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SN 1988Z: THE MOST DISTANT RADIO SUPERNOVA

SCHUYLER D. VAN DYK[1] AND KURT W. WEILER
Remote Sensing Division, Naval Research Laboratory, Code 7215, Washington, DC 20375-5351
RICHARD A. SRAMEK
P.O. Box 0, National Radio Astronomy Observatory, Socorro NM 87801
AND
NINO PANAGIA[2,3]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
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ABSTRACT

We present observations of the early radio emission from the unusual supernova SN 1988Z in MCG +03-28-022 made with the Very Large Array at 20, 6, 3.6, and 2 cm from 1989 December, 1 year after optical discovery, through 1992 December. At the redshift $z = 0.022$ of the parent galaxy, SN 1988Z is the most distant radio supernova ever discovered. With a 6 cm maximum flux density of 1.90 mJy, SN 1988Z is ~ 1.2 times more luminous than the unusually powerful radio supernova SN 1986J in NGC 891, making SN 1988Z also one of the most luminous radio supernovae ever discovered. Our analysis and model fitting of these initial light curves indicates that the overall radio properties of SN 1988Z are quite similar to those of SN 1986J and can be described by a modified Chevalier model involving the supernova shock interacting with a high-density circumstellar cocoon, with an additional component of internal thermal absorbers and non-thermal emitters. The radio properties of SN 1988Z indicate that the cocoon resulted from a very high mass-loss rate ($\dot{M} \sim 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$) in the late stages of the evolution of a very massive (20–30 $M_{\odot}$) presupernova star.

Subject headings: galaxies: individual (MCG +03-28-022, Zw 095-049) — radio continuum: stars — supernovae: individual (SN 1988Z)

1. INTRODUCTION

The discovery and the subsequent study of the highly luminous and unusual radio supernova (RSN) SN 1986J in NGC 891 (Weiler, Panagia, & Sramek 1990) indicated the existence of a relatively rare subclass of Type II supernovae (SNs) produced by very massive progenitors. This new subclass of Type II SNs may correspondingly exist in the optical, with spectral characteristics including blue continua, narrow emission lines superposed on broader emission lines, lack of well-defined P Cygni profiles, and slow evolution (Schlegel 1990; Filippenko 1990, 1991). In this *Letter* we consider the radio emission from a second example of this subclass, the unusual supernova (SN) SN 1988Z in MCG +03-28-022 (Zw 095-049).

SN 1988Z was independently discovered after optical maximum by both G. Candeo on 1988 December 12 (Cappellaro & Turatto 1988) and C. Pollas on 1988 December 14 (Pollas 1988). The SN was classified as Type II based on hydrogen emission lines in the optical spectra, which indicated that the SN is also quite distant, with redshift $z \simeq 0.022$ (Stathakis & Sadler 1991). However, the spectra revealed even at early times that this SN was peculiar, with a remarkably blue color, a lack of absorption lines and P Cygni profiles, very narrow ($\lesssim 100$ km s^{-1} FWHM) [O III] circumstellar emission lines, and a steadily growing, relatively narrow (~ 2000 km s^{-1} FWHM) component to the H I and He I lines (Stathakis & Sadler 1991; Filippenko 1990, 1991). The properties of the optical spectra and light curves at later times indicate strong SN shock–circumstellar shell interaction (Filippenko 1990, 1991; Turatto et al. 1993). The SN's optical characteristics, and its resemblance to SN 1986J (Filippenko 1990, 1991; see also Rupen et al. 1987 and Leibundgut et al. 1991), strongly suggested that SN 1988Z should be a very luminous RSN.

Sramek, Weiler, & Panagia (1990) reported the radio detection of SN 1988Z with the Very Large Array (VLA).[4] The supernova is located at $\alpha(1950.0) = 10^{h}49^{m}10\overset{s}{.}614 \pm 0\overset{s}{.}01$, $\delta(1950.0) = +16°15'56\overset{''}{.}46 \pm 0\overset{''}{.}2$, which is coincident to within the uncertainties with its optical position (α[1950.0] = $10^{h}49^{m}10\overset{s}{.}6$, δ([1950.0] = +16°15′57″; Kirshner, Leibundgut, & Smith 1989). We present in this *Letter* the results of our monitoring with the VLA of this supernova, and we provide and analyze the initial radio light curves for SN 1988Z.

2. RADIO OBSERVATIONS

The radio observations of SN 1988Z were made with the VLA at 20 cm (1.490 GHz), 6 cm (4.860 GHz), 3.6 cm (8.440 GHz), and 2 cm (14.940 GHz) from 1989 December through 1992 December. Since monitoring of an evolving radio source requires measurement at frequent intervals, we were not able to request the specific VLA configuration and consequently have measurements at various array sizes. However, even in the most compact arrays, the radio emission from the disk of the parent galaxy was never detectable and therefore never

[1] Naval Research Lab/National Research Council Cooperative Research Associate.
[2] Affiliated with the Astrophysics Division, Space Science Department of ESA.
[3] Also University of Catania, Italy.
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TABLE 1
FLUX DENSITY MEASUREMENTS FOR SN 1988Z

Observation Date	Days after Explosion[a]	VLA Configuration	Flux Density (mJy)							
			S_{20}	σ_{20}	S_6	σ_6	$S_{3.6}$	$\sigma_{3.6}$	S_2	σ_2
1989 Dec 21	716	D	...	...	0.67	0.07	...	...	...	...
1990 Feb 12	770	D/A	...	...	0.77	0.09	...	...	...	...
1990 May 29	875	A	...	...	1.21	0.09	...	...	...	...
1990 Jul 12	919	A/B	<0.27[b]	...	1.26	0.09	2.10	0.15	...	...
1990 Sep 7	976	B	<0.39[b]	...	1.38	0.09	...	...	1.15	0.21
1990 Dec 14	1074	C	<0.48[b]	...	1.78	0.10	2.09	0.13	1.43	0.15
1991 Jun 11	1253	A	0.47	0.07	1.90	0.11	1.68	0.10	1.31	0.22
1991 Sep 17	1351	A	...	...	1.85	0.11	1.48	0.09	0.59	0.20
1992 Jan 26	1482	B/C	1.05	0.13	1.67	0.10	1.50	0.09	1.17	0.14
1992 Oct 13	1743	A	0.91	0.08	1.57	0.09	1.22	0.10	0.91	0.21
1992 Dec 19	1810	A	1.45	0.11	1.72	0.11	1.04	0.08	0.78	0.17

[a] The best-fit date of explosion is found to be 1988 Jan 23.
[b] 3 σ upper limit.

posed a problem for flux density measurement of the SN. VLA phase and flux density calibration and data reduction followed standard procedures, such as those described in Weiler et al. (1990).

3. RESULTS

We present the results of our flux density measurements in Table 1 and Figure 1. The solid lines are the "best-fit" model light curves discussed below. What is clear is that the radio emission from SN 1988Z turned on relatively slowly with time and is, considering its large distance, extraordinarily luminous for a RSN. After peak flux density it has shown a constant rate of decline at each frequency (the 20 cm light curve is still rising). SN 1986J developed similarly (Weiler et al. 1990).

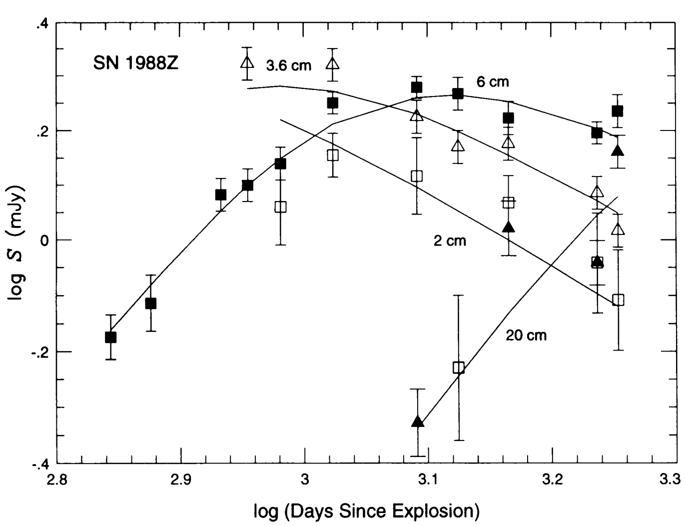

FIG. 1.—Radio "light curves" for SN 1988Z in MCG +03-28-022. The four wavelengths, 20 cm (*filled triangles*), 6 cm (*filled squares*), 3.6 cm (*open triangles*), and 2 cm (*open squares*), are shown together. The age of the supernova is measured in days from the estimated date of explosion of 1988 January 23. The solid lines represent the best-fit light curves of the form defined by eqs. (1), (2), and (3) with $\delta \equiv \alpha - \beta - 3$ and $\delta' \equiv 5\delta/3$.

4. DISCUSSION

4.1. *Model Radio Light Curves for SN 1988Z*

It was shown by Weiler et al. (1990) that a model consisting of purely external, thermal-absorbing gas, which Weiler et al. (1986) have shown provides a good fit to the data for all other RSNs, provides a poor fit to the data for SN 1986J. However, adding to that model an expanding, mixed, internal thermal-absorbing/nonthermal-emitting gas component proves to be much more satisfactory. The same model also provides a much better description of the SN 1988Z data and can be expressed as (see Weiler et al. 1986, 1990)

$$S(\mathrm{mJy}) = K_1\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha}\left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\beta} e^{-\tau}(1 - e^{-\tau'})\tau'^{-1}\ , \quad (1)$$

with

$$\tau = K_2\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\delta}\ , \quad (2)$$

and

$$\tau' = K_3\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\delta'}\ , \quad (3)$$

where K_1, α, and β describe the nonthermal emission process and τ, K_2, and δ are related to the external thermal absorbing medium (which assumes free-free absorption in a fully ionized medium with a radial density dependence of r^{-2} from a constant speed, red supergiant wind). The parameters τ', K_3, and δ' describe an internal thermal absorbing medium mixed with a nonthermal-emitting gas (where "mixing" here is in the statistical sense, and may imply an irregular preejecta shock front and/or high-level filamentation in the ejecta). The quantities K_1, K_2, and K_3 are scaling factors for the units of choice (mJy, GHz, and days) and formally correspond to the flux density, external optical depth, and internal optical depth, respectively, at 5 GHz 1 day after explosion. Finally, the parameter t_0 is the date of explosion.

The Chevalier (1982) "minishell" model has previously been shown to provide a very satisfactory description of all known RSNs (see Weiler et al. 1986, 1991, 1992; Van Dyk et al. 1992, 1993) and fixes $\delta \equiv \alpha - \beta - 3$. It can further be shown that

$\delta' \equiv 5\delta/3$ must also hold (Weiler et al. 1990), reducing the overall number of free parameters for which to solve.

A search of parameter space for a minimum reduced χ^2_{red} with equations (1), (2), and (3), with δ and δ' defined as above, yields our initial set of parameter values for SN 1988Z listed in Table 2. These values are then used to calculate the model curves which are shown as solid lines in Figure 1. A $\chi^2_{red} \sim 1.6$ is found for the light curves. An additional minimum measurement error of 6% (see, e.g., Weiler et al. 1986) brings down $\chi^2_{red} \sim 1.0$ per degree of freedom. As can be seen in the figures, the fit to the data is quite satisfactory, especially considering the simplicity of the model.

As can be seen from Table 2, α and β are tightly constrained, while K_1 and K_3 are less so. K_2 is very poorly determined and could be zero, showing that the emission turn-on is dominated by the internal absorption, K_3. The best fit for t_0 is 313 days (i.e., almost a year) before 1988 December 1, the presumed explosion date adopted by Stathakis & Sadler (1991), or 1988 January 23, with an indeterminacy of +217, −200 days.

4.2. *A Comparison of SN 1988Z with SN 1986J*

Comparing the values and range of uncertainties in the fitting parameters for SN 1988Z in Table 2 with those for SN 1986J in Table 9 of Weiler et al. (1990; reproduced in our Table 2), we can see that the radio properties are quite similar for the two RSNs. The spectral indices $\alpha \sim -0.7$ agree and are consistent with those found for other Type II RSNs (see Weiler et al. 1986, 1991, 1992; Van Dyk et al. 1992), while the decline rate β is only slightly steeper for SN 1988Z than for SN 1986J. Comparing their initial 6 cm model spectral luminosities ($\propto K_1 d^2$) using the distances $d = 9.6$ Mpc for NGC 891 (SN 1986J) from Tully (1988) and $d \simeq 89$ Mpc for MCG +03-28-022 (SN 1988Z) from its observed redshift z (assuming $H_0 = 75$ km s^{-1} Mpc^{-1}), we find that $L \simeq 7 \times 10^{31}$ ergs s^{-1} Hz^{-1} for SN 1986J and $L \simeq 9 \times 10^{32}$ ergs s^{-1} Hz^{-1} for SN 1988Z, implying that SN 1988Z was initially $\gtrsim 10$ times more powerful than SN 1986J. Even comparing their observed peak 6 cm flux densities of 128 mJy for SN 1986J and 1.9 mJy for SN 1988Z, we find that SN 1988Z was ~20% higher in observed 6 cm peak spectral luminosity than SN 1986J. Internal absorption, K_3, dominates over external absorption, K_2, for both RSNs, with the values of K_3 being comparable, although somewhat larger for SN 1986J.

The value of $\delta = -2.29$ for SN 1988Z implies that motion of the SN shock front is strongly decelerated, i.e., $R \propto (t - t_0)^m$, where R is the shock radius and $m = -\delta/3 = 0.76$, even more so than was the shock front for SN 1986J (see Weiler et al. 1990). In both cases the shock appers to be more decelerated than "normal" Type II RSNs such as SN 1979C (see Weiler et al. 1991), which suggests that there exists a less steep density gradient in the ejecta (i.e., $\rho_{ejecta} \propto r^{-8}$ for SN 1988Z compared with $\rho_{ejecta} \propto r^{-16}$ for SN 1979C).

Assuming that the external absorbing matter corresponds to a circumstellar cocoon established by mass loss from a red supergiant SN progenitor in the final stages of stellar evolution, we can estimate a mass-loss rate for the progenitor using equation (16) of Weiler et al. (1986). If we adopt a red supergiant wind temperature $T \simeq 10^4$ K and an ejecta expansion velocity $v_i \simeq 2 \times 10^4$ km s^{-1} on day 45 (Stathakis & Sadler 1991), and assume a constant red supergiant wind velocity $w = 10$ km s^{-1} with the optical depth at 5 GHz on day 1 given by K_2, we find that the probable mass-loss rate is $\dot{M} \simeq 7 \times 10^{-5}$ $M_\odot$ yr^{-1}, which is comparable to the rate ($\dot{M} \sim 2 \times 10^{-4}$ $M_\odot$ yr^{-1}) estimated for SN 1986J (Weiler et al. 1990), with large uncertainties, due to the large range in K_2. However, this mass-loss rate is very high and is consistent with a very massive progenitor star with 20 $M_\odot \lesssim M_{ZAMS} \lesssim 30$ $M_\odot$.

5. CONCLUSIONS

The unusual Type II SN 1988Z is the most distant and one of the most luminous RSNs ever discovered, with radio properties very similar to those of the previously unequaled SN 1986J. The presently available data for SN 1988Z are fitted quite well by a model which includes mixed internal thermal absorption and nonthermal emission, as well as thermal, external absorption. SN 1988Z may have exploded in 1988 January, yet, because of the high absorption, due to a very dense circumstellar medium, it was not detectable at 6 cm until more than 1 yr after explosion. However, interaction of the SN shock with this same high-density absorbing region has led to copious relativistic particle acceleration and magnetic field generation to produce a high radio luminosity.

TABLE 2

FITTING PARAMETERS

PARAMETER	SN 1988Z		SN 1986J[a]	
	Value	Deviation Range[b]	Value	Deviation Range
K_1	$8.99 \times 10_4$	$(6.61–11.5) \times 10^4$	6.7×10^5	$(3.8 - 9.2) \times 10^5$
α	−0.74	−(0.69–0.78)	−0.67	−(0.59–0.71)
β	−1.45	−(1.43–1.47)	−1.18	−(1.16–1.22)
K_2	1.87×10^5	$(0–20.6) \times 10^5$	3×10^5	$(0–63) \times 10^5$
$\delta (\equiv \alpha - \beta - 3)$ ..	−2.29	−(2.22–2.35)	−2.49	−(2.19–2.69)
K_3	6.35×10^{11}	$(4.01–11.1) \times 10^{11}$	4×10^{12}	$(2–12) \times 10^{12}$
$\delta' (\equiv 5\delta/3)$	−3.82	−(3.70–3.92)	−4.15	−(3.65–4.45)
t_0	1988 Jan 23	1987 Jun 20–1988 Aug 10	1982 Sep 13	1982 Feb 25–1983 Jul 10
$\dot{M}$ ($M_\odot$ yr^{-1})	7.1×10^{-5}	...	2.4×10^{-4}	...

[a] The values and deviation ranges for the fitting parameters, as well as the estimate for the mass-loss rate, for SN 1986J are from Weiler et al. 1990.

[b] The deviation range for each parameter is the amount that the parameter must deviate from the best-fit value in order to increase χ^2_{red} from ~1 to ~8 (Abramowitz & Stegun 1965). This is appropriate for fitting six free parameters (K_1, K_2, K_3, α, β, and t_0) and determines the 67% probability intervals within which the true values lie; i.e., the error range analogous to the 1 σ uncertainty for a single-parameter fit.

We conclude that both SN 1988Z and SN 1986J probably represent a class of rare, peculiar Type II SNs, which arise from the endpoints of stellar evolution for highly massive progenitors [$20 \lesssim M(M_\odot) \lesssim 30$] which experience a period of high mass loss ($\gtrsim 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$) before explosion. The discovery of the unusual SN 1978K in NGC 1313, which is also highly luminous both in the radio and X-rays (Petre et al. 1992; Filippenko 1992; Ryder et al. 1993), possibly adds a third member to this class. We discount SN 1986J, and likewise, SN 1988Z, from being either a LBV superoutburst (Uomoto 1991) or a Type Ib SN (Leibundgut et al. 1991), since both RSNs have radio luminosities several orders of magnitude too high compared to that expected from a LBV superoutburst (following the discussion for SN 1978K by Ryder et al. 1993) and have radio properties very different from those of Type Ib/c RSNs (see Sramek, Panagia, & Weiler 1984; Weiler et al. 1986; Van Dyk et al. 1993). Finally, we note that the recent X-ray detection of SN 1986J with *ROSAT* by Bregman & Pildis (1992) makes SN 1988Z a possibly attractive X-ray target as well.

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