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THE FADING RADIO EMISSION FROM SN 1961V: EVIDENCE FOR A TYPE II PECULIAR SUPERNOVA?

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ABSTRACT

Using the Very Large Array (VLA), we have detected radio emission from the site of SN 1961V in the Sc galaxy NGC 1058. With a peak flux density of 0.063 ± 0.008 mJy beam^{-1} at 6 cm and 0.147 ± 0.026 mJy beam^{-1} at 18 cm, the source is nonthermal, with a spectral index of -0.79 ± 0.23. Within errors, this spectral index is the same value reported for previous VLA observations taken in 1984 and 1986. The radio emission at both wavelengths has decayed since the mid-1980s observations with power-law indices of $\beta_{20\,\mathrm{cm}} = -0.69 \pm 0.23$ and $\beta_{6\,\mathrm{cm}} = -1.75 \pm 0.16$. We discuss the radio properties of this source and compare them with those of Type II radio supernovae and luminous blue variables.

Key words: galaxies: individual (NGC 1058) — galaxies: general — supernovae: general — supernovae: individual (SN 1961V) — radio continuum

1. INTRODUCTION

SN 1961V, the prototype of Zwicky's type V supernova (SN; now classified as either a Type II peculiar SN or a luminous blue variable [LBV]), was unique in several respects (Branch & Greenstein 1971). Its progenitor was visible as an 18th magnitude star from 1937 to 1960. It is the first SN, prior to SN 1987A, whose parent star was identified before it exploded (assuming a SN interpretation is correct for this event). The bolometric correction, the exact distance, and the extinction are all uncertain, but its preoutburst luminosity apparently exceeded 10^{41} ergs s^{-1}, which is the Eddington limit for a 240 $M_{\odot}$ star. After the explosion in late 1961, the initial peak of the optical light curve was more complex and much broader than for any supernova ever observed. Subsequently, the optical light curve decayed more slowly, by about 5 mag in 8 yr. Few SNe have been followed optically for more than 2 yr. Optical spectra taken during this extended bright phase showed that the characteristic expansion velocity of SN 1961V was 2000 km s^{-1}, which differs from the typical value of 10,000 km s^{-1} for most SNe. This velocity is similar to novae expansion velocities. However, no novae are this strong, and none have persisted for this long in the radio. This velocity is in fact consistent with the measurements of SN 1986J (another Type II peculiar SN), which had an expansion velocity (taken well after maximum optical brightness) of 1000 km s^{-1} (van Gorkom et al. 1986; Rupen et al. 1987; Weiler & Sramek 1988).

Using the Very Large Array (VLA),[4] observations of SN 1961V were made in the mid-1980s, with the most definitive search being in 1986 (Cowan, Henry, & Branch 1988, hereafter CHB). CHB detected a nonthermal radio source at the precise position of SN 1961V. Fesen (1985) also reported recovering SN 1961V in the optical. CHB later detected an optical counterpart to SN 1961V, which was identified as an H II region using filter photometry. (CHB also detected another slightly fainter radio source to the west of SN 1961V with a similar nonthermal spectral index. This source was identified as a supernova remnant [SNR] not previously identified. This SNR also has an associated optical counterpart [i.e., an H II region].) At the distance of NGC 1058 (9.3 Mpc; Tully 1980; Silbermann et al. 1996), SN 1961V is as radio luminous as the bright Galactic SNR Cas A. SN 1961V's luminosity is also comparable to several historical, decades-old (also known as intermediate-age) radio supernovae (RSNe), including SNe 1923A, 1950B, 1957D, 1968D, 1970G, and 1986J (Cowan, Goss, & Sramek 1991; Cowan, Roberts, & Branch 1994; Eck, Cowan, & Branch 1998; Eck et al. 2001; Hyman et al. 1995; Weiler & Sramek 1988).

Recently, however, there has been some question about whether the event identified as SN 1961V was actually a supernova. Goodrich et al. (1989) suggest instead that this event was an LBV similar to η Carinae, and the supposed supernova was an outburst of the variable star. Subsequently, Filippenko et al. (1995) observed SN 1961V using the *Hubble Space Telescope* (*HST*), although at that time the *HST* had not been refurbished. Those observations seemed to suggest that a (very faint) star is still present at the site, which might or might not argue against a supernova origin. Among the brightest LBVs (e.g., η Car, P Cygni, and V12 in NGC 2403), η Car is reported to have been the most luminous, reaching $M_{\mathrm{Bol}} \simeq -14$. In comparison, SN 1961V was reported to have peaked at $M_{\mathrm{Bol}} \simeq -17$ (Humphreys & Davidson 1994). This peak estimate for SN 1961V is likely underestimated by 1.2 mag if one accounts for the more recently derived Cepheid distance (Silbermann et al. 1996). This would make SN 1961V nearly 50 times brighter in the optical than η Car at maximum brightness (Humphreys & Davidson 1994).

To assess the exact nature of this event, we have performed a series of observations at various wavelengths, employing the phased VLA with the Very Large Baseline Interferometer (VLBI) and the *ROSAT* X-ray satellite. In this paper, we report on our recent VLA radio observations

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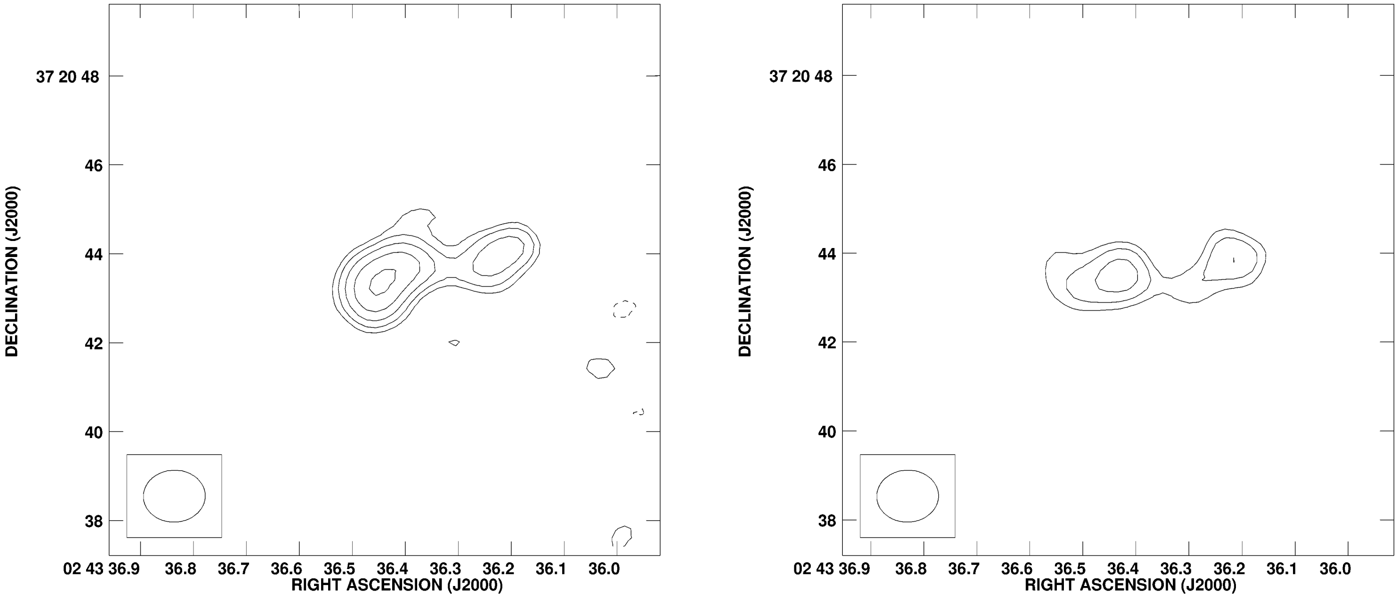

Fig. 1*a*

Fig. 1*b*

FIG. 1.—(*a*) Radio contour map at 20 cm (1.5 GHz) of SN 1961V (the strong eastern source) and a neighboring SNR (western source). Contour levels are −0.11, −0.08, −0.06, 0.06, 0.08, 0.11, 0.16, 0.23, and 0.32 mJy beam^{-1}, with a beam size of 1.″26 × 1.″05, a P.A. = 89°, and an rms noise of 0.020 mJy beam^{-1}. Observations were taken with the VLA in A configuration on 1984 November 15. (*b*) Radio contour map at 18 cm (1.7 GHz) of the same region. Contour levels are −0.11, −0.08, −0.06, 0.06, 0.08, 0.11, 0.16, 0.23, and 0.32 mJy beam^{-1}, with a beam size of 1.″20 × 1.″01, a P.A. = 82°, and an rms noise of 0.026 mJy beam^{-1}. Observations were taken with the VLA in A configuration on 1999 September 14.

of SN 1961V and what they indicate about the nature of this event. The VLBI and *ROSAT* results are reported in Stockdale (2001).

2. OBSERVATIONS AND RESULTS

The new VLA data on SN 1961V are taken from three observing runs. In the first, SN 1961V was observed for 12 hr on 1999 September 14 at 18 cm (1.67 GHz) using the VLA's most extended (A) configuration, with a maximum baseline of 34 km. These data were taken while the VLA was being used in phased-array mode for a VLBI run, and the total bandwidth was 50 MHz in each of the two orthogonal circular polarizations. The phase calibrator was J0253+3835, and both 3C 286 and 3C 48 were used to set the flux density scale. The total time on-source was 4.7 hr.

During the second pair of observing runs, on 2000

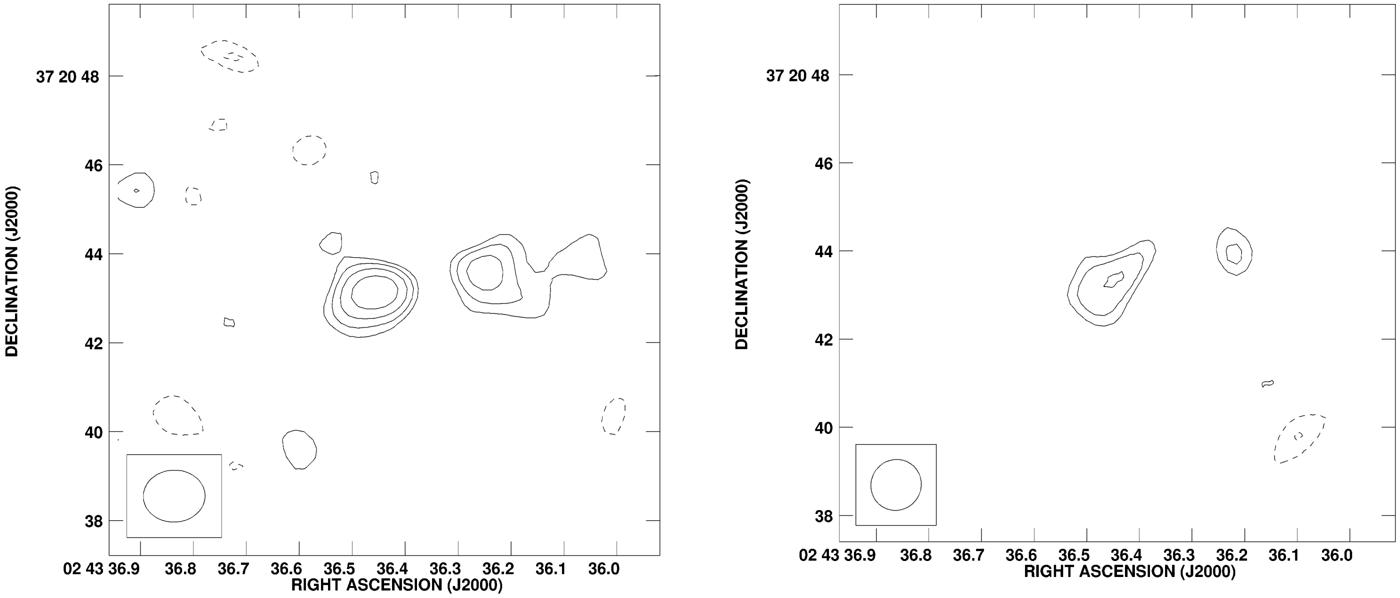

Fig. 2*a*

Fig. 2*b*

FIG. 2.—(*a*) Same as Fig. 1, but at 6 cm (4.9 GHz). Contour levels are −0.07, −0.05, −0.03, 0.03, 0.05, 0.07, 0.10, 0.14, and 0.19 mJy beam^{-1}, with a beam size of 1.″39 × 1.″17, a P.A. = −89°, and an rms noise of 0.013 mJy beam^{-1}. Observations were taken with the VLA in B configuration on 1986 August 13. (*b*) Same as Fig. 1, but at 6 cm (4.9 GHz). Contour levels are −0.07, −0.05, −0.03, 0.03, 0.05, 0.07, 0.10, 0.14, and 0.19 mJy beam^{-1}, with a beam size of 1.″17 × 1.″13, a P.A. = −35°, and an rms noise of 0.008 mJy beam^{-1}. Observations were taken with the VLA in B configuration on 2000 January 21 and 25.

TABLE 1

RADIO OBSERVATIONS OF THE REGION NEAR SN 1961V

Parameters	SN 1961V	Western Source
Right ascension (J2000)	02 43 36.46 ± 0.02	02 43 36.24 ± 0.01
Declination (J2000)...........	+37 20 43.2 ± 0.2	+37 20 43.8 ± 0.4
18 cm (1999 Sep 14)[a]	0.147 ± 0.026	0.117 ± 0.026
6 cm (2000 Jan 21 and 25)[a]...	0.063 ± 0.008	0.056 ± 0.008
Spectral Index $\alpha_{6\ \mathrm{cm}}^{18\ \mathrm{cm}}$[b]	−0.79 ± 0.23	−0.64 ± 0.28
20 cm (1984 Nov 15)[a]	0.229 ± 0.020	0.160 ± 0.020
6 cm (1986 Aug 13)[a]..........	0.135 ± 0.013	0.070 ± 0.013
Spectral Index $\alpha_{6\ \mathrm{cm}}^{20\ \mathrm{cm}}$[b]	−0.44 ± 0.15	−0.98 ± 0.22

[a] Peak flux density (mJy beam^{-1}).

[b] Obtained by $S \propto \nu^{\alpha}$.

January 21 and 25 , the VLA was in its B configuration (maximum baseline of 10 km) and observed at 6 cm (4.89 GHz) for a total of 12 hr. Here we used the standard VLA continuum mode, obtaining a total of 100 MHz bandwidth in each of the two orthogonal circular polarizations. The phase calibrator was J0251+4032, and 3C 48 was used to set the flux density scale. In all observations, the pointing center was CHB's radio position for SN 1961V, and flux densities for 3C 48 and 3C 286 were taken from Perley, Butler, & Zijlstra (2001).

Data were Fourier-transformed and deconvolved using the CLEAN algorithm as implemented in the AIPS routine IMAGR. The data were weighted using Brigg's robustness parameter of −1, which yields a reasonably small point-spread function at the cost of a few percent loss in sensitivity. We have also reanalyzed the CHB observations of the region, using the same data reduction procedures and inputs as were used on the current data. The results of our analyses are presented in Table 1 and Figures 1 and 2. To derive the flux density and position for SN 1961V, a JMFIT two-source Gaussian fit yielded the best results for all four observations, while a single-source Gaussian model yielded the best results for the other sources in the field of view. The positions reported in Table 1 are weighted averages of the radio positions for these sources at the various wavelengths and epochs. Uncertainties in the peak intensities are reported as the rms noise from the observations. To check that the changes in measured flux densities are real, we also measured the flux density of a resolved background source present at all epochs. The background source's integrated flux densities for each wavelength band are relatively unchanged at both epochs. Our remeasurements of the CHB data are consistent, within the error bars, with those of Cowan et al. (1991).

3. DISCUSSION

We have recovered a radio source at the position of SN 1961V at 18 and 6 cm, coincident with the CHB positionwithin the error limits. Our measured flux densities at both wavelengths indicate a clear decline in the radio emissions from SN 1961V from the previous CHB observations, as indicated in Figures 1 and 2. The recently measured 18 cm flux, when scaled to 20 cm using the newly determined spectral index, indicates a reduction in the 20 cm peak flux intensity by 36% from 1984 to 1999 (see Table 1). The 6 cm peak flux intensity has also dropped by 54% in the interval from 1986 to 2000. (The western source shows no change in peak intensity for either the 6 cm or the 20 cm measurements within noise limits.) The radio emission from the vicinity of SN 1961V appears to be much more complicated than originally thought. Our new observations and reanalysis of the CHB data indicate there is at least one previously undetected radio source within 0″.9 of SN 1961V. The radio emission from this source is nonthermal at both epochs and has decayed by 50% at 20 cm and by 33% at 6 cm. The region in which SN 1961V is located in NGC 1058 is clearly one of recent star formation. The peak flux density of this new source near SN 1961V is 0.040 ± 0.008 mJy beam^{-1} (at 6 cm) and 0.082 ± 0.026 mJy beam^{-1} (at 20 cm). These values are comparable to that of the distinct western source reported by CHB, so this new source may likely be a previously undetected SNR.

The decline in the radio flux density of SN 1961V is consistent with models for radio emission from SNe (Chevalier 1984). Synchrotron radiation is produced in the region of interaction between the ejected supernova shell and the circumstellar shell that originated from the prior mass loss of the progenitor star. In such models, the radio emission drops as the expanding shock wave propagates outward through the surrounding and decreasingly dense circumstellar material (CSM). The decline in the flux density of SN 1961V is also consistent with Gull's (1973) model for radio emission from SNRs. This predicts an initial decline in the emission of RSNe for the first 100 yr as the shock overcomes the CSM and later a turn-on as the buildup of material from the interstellar medium (ISM) results in an increase of synchrotron emission as the object enters the SNR phase. Thus, the radio emission from these intermediate-age SNe, sources with ages comparable to SN 1961V, probes the transition region between fading SNe and the very youngest SNRs. In Figure 3, we illustrate the radio light curves of several intermediate-aged SNe, along with a few SNRs, plotting the time since supernova explosion versus the luminosity at 20 cm. It is clear that the radio emission of SN 1961V at an age of ≃38 yr is very similar to known radio SNe at comparable ages, and particularly the radio luminosities of SN 1961V in NGC 1058 and the Type II SN 1950B in M83 are virtually identical at similar ages.

As shown in Table 1, our new observations indicate that SN 1961V remains a nonthermal radio source. The spectral index, α, is relatively unchanged although the error bars are rather large. The spectral index was derived using the peak intensities, in order to limit the contribution from the surrounding H II region. We might expect a possible flattening of the radio spectrum as the emission from SN 1961V continues to fade. This would be an indication of the increasing contribution from the thermal emission of the associated H II region. Such was the case for the radio (Cowan et al. 1994) and optical (Long, Winkler, & Blair 1992) emissions of SN 1957D in M83 which has now faded below the level of an associated H II region. The current and previous values of α for SN 1961V are still consistent with spectral indexes of intermediate-age RSNe at similar wavelengths, as shown in Table 2. The nonthermal nature of these sources is well documented, as are those for young radio SNRs, such as Cas A, the youngest, whose spectral index ranges from −0.92 to −0.64 (Anderson et al. 1991).

We can also compare the rate of decline of radio emission for SN 1961V, as measured by a power-law index ($S \propto t^{\beta}$), with decline rates of known Type II RSNe (see Fig. 3). The power-law indices for SN 1961V were determined from

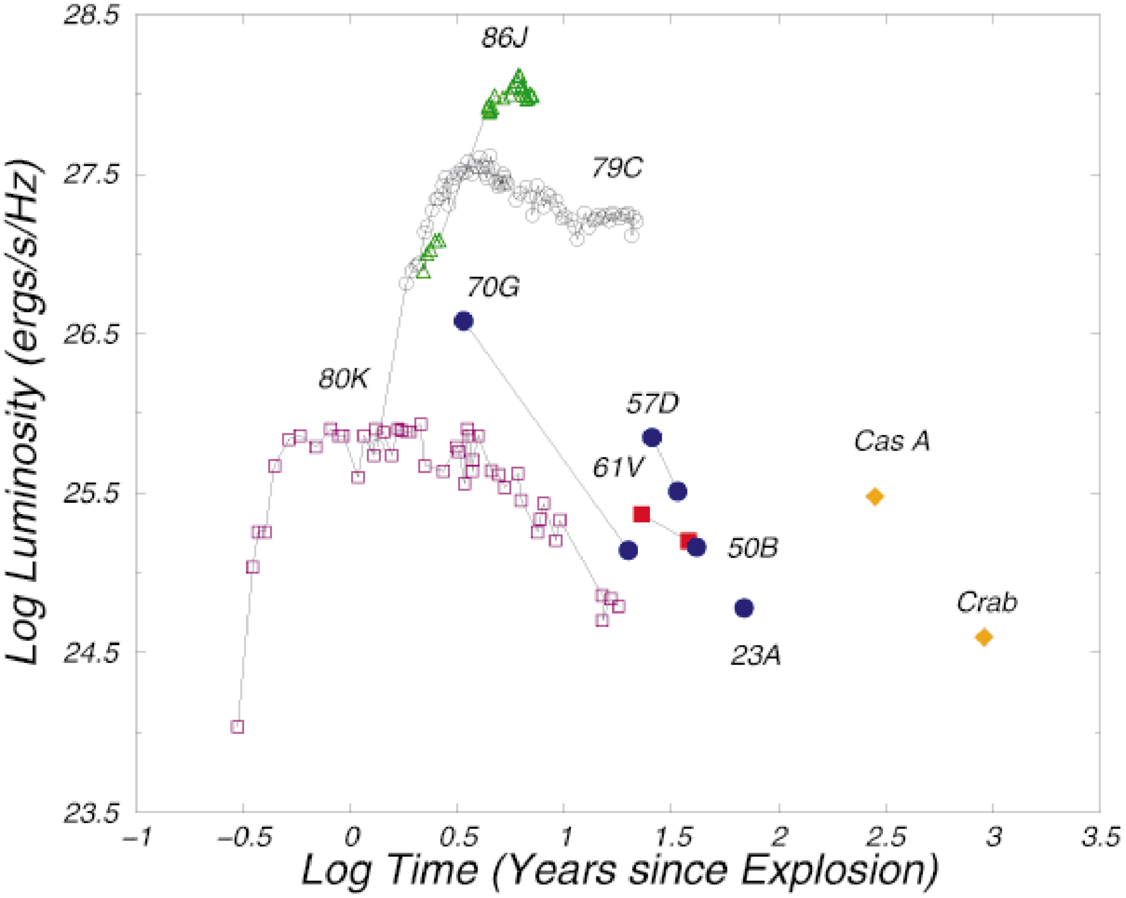

FIG. 3.—Radio light curve for SN 1961V at 20 cm compared with several RSNe and SNRs. Data, fits, and distances for SN 1923A are taken from Eck et al. (1998) and Saha et al. (1995); for SN 1950B and 1957D, from Cowan et al. (1994) and Saha et al. (1995); for SN 1961V, from this paper and Silbermann et al. (1996); for SN 1970G, from Cowan et al. (1991) and Kelson et al. (1996); for SN 1979C, from Weiler et al. (1986, 1991), Montes et al. (2000), and Ferrarese et al. (1996); for SN 1980K, from Weiler et al. (1986, 1992), Montes et al. (1998), and Tully (1988); and for SN 1986J, from Rupen et al. (1987), Weiler, Panagia, & Sramek (1990), and Silbermann et al. (1996). Luminosities for Cas A and the Crab Nebula are taken from Eck et al. (1998).

the peak intensities to be $\beta_{20\ \mathrm{cm}} = -0.69 \pm 0.23$ and $\beta_{6\ \mathrm{cm}} = -1.75 \pm 0.16$. The decay indices for SN 1961V fall within a range of previously measured indices for some intermediate-age RSNe (see Table 2). In particular, SN 1957D and 1970G both have fairly rapid decline rates, while the younger Type II RSNe (SNe 1979C and 1980K) indicate a slower rate of decline. We also note that while the radio emission from SN 1980K has abruptly dropped after approximately 10 yr (Weiler et al. 1992; Montes et al. 1998), SN 1979C (at a greater distance than SN 1980K) is still emitting at detectable levels (Weiler et al. 1991). Recently, the radio emission of SN 1979C appears to have flattened, as indicated in Figure 3. This may be a result of the shock wave hitting a denser region of CSM (Montes et al. 2000). The implications of these comparisons with SN 1961V are that its shock may be traveling through considerably more CSM than similarly aged RSNe, e.g., SN 1957D. As a result, its radio flux continues to drop at a slower rate more akin to the younger RSNe, i.e., SNe 1979C, 1980K, and 1986J (the only other identified Type II peculiar SN). Consistent with this interpretation is the very rapid decline in the radio emissions of Type Ib RSNe, e.g., SNe 1983N and 1984L, which presumably have less CSM (see Table 2). Based on these comparisons, the radio observations of SN 1961V are consistent with Type II RSNe.

TABLE 2

COMPARISON WITH RADIO SUPERNOVAE

Name	SN Type	Spectral Index (α)[a]	Decay Index (β)[b]
SN 1923A ...	II-P	-1.00 ± 0.30	-6.9 ± 4.0 (6 cm)
SN 1950B ...	II?	-0.45 ± 0.08	Insufficient observations
SN 1957D...	II?	-0.30 ± 0.02	-2.90 ± 0.07 (20 cm)
...	...	...	-1.70 ± 0.04 (6 cm)
SN 1961V ...	II pec	-0.79 ± 0.23	-0.69 ± 0.23 (20 cm)
...	...	...	-1.75 ± 0.16 (6 cm)
SN 1970G...	II	-0.56 ± 0.11	-1.95 ± 0.17 (20 cm)
SN 1979C ...	II-L	-0.72 ± 0.05	-0.71 ± 0.08 (20 and 6 cm)
SN 1980K...	II-L	-0.50 ± 0.06	-0.65 ± 0.10 (20 and 6 cm)
SN 1986J....	II pec	-0.30 ± 0.06	$-1.18^{+.02}_{-.04}$ (20 and 6 cm)
SN 1983N...	I-SL	-1.0 ± 0.2	-1.5 ± 0.3 (20 and 6 cm)
SN 1984L ...	I-SL	-1.03 ± 0.06	-1.59 ± 0.08 (20 and 6 cm)

[a] Obtained by $S \propto t^{\beta}$.
[b] Obtained by $S \propto \nu^{\alpha}$.

REFERENCES.—Data are from Cowan et al. 1991; Cowan et al. 1994; Eck et al. 1998; Panagia, Sramek, & Weiler 1986; Rupen et al. 1987; Weiler et al. 1986, 1992, 1991.

Radio comparisons between η Car, the superluminous LBV, and SN 1961V are more problematic, since the first radio observations of η Car were made 100 yr after its eruption. η Car, with a 20 cm flux density of 0.9 ± 0.3 Jy (Retallack 1983), is in fact not a strong radio source when compared with SN 1961V. In order to determine η Car's 20 cm flux at the current age of SN 1961V, we have naively assumed a range of potential β values for η Car from -1, our measured index for the decline of the flux at 20 cm of SN 1961V, to -3, the index for the decline of SN 1957D. Applying these constant decay rates to η Car, its 20 cm flux (40 yr after outburst) would range from 5 to 65 times the Retallack (1983) measurement. This would result in η Car being at least 1000 times weaker than the radio source at the position of SN 1961V reported in this paper. η Car's 3 cm flux was measured over a period of 5 yr by Duncan, White, & Lim (1997) and found to vary between 0.5 and 2.8 Jy, well below the levels of 6 and 20 cm emissions of SN 1961V. They further report that η Car's spectral index between 3 and 6 cm appears to peak at $+1.8$ at the position of η Car and then drops radially toward an index of 0. The source of the radio emission is believed to be thermal radiation from H II regions associated with η Car (Retallack 1983). The spectral index derived from radio observations at 2 and 6 cm of Skinner et al. (1998) of P Cyg, another LBV, is 0.47 ± 0.12. (P Cyg's last reported outburst was in the seventeenth century.) The positive values of the LBV spectral indexes are obviously very different from the negative (i.e., nonthermal) indices for such events as SN 1961V, SN 1923A (the oldest RSN), and Cas A (the youngest radio SNR; Anderson et al. 1991; Cowan et al. 1991; Eck et al. 1998). The nonthermal spectral indexes for SNe and SNRs result from a shock front interacting with the CSM and ISM. As the referee has pointed out, it is possible that P Cyg and η Car may have been nonthermal radio sources immediately following their initial outbursts. Unfortunately, there is no observational evidence to support or refute this possibility. Furthermore, it is uncertain whether the radiation from an LBV event would remain nonthermal this long after the outburst. One of the most recent LBV events in the Small Magellanic Cloud, HD 5980, was observed in the radio by Ye, Turtle, & Kennicutt (1991) prior to LBV outbursts in 1993 and 1994. It was later observed in 1996 using the Australian Telescope Compact Array at 3 and 6 cm for ~1 hr. No compact radio emission was detected from the vicinity of the star, with an upper limit threshold of a few millijanskys (S. M. White 2001, private communication).

4. CONCLUSIONS

Our radio measurements have detected a source at the position of SN 1961V. The source's radio luminosity, spectral index, and decay index are all consistent with values reported for Type II RSNe and thus appear to support a supernova interpretation. However, the lack of radio observations of similarly aged bright LBVs prevents a definitive identification of the true nature of SN 1961V. Additional multiwavelength observations of SN 1961V as it evolves will clearly be needed to make a final judgment about the nature of this enigmatic event. These should include further monitoring with the VLA and using the Space Telescope Imaging Spectrograph to analyze nebular emission lines from the region near SN 1961V to discriminate LBV ejecta nebulae ([N II]-bright), decades-old SNe ([O III] and [O I]-bright), and mature SNRs ([S II]-bright). The latter observations could be very useful in ruling out one of the two scenarios for SN 1961V.

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