 km s^{-1}, much faster than the expansion of the supernova envelope measured from optical spectra. This conclusion was further supported both for SN 1983n and for another type Ib supernova SN 19841. However, direct VLBI measurements of the expansion velocity of type Ib supernovae are not yet available.

2. OBSERVATIONS

As was mentioned in the Introduction, the first observations of the radio emission from a supernova were carried out by Gottesman *et al.* (1972) who determined very roughly the radio flux of the supernova 1970g. Only rather recently, much more detailed observations became possible. Here are some results of the observations briefly reviewed.

1979c

The radio emission of this supernova in the galaxy NGC 4321 (M100) was investigated in detail due to its exceptional brightness. Figure 1 shows 2 radio images of the galaxy M100, obtained with the VLA one year apart. On the upper picture one sees the central part of the galaxy while on the lower picture, taken one year later, one can see also a bright point source in the lower left corner. Light curves at two frequencies are shown on Figure 2. The light curves show some typical features. First, the radio emission appears not simultaneously with the explosion but with some delay, the lower the frequency the bigger delay. Second, the rise of the radio emission is much faster than its decay. Third, maximum flux density was reached earlier at high frequencies and later at lower

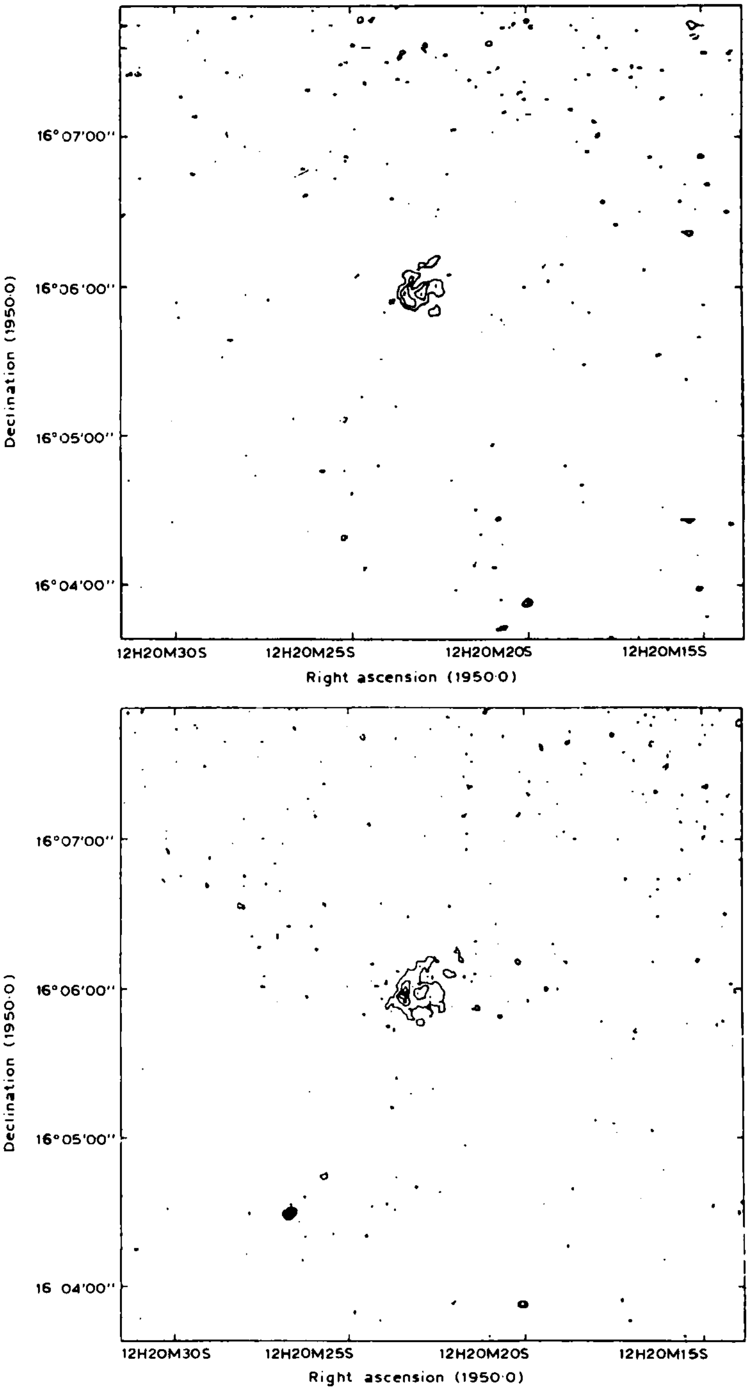

Figure 1 Contour map showing SN 1979c before (up) and after (down) explosion in the galaxy M100 (NGC 4321) (Weiler and Sramek, 1988).

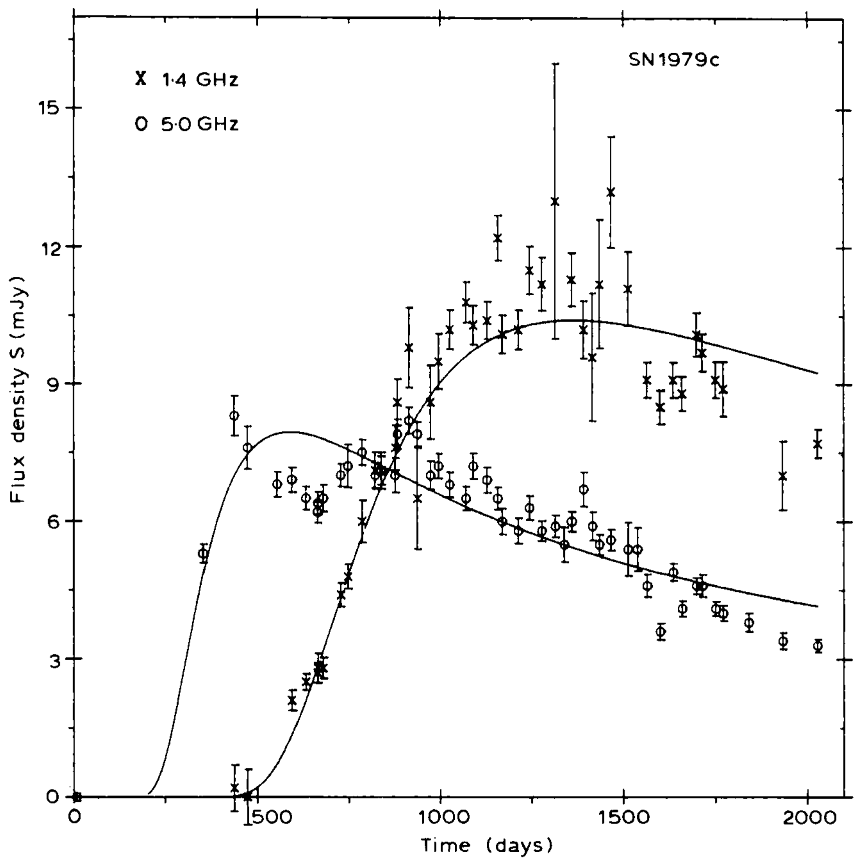

Figure 2 Radio light curves at 1.4 and 5 GHz for the supernova SN 1979c (after Weiler *et al.* 1986).

frequencies. No maximum was observed at the highest frequency used, 15 GHz, perhaps because it occurred before the first observation was made.

Spectra of the radio emission at different times all have maxima with a sharp cut-off at low frequencies and apparently a power-law fall-off at high frequencies with exponent $\alpha = -0.75$ (Figure 3). The position of the maximum has shifted from 5 GHz on day 450 after explosion to 1 GHz on day 1415.

The angular size of the SN 1979c radio envelope was measured with VLBI at several epochs. Figure 4 shows visibility functions at 5 GHz, while Figure 5 shows variation of the angular size with time calculated from the visibility functions (Bartel, 1990). One can see from the Figure 5 that in 3.5 years, between the first and last measurements, the angular size has increased substantially. If the variation of the angular size with time is described by a power-law $\vartheta \propto t^m$, then observations would correspond to $m = 1.03 \pm 0.15$ which does not contradict to the uniform expansion ($m = 1$). The angular velocity of the uniform expansion, shown on Figure 5 by a straight line, is $\dot{\vartheta} = 0.11$ mas yr^{-1}. If the expansion velocity of the radio envelope is the same as that measured from optical lines $v = 11{,}000$ km s^{-1}, then an estimate of the distance to the supernova can be

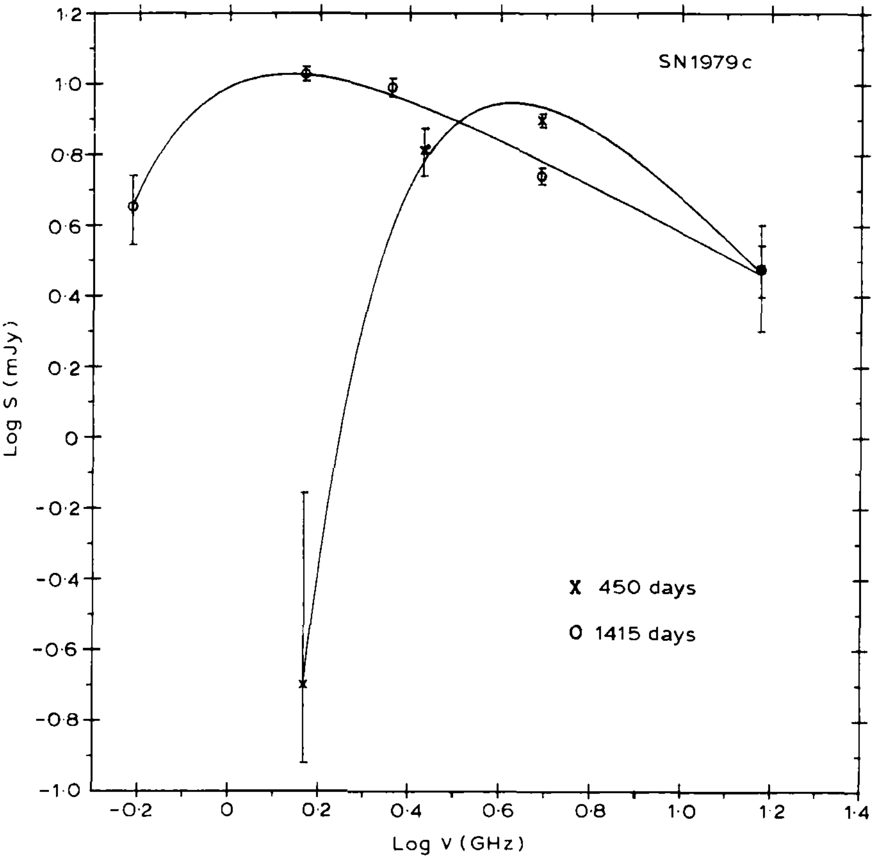

Figure 3 Spectrum of the radio emission from SN 1979c 450 and 1415 days after explosion.

made, $D = 22$ Mpc. This result was used by Bartel *et al.* (1985) for an independent determination of the Hubble's constant.

1980k

Similar light curves are shown on Figure 6 for the supernova 1980k in the galaxy NGC 6946. The only substantial difference is a much faster evolution: as is evident on Figure 6, the time scale for the supernova 1980k is a factor of 3 less than for the supernova 1979c; the flux density of this supernova is also a factor of 3 lower. VLBI measurements at 13 cm 930 days after explosion have determined only an upper limit of angular size of 1 mas (Bartel, 1990), which is consistent with optical data.

1983n

Still faster, the radio spectrum of the supernova 1983n in the galaxy M83 was evolving (Figure 7). The half-power width of the light curve at 6 cm was only 28 days, while for 1980k it was 400 days and for 1979c 1500 days.

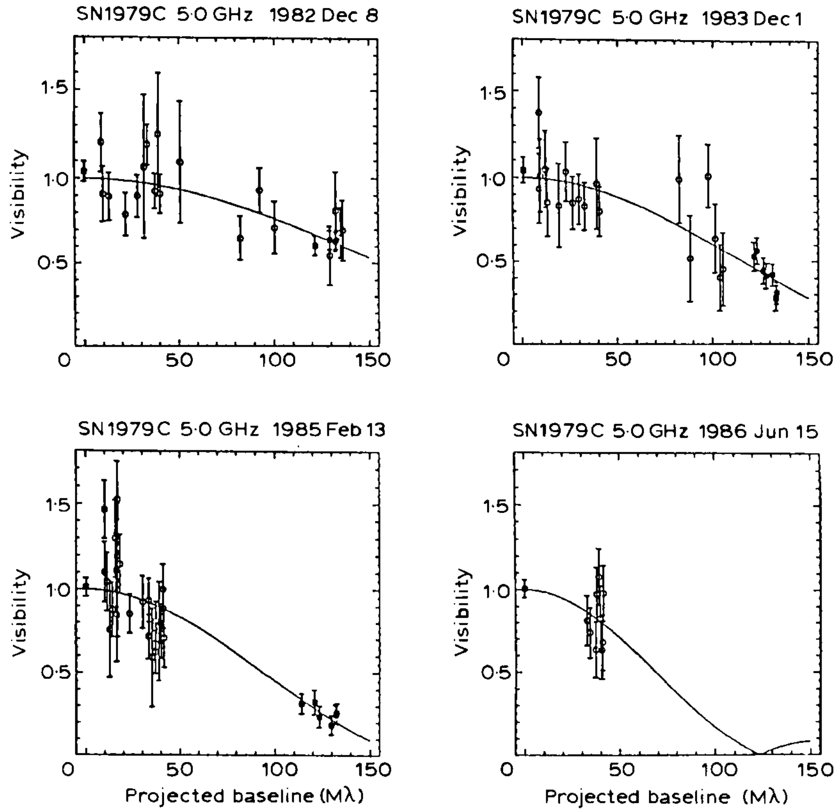

Figure 4 Measured visibility amplitudes at 5 GHz and the fit of a uniform sphere model (Bartel, 1990).

1986j

This was so far the brightest radio supernova known: at wavelength 6 cm, the flux density of 120 mJy was reached. The light curves measured at several wavelengths show a rather slow evolution (Figure 8) (Weiler *et al.* 1990). The radio emission at 6 cm initially has been raising rapidly and passing a maximum about 1400 days after the explosion started a slow decline. The light curve at the wavelength 20 cm showed a similar behaviour with a distinction that the maximum was reached 2000 days after explosion. At shorter wavelengths, the data are less complete: the first observations at wavelengths of 2 and 1.35 cm were made after the maximum, and only a slow decline, was observed. Two measurements at the wavelength of 1.2 mm were made showing a rather fast decline between days 1500 and 1800 after explosion. The value of the flux density at 1.2 mm however is not consistent with the results of the lower frequency observations. A possible maximum of the light curve around day 2050 was observed at the longest wavelength of 92 cm, but the shape of the light curve and the level of the flux density is not consistent with more detailed and more accurate data at wavelength of 6 and 20 cm. It is possible that free-free absorption in the ionized gas of the galactic disc of the edge-on galaxy NGC 891 is important, or an absorption in the near-by HII-region. Bartel (1990) has constructed VLBI

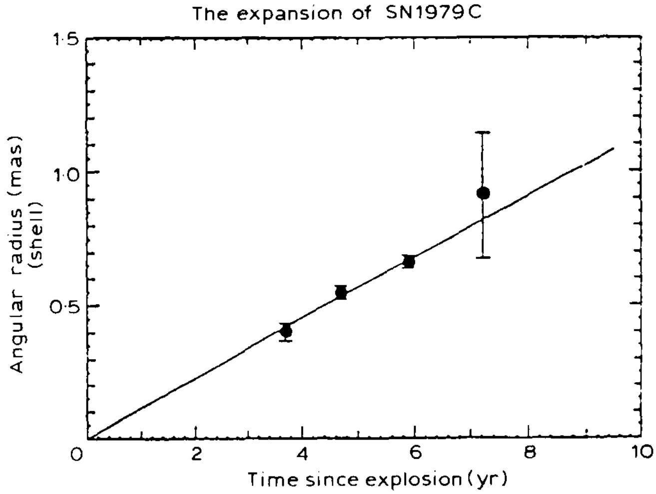

Figure 5 The expansion of SN 1979c. The solid line represents uniform expansion ($m = 1$), which is consistent with weighted least-squares solution $m = 1.03 \pm 0.15$ (Bartel, 1990).

image of this supernova (Figure 9), which shows an irregular shaped envelope 1.6 mas in diameter. The supernova was 2200 days old at this moment. At a distance of 5 Mpc assumed for the parent galaxy NGC 891, this corresponds to a uniform expansion velocity of 3000 km s^{-1} in a reasonable agreement with an optical estimate of 3500 km s^{-1} (Kirshner and Blair, 1980).

1987a

The radio emission from the supernova in the Large Magellanic Cloud was discovered only 2 days after explosion. The timing of the explosion was very accurately determined by the neutrino burst (Turtle *et al.* 1987). The light curves at frequencies of 0.843 and 1.4 GHz are similar to the light curves of other supernovae with a fast rise of flux and slow decline after the maximum (Figure 10). A delay of the maximum at the low frequency relative to that at the high frequency is evident. At 2.3 and 8.4 GHz, observations apparently started after the maximum. As compared to other supernovae, the evolution of the radio spectrum of the supernova 1987a was a factor of 10 (1983n), or even a factor of 500 (1979c) faster, and the radio luminosity was by 3 to 4 orders of magnitude lower. VLBI observations at 2.3 GHz, undertaken 5 days after the explosion, showed that the source was completely resolved on the base line Australia–South Africa, which means an angular diameter larger than 2.5 mas; under assumption of an uniform expansion, this corresponds to the expansion velocity higher than 19,000 km s^{-1} (Jauncey *et al.* 1988); this is in agreement with the expansion velocity determined from H_α absorption line.

3. INTERPRETATION OF RADIO SPECTRA EVOLUTION

3.1. *Interaction with the Stellar Wind of the Pre-supernova*

As was mentioned earlier, one of the most characteristic features of the supernova radio emission is the presence of a peak both on the light curves and in

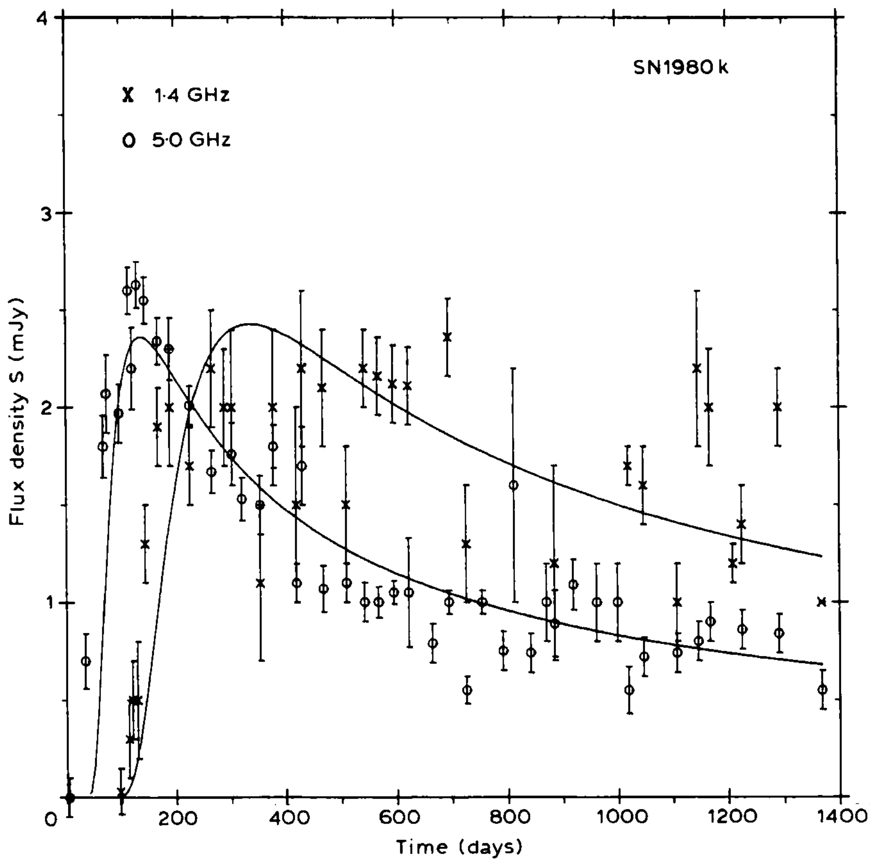

Figure 6 Radio light curves at 1.4 and 5 GHz for the supernova SN 1980k in NGC 6946 (after Weiler *et al.*, 1986).

the radio spectra. The natural hypothesis about the cause of the presence of the peaks would be the effect of an absorption. Chevalier (1982) suggested that the absorption was caused by the circumstellar ionized gas surrounding the supernova envelope. The free-free absorption produces a cut-off of the spectra at low frequencies. The density of the gas is higher close to the center, so the absorption was stronger at early phases when the envelope had a smaller radius; as the envelope is expanding, the gas density becomes lower and the absorption smaller. This process explains the initial flux rise on the light curves. By applying this model, Weiler *et al.* (1986) were able to fit light curves of several supernovae and to determine some parameters.

In the model, it was assumed that the free-free absorption optical depth τ was formed on the path starting from the edge of the radio envelope R to the infinity:

$$\tau = \int_R^\infty n_e n_i k_{f-f} dr, \qquad (1)$$

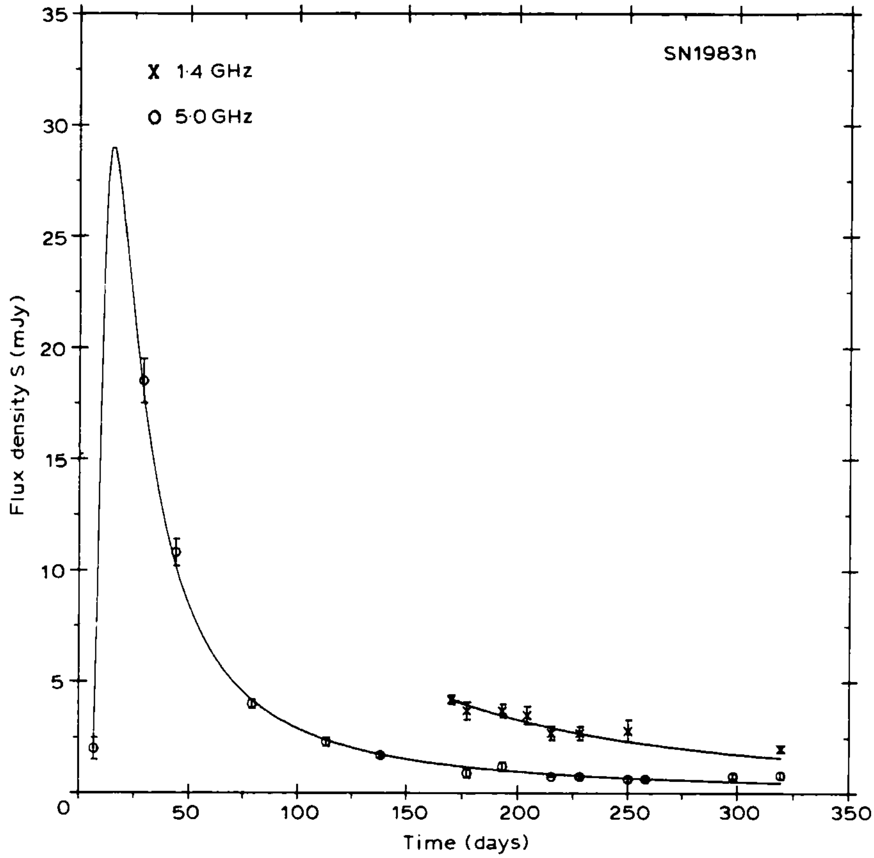

Figure 7 Radio light curves at 1.4 and 5 GHz for the supernova SN 1983n in M83 (after Weiler *et al.*, 1986).

where n_e and n_i are density of electrons and ions and:

$$k_{f-f} = 3.62 \times 10^{-27}\left(\frac{\nu}{5\,\mathrm{GHz}}\right)^{-2.1}\left(\frac{T}{10^4\,\mathrm{K}}\right)^{-1.35} \tag{2}$$

is the absorption coefficient, ν is the frequency, T is temperature. It is assumed that the circumstellar matter was accumulated by mass loss in a stellar wind before the supernova explosion; the density of the stellar wind falls-off as r^{-2}:

$$n_e = \frac{\dot{M}}{4\pi r^2 v \mu m_H}, \tag{3}$$

where $\dot{M}$ is the mass loss rate ($\mathrm{g\,s^{-1}}$), v is stellar wind velocity ($\mathrm{cm\,s^{-1}}$), m_H is hydrogen atom mass,

$$\mu = \frac{\sum X_j m_j}{\sum X_j Z_j}, \tag{4}$$

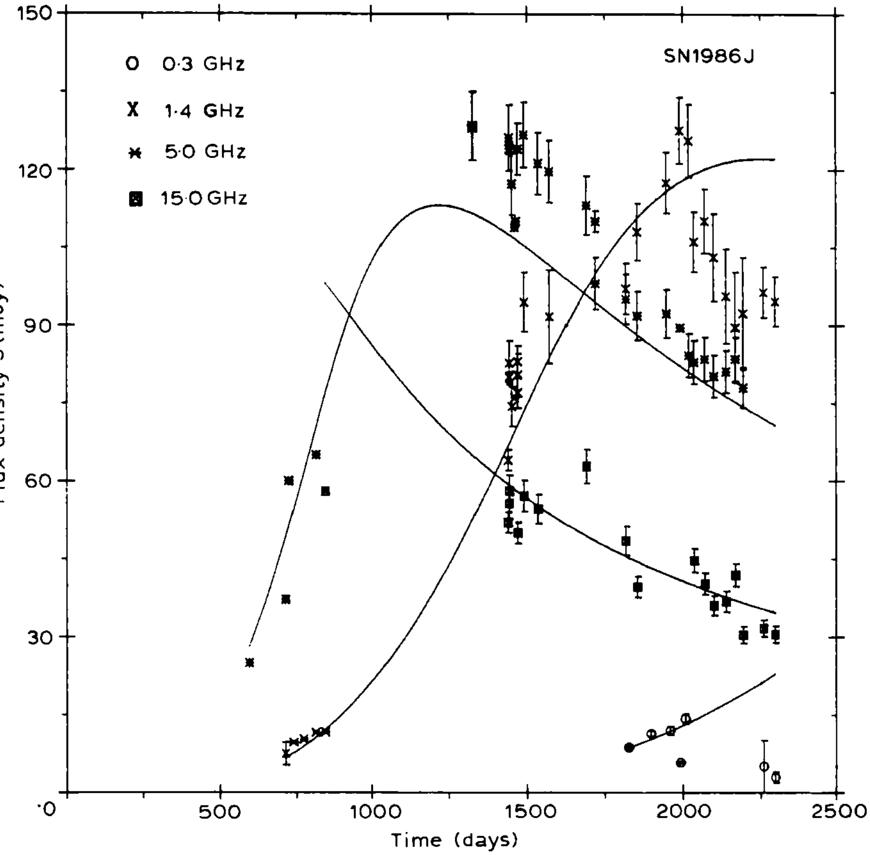

Figure 8 Radio light curves at 0.3, 1.4, 5, and 15 GHz for the supernova SN 1986j in NGC 891 (after Weiler, Panagia, and Sramek, 1990).

where X_j, Z_j, and m_j are the fraction by number, charge, and the atomic mass, respectively, of the jth ion; the ion density is:

$$n_i = \bar{Z} n_e, \tag{5}$$

with:

$$\bar{Z} = \frac{\sum X_j Z_j^2}{\sum X_j Z_j}. \tag{5'}$$

Substituting n_e and n_i in Eq. (1) one obtains:

$$\tau = \frac{\dot{M}^2 \bar{Z} k_{f-f}}{3(4\pi)^2 R^3 \mu^2 m_H^2 v^2}. \tag{6}$$

Thus the optical depth in the process of expansion decreases as R^{-3}. In the Chevalier model, it was assumed that the envelope is expanding according to the power law:

$$R \propto t^m, \tag{7}$$

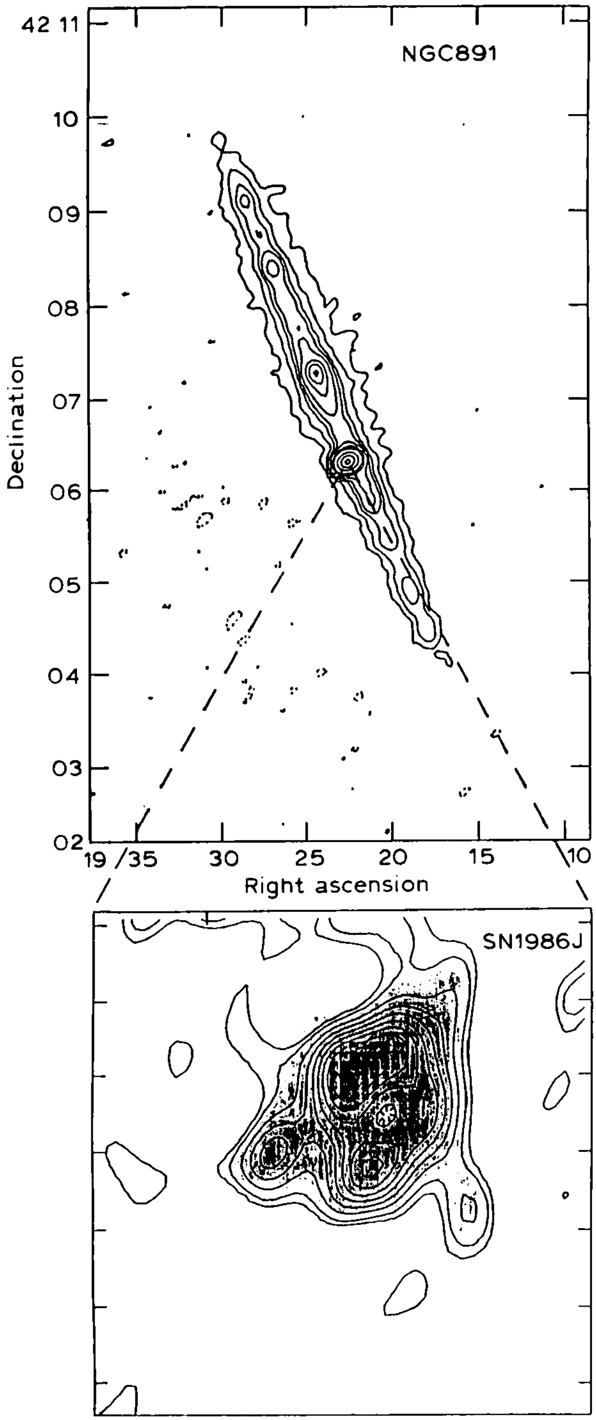

Figure 9 VLBI radio image of SN 1986j on day 220 after explosion (Bartel, 1990).

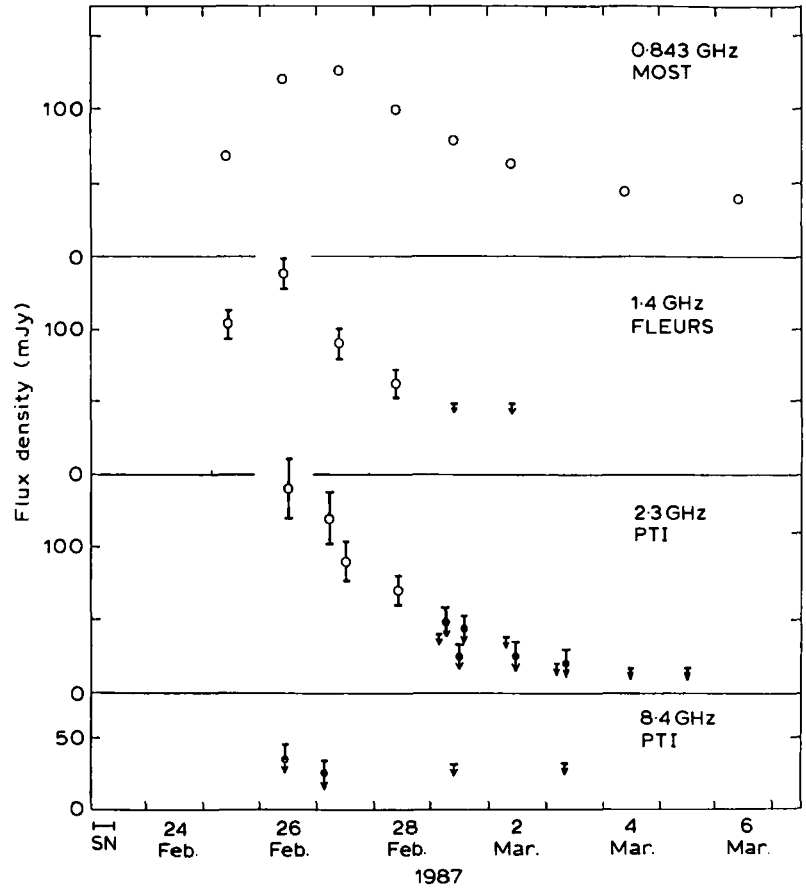

Figure 10 Radio light curves at 0.8, 1.4, 2.3, and 8.4 GHz for the supernova 1987a in the Large Magellanic Cloud (Turtle *et al.*, 1987).

where $m = (n-3)/(n-2)$. This law of expansion follows from a consideration of the interaction between the supernova envelope with a density distribution $p \propto r^{-n}$ and the stellar wind gas with a density distribution $p \propto r^{-2}$ (Chevalier, 1982). Thus the time dependence of the optical depth may be found:

$$\tau \propto R^{-3} \propto t^{\delta}, \tag{8}$$

where $\delta = -3m = -3(n-3)/(n-2)$. Chevalier (1982) also proposed that the synchrotron emission of the envelope is generated by relativistic electrons that are in equipartition with the magnetic field, and their energy density is proportional to the thermal energy behind the shock front. Under these assumptions it is possible to find a dependence of the radio emission flux density on radius and ultimately on time:

$$S \propto K_e B_{\perp}^{(1+\gamma)/2} \nu^{(1-\gamma)/2} R^3, \tag{9}$$

where K_e is a coefficient proportional to the density of relativistic electrons in the power law energy E distribution function:

$$N(E) = K_e E^{-\gamma}, \tag{10}$$

with an exponent γ. According to the assumption that the energy density of relativistic electrons is proportional to the thermal energy density behind the shock front, one has:

$$K_e \propto n_e m_i v_s^2, \tag{11}$$

where v_s is the shock front velocity, which is according to Eq. (7) equal to:

$$v_s = dR/dt \propto t^{m-1}. \tag{12}$$

In the stellar wind $n_e \propto R^{-2}$, taking into account Eq. (7) and the assumption of the equipartition, one gets:

$$K_e = B_\perp^2 \propto t^{-2}. \tag{13}$$

Substitution in Eq. (9) gives:

$$S \propto t^\beta \nu^\alpha, \tag{14}$$

where $\alpha = (1-\gamma)/2$, $\beta = 3m + \alpha - 3$.

The light curves from observations were approximated by the following expressions (Weiler *et al.* 1986):

$$S(mJy) = K_1 \left(\frac{\nu}{5\ \text{GHz}}\right)^\alpha \left(\frac{t-t_0}{1\ \text{day}}\right)^\beta e^{-\tau}, \tag{15}$$

where:

$$\tau = K_2 \left(\frac{\nu}{5\ \text{GHz}}\right)^{-2.1} \left(\frac{t-t_0}{1\ \text{day}}\right)^\delta, \tag{16}$$

and parameters α, β, and γ have the same meaning as in Eqs. (8) and (14) describing the model of Chevalier. A rather good fit of Eqs. (15) and (16) to the observed light curves for supernovae was obtained. Table 1 gives values of the parameters of the fit. Comparing them with the model one can determine some properties of the envelope and stellar wind. Thus, the parameter δ according to Eq. (8), gives $m = -\delta/3$, a parameter that describes the rate of deceleration of

Table 1 Fitting parameters

SN name	K_1	α	β	δ^a	K_2	*m*	*Ref.*
1979c	810 ± 100	-0.76 ± 0.05	-0.69 ± 0.08	-2.81 ± 0.06	$(1.4 \pm 0.1) \times 10^7$	0.94	1
1980k	69 ± 11	-0.50 ± 0.10	-0.64 ± 0.07	-2.82 ± 0.27	$(2.4 \pm 0.3) \times 10^5$	0.94	1
1983n	4400 ± 600	-1.03 ± 0.06	-1.59 ± 0.08	-2.44 ± 0.05	530 ± 30	0.81	1
1984l	275^{+927}_{-212}	-1.01 ± 0.17	-1.48 ± 0.33	-2.54 ± 0.36	690^{+2775}_{-554}	0.85	2
1986j	$\left(6.7^{+2.5}_{-2.9}\right) \times 10^5$	$-0.67^{+0.12}_{-0.04}$	$-1.18^{+0.06}_{-0.04}$	$-2.49^{+0.30}_{-0.20}$	$(3 \pm 3) \times 10^6$	0.83	3
1987a	411 ± 51	-0.46 ± 0.22	-1.37 ± 0.33	-2.64 ± 0.09	0.3 ± 0.03	0.88	4

References: (1) Weiler *et al.* (1986); (2) Panagia, Sramek, and Weiler (1986); (3) Weiler, Panagia, and Sramek (1990)—additional absorption in the envelope; (4) present work.

[a] For SN 1983n and 1984l it was assumed that $\beta = \alpha - 3 - \delta$ (Chevalier model).

the envelope. One can see that in all cases m exceeds 0.8 and is close to unity; this means that the envelope expands almost without deceleration: for $m > 0.81$ the parameter n that describes density distribution in the envelope is always larger than 7; this means that the density in the envelope falls off very sharply.

If the envelope expands without deceleration ($m = 1$, $n = \infty$) then Eq. (14) transforms to:

$$S \propto t^{\alpha} \nu^{\alpha}, \tag{17}$$

that is $\alpha = \beta$. As is evident from Table 1, β is always quite close to α as predicted by Chevalier model (with the exceptions of pts. 3 to 5 where the model was put into the fitting procedure).

3.2. *The Synchrotron Self-absorption*

Although the model with free-free absorption in the gas of stellar wind of the pre-supernova was quite successful in describing the evolution of radio spectra, it requires rather large stellar mass-loss rate. For supernova 1979c, the rate should be 6×10^{-5} solar mass per year, and for supernova 1986j—as large as 2.4×10^{-4} solar mass per year (Weiler *et al.*, 1986, 1990). It was suggested that the peak in the spectra of supernova radio emission was caused by the absorption not by thermal but rather by relativistic electrons which are responsible for the synchrotron emission (Slysh, 1990). The synchrotron self-absorption does not require any absorbing agent except the emitting relativistic electrons themselves.

4. ACCELERATION OF RELATIVISTIC ELECTRONS

4.1. *The Mechanism and the Place of Acceleration*

The most likely place where acceleration to relativistic energies of particles responsible for the radio emission can occur is the shock wave travelling ahead of the expanding supernova envelope. It was also suggested that a pulsar acceleration by the stellar remnant in the center of the supernova may be responsible for relativistic particles (Shklovsky, 1981, Pacini and Salvati, 1973). Although this mechanism seems to be very attractive, it cannot provide a supply of relativistic particles for the radio emission at early phases, since the particles are prevented from coming out through a very thick supernova envelope. The acceleration by neutrinos, released when a neutron star is forming, was suggested by Bisnovatyi-Kogan *et al.* (1988). They showed that the interaction of the neutrinos with the matter of supernova envelope may lead to acceleration of particles (mostly positrons) to an energy of about 15 MeV. The principal reaction is:

$$\tilde{\nu}_e + p \Rightarrow n + e^+, \tag{18}$$

which has a cross-section $\sigma = 2 \times 10^{-42}\,\mathrm{cm}^2$. The total number of fast positrons released by the collapsing star is about 2×10^{41}. This is far less than is needed to produce radio emission even from the intrinsically weakest supernova 1987a. Additional acceleration in the shock region was demanded by the authors.

In the model of Chevalier (1982) no details of the acceleration were specified. It was suggested that some modification of the statistical acceleration mechanism proposed by Gull (1973) for SNR's is responsible for the production of relativistic particles in radio supernovae. The mechanism is the second-order Fermi acceleration on turbulent irregularities arising due to Rayleigh-Taylor instability. For such a fast phenomenon as supernova explosion, the statistical second-order Fermi acceleration has too low rate of energy increase. The first-order Fermi acceleration, like the shock wave acceleration proposed by Krymsky (1977), is more promising in this respect. The time scale for the first-order Fermi acceleration is $(v_s/v_A)^2 \cong 10^4$ less than the time scale of the statistical second-order Fermi acceleration (v_s is the shock velocity about 10,000–20,000 km s^{-1}, v_A is Alfven velocity of about 200 km s^{-1}) (Berezhko Krymsky, 1988). Therefore, only the first-order acceleration will be considered here.

4.2. *The First-order Fermi Acceleration*

We will discuss the earliest stage of supernova evolution when the envelope is expanding freely, practically without any deceleration in the surrounding medium. The expanding envelope acts as a piston on the surrounding matter resulting in a shock wave travelling ahead of it. The surrounding medium is assumed to be a gas of the stellar wind, which was emitted by the presupernova before the explosion; the gas contained a magnetic field frozen in it. The gas density in the stellar wind varies with the distance from the star R as R^{-2}; in that case the shock wave travels ahead of the piston with a velocity 1.19 times the velocity of the piston for strong shocks (Parker, 1961). In the region between the shock front and the piston (envelope), all gas, swept by the shock wave during expansion is located. Its density at the shock front is 4 times the density of the undisturbed stellar wind gas adjacent to the shock front, and increases towards the envelope. The gas velocity just behind the shock front is 3/4 of the shock velocity v_s, and the temperature is $kT = (3/32)m_p v_s^2$, where m_p is the proton mass (Parker, 1961); the temperature decreases towards the envelope. At the shock front velocity of 10,000–20,000 km s^{-1}, typical for supernovae, the temperature behind the shock may reach $(1\text{–}4) \times 10^9$ K, or 100–400 keV.

The most energetic particles, those which can traverse the shock front without appreciable curving of the trajectory, will increase their energy by $\Delta E = (v_s/c)E$ (for relativistic particles) after each crossing of the front (Krymsky, 1977). On both sides of the shock front there are regions of intense turbulence, from which the particles will be reflected and cross the front many times. As a result, a systematic acceleration of the particles takes place, and a power law energy distribution is established with an exponent very close to what is observed. The time scale of the acceleration can be estimated as follows. The energy of the particles is increasing according to:

$$\ln(E/E_0) = (4/3)i(u_1 - u_2)/c. \quad (19)$$

where E_0 is initial energy of the particle, i is the number of shock front crossings by the particle, u_1 and u_2 are velocities of the upstream gas and of the gas flowing from the shock front downstream, respectively, in the coordinate frame co-moving with the shock front (Bell, 1978a). For strong shocks $(u_1 - u_2) = (3/4)v_s$. The number of crossings needed to acquire energy E is found from the Eq. (19):

$$i = (c/v_s)\ln(E/E_0). \quad (19')$$

If the initial energy of electrons $E_0 \sim m_e c^2 = 511$ keV and the shock velocity is $v_s = 20{,}000\ \mathrm{km\,s^{-1}}$, then the energy $E = 200 m_e c^2$ (typical energy for emission at 6 cm) will be acquired by the electron after 80 crossings. The thickness of the region behind the shock front where most of the accelerated particles are concentrated is about $0.07R_s$ (R_s is radius of the shock front) (see below). At each crossing, a particle traverses this region twice (forth and back). Therefore the total acceleration time is:

$$t_{\mathrm{acc}} = 2 \times 0.07 R_s i / v. \tag{20}$$

Particle velocity is $v \sim c$, so using Eq. (19′) one has:

$$t_{\mathrm{acc}} = 0.14 t_{\mathrm{env}} \ln(E/E_0), \tag{20'}$$

where $t_{\mathrm{env}} = R_s/v_s$ is the envelope expansion time. For $E = 200 m_e c^2$ $t_{\mathrm{acc}} = 0.74 t_{\mathrm{env}}$, which means that at every stage of the expansion, the particles will have enough time to be accelerated up to the energy of $200 m_e c^2$. Using Eq. (20′) one can estimate maximum energy, which the particles may reach during expansion: $E/E_0 = 1265$, or about 600 MeV.

For this type of acceleration, Bell (1978b) calculated the volume synchrotron emissivity of particles accelerated by the shock:

$$\begin{aligned}\varepsilon(\nu) = {} & 2.94 \times 10^{-34} (1.435 \times 10^5)^{0.75-\alpha} \xi(2\alpha + 1) \\ & \times \left(\frac{\varphi_e}{10^{-3}}\right)\left(\frac{\psi_e}{4}\right)^{2\alpha}\left(\frac{\alpha}{0.75}\right)\left(\frac{n_e}{\mathrm{cm^{-3}}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^{-\alpha}\left(\frac{v_s}{10^4\ \mathrm{km\,s^{-1}}}\right)^{2\alpha} \\ & \times \left(\frac{B}{10^{-4}\ \mathrm{G}}\right)^{\alpha+1}\left[1 + \left(\frac{\psi_e}{4}\right)^{-1}\left(\frac{v_s}{7000\ \mathrm{km\,s^{-1}}}\right)^{-2}\right]^{\alpha} \mathrm{Wm^{-3}\,Hz^{-1}},\end{aligned} \tag{21}$$

(the power index of v_s must be 2α, not 4α as quoted by Bell), where α is the spectral index, ν is the frequency, B is the magnetic field, $\xi(2\alpha + 1)$ is a function of the order of unity weakly depending on α, n_e is plasma electron density behind the shock front, φ_e is a fraction of electrons with the energy ψ_e times exceeding $m_p v_s^2/2$. It is the so called injection energy needed to start the acceleration mechanism that is to provide crossing of the shock front by particles. The mechanism of supply of such particles was not specified, this could be some type of plasma instability. Using experimental data from the Earth's bow shock, Bell (1978b) made an estimate of the fraction of the injected electrons $\psi_e = 10^{-3}$ and of their energy $E_0 = 4 \times (m_p v_s^2/2)$, or $\varphi_e = 4$.

The piston velocity in young type II supernovae may be determined using radial velocity of Balmer absorption lines. The effective volume of the radio emitting region can be roughly calculated using Krymsky and Petukhov (1980) distribution of the accelerated particle density, which is increasing approaching the shock front (behind it) as d^{12}, where d is the distance to the shock front. Upstream, ahead of the shock front, the particle density falls off exponentially, and the contribution from this region may be neglected. This distribution was obtained for the model of the point explosion, while here, we are dealing with the piston; nevertheless, we will use the distribution for crude estimates. It is easy to show that the effective volume of that distribution terminated at R_s and concentration, varying as d^{12} is:

$$V_{\mathrm{eff}} = 4\pi R_s^3/15 \tag{22}$$

and the effective thickness if $0.07R_s$.

Now we are in a position to determine physical properties of the stellar wind and magnetic field needed to generate radio emission from young supernovae. According to the model, assuming that the generation takes place in the region just behind the shock front, and the shock is strong, the density in this region must be 4 times ambient density of the undisturbed gas of stellar wind. The electron density upstream of the shock front can be calculated assuming free-free absorption following the Chevalier (1982) and Weiler *et al.* (1986) model of absorption by the stellar wind gas. The temperature is taken 10^4 K. The results of such calculations are given in Table 2. The velocity of the shock front was taken to be 1.19 of the envelope velocity as given by the optical spectra. Using Eq. (21), the quantity $n_e B^{1+\alpha}$ was calculated. Taking into account a factor of 4, compression in the region of generation behind the shock front of the gas density and magnetic field and using electron density n_{e0} determined from the free-free absorption ($n_e = 4n_{e0}$), one can find the magnitude of the magnetic field B_0 in the undistrubed region ($B = 4B_0$) upstream of the shock front. There are also values of the Alfven velocity in the stellar wind given in Table 2 $v_A = B_0/(4\pi n_0 m_p)^{1/2}$. The velocity of the stellar wind has to be much greater than the Alfven velocity, otherwise the gas motion will be controlled by the magnetic field. The solar wind velocity is, for example, an order of magnitude higher than Alfven velocity, that is why the coronal and interplanetary magnetic field is pulled out by the solar wind in radial direction, and its magnitude is inversely proportional to the distance. The magnetic field in the stellar wind should be of similar configuration. If we make an assumption that the stellar wind velocity is 5 times the Alfven velocity, then from the values of the Alven velocity given in Table 2, the stellar wind velocity exceeding $1000\,\mathrm{km\,s^{-1}}$ is deduced, which is typical for the stellar wind of hot OB stars. The last row of Table 2 gives stellar wind rates calculated with this assumptions. For the supernova 1987a it is known almost certainly that the pre-supernova was a hot blue supergiant of type B3Ia, which could have a stellar wind with the velocity $550\,\mathrm{km\,s^{-1}}$ and a rate of 2×10^{-6} solar mass per year (Chevalier and Fransson, 1987), in reasonable agreement with Table 2. Therefore, in the case of the supernova 1987a, in the Large Magellanic Cloud, the stellar wind properties of the pre-supernova may satisfy requirements for the first-order Fermi acceleration on the shock front to provide the observed power of radio emission.

Other type II supernovae 1980k and especially 1979c, had radio luminosity much higher than supernova 1987a, mostly because of the much larger emitting volume. The parameters of the stellar wind were almost the same as for 1987a,

Table 2 Magnetic field and presupernova stellar wind as determined from the first-order Fermi acceleration

SN name	*Age (days)*	*Radius (cm)*	*5 GHz volume emissivity* $(W\,m^{-3}Hz^{-1})$	$n_e\left(\frac{B}{10^{-4}}\right)^{1+\alpha}$	n_{e0} (cm^{-3})	B_0 *(Gauss)*	v_A $(km\,s^{-1})$	$\dot{M}$ $(M.\,yr^{-1})$
1979c	349	3.3×10^{16}	1.5×10^{-23}	1.5×10^{11}	1.6×10^{5}	0.028	157	4.3×10^{-3}
1980k	81	4.8×10^{15}	2.5×10^{-22}	1.6×10^{11}	4.2×10^{5}	0.053	183	2.7×10^{-4}
1983n	13	2.3×10^{15}	4.2×10^{-22}	4.3×10^{15}	6.0×10^{5}	0.90	2600	1.3×10^{-3}
1986j	399	8.2×10^{15}	8.1×10^{-21}	5.36×10^{13}	3.2×10^{5}	0.92	3600	1.2×10^{-2}
1987a	0.63	1.9×10^{14}	3.6×10^{-20}	4.7×10^{12}	2.1×10^{6}	0.22	340	4.2×10^{-6}

but at much greater distance from the star. As a result, the stellar wind rate has to be greater by 2 to 3 orders of magnitude and exeed 10^{-3} solar mass per year with the velocity of 700 to 1000 km s^{-1}. This means that the presupernovae had to be hot supergiants of spectral type O having very intense stellar wind. This conclusion is different from the results of Chevalier and Fransson (1987), who proposed a slow dusty wind from a red supergiant for the supernovae 1979c and 1980k. Weiler *et al.* (1986) also assumed slow stellar wind with a velocity 10 km s^{-1}, and for this reason their estimate of the stellar wind rate is much lower than ours. One can reduce the electron density by giving up the assumption of constant gas temperature 10^4 K. Because of radiation and adiabatic cooling, the stellar wind temperature may drop to a much lower level. In the case of supernovae 1979c and 1980k radio emission at the frequency 1.4 GHz has appeared 870 and 200 days after explosion, respectively, when the intensity of ultraviolet ionizing radiation providing heating had dropped to a very low level. The time scale of the radiation cooling of the stellar wind with density 5×10^4 cm^{-3} and temperature 10^4 K is about 150 days. Therefore, the temperature may drop to several thousand K. We have performed calculations for temperature of 1000 K. Although the electron density needed, decreased almost by a factor of 5, the Alfven velocity increased by a greater amount, and the stellar wind rate became somewhat higher. Thus, the decrease of the temperature does not reduce the rate of the stellar wind.

The exceptionally high stellar wind rate required for the first-order Fermi acceleration mechanism makes its operation in radio supernovae unlikely. Therefore, the high density stellar wind free-free absorption is not needed any more, since the low frequency absorption can be provided by the synchrotron self-absorption.

4.3. *Shock Drift Acceleration*

The diffusive or the first-order Fermi acceleration is generally invoked for shocks that propagate parallel to the magnetic field direction. At oblique or quasi-perpendicular shock, the shock drift acceleration is more effective (Pesses *et al.* 1982). Such shocks contain a strong electric field in the shock front due to the motion of the plasma across the magnetic field:

$$E = -\frac{v_s}{c} B \sin \Theta_{Bn}, \tag{23}$$

where Θ_{Bn} is the angle between the shock normal and the magnetic field. The electric field is directed perpendicular both to the shock normal and to the magnetic field, so its vector lays in the plane of the shock. Energetic particles encounter the shock and drift along it in the direction of the electric field due to the gradient of the magnetic field at the shock with a drift velocity:

$$v_d = \frac{c\bar{\nabla} \times \bar{B}}{4\pi ne} \tag{24}$$

and can be accelerated by the electric field if they remain in the shock front long enough, or can return to the shock frequently enough. If a particle travels distance Λ without changing direction, the maximum energy gained is:

$$E = e\frac{v_s}{c} B\Lambda. \tag{25}$$

When the ambient particle density and energy density of waves is low enough Λ is of the order of characteristic scale of the shock. Thus, for the Earth's bow shock $\Lambda \sim 10{,}000$ km, and with $B = 3 \times 10^{-4}$ G and $v_s = 300$ km s^{-1} $E = 90$ keV, in agreement with observations. For supernovae $\Lambda = 10^{15}$–10^{16} cm, $B = 0.1$ G, $v_s = 10{,}000$–$30{,}000$ km s^{-1}, and $E = 10^{15}$–3×10^{16} eV far in excess of the particle energy necessary to produce the radio emission. This flux of energetic particles will be unstable and will generate plasma waves that can stabilize the particle flux at a certain level. Unfortunately there is no way at this moment to exactly calculate energy distribution and density of accelerated particles, and one can rely only on the experimental data from measurements in the bow shock.

4.4. *Acceleration by Lower-hybrid Waves*

This is a mechanism also efficient in quasi-perpendicular shocks. For solar bursts of type II associated with coronal shocks, it was proposed (Lampe and Papadopoulos, 1977) that the drift current $\bar{\nabla} \times \bar{B}$ generates lower-hybrid waves that can stochastically accelerate electrons up to relativistic velocity. The acceleration is possible if the velocity of the waves is greater than electron thermal velocity and it may be as great as the speed of light. This is possible for waves with wave vector highly inclined to the magnetic field direction. Another possibility to excite the lower–hybrid waves is by ions reflected from the shock through the two-stream instability (Galeev, 1984). The energy that can be acquired by electrons with thermal distribution of temperature T_e is (Lesch *et al.* 1989):

$$E = 0.6\,\text{GeV}\left(\frac{B}{\text{mG}}\right)^{-1/2}\left(\frac{T_e}{10^8}\right)^{-1/4}\left(\frac{n_e}{10^{-4}}\right)^{1/2}. \tag{26}$$

For supernovae with $n_e = 10^5$ cm^{-3}, $T_e = 10^4$ K and $B = 0.1$ G $E = 200$ eV, which is too small. On the other hand one can get higher energies using Galeev's (1985) estimate of the maximum energy of accelerated electrons:

$$E_{\max} = m_e c^2 \left(\frac{m_i v_b^3}{m_e c^3}\right)^2 \frac{\omega_{pe}}{\omega_{ce}}. \tag{27}$$

where v_b is reflected ion velocity approximately equal to the shock velocity, ω_{pe} and ω_{ce} are the electron plasma and cyclotron frequencies. With $v_b = 30{,}000$ km s^{-1} and the above parameters for supernovae $E_{\max} = 17$ MeV. This is still about an order of magnitude less than is needed to generate radio emission. Moreover, the relaxation parameter z describing the excitation of waves by the reflected ions (Galeev, 1984) is so small in this case that the energy balance between ions and waves is not established and the Eq. (27) does not hold. We conclude that the acceleration by lower-hybrid waves is not able to supply electrons of sufficient energy for radio supernovae.

4.5. *Experimental Evidence for the Shock Acceleration*

The evidence for the shock related energetic electrons comes from measurements made in the planetary bow shocks, interplanetary travelling shocks, and coronal shocks associated with type II solar bursts. For the latter, a so called herringbone structure may serve as a manifestation of the energetic electron acceleration. The herringbone structure is a series of short radio bursts similar to type III bursts, which emanate from the main type II burst generated by the coronal shock (Cairns and Robinson, 1987). From the frequency drift of the herringbone bursts, electron velocity of $0.05c$–$0.5c$ was deduced. In the interplanetary travelling shocks, electrons accelerated up to 2 MeV were observed by spacecraft particle counters (Sarris and Krimigis, 1985). Finally near the Earth's bow shock energetic electrons with energies up to hundreds of electron-volts were observed in detail (for example, Anderson, 1974). So there is ample experimental evidence that shocks are able to accelerate energetic electrons. Numerical simulation also show the possibility of accelerating electrons to relativistic energies by shock waves (Ohsawa and Sakai, 1988). To know whether supernova shocks can produce electrons with still higher energies, it is necessary to extrapolate from existing experimental data or to use a good theoretical model. As compared to interplanetary or planetary shocks, the supernova shocks have much higher velocities (up to $0.1c$) and Mach numbers. From the observed evidence that the herringbone structure in type II solar bursts is present only in strongest bursts (Cane and White, 1987) and that the intenstiy of type II bursts is proportional to the shock velocity in power of 2.4–3.1 (Lengyelle-Frey and Stone, 1989), one can expect that supernova shocks may produce more energetic electrons of higher energy. All available experimental evidence indicate that quasi-perpendicular shocks are more efficient than quasi-parallel shocks in acceleration of electrons. For interplanetary shocks, this was shown by Pyle *et al.* (1984): to accelerate electrons above 2 keV, minimum shock velocity of $20\,\mathrm{km\,s^{-1}}$ is sufficient for quasi-perpendicular shocks, while for quasi-parallel shocks the velocity should exceed $160\,\mathrm{km\,s^{-1}}$. The quantity that is more relevant is $v_{sB} = v_s/\cos\Theta_{Bn}$, where Θ_{Bn} is the angle between the shock normal and the magnetic field, and v_s is the shock velocity.

According to Pyle *et al.* (1984), the energetic particles were observed for shocks with $v_{sB} \geq 400\,\mathrm{km\,s^{-1}}$, that is for large v_s and small $\cos\Theta_{Bn}$ or quasi-perpendicular shocks. In the Earth's bow shock the energetic electrons are commonly found near perpendicular and quasi-perpendicular portions of the shock where the interplanetary magnetic field lines are tangent to the bow shock, but are rarely present near quasi-parallel portions (Gosling *et al.* 1989). So all the evidence seems to show that quasi-perpendicular acceleration is responsible for the acceleration of electrons. The quasi-parallel or diffusive shock acceleration evidently is not important. As was discussed in the previous section, two acceleration mechanisms were proposed for quasi-perpendicular shocks: shock drift and by lower-hybrid waves. The latter requires that intense lower-hybrid wave turbulence be present upstream and at the shock. This is not observed. The energy density of accelerated electrons is 5–6 orders of magnitude higher than the energy density of waves. Neugebauer *et al.* (1971) have measured the energy density of electrons in the energy interval 100–200 eV from 1 to $5\,\mathrm{keV\,cm^{-3}}$, or from 1.6×10^{-9} to $8 \times 10^{-9}\,\mathrm{erg\,cm^{-3}}$, while the intensity of the waves near frequency 10 Hz, where the lower-hybrid frequency is located, can be estimated as about $200 \times 10^{-5} \gamma\, Hz^{-1/2}$, or $4 \times 10^{-15}\, erg\, cm^{-3}$. Similar values for the electromagnetic turbulence in the frequency interval from 20 Hz to 4 kHz of $2.4 \times 10^{-15}\, erg\, cm^{-3}$ were given by Rodriguez and Gurnett (1976). Thus, the waves are only minor energy component at the shock and cannot be the source of energetic electrons. Besides, as was shown in the previous section, the lower-hybrid wave mechanism is not able to supply electrons of sufficiently high energy. One is left with the shock drift as a promising acceleration mechanism. Measurements of suprathermal electrons at the Earth's bow shock by Gosling *et al.* (1989) may provide some details of the acceleration process. It was found that at energies below 20 keV the suprathermal electrons are most intense immediately downstream from the shock and decrease in intensity deeper into the magnetosheath. The energetic electron spectrum extends smoothly out of the shocked solar wind spectrum as a power law in energy with an exponent in the range from −3 to −4, their angular distribution is generally isotropic immediately downstream of the shock ramp, but with increasing penetration into the magnetosheath an anisotropy perpendicular to the magnetic field develops. Upstream, the suprathermal electrons are observed as escaping along the magnetic field. These observations are interpreted as an acceleration of the suprathermal electrons out of the solar wind thermal population as the solar wind convects across the shock. In this case, the number of accelerated electrons should be proportional to the upstream density of the wind. In the case of supernovae the upstream density $n_{e0} \sim 10^5$–$10^6\, cm^{-3}$ (see Table 2), or 4 to 5 orders of magnitude higher than the solar wind density. The energy of electrons as estimated in section 4.3 can be as high as 10^{15}–10^{16} eV, or a factor of 10^{10}–10^{11} higher than in the Earth's bow shock, if the shock drift mechanism is operating. So the energy density of relativistic electrons in the supernova shocks may be a factor of 10^{14}–10^{16} higher than in the Earth's bow shock, or 10^{17}–$10^{19}\, eV\, cm^{-3} = 1.6 \times 10^5$–$1.6 \times 10^7\, erg\, cm^{-3}$. This is unrealistic since the energy density cannot exceed kinetic energy density of the shock, which is only 0.1–1 $erg\, cm^{-3}$, and must be close to the magnetic field energy density $3 \times 10^{-5} - 3 \times 10^{-2}\, erg\, cm^{-3}$ as in the Earth's bow shock. The limiting energy density of energetic electrons seems to be close to the equipartition with the magnetic field energy density.

5. SUMMARY

The radio emission that accompanies optical emission just after supernova explosions may be a common phenomenon. This emission is produced by relativistic electrons accelerated by the expanding envelope of supernovae. The exact mechanism of the acceleration at present cannot be specified, although there are evidences that the interaction of the supernova envelope with the circumstellar matter plays an important role. The second possibility, acceleration by a pulsar, seems to be unrealistic. There are observational indications of the existence of the circumstellar matter around supernova stars. Its origin could be stellar wind emitted by the star before explosion. This matter may be responsible for the low-frequency absorption in the spectrum of radio emission, although the synchrotron self-absorption could as well give rise to the low-frequency cut-off. A shock wave travelling ahead of the envelope is the most likely place where the acceleration occurs. The Earth's bow shock resulting from the interaction of the solar wind with the magnetosphere is known to accelerate electrons to high energies. By analogy one can speculate that the same process on a much larger scale is taking place at the supernova shocks. Three possible acceleration mechanisms were considered here. The first-order Fermi, or diffusive shock acceleration was applied to the supernova acceleration problem following Bell's (1978b) prescription. A set of reasonable parameters was deduced for known radio emitting supernovae but the magnetic field proved to be rather high. The mass loss rates of stellar wind were also found to be too high. Also, the diffusive acceleration is evidently not responsible for the acceleration at the Earth's bow shock. Thus, two mechanisms that can operate at quasi-perpendicular shocks were also considered. The acceleration by lower-hybrid waves generated at the shock was found not effective for supernovae but the shock drift acceleration is a more profitable mechanism. At the Earth's bow shock it can produce energetic electrons with the energy density close to the magnetic field energy density. By extrapolating to the supernova shock parameters it was possible to get relativistic electrons in quantities sufficient for the equipartition with the magnetic field. It seems likely that the radio emission from supernovae can be produced by electrons accelerated by the shock drift mechanism.

References

Anderson, K. A. (1974). Intensity and energy spectrum of electrons accelerated in the Earth's bow shock. *Journal of Geophysics,* **40,** 701–709.

Bartel, N. (1990). VLBI observations of supernovae and their remnants. In *Supernovae,* edited by S. E. Woosley, New York: Springer Verlag (in press).

Bartel, N., Rogers, A. E. E., Shapiro, I. I., Gorenstein, M. V., Gwinn, C. R., Marcaide, J. M., *et al.* (1985). Hubble's constant determined using very-long baseline interferometry of a supernova. *Nature,* **318,** 25–30.

Bell, A. R. (1978a). The acceleration of cosmic rays in shock fronts I. Monthly Notices of the Royal Astronomical Society, **182,** 147–156.

Bell, A. R. (1978b). The acceleration of cosmic rays in shock fronts II. Monthly Notices of the Royal Astronomical Society, **182,** 443–455.

Berezhko, E. G. and Krymsky, G. F. (1988). Acceleration of cosmic rays by shock waves (in Russian). *Uspekhi Fizicheskikh Nauk,* **154,** 49–64.

Bisnovatyi-Kogan, G. S., Illarionov, A. F. and Slysh, V. I. (1988). Radio emission from a collapsed star (in Russian). *Preprint IKI* N 1404.

Cairns, I. H. and Robinson, R. D. (1987). Herring-bone bursts associated with type II solar radio emission. *Solar Physics,* **111,** 365–383.

Cane, V. and White, S. M. (1989). On the source conditions for herring-bone structure in type II solar radio bursts. *Solar Physics,* **120,** 137–144.

Chevalier, R. A. (1982). Radio and X-ray emission of type II supernovae. *Astrophysical Journal,* **259,** 302–310.

Chevalier, R. A. and Fransson, C. (1987). Circumstellar matter and the nature of SN 1987a progenitor star. *Nature,* **328,** 44–45.

Galeev, A. A. (1984). Generation of relativistic electrons by shock waves and their synchrotron radiation. *Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki,* **86,** 1655–1666.

Galeev, A. A. (1985). Electron acceleration by subrelativistic shocks in plasma. In *Advances in Space Plasma Physics,* edited by B. Buti, pp. 272–276, Singapour: World Scientific.

Gosling, J. T., Thomsen, M. F. and Bame, S. J. (1989). Suprathermal electrons at Earth's bow shock. *Journal of Geophysical Research,* **94,** 10011–10025.

Gottesman, S. T., Broderick, J. J., Brown, R. L. and Balick, B. (1972). First-epoch radio observations of supernova 1970g. *Astrophysical Journal,* **174,** 383–388.

Gull, S. F. (1973). A numerical model of the structure and evolution of young supernova remnants. *Monthly Notices of the Royal Astronomical Society*, **161,** 47–69.

Hanuschik, R. W. and Dachs, J. (1987). H_α velocity structure during first month of SN 1987a. *Astronomy and Astrophysics*, **182,** L29–L30.

Jauncey, D. L., Kemball, A., Bartel, N., Whitney, A. R., Rogers, A. E. E., Shapiro, I. I. *et al.* (1988). Supernova 1987a: radiosphere resolved with VLBI five days after the neutrino burst. *Nature*, **334,** 412–415.

Kirshner, R. P. and Blair, W. P. (1980). The extraordinary extragalactic supernova remnant in NGC4449, *Astrophysical Journal*, **236,** 135–142.

Krymsky, G. F. (1977). A regular mechanism for the acceleration of charged particles on the front of a shock wave. *Soviet Physics Doklady*, **22,** 327–330.

Krymsky, G. F. and Petukhov, S. I. (1980). Acceleration of particles by a regular mechanism in the presence of spherical shock wave (in Russian). *Pis'ma v Astronomichesky Zhurnal*, **6,** 227–231.

Lampe, M. and Papadopoulos, K. (1977). Formation of fast electron tails in type II solar bursts. *Astrophysical Journal*, **212,** 886–890.

Lengyell-Frey, D. and Stone, R. G. (1989). Characteristics of interplanetary type II radio emission and the relationship to shock and plasma properties. *Journal of Geophysical Research*, **94,** 159–167.

Lesch, H., Appl, S. and Camenzand, M. (1989). Collective plasma process in extragalactic radio sources. *Astronomy and Astrophysics*, **225,** 341–352.

Neugebauer, M., Russel, C. T. and Olson, J. V. (1971). Correlated observations of electrons and magnetic fields at the Earth's bow shock. *Journal of Geophysical Research*, **76,** 4366–4380.

Ohsawa, Y. and Sakai, J. (1988). Prompt simultaneous acceleration of protons and electrons to relativistic energies by shock waves in solar flares. *Astrophysical Journal*, **332,** 439–444.

Pacini, F. and Salvati, M. (1973). On the evolution of supernova remnants. I. Evolution of the magnetic field, particles, content and luminosity. *Astrophysical Journal*, **186,** 249–265.

Panagia, N., Sramek, R. A. and Weiler, K. W. (1986). Subluminous, radio emitting type I supernovae. *Astrophysical Journal (Letters)*, **300,** L55–L58.

Parker, E. N. (1961). Sudden expansion of the corona following a large solar flare and the attendant magnetic field and cosmic-ray effects. *Astrophysical Journal*, **133,** 1014–1033.

Pesses, M. S., Decker, R. B. and Armstrong, T. P. (1982). The acceleration of charged particles in interplanetary shock waves. *Space Science Review*, **32,** 185–204.

Pyle, K. R., Simpson, J. A., Barnes, A., Mihalov, J. D. (1984). Shock acceleration of nuclei and electrons in the heliosphere beyond 24 a.u. *Astrophysical Journal (Letters)*, **282,** L107–L111.

Rodriguez, P. and Gurnett, D. (1976). Correlation of bow shock plasma wave turbulence with solar wind parameters. *Journal of Geophysical Research*, **81,** 2871–2882.

Sarris, E. T. and Krimigis, S. M. (1985). Quasi-perpendicular shock acceleration of ions to 200 MeV and electrons to 2 MeV observed by Voyager 2. *Astrophysical Journal*. **298,** 676–683.

Shklovsky, J. S. (1960). On a possible secular variation of the flux and intensity of radio emission from some discrete sources (in Russian). *Astronomichesky Zhurnal*, **37,** 256–264.

Shklovsky, J. S. (1962). Supernova outbursts and the interstellar medium (in Russian). *Astronomichesky Zhurnal*, **39,** 209–215.

Shklovsky, J. S. (1980). On supernovae in multiple binary systems (in Russian). *Astronomichesky Zhurnal*, **57,** 673–676.

Shklovsky, J. S. (1981). Radio emitting supernovae–young plerions. *Soviet Astronomy Letters*, **7(4),** 263–264.

Shklovsky, J. S. (1985). The synchrotron self absorption of radio emission of the supernova 1983. 51 (in Russsian). *Pis'ma v Astronomichesky Zhurnal*, **11,** 261–264.

Slysh, V. I. (1990). Synchrotron self-absorption of radio emission from supernovae. *Pis'ma v Astronomichesky Zhurnal*, **16,** 790–798.

Turtle, A. J., Campbell-Wilson, D., Bunton, J. D., Jauncey, D. L., Kesteven, M. J., Manchester, R. N. *et al.* (1987). A prompt radio burst from supernova 1987a in the Large Magellanic Cloud. *Nature*, **327,** 38–40.

Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M. and Salvati, M. (1986). Radio supernovae. *Astrophysical Journal*, **301,** 790–812.

Weiler, K. W. and Sramek, R. A. (1988). Supernovae and supernova remnants. *Annual Review of Astronomy and Astrophysics*, **26,** 295–341.

Weiler, K. W., Panagia, N. and Sramek, R. A. (1990). Radio emission from supernovae. II. SN 1986j–a different kind of type II. *Astrophysical Journal*, **364,** 611–625.