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THE RADIO DETECTION OF SN 1968D IN NGC 6946

SCOTT D. HYMAN
Department of Physics, Sweet Briar College, Sweet Briar, VA 24595

SCHUYLER D. VAN DYK
Astronomy Department, University of California, Berkeley, CA 94720-3411

KURT W. WEILER
Remote Sensing Division, Naval Research Laboratory, Code 7216, Washington, DC 20375-5351

AND

RICHARD A. SRAMEK
P.O. Box 0, National Radio Astronomy Observatory, Socorro, NM 87801
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ABSTRACT

We report the radio detection of the Type II supernova SN 1968D in the nearby spiral galaxy NGC 6946 from continuum observations at 6 and 21 cm using the Very Large Array. This radio detection is ~26 yr after its optical discovery. SN 1968D is only the fourth "intermediate-age" SN ever recovered in the radio. The current flux densities of this supernova at these wavelengths are consistent with the extrapolated radio behavior of another Type II supernova in this galaxy, the well-studied supernova SN 1980K. It is therefore likely that the radio emission from SN 1968D arises from the same mechanism as for SN 1980K and other known radio supernovae, i.e., interaction of the supernova shock with preexisting circumstellar matter.

Subject headings: radio continuum: stars — stars: evolution — supernova remnants — supernovae: general — supernovae: individual (SN 1968D)

1. INTRODUCTION

A growing list of supernovae (SNs) are known to show detectable radio emission. Many of these radio supernovae (RSNs) have been monitored and successfully modeled, following the basic tenets of the Chevalier (1984) "minishell" model, as the interaction of the SN shock with the circumstellar wind matter produced in the last stages of stellar evolution of a progenitor red supergiant star (see, e.g., Weiler et al. 1986; Weiler, Panagia, & Sramek 1990; Weiler et al. 1991, 1992). The first undisputed detection of radio emission from a SN was for SN 1970G (Gottesman et al. 1972; see Weiler et al. 1986), and the first detailed radio light curve for a RSN was for SN 1979C (Weiler et al. 1981, 1986). On the other hand, the youngest known supernova remnant (SNR), Cas A (SN ~ 1670), is over 300 yr old, and little or nothing is known about the radio behavior of SNs for the time interval $20 \lesssim t(\text{yr}) \lesssim 300$, i.e., the so-called intermediate-age SNs (cf. Weiler & Sramek 1988).[1] The beginning of a partial solution has emerged with the radio detection of SN 1957D, and the probable detection of SN 1950B, in M83 (Cowan & Branch 1985; Cowan, Roberts, & Branch 1994). SN 1961V has also been detected in the radio (see Branch & Cowan 1985; Cowan, Henry, & Branch 1988), but compelling evidence exists that this was not a SN, but instead was likely the superoutburst from a luminous blue variable star (Goodrich et al. 1989; Filippenko et al. 1995). Recently the RSN SN 1970G in M101 (Gottesman et al. 1972; Allen et al. 1976; Weiler et al. 1986) has been recovered in the radio at an age ~23 yr (Cowan, Sramek, & Goss 1991). With so few examples available for study, each new example is extremely valuable.

In this *Letter* we report the radio detection of SN 1968D in the nearly face-on, nearby spiral galaxy NGC 6496. SN 1968D was independently discovered optically by both Dunlap (1968) and Wild (1968). A spectrum by Sargent (1968) showed it to be Type II.

NGC 6946 has been host to six historical SNs. Radio emission has also been detected and monitored from SN 1980K (Weiler et al. 1986, 1992). SN 1968D thus represents the second RSN to be detected in NGC 6946 and only the fourth intermediate-age SN to have ever been detected in the radio. It therefore provides important clues to the nature of RSNs and to the connection between SNs and SNRs.

2. RADIO OBSERVATIONS AND RESULTS

Over the past decade we have monitored at 6 and 20 cm wavelength the behavior of SN 1980K (see Weiler et al. 1986, 1992) using the Very Large Array (VLA).[2] This monitoring resulted in a large radio database, which has been utilized to obtain very sensitive maps of NGC 6946 and its component features, such as bright H II regions, SNRs, and the structure of the distributed nonthermal emission (Hyman et al. 1995). The resulting radio maps have already yielded detection of a source that is likely the radio counterpart (Van Dyk et al. 1994b) to a luminous SNR in NGC 6946 seen in X-rays (Schlegel 1994a) and in the optical (Blair & Fesen 1994).

We searched these deep radio maps for emission from the five known SNs previous to SN 1980K. While our map at 20

[1] In order to establish a consistent nomenclature, we will define as "intermediate age" any RSN/SNR which lies in the age gap between the oldest well-studied RSN SN 1979C and the youngest well-studied SNR Cas A (SN ~ 1670).

[2] The VLA is a telescope of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

cm showed an unresolved 0.65 mJy radio source within ~2″ of the reported nuclear offset position of SN 1968D (45″ E, 20″ N; Wild 1968), our 6 cm map showed only a possible detection marginally above the noise at this position. However, since the monitoring observations were centered on SN 1980K, at 280″ E and 165″ S of the nucleus of NGC 6946, the resolution and sensitivity of the maps at the position of SN 1968D were seriously degraded by bandwidth smearing at 20 cm and by primary beam attenuation at 6 cm.

Therefore, to confirm the possible detection, we conducted further radio observations of a field centered on the position of SN 1968D with the VLA in "A" configuration (36.6 km maximum baseline) for 3.4 hr on 1994 April 26 (UT) at 6 cm (4.860 GHz) and for a total of 0.8 hr on 1994 April 2, 21, and 26 at 21 cm (1.425 GHz). VLA phase and flux density calibration and data reduction with AIPS followed standard procedures, such as those described in Weiler et al. (1990). The map at 6 cm has a resolution 0″.44 × 0″.34 (FWHM) and an rms noise level of 28 μJy beam^{-1}. The data from the three observations at 21 cm were combined and mapped to give a resolution of 1″.49 × 1″.16 (FWHM) and an rms noise level of 27 μJy beam^{-1}.

We show in Figure 1 contour maps of the SN at these two frequencies. An unresolved pointlike source is clearly seen at the center of both maps. This source has a 6 cm position of α[1950.0] = 20^{h}33^{m}55^s.298($\pm$0^s.03), δ[1950.0] = +59°59′09″.07 ($\pm$0″.2). The nucleus has a radio position of α[1950.0] = 20^{h}33^{m}49^s.174, δ[1950.0] = +59°58′49″.31, yielding a nuclear offset position for the detected source of 45″.8 E, 19″.7 N, in excellent agreement with the reported optical nuclear offset of SN 1968D. This likely detection of radio emission from SN 1968D was first reported by Van Dyk et al. (1994a). The source has flux densities 0.20 $\pm$ 0.03 and 0.62 $\pm$ 0.04 mJy at 6 and 21 cm, respectively, yielding a rather steep spectral index of $\alpha = -0.92 \pm 0.13$ (flux density $S \propto \nu^\alpha$). The excellent positional coincidence and nonthermal spectral index of the radio source provides, we believe, very convincing evidence that SN 1968D has indeed been recovered in the radio.

3. DISCUSSION

Since both SN 1968D and SN 1980K are in the same galaxy and at the same distance, their flux densities can be compared directly. In Figure 2 we have plotted the 6 and 21 cm data points for SN 1968D with the best-fit model 6 and 20 cm light curves for SN 1980K (Weiler et al. 1992). Figure 2 suggests that SN 1980K, assuming that it continues evolving in the expected manner, will be quite similar when it reaches the age of SN 1968D. SN 1968D does appear to have a steeper spectral index (α[1980K] = -0.65, Weiler 1994; α[1968D] = -0.92, this *Letter*), but the indices are not completely inconsistent to within the errors. Other Type II RSNs, e.g., SN 1979C in M100 ($\alpha = -0.74$; Weiler et al. 1991) and SN 1993J in M81 ($\alpha = -0.99$; Van Dyk et al. 1994c), also have slightly steeper spectral indices relative to SN 1980K. These similarities between the radio emission from SN 1980K and SN 1968D presumably arise from the same SN shock/circumstellar matter interaction mechanism thought responsible for the radio emission from other RSNs.

It is interesting to note that the spectral index $\alpha = -0.92$ for SN 1968D is considerably steeper than that observed for the three other intermediate-age RSNs (see Cowan et al. 1991; Cowan et al. 1994), SN 1957D ($\alpha = -0.30 \pm 0.02$), SN 1950B ($\alpha = -0.45 \pm 0.08$), and SN 1970G ($\alpha = -0.56 \pm 0.11$). However, the significance of this is not clear at present.

We show in Figure 3 the 6 cm spectral luminosity as a function of age, for the intermediate-age RSNs, including SN 1968D, for a representative sample of younger RSNs, and for the young Galactic SNRs. The luminosity evolution for the RSNs is represented in each case by the best-fit model 6 cm light curves. The model values for the Type II RSNs SN 1979C,

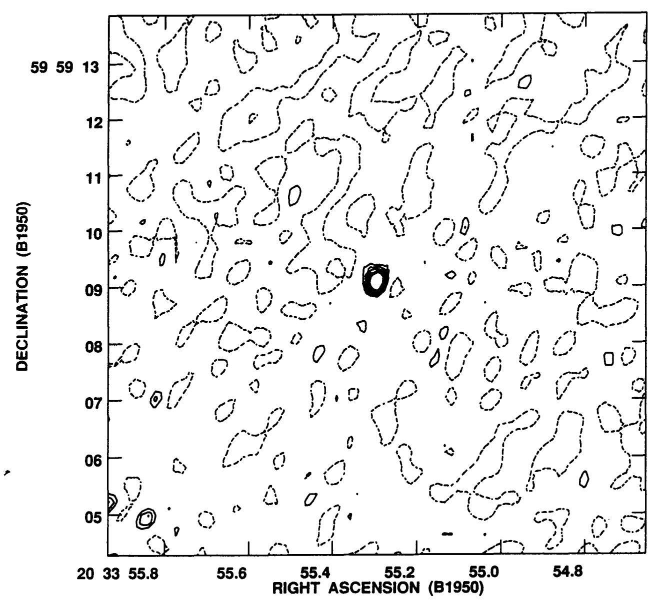

FIG. 1*a*

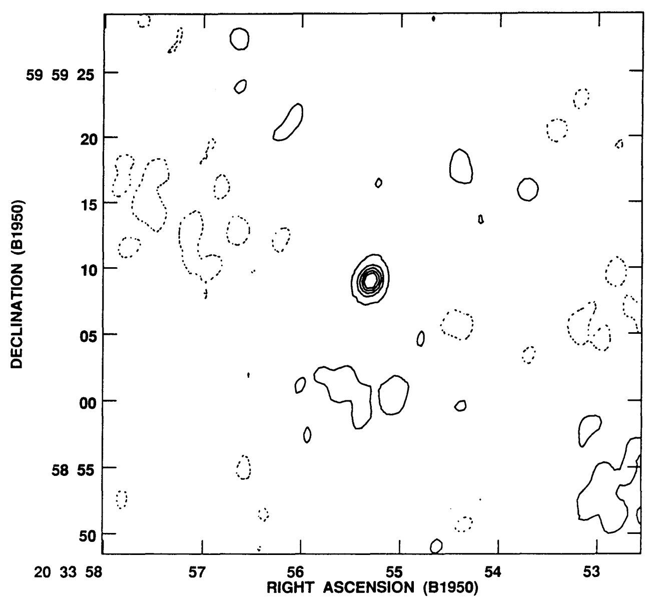

FIG. 1*b*

FIG. 1.—The (*a*) 6 and (*b*) 21 cm VLA maps of the field including the Type II Supernova SN 1968D in the galaxy NGC 6946. The SN is clearly seen at the centers of both maps as a compact radio source. The 6 cm map has a beam size (FWHM) of 0″.44 × 0″.34 and 0.028 mJy beam^{-1} rms noise, while the 21 cm map has a beam size (FWHM) of 1″.49 × 1″.16 and 0.027 mJy beam^{-1} rms noise. The contours shown for the 6 cm map are -0.02, 0.06, 0.08, 0.10, 0.12, and 0.14 mJy beam^{-1}; the contours for the 21 cm map are -0.02, 0.02, 0.10, 0.18, 0.26, and 0.34 mJy beam^{-1}.

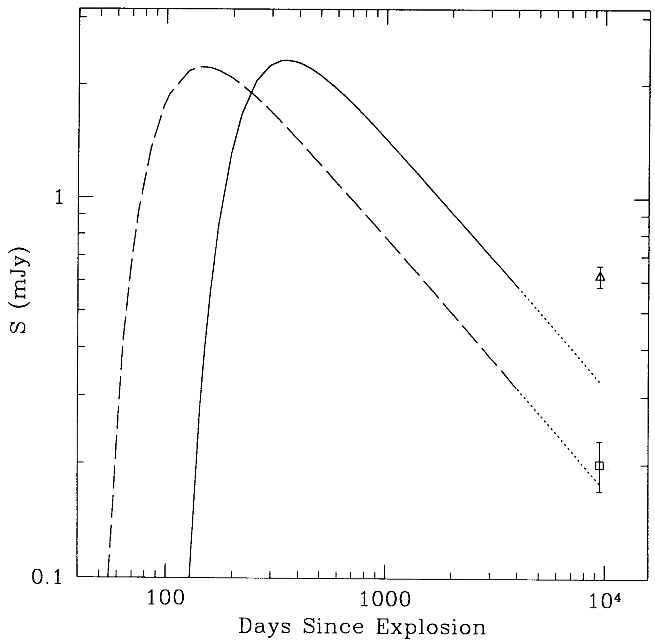

FIG. 2.—The 6 cm (*open square*) and 21 cm (*open triangle*) flux densities for SN 1968D, plotted together with the best-fit model radio "light curves" at 6 cm (*dashed curve*) and 20 cm (*solid curve*) for SN 1980K (Weiler et al. 1992), also in NGC 6946. (The dotted curves at both frequencies are the extrapolations of the best-fit model light curves for SN 1980K to the age of SN 1968D.)

1980K, and SN 1993J are from Weiler et al. (1991), Weiler et al. (1992), and Van Dyk et al. (1994c), respectively. For comparison, we also show the model light curves for the Type Ib supernova SN 1983N (Weiler et al. 1986) and for the peculiar Type II supernova SN 1986J (Weiler et al. 1990). The data for the SNRs is from Weiler et al. (1986). At a distance of 5.5 Mpc for

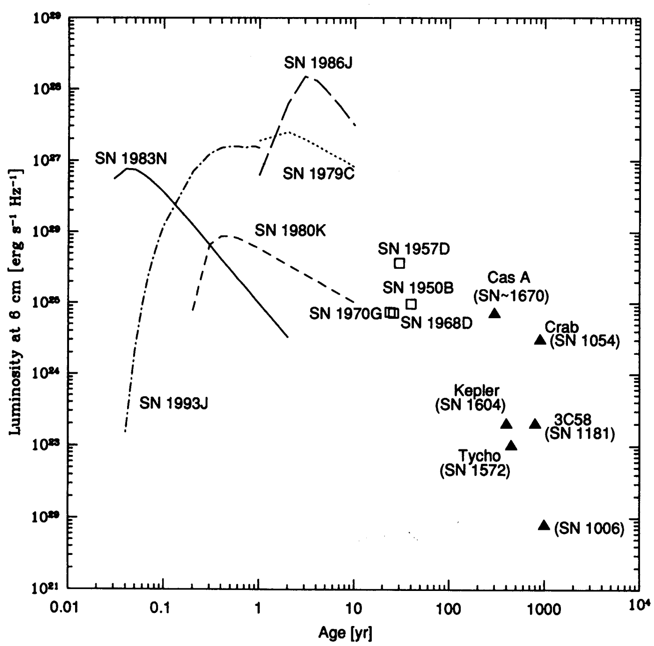

FIG. 3.—Spectral radio luminosity at 6 cm as a function of SN age, in years, for several young RSNs (model *curves*), the intermediate-age RSNs (*open squares*), including SN 1968D, and young Galactic SNRs (*solid triangles*). See text for sources of data and discussion.

NGC 6946 (Tully 1988), the 6 cm luminosity of SN 1968D is 7.2×10^{24} ergs s^{-1} Hz^{-1}, which is comparable to the luminosity of Cas A, the brightest radio SNR in the Galaxy. In Figure 3 we see that both SN 1968D and SN 1970G are fainter than SN 1957D and SN 1950B. The recently radio recovered SN 1970G has a 6 cm luminosity of 7.4×10^{24} ergs s^{-1} Hz^{-1} (Cowan et al. 1991), very similar to that of SN 1968D, and this implies that they both represent the evolved stage of normal Type II RSNs, such as SN 1980K.

From Figure 3, it is tempting to make a direct evolutionary connection between the young RSNs, the intermediate-age RSNs, and the SNRs, with the RSNs evolving into the intermediate-age RSNs and continuing to age, with a relatively constant power-law decline, into the SNRs. However, several caveats must be heeded. First, the nature of log-log plots, such as Figure 3, can be deceptive, compressing order-of-magnitude differences. Second, we expect that, at some point, the SN shock will reach the boundary of the circumstellar matter, established by the red supergiant star progenitor, and the radio emission will abruptly decline for the RSNs (Weiler et al. 1986). Third, radio emission from SNRs is thought to only become strong after ~100 yr, when the shock sweeps up enough interstellar matter, or a pulsar excites the surrounding medium, to form a young SNR (Gull 1973).

We have essentially no observational information to fill in the gap between SN 1950B and Cas A (SN ~ 1670) and little detailed light curve information prior to SN 1979C. Thus, the evolutionary path of SNs to SNRs is poorly understood at this time, and it may be that the processes responsible for each phase are not physically related.

Finally, one must keep in mind that SNRs, such as Kepler (SN 1604), Tycho (SN 1572), and SN 1006 are shock-driven shells, thought to arise from Type Ia SNs, while SNRs, such as the Crab Nebula (SN 1054) and 3C 58 (SN 1181), are pulsar-driven plerions, thought to arise from Type II SNs. If these relations are correct, then non–radio-emitting Type Ia SNs (see Weiler et al. 1989) leading to the formation of shell-type SNRs, and shock-driven Type II RSNs leading to the formation of pulsar-driven plerions, must be indirect. The so-called composite SNRs (e.g., Weiler & Sramek 1988) at least offer a morphologically consistent picture, since they are thought to originate from massive star explosions and still show shock-driven radio shells.

4. CONCLUSIONS

New observations have detected radio emission from SN 1968D in NGC 6946. It is only the fourth intermediate-age SN to have been recovered in the radio, with SN 1950B, SN 1957D, and SN 1970G being the only other known examples. Although few in number, these objects serve as a bridge in our understanding between the well-studied, young ($\lesssim 20$ yr) RSNs and the youngest, but still much older ($\gtrsim 300$ yr), SNRs.

Additionally, it is interesting to note that the SN shock/circumstellar wind interaction that is responsible for the radio emission from RSNs appears to be the mechanism for both X-ray emission from young SNs and the long-term optical emission from some SNs (Chevalier & Fransson 1994). Fesen (1993) has optically recovered SN 1970G ~2 yr after its radio recovery (Cowan et al. 1991). After radio detection, SN 1957D was also recovered in the optical by Long, Blair, & Krzeminski (1989), and more recent observations in 1991 (Long, Winkler, & Blair 1992) show that the optical flux of SN 1957D had declined by a factor of ~5 from the observations 4 yr earlier. A presumably related drop in the radio flux density was also observed over a similar time period (Cowan et al. 1994).

So far, no new optical counterpart to SN 1968D has been found. SN 1968D may have been recovered by *ROSAT* from observations of NGC 6946, but the field is too confused in X-rays to be certain (Schlegel 1994b). However, such optical and X-ray recoveries would be very interesting, since they would add significantly to our understanding of the radiation from intermediate-age SNs and evolving RSNs.

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Note added in proof.—It has been kindly pointed out to us by S. Ryder that SN 1978K (S. Ryder et al. ApJ, 416, 167 [1993]) can be included along with SN 1979C to define the time point we have chosen to separate "intermediate-age" from "young" SNRs.