Radio detection of SN 1986E in NGC 4302

Marcos J. Montes
Remote Sensing Division, Naval Research Laboratory, Code 7214, Washington, DC 20375-5320; mmontes@moon.nrl.navy.mil

Schuyler D. Van Dyk
Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095; vandyk@jean.astro.ucla.edu

Kurt W. Weiler
Remote Sensing Division, Naval Research Laboratory, Code 7214, Washington, DC 20375-5320; kweiler@SNe.nrl.navy.mil

Richard A. Sramek
P.O. Box 0, National Radio Astronomy Observatory, Socorro, NM 87801; dsramek@nrao.edu

And

Nino Panagia
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; panagia@stsci.edu

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Abstract

Radio observations of SN 1986E show a clear detection of emission at 6 cm wavelength about 8 months after optical discovery. Combined with a number of new upper limits and a study of the possible models, these observations suggest that SN 1986E was probably a fairly normal Type IIL supernova, somewhat similar to SN 1980K, with radio emission at roughly the expected levels. This detection agrees with the general correlation between radio detection and late-time optical emission.

Subject heading: supernovae: individual (SN 1986E)

1. Introduction

Discovered by G. Candeo at $m_B = 14.5$ on 1986 April 13 in NGC 4302 (Rosino 1986), with a precise optical position of $\alpha(B1950) = 12^{h}19^{m}09^{s}.05$, $\delta(B1950) = +14^{\circ}54^{\prime}33^{\prime\prime}.3$ given by King (1986), SN 1986E attracted little initial attention from observers. Recently, interest in this supernova (SN) has revived with the discovery of its late-time optical emission (Cappellaro, Danziger, & Turatto 1995), a relatively rare phenomenon for SNe, leading to a comparison with other late-time optically emitting SNe, e.g., SNs 1957D, 1970G, 1979C, and 1980K (Cappellaro et al. 1995; see also Ryder et al. 1993 for SN 1978K and Rupen et al. 1987 and Leibundgut et al. 1991 for SN 1986J). Because of these optical similarities and because the other late-time optically emitting SNe are all radio supernovae (RSNs), Cappellaro et al. (1995) predicted possible radio emission for SN 1986E with flux density as high as $0.5$–$5$ mJy at 20 cm in 1995, ~9 years after optical discovery. This prediction was followed by a search for radio emission in 1995 by Eck et al. (1996), who were unable to detect the SN, with very low limits at both 6 cm ($S_{6\text{ cm}} < 0.038$ mJy; 3 $\sigma$) and 20 cm ($S_{20\text{ cm}} < 0.169$ mJy; 3 $\sigma$). Because of this apparent lack of radio emission, Eck et al. (1996) concluded that SN 1986E is surprising in being apparently radio faint and suggested that it is the first old SN that has been seen in the optical but not in the radio.

The work by Cappellaro et al. (1995) and by Eck et al. (1996) has prompted us to reexamine observations of SN 1986E taken with the NRAO3 Very Large Array (VLA) at times closer to the explosion date than those previously considered; one of these observations had showed a possible weak detection. Applying additional processing, we were able to obtain a clear detection of SN 1986E at 6 cm in the data of 1986 December 5 and to establish a number of new upper limits at both 6 and 20 cm. These new data constrain rather well the range of possible models for the radio emission from SN 1986E, so that a comparison with other Type IIL SNe such as SN 1979C and SN 1980K can be made. From these results we conclude that the Cappellaro et al. (1995) predicted flux density for SN 1986E is far too high and that, while SN 1986E was probably a reasonably typical Type IIL SN in its radio emission, Eck et al. (1996) failed to detect it because of limited VLA sensitivity and because of the relatively large age of the SN at the time of their search.

2. Observations

A number of observations were taken of SN 1986E at the 6 cm (4.860 GHz) and 20 cm (1.425 GHz) wavelengths with the VLA over an interval extending from 17 days to 991 days after the optical discovery. The observations were calibrated with assumed flux densities for the primary calibrator, 3C286, of 14.45 Jy at 1.425 GHz and 7.42 Jy at 4.860 GHz. Following the normal procedure for the VLA, 3C286 was used to obtain flux densities for the compact secondary, possibly variable, calibrator 1252+119, which was then used as both the amplitude and the phase calibrator for observations of the SN 1986E field. (More details of VLA calibration procedures for SN observations can be found in Weiler et al. 1986 and, particularly for 1252+119, in Weiler et al. 1991.) The derived flux densities for 1252+119 used for amplitude calibration are listed in Table 1, and the position of 1252+119 used for phase

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1 Visiting scientist.
2 Affiliated with the Astrophysics Division, Space Science Department, ESA.
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The radio position of the 1986E resulted in a weak but significant detection of 0.304 mJy at 6 cm on 1986 December 5. The radio position of the emission, $\alpha(B1950) = 12^h19^m09^s.83$, $\delta(B1950) = +14^\circ54'35''0''$, agrees with the optical (King 1986) position to within 1 arcsec. This positional coincidence, along with the lack of detection of any similar level of emission either before or after the single detection date, indicates that the emission is almost certainly from SN 1986E. A 6 cm contour map of the area around the position of SN 1986E is shown in Figure 1, with the emission from the SN indicated.

Two relatively strong background sources, labeled $\beta$ and $\gamma$ by Eck et al. (1996), are clearly seen in Figure 1. The Eck et al. (1996) source $\delta$, while outside of the field shown in Figure 1, was also detected.

The 6 cm flux densities for these three field sources, taken as an average of the results from 1986 August 11 (VLA B array) and 1986 December 5 (C array) are listed in Table 2. One observation from 1987 August 28 was not used for Table 2 because the high resolution of the A array on that date partially resolved the sources. The positions for the three field sources [source $\beta$: $\alpha(B1950) = 12^h19^m09^s.83$, $\delta(B1950) = +14^\circ54'35''0''$, source $\gamma$: $\alpha(B1950) = 12^h19^m14^s.06$, $\delta(B1950) = +14^\circ53'35''0''$, source $\delta$: $\alpha(B1950) = 12^h19^m01^s.31$, $\delta(B1950) = +14^\circ53'50''7''$] are in good agreement with the results of Eck et al. (1996).

### Table 1

| Observation Date | Reference Date (1986 Apr 13) | VLA Configuration | Flux Densities or $\sigma$ Limits (mJy) | Error (mJy) | Frequency (GHz) | Calibrator Flux (1252 + 119 Jy) |
|------------------|------------------------------|-------------------|----------------------------------------|-------------|-----------------|----------------------------------|
| 1986 Apr 30       | 17                           | A                 | <0.330                                 | 0.110       | 4.860           | 0.632                            |
| 1986 Jun 26       | 74                           | A/B               | <0.255                                 | 0.085       | 4.860           | 0.632                            |
| 1986 Aug 11       | 120                          | B                 | <0.203                                 | 0.068       | 4.860           | 0.632                            |
| 1986 Aug 11       | 120                          | B                 | <0.540                                 | 0.180       | 1.425           | 0.938                            |
| 1986 Dec 05       | 236                          | C                 | 0.304                                  | 0.034       | 4.860           | 0.635                            |
| 1986 Dec 05       | 236                          | C                 | <0.630                                 | 0.210       | 1.425           | 0.954                            |
| 1987 Aug 28       | 502                          | A                 | <0.180                                 | 0.060       | 4.860           | 0.606                            |
| 1988 Dec 29       | 991                          | A                 | <0.150                                 | 0.050       | 4.860           | 0.594                            |
| 1995 Jul 14       | 3379                         | A                 | <0.169                                 | 0.056       | 1.425           | 0.754                            |
| 1995 Dec 04       | 3522                         | B                 | <0.038                                 | 0.013       | 4.860           | 0.748                            |

* From Eck et al. (1996).

**3. PARAMETERIZED MODEL**

Weiler et al. (1986) have discussed the common properties of radio SNe (RSNs), including nonthermal synchrotron emission with high brightness temperature, turn-on delay at longer wavelengths, power-law decline after maximum with index $\beta$, and spectral index $\alpha$ asymptotically decreasing to an optically thin value. Weiler et al. (1986) have also shown that the “mini-shell” model of Chevalier (1982a, 1982b) adequately describes the known Type II RSNs. In this model, the relativistic electrons and enhanced magnetic fields necessary for synchrotron emission are generated by the SN shock interacting with a relatively high-density ionized circumstellar envelope. This dense cocoon is presumed to have been established by a high mass-loss rate ($M > 10^{-5} M_\odot$ yr$^{-1}$), low-velocity ($w_{wind} \sim 10$ km s$^{-1}$) wind from a red supergiant (RSG) SN progenitor that was ionized and heated by the initial SN UV/X-ray flash.

The rapid rise in radio flux density results from the shock overtaking progressively more of the matter in the wind, leaving less matter along the line of sight to absorb the emission from the shock region.

Following Weiler et al. (1986), we adopt the parameterized model

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

(1)

where

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

(2)

with $K_1$ and $K_2$ corresponding formally to the flux density ($K_1$) and uniform absorption ($K_2$) at 5 GHz one day after the explosion date $t_0$. The term $e^{-\tau}$ describes the attenuation due to a local medium that uniformly covers the emitting source ("uniform external absorption"). This absorbing medium is assumed to be purely thermal ionized hydrogen with absorption frequency dependence $\nu^{-2.1}$. The parameter $\delta$ (not to be confused with source $\delta$ from Eck et al. 1996) describes the time evolution of the shock position. The parameter $\alpha$ describes the spectral index of the synchrotron emission.
dependence of the optical depth for this local uniform medium. For an undecelerated SN shock, \( \delta = -3 \) is appropriate (Chevalier 1982a).

This parameterization has been found generally applicable to other Type II L SNs, such as SN 1979C (Weiler et al. 1991) and SN 1980K (Weiler et al. 1992), with values of \( \delta \) close to the undecelerated value \( (\delta_{SN\ 1979C} = -3.12, \delta_{SN\ 1980K} = -2.74; \) see Table 3).

4. SN 1986E MODEL PARAMETER VALUES/LIMITS

With only one radio detection available in Table 1, it is certainly not possible to determine the six parameters \( (K_1, K_2, \alpha, \beta, \delta, t_0) \) in equations (1) and (2) through a fitting procedure. However, if we assume no shock deceleration \( (\delta = -3) \), if we assign a “typical” spectral index for a Type II L RSN of \( \alpha = -0.65 \) \( (\alpha_{SN\ 1979C} = -0.73, \alpha_{SN\ 1980K} = -0.58; \) see Table 3), and if we take \( t_0 = -30 \) days before optical maximum (optical discovery date in the case of SN 1986E), as we did for SN 1980K (Weiler et al. 1992), only \( K_1, K_2, \) and \( \beta \) remain undetermined.

We still have too many parameters to determine all parameters unambiguously from only one detection, but through the use of the 3 \( \sigma \) upper limits available at 6 cm on 1986 August 11 (4 months before the detection) and on 1987 August 28 (8 months after the detection), we can place limits on the possible values of the parameters. These limits are listed in Table 3 and the resulting model radio light curves are shown along with the available data in Figure 2.

Accepting these limits for \( K_1 \) and \( \beta \), the two parameters that predict the late-time radio behavior, implies that SN 1986E would have had a flux density <0.060 mJy at 20 cm on 1995 July 14 and <0.026 mJy at 6 cm on 1995 December 04, the epochs of the Eck et al. (1996) observations. These limits are both less than their reported 3 \( \sigma \) upper limits (see Table 1) and

5. SN 1986E ESTIMATED PROPERTIES

Using these “best estimate” parameters for SN 1986E and taking a distance to NGC 4302 of 16.8 Mpc (Tully 1988) yields a 6 cm peak spectral luminosity of \( L_{6\ cm\ peak} \approx 1.1 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1} \). Though less radio-luminous than SN 1979C by more than an order of magnitude at peak \( (L_{6\ cm\ peak} = 2.6 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}; \) see Table 3), SN 1986E is comparable in 6 cm peak luminosity to SN 1980K \( (L_{6\ cm\ peak} = 1.0 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}; \) see Table 3).

Further, using the parameters from Table 3 and the formulation of Weiler et al. (1986), equation (16), we can obtain an estimate of the ratio of the presupernova mass-loss rate \( (\dot{M}) \) to the presupernova stellar wind velocity \( (w_{wind}) \) of \( \dot{M}/w_{wind} > 4.7 \times 10^{-6} M_\odot \text{ yr}^{-1} (\text{ km s}^{-1})^{-1} \), or \( \dot{M} > 4.7 \times 10^{-3} M_\odot \text{ yr}^{-1} (M_{SN\ 1979C} = 1.9 \times 10^{-6} M_\odot \text{ yr}^{-1}, M_{SN\ 1980K} = 2.0 \times 10^{-5} M_\odot \text{ yr}^{-1}; \) see Table 3), for the commonly assumed parameters of \( w_{wind} = 10^2 \text{ km s}^{-1}, T = 20,000 \text{ K}, \) and \( v_{shock} = 13,000 \text{ km s}^{-1} \).

A comparison of the model and physical parameters derived for SN 1986E, SN 1979C, and SN 1980K is shown in Table 3. As is clear from examination of Table 3, SN 1986E was probably a fairly typical Type III SN with properties somewhat similar to those of SN 1980K.

6. CONCLUSIONS

Although our radio data sample is extremely limited, with only one detection at one frequency, by including new upper limits it is possible to show, with reasonable assumptions and parameter estimates, that SN 1986E was probably a fairly “normal” Type III SN in its radio behavior. The best parameter estimates imply that the late-time radio upper limits determined by Eck et al. (1996) are not in conflict with the estimated properties of SN 1986E, and their conclusion that SN 1986E represents the first example of a late-time optically detectable SN that has not been seen in the radio is not supported. SN 1986E could, in fact, have been rather similar to SN 1980K. Thus, the strong correlation between the presence of radio emission and late-time optical emission is maintained.

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