

RADIO EMISSION FROM SN 2001gd IN NGC 5033

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ABSTRACT

We present the results of monitoring the radio emission from the Type IIb supernova SN 2001gd between 2002 February 8 and 2002 October 28. Most of the data were obtained using the Very Large Array at the five wavelengths of 1.3 cm (22.4 GHz), 2.0 cm (14.9 GHz), 3.6 cm (8.44 GHz), 6.2 cm (4.86 GHz), and 21 cm (1.4 GHz). Observations were also made with the Giant Meterwave Radio Telescope at 21 cm (1.4 GHz). The object was discovered optically well after maximum light, making any determination of the early radio evolution difficult. However, subsequent observations indicate that the radio emission has evolved regularly in both time and frequency and is well described by the supernova shock–circumstellar medium interaction model.

Subject headings: galaxies: individual (NGC 5033) — radio continuum: stars — stars: mass loss — supernovae: general — supernovae: individual (SN 2001gd)

1. INTRODUCTION

Supernova (SN) 2001gd in NGC 5033 was discovered at magnitude 16.5 on 2001 November 24.820 UT by Nakano et al. (2001) at R.A. = 13^h13^m23^s.89, decl. = +36°38′17″.7 (J2000.0), with independent discoveries by other observers following quickly. No source had been detected at that position (limiting magnitude ~ 18.5) on a previous image taken on 2001 May 8, and nothing is visible on the Palomar Sky Survey red and blue plates (Nakano et al. 2001). Ten days later Matheson et al. (2001) confirmed the discovery as a Type IIb supernova well past maximum light, stating “the spectrum is almost identical to one of SN 1993J obtained on day 93 after explosion.” By using this suggestion to constrain the explosion date for the source, the optical discovery occurred 83 days after the explosion (Nakano et al. 2001), and the first radio observation was 158 days after the explosion. Tully (1988) determined a distance of 18.7 Mpc (assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$) to NGC 5033. Accepting the Tully (1988) distance and using $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, we will adopt the distance to the SN of 21.6 Mpc, which results in an absolute visible magnitude at discovery of less

than -15 , although it is not known what the magnitude was at maximum optical brightness (Nakano et al. 2001). We use the Tully distance method to maintain uniformity with our distance determinations to other radio SNe, including SN 1985L (Van Dyk et al. 1998).

Stockdale et al. (2002) detected radio emission from SN 2001gd on 2002 February 8.54 with the Very Large Array (VLA)³ at 22.485 GHz (1.3 cm), 8.435 GHz (3.6 cm), 4.885 GHz (6.1 cm), and 1.465 GHz (21 cm). The radio position of R.A. = 13^h13^m23^s.90, decl. = +36°38′18″.1 (J2000.0), with an uncertainty of $\pm 0''.2$ in each coordinate (Stockdale et al. 2002), is in agreement with the optical position to within the errors. Since this first detection, we have made and will continue to make radio observations with the VLA. We note that NGC 5033 is also the host galaxy of two other historical supernovae, SN 1950C and SN 1985L (Kowal, Sargent, & Zwicky 1970; Aksenov et al. 1985). The latter was also detected in the radio in 1986 (Van Dyk et al. 1998). Stockdale et al. (2002) did not detect radio emission from either of these historical supernovae, nor do we in any of our subsequent observations.

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TABLE 1
CALIBRATOR MEASUREMENTS FOR J1310+323

OBS. DATE	REFERENCE EPOCH (days)	TELESCOPE CONFIGURATION	S (Jy)				
			21 cm	6 cm	3.6 cm	2 cm	1.2 cm
2001 Nov 24	$\equiv 0.00$	...	...	...	...	...	...
2002 Feb 08	75.72	VLA A	1.703	1.659	1.765	...	2.145
2002 Mar 02	97.60	VLA A	1.703 ^a	1.687	1.745	2.027	2.164
2002 Mar 14	109.66	VLA A	1.700	...	...	...	...
2002 Mar 23	118.42	VLA A	1.681	...	1.798 ^a	2.077	2.315
2002 Apr 06	132.38	VLA A	1.690	1.700 ^a	1.833 ^a	2.073	...
2002 Jun 12	199.30	VLA B	1.668	1.726	2.005	...	...
2002 Jul 16	234.17	VLA B	1.722	1.773	2.045	...	...
2002 Oct 28	337.15	VLA C	...	...	2.130	2.551	2.728

^a Interpolated from other calibrator measurements.

2. RADIO OBSERVATIONS

The VLA radio observations reported here were made between 2002 February 8 and 2002 October 28. VLA phase and flux density calibration and data reduction followed standard procedures (Weiler et al. 1986; Weiler, Panagia, & Sramek 1990), using 3C 286 as the primary flux density calibrator and J1310+323 as the phase calibrator and as a secondary flux density calibrator.

In Table 1, we list the flux density observations of the secondary calibrator source J1310+323, which are plotted in Figure 1. The defined position for J1310+323 for phase reference is R.A. = $13^{\text{h}}10^{\text{m}}28^{\text{s}}.66$, decl. = $+32^{\circ}20'43''.8$ (J2000.0).

In Table 2, we list the flux density measurements for SN 2001gd and Figure 2 plots the data. The data appear to be well described by a parameterized model described below and illustrated in Figure 2.

The flux density measurement error given for the VLA measurements in Table 2 is a combination of the rms map

error, which measures the contribution of small unresolved fluctuations in the background emission and random map fluctuations due to receiver noise, and a basic fractional error, ϵ , included to account for the normal inaccuracy of VLA flux density calibration and possible deviations of the primary calibrator from an absolute flux density scale. The final errors (σ_f) as listed in Table 2 are taken as

$$\sigma_f^2 \equiv (\epsilon S_0)^2 + \sigma_0^2, \quad (1)$$

where S_0 is the measured flux density, σ_0 is the map rms for each observation, and $\epsilon = 0.10$ at 21 cm, 0.05 at 6 cm, 0.05 at 3.6 cm, 0.075 at 2 cm, and 0.10 at 1.2 cm.

3. DISCUSSION

Common properties of radio SNe (RSNe) include non-thermal synchrotron emission with high brightness temperature, turn-on delay at longer wavelengths, power-law decline after maximum with index β , and spectral index α

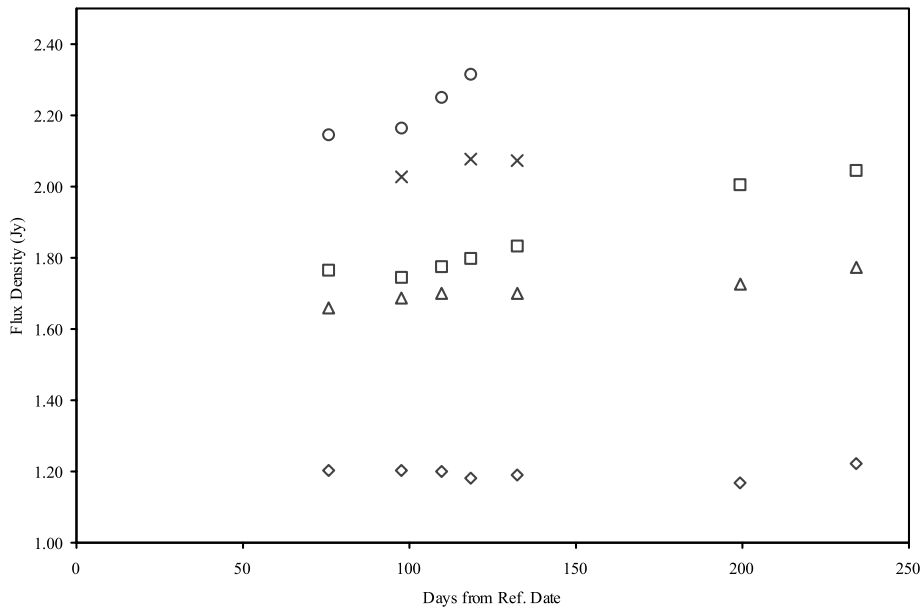


FIG. 1.—Plot of the flux density of the VLA calibrator source J1310+323 at 1.3 cm (circles), 2 cm (crosses), 3.6 cm (squares), 6 cm (triangles), and 21 cm (diamonds). Note that the values for 21 cm are all reduced by 0.5 Jy to avoid confusion on the plot.

TABLE 2
FLUX DENSITY MEASUREMENTS FOR SN 2001gd

OBS. DATE	REFERENCE EPOCH (days)	TELESCOPE CONFIGURATION	$S \pm \sigma_f$ (mJy)				
			21 cm	6 cm	3.6 cm	2 cm	1.2 cm
2001 Nov 24 ^a	$\equiv 0.00$	...	...	...	...	...	...
2002 Feb 08.....	75.72	VLA A	0.848 ± 0.129	5.050 ± 0.257	4.090 ± 0.208	...	1.370 ± 0.176
2002 Mar 02.....	97.60	VLA A	1.414 ± 0.177	5.414 ± 0.284	3.732 ± 0.195	2.183 ± 0.242	1.335 ± 0.182
2002 Mar 14.....	109.66	VLA A	1.840 ± 0.352	...	...	...	...
2002 Mar 23.....	118.42	VLA A	1.830 ± 0.339	...	3.660 ± 0.208	2.330 ± 0.322	1.000 ± 0.187
2002 Apr 06.....	132.38	VLA A	1.990 ± 0.344	5.330 ± 0.277	3.780 ± 0.212	2.660 ± 0.304^b	...
2002 Jun 12.....	199.30	VLA B	3.230 ± 0.365	4.842 ± 0.249	3.100 ± 0.168	...	...
2002 Jul 16.....	234.17	VLA B	2.733 ± 0.314	4.260 ± 0.234	2.390 ± 0.137	...	...
2002 Sep 22.....	301.40	GMRT	3.550 ± 0.220^c	...	...	...	...
2002 Oct 28.....	337.15	VLA C	...	...	2.071 ± 0.136	0.893 ± 0.178	0.809 ± 0.155

^a Nakano et al. 2001; Matheson et al. 2001; SN 2001gd is believed to have exploded roughly 83 days prior to its initial optical detection. See § 1 for further explanation.

^b This value was not included in the modeling.

^c Chandra, Ray, & Bhatnagar 2002.

asymptotically decreasing to an optically thin value (Weiler et al. 1986). Weiler et al. (1986, 1990) have shown that the “minishell” model of Chevalier (1982a, 1982b) adequately describes previously known RSNe. 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 envelope of circumstellar material (CSM) that has been ionized and heated by the initial UV/X-ray flash. This dense cocoon is presumed to have been established by a constant mass-loss (\dot{M}) rate, in a constant-velocity wind (w_{wind} , i.e., $\rho_{\text{CSM}} \propto \dot{M}/w_{\text{wind}}r^2$) from a red supergiant SN progenitor or companion. This

ionized CSM is also the source of the initial absorption. The rapid rise in radio flux density results from the shock overtaking progressively more of the wind matter and leaving less of it along the line of sight to the observer to absorb the more slowly decreasing synchrotron emission from the shock region.

3.1. Parameterized Model

Following Weiler et al. (1986, 1990, 2002) and Weiler, Panagia, & Montes (2001), Montes, Weiler, & Panagia (1997), and Chevalier (1998), we adopt the parameterized

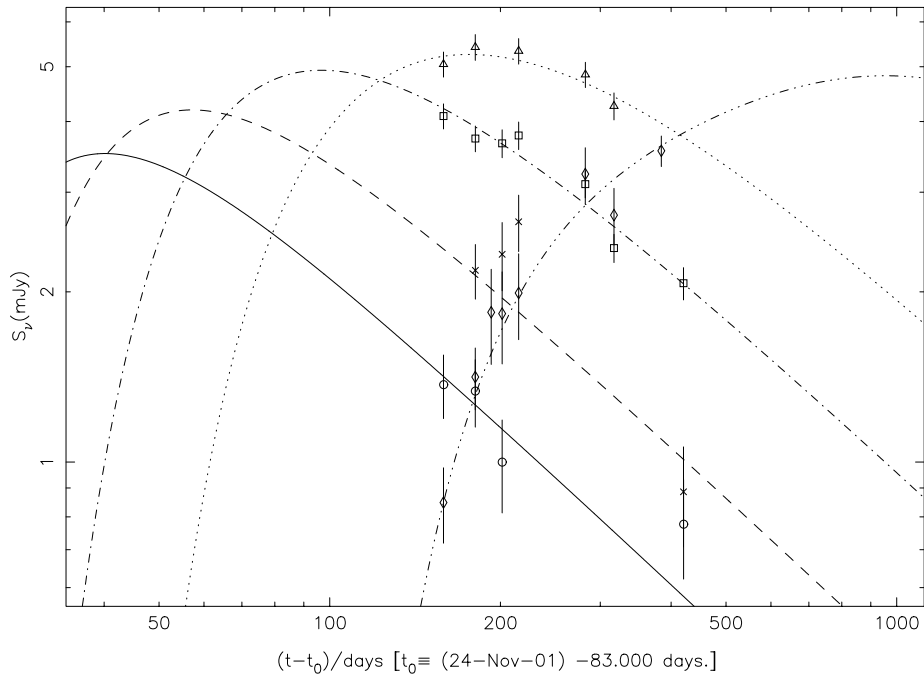


FIG. 2.—Radio measurements and parameterized model for SN 2001gd at 1.3 cm (circles; solid line), 2 cm (crosses; dashed line), 3.6 cm (squares; dash-dotted line), 6 cm (triangles; dotted line), and 21 cm (diamonds; dash-triple-dotted line). The lines represent the best-fit model as described in the text with the parameters listed in Table 2. SN 2001gd is believed to have exploded 83 days prior to its initial optical discovery; see § 1 for further explanation (Nakano et al. 2001; Matheson et al. 2001).

model,

$$S(\text{mJy}) = K_1 \left(\frac{\nu}{5 \text{ GHz}} \right)^\alpha \left(\frac{t - t_0}{1 \text{ day}} \right)^\beta \times e^{-\tau_{\text{ext}}} \left(\frac{1 - e^{-\tau_{\text{CSM}_{\text{clmp}}}}}{\tau_{\text{CSM}_{\text{clmp}}}} \right) \left(\frac{1 - e^{-\tau_{\text{int}}}}{\tau_{\text{int}}} \right), \quad (2)$$

with

$$\tau_{\text{ext}} = \tau_{\text{CSM}_{\text{hom}}} + \tau_{\text{dist}}, \quad (3)$$

where

$$\tau_{\text{CSM}_{\text{hom}}} = K_2 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t - t_0}{1 \text{ day}} \right)^\delta, \quad (4)$$

$$\tau_{\text{CSM}_{\text{clmp}}} = K_3 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t - t_0}{1 \text{ day}} \right)^{\delta'}, \quad (5)$$

$$\tau_{\text{dist}} = K_4 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1}, \quad (6)$$

with K_1 , K_2 , K_3 , and K_4 corresponding, formally, to the flux density (K_1), homogeneous absorption (K_2 and K_4), and clumpy (or filamentary) absorption (K_3) at 5 GHz 1 day after the explosion date t_0 , and subscripts indicating “internal,” “external,” “homogeneous,” “distant,” and “clumps.” The terms $\tau_{\text{CSM}_{\text{hom}}}$ and $\tau_{\text{CSM}_{\text{clmp}}}$ describe the attenuation of a local homogeneous and clumpy CSM that are near enough to the supernova progenitor that they are affected by the expanding blast wave. The $\tau_{\text{CSM}_{\text{hom}}}$ absorption term is due to an ionized medium that uniformly covers the emitting source. The $\tau_{\text{CSM}_{\text{clmp}}}$ absorption term describes the attenuation produced by an inhomogeneous medium (see Natta & Panagia 1984 for a more detailed discussion). The τ_{dist} term describes the attenuation produced by a homogeneous medium that uniformly covers the source but is so far from the SN progenitor that it is not affected by the blast wave and is constant in time.

All external and clumpy absorbing media are assumed to be purely thermal singly ionized gas that absorbs via free-free transitions with frequency dependence $\nu^{-2.1}$ in the radio. The parameter δ describes the time dependence of the optical depth for the local uniform medium. For an undecel-

erated SN shock, $\delta = -3$ is appropriate,⁴ and we have assumed this value for our parameterization since the data are insufficient to properly determine δ at this time. The parameter δ' describes the time dependence of the optical depth for the nonuniform (clumpy) absorbing medium. For this source and at this epoch, we neglect the K_4 term because any distant time-independent absorption effects will likely be evident only at lower frequencies and later times than are available in our current data set (see, e.g., Montes et al. 1997; Schlegel et al. 1999 for SN 1978K).

Chevalier (1998) proposed that synchrotron self-absorption (SSA) may be a significant source of absorption at high frequencies and early times for some RSNs. Given the relatively poor sampling of the radio emission turn-on at early times, SSA is not expected to be significant and our parameterization of SN 2001gd is not improved by the inclusion of SSA component.

A search for the best parameter fit to equations (2)–(6) was carried out by minimizing the reduced χ^2 (χ_{red}^2). The best-fit parameter values and comparisons with the Type IIb SN 1993J and the other recent RSN in NGC 5033, SN 1985L, are listed in Table 3. The resulting model curves are plotted in Figure 2. The errors listed for the parameter values, determined by the “bootstrap” method, are at the 1σ uncertainty level.

The fitting procedure and examination of Figure 2 indicates that the gross properties of the radio emission from SN 2001gd are relatively well described by a purely thermal absorption model such as that given by equations (2)–(6), with parameter values listed in Table 3. The requirement for nonzero K_2 and K_3 parameter values implies the existence of a clumpy or filamentary absorption component embedded in a relatively homogeneous medium (on a more detailed level, this is consistent with case 2 discussed by Weiler et al. 2001, 2002). The distant absorption term (K_4) was set to zero for reasons discussed previously. The parameter values are typical of values determined for other Type II SNe, although they are not tightly constrained by the relatively sparse data set.

⁴ Weiler et al. 1986 show that the absorption term $\tau_{\text{CSM}_{\text{hom}}} \propto r^{-3}$. Since $r \propto t^1$ for an undecelerated shock, $\tau_{\text{CSM}_{\text{hom}}} \propto t^{-3}$, from eq. (4) it follows that $\delta = -3$ in this case.

TABLE 3
FIT OF SN 2001gd AND COMPARISON WITH OTHER TYPE II SUPERNOVAE

Parameter ^a	SN 2001gd	SN 1993J ^b	SN 1985L ^c
K_1	$(1.49^{+1.88}_{-1.09}) \times 10^3$	4.14×10^3	4.8×10^3
α	$-1.38^{+0.13}_{-0.12}$	-0.99	> -0.58
β	$-0.96^{+0.24}_{-0.13}$	-0.64	< -0.71
K_2	$(3.25^{+4.55}_{-1.31}) \times 10^6$	1.35×10^3	$> 7.00 \times 10^6$
δ	$\equiv -3.00$	-1.99	$\equiv -3.00$
K_3	$(1.05^{+1.31}_{-0.93}) \times 10^3$	2.54×10^4	0.00
δ'	$-1.27^{+0.40}_{-0.15}$	-2.02	0.00
Time to L (6 cm peak) (days).....	173^{+10}_{-15}	168	$\equiv 30$
L (6 cm peak) (ergs s ⁻¹ Hz ⁻¹).....	$(2.91^{+0.13}_{-0.04}) \times 10^{27}$	1.45×10^{27}	$\sim 3.1 \times 10^{26}$
\dot{M} (M_\odot yr ⁻¹).....	3.0×10^{-5}	2.1×10^{-5}	$> 6.3 \times 10^{-5}$

^a Assumes a constant mass-loss rate, constant velocity, wind-established CSM, i.e., $\rho \propto r^{-2}$.

^b Van Dyk et al. 1994.

^c Van Dyk et al. 1998.

3.2. Comparison with Other RSNe

It is useful to make distance-independent comparisons between SN 2001gd to SN 1985L, also in NGC 5033. Van Dyk et al. (1998) reported only two 6 cm detections of SN 1985L approximately 1 year after explosion, with numerous nondetections. SN 1985L was identified as Type II-L by Filippenko & Sargent (1985) and Kriss (1985). Despite the relatively small amount of radio data available for the SN 1985L, there are some valid comparisons that can be made. SN 2001gd [$L(6 \text{ cm peak}) = 2.91 \times 10^{27} \text{ ergs s}^{-1} \text{ Hz}^{-1}$] is almost 10 times more luminous at the 6 cm peak flux density than SN 1985L [$L(6 \text{ cm peak}) = 3.10 \times 10^{26} \text{ ergs s}^{-1} \text{ Hz}^{-1}$; Van Dyk et al. 1998].⁵ The 6 cm peak luminosity of SN 2001gd also lies within a range of other Type II SNe, for example, SN 1979C ($2.55 \times 10^{27} \text{ ergs s}^{-1} \text{ Hz}^{-1}$) and SN 1980K ($1.18 \times 10^{26} \text{ ergs s}^{-1} \text{ Hz}^{-1}$). SN 2001gd and SN 1985L also have very different times from explosion to 6 cm peak, although in both cases there is great uncertainty in this timescale. SN 2001gd has a much steeper spectral index ($\alpha = -1.4$) than any other well-observed RSN. Weiler et al. (2002) demonstrate that most Type II SNe have a spectral index ($\alpha > -1.0$), similar to SN 1985L, which has a moderate value of $\alpha = -0.58$. The power-law decline index for SN 2001gd ($\beta \sim -0.96$) is comparable to that of other Type II RSNe.

It is also useful to make some comparisons between SN 2001gd and SN 1993J since both are Type IIb SNe, and SN 1993J was much better sampled than SN 2001gd. Both have relatively equivalent 6 cm peak luminosities, as reported in Table 3. The time to 6 cm peak for SN 1993J is in relatively close agreement with SN 2001gd (~ 170 days), although this value is somewhat atypical when compared with other Type II SNe. Type Ib/Ic SNe typically achieve their 6 cm peak luminosity in less than 40 days, while most Type II SNe take from a few as ~ 100 days to well over 1 year (Weiler et al. 2002). Both SN 2001gd and SN 1993J have spectral indices less than -1.0 , which is more typical of Type Ib/Ic SNe (Weiler et al. 2002). But SN 2001gd appears to have a power-law decline index comparable to that of SN 1993J and other Type II SNe, unlike values reported for Type Ib SN 1983N and SN 1984L ($\beta \sim -1.6$; Sramek, Panagia, & Weiler 1984; Weiler et al. 1986; Panagia, Sramek, & Weiler 1986).

3.3. Estimates of Mass-Loss Rates

Using the derived parameter values from the radio light curves, we can estimate the presupernova mass-loss rate of the SN 2001gd progenitor star (Weiler et al. 1986, 1990, 2001, 2002) as

$$\frac{\dot{M}/(M_{\odot} \text{ yr}^{-1})}{w_{\text{wind}}/(10 \text{ km s}^{-1})} = 3.0 \times 10^{-6} \langle \tau_{\text{eff}}^{0.5} \rangle m^{-1.5} \left(\frac{v_i}{10^4 \text{ km s}^{-1}} \right)^{1.5} \times \left(\frac{t_i}{45 \text{ days}} \right)^{1.5} \left(\frac{t}{t_i} \right)^{1.5m} \left(\frac{T}{10^4 \text{ K}} \right)^{0.68}, \quad (7)$$

⁵ We have adjusted the luminosity of SN 1985L to account for a Tully 1988 distance to NGC 5033 of 21.6, assuming $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Van Dyk et al. 1998 assumed $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for a Tully 1988 distance of 20 Mpc.

where

$$\langle \tau_{\text{eff}}^{0.5} \rangle = 0.67 [(\tau_{\text{CSM}_{\text{hom}}} + \tau_{\text{CSM}_{\text{clmp}}})^{1.5} - \tau_{\text{CSM}_{\text{hom}}}^{1.5}] \tau_{\text{CSM}_{\text{clmp}}}^{-1}. \quad (8)$$

This estimate depends on the parameterized model, as well as on assumptions of temperature ($T_{\text{CSM}} = 2 \times 10^4 \text{ K}$), pre-SN wind speed ($w_{\text{wind}} = 10 \text{ km s}^{-1}$), shock velocity ($v_i = 10^4 \text{ km s}^{-1}$), and t_i , which accounts for the time between the appearance of optical lines from which the expansion velocity is determined and the explosion date of the SN, typically assumed to be 45 days (Weiler et al. 1986). Equation (7) is derived⁶ from case 2 presented by Weiler et al. (2001, 2002). Since the SN was detected at such a late time, we can only approximately estimate the shock velocity and temperature at early times, making the mass-loss rate estimates for SN 2001gd rather uncertain. However, the estimated mass-loss rate of $3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ is close to the values found for both SN 1993J and SN 1985L. As one might expect since they are both Type IIb SNe, there are many similarities between SN 2001gd and SN 1993J, especially in that they require the presence of both uniform and clumpy (or filamentary) media to account for the radio light-curve behavior; while the mass-loss rate for SN 2001gd appears to be in the lower range of known mass-loss rates for Type II SNe (1×10^{-5} to $1 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$), it clearly exceeds the values for typical Ib/Ic SNe (7×10^{-7} to $1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$; Weiler et al. 2002).

4. CONCLUSIONS

We present new observations of SN 2001gd at multiple radio wavelengths for the first year after explosion. Modeling implies that the evolution of the radio emission from SN 2001gd behaves in a systematic fashion and is consistent with the nonthermal-emitting, thermal-absorbing model previously used successfully for other RSNe. The CSM required by the model fits is best described as a “filamentary” or “clumpy” medium embedded in a uniform component and appears similar to that suggested for the Type IIb SN 1993J (Van Dyk et al. 1994). In general, SN 2001gd is very similar to SN 1993J, suggesting that Type IIb SNe may be relatively uniform in their properties. By comparison, the Type II-L SN 1985L in the same galaxy as SN 2001gd appears significantly different in its radio properties, illustrating the general diversity of Type II RSNe.

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⁶ Case 1 is a uniform external absorbing medium, case 2 is a clumpy or filamentary medium with a statistically large number of clumps, and case 3 is similar to case 2 but with a statistically small number of clumps.

⁷ Additional information and data on radio supernovae can be found on <http://rsd-www.nrl.navy.mil/7214/weiler/> and linked pages.

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