EXPANDED VERY LARGE ARRAY OBSERVATIONS OF THE RADIO EVOLUTION OF SN 2011dh

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ABSTRACT

We report on Expanded Very Large Array observations of the Type IIb supernova 2011dh, performed over the first 100 days of its evolution and spanning 1–40 GHz in frequency. The radio emission is well described by the self-similar propagation of a spherical shockwave, generated as the supernova ejecta interact with the local circumstellar environment. Modeling this emission with a standard synchrotron self-absorption (SSA) model gives an average expansion velocity of $v \approx 0.1c$, supporting the classification of the progenitor as a compact star $(R_{\star} \approx 10^{11} \text{ cm})$. We find that the circumstellar density is consistent with a $\rho \propto r^{-2}$ profile. We determine that the progenitor shed mass at a constant rate of $\approx 3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, assuming a wind velocity of 1000 km s⁻¹ (values appropriate for a Wolf-Rayet star), or $\approx 7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ assuming 20 km s⁻¹ (appropriate for a yellow supergiant [YSG] star). Both values of the mass-loss rate assume a converted fraction of kinetic to magnetic energy density of $\epsilon_B = 0.1$. Although optical imaging shows the presence of a YSG, the rapid optical evolution and fast expansion argue that the progenitor is a more compact star—perhaps a companion to the YSG. Furthermore, the excellent agreement of the radio properties of SN 2011dh with the SSA model implies that any YSG companion is likely in a wide, non-interacting orbit.

Key word: supernovae: individual (SN 2011dh)

Online-only material: color figures

1. INTRODUCTION

Type IIb supernovae (SNe IIb) were first identified as a distinct class of core-collapse events after detailed observations of the "canonical" Type IIb SN 1993J revealed broad hydrogen and helium features (Filippenko 1997). Recent studies have shown that this spectroscopic class shows a broad diversity in properties including H α strength, profile, and evolution (e.g., compare with SN 2003bg; Matheson et al. 2001; Hamuy et al. 2009; Mazzali et al. 2009). In several cases, yellow supergiant (YSG) stars with extended radii, $R_* \sim 100 R_{\odot}$, have been identified at the explosion sites of SNe II (1993J, 2008cn, 2009kr, 2011dh; Maund & Smartt 2009; Maund et al. 2011; Van Dyk et al. 2011; Elias-Rosa et al. 2009, 2010). Yet progenitor diagnostics from multi-wavelength studies indicate that some SNeIIb bear stronger similarity to hydrogen-poor Type Ibc SNe commonly associated with compact progenitors, $R_* \approx R_{\odot}$ (hereafter SNe cIIb; Chevalier & Soderberg 2010). In particular, radio-derived estimates for the shockwave velocities are typically high, $v \ge 0.1c$, and difficult to explain in the context of shock breakout from an extended object (Nakar & Sari 2010). Furthermore, stellar evolution tracks place YSGs outside of the SN explosion phase space of the H-R diagram (Meynet & Maeder 2005, but see Georgy 2012). In addition, Chevalier & Soderberg (2010) find that all proposed SNe cIIb for which there is sufficient radio data show light curve variations indicative of density modulations in the explosion environment, consistent with wind variability from a compact progenitor. Finally, binary companions have been reported for two SNeIIb to date (1993J and 2001ig; Woosley et al.

1994; Ryder et al. 2006; Maund et al. 2007). Similarly, the YSG may be a binary companion rather than the progenitor star.

Probing the distinguishing differences between SNe cIIb and extended Type IIb SNe requires early discovery, since rapid follow-up observations are crucial for identifying unique characteristics. Since the advent of dedicated transient surveys and improvements in amateur astronomical equipment, such early discoveries are becoming more common. In 2011 June, an optical transient was found in M51 by amateur astronomer Amédée Riou (Griga et al. 2011). Prompt spectroscopic followup indicated that it was a Type II SN, and further spectroscopy revealed that the object most closely resembled a Type IIb (Arcavi et al. 2011; Marion et al. 2011). A YSG was identified in pre-explosion Hubble Space Telescope imaging at the position of the SN (Maund et al. 2011; Van Dyk et al. 2011), similar to the case of SN 1993J. However, rapid optical follow-up observations from the Palomar Transient Factory (Law et al. 2009) pointed to a compact progenitor star, as evidenced by its short-lived ($\Delta t \approx 1$ day) cooling-envelope emission (Arcavi et al. 2011). In our recent paper (Soderberg et al. 2011, hereafter Paper I) we reported on early radio, millimeterband and X-ray emission. Based on modeling of the nonthermal emission, we found that the shockwave velocity was $v \sim 0.1c$, more typical of an SN Ibc (assumed to have a compact Wolf-Rayet progenitor) than the explosion of an extended supergiant. If SN 2011dh did, in fact, have a YSG progenitor, it would be necessary to explain the high shockwave velocity and rapid optical evolution in the context of an extended star.

| Date | MJD | Day ^b | Frequency (GHz) | | | | | | |
|------------------------|---------|------------------|-------------------|-----------------|-------------------|-------------------|-------------------|-------------------|--|
| | | | 1.4 | 1.8 | 2.5 | 3.5 | 4.9 | 6.7 | |
| Image rms ^c | | | 0.045 | 0.037 | 0.033 | 0.026 | 0.026 | 0.019 | |
| Jun 17 | 55729.2 | 16.4 | | | | | 2.430 ± 0.044 | 4.090 ± 0.063 | |
| Jun 21 | 55733.2 | 20.4 | < 0.13 | < 0.12 | 0.540 ± 0.079 | 1.400 ± 0.055 | 3.150 ± 0.043 | 4.800 ± 0.055 | |
| Jun 26 | 55738.2 | 25.4 | 0.243 ± 0.079 | 0.800 ± 0.066 | 1.626 ± 0.070 | 2.920 ± 0.061 | 4.920 ± 0.063 | 5.980 ± 0.070 | |
| Jul 6 | 55748.1 | 35.3 | 0.331 ± 0.072 | 1.236 ± 0.067 | 2.982 ± 0.073 | 4.908 ± 0.072 | 6.871 ± 0.091 | 7.222 ± 0.078 | |
| Jul 16 | 55758.1 | 45.3 | 0.719 ± 0.074 | 1.858 ± 0.069 | 4.092 ± 0.083 | 6.188 ± 0.080 | 7.836 ± 0.086 | 6.987 ± 0.077 | |
| Jul 29 | 55771.0 | 58.2 | 2.47 ± 0.12 | 3.31 ± 0.11 | 5.84 ± 0.15 | 7.33 ± 0.14 | 7.47 ± 0.12 | 6.11 ± 0.11 | |
| Sep 1 | 55805.7 | 92.9 | 3.45 ± 0.11 | 5.00 ± 0.12 | 7.02 ± 0.17 | 6.98 ± 0.13 | 4.884 ± 0.073 | 3.941 ± 0.061 | |

 Table 1

 1–8 GHz Radio Flux Densities (mJy)^a

Notes.

^a Quoted upper limits are 3σ .

^b Days from 2011 June 1 (MJD 55712.8).

^c Mean image rms for the first five epochs. The final two epochs have rms values $\approx \sqrt{8}$ times higher, since the available bandwidth was 1/8 that of previous observations.

In this paper, we present our detailed Expanded Very Large Array (EVLA; Perley et al. 2011) observations of SN 2011dh spanning $\Delta t \approx 100$ days after explosion. This project capitalizes on the nearly continuous coverage now available from 1 to 40 GHz with the EVLA. We model the synchrotron emission over seven epochs to derive the evolution of the shockwave radius and magnetic field as a function of time. We confirm the initial results of Paper I and find that the radio emission over the course of these observations evolves smoothly, with no evidence as yet for the circumstellar density variations seen in other compact SNe IIb.

2. OBSERVATIONS AND DATA REDUCTION

We obtained multi-frequency monitoring observations with the EVLA beginning 17 days after explosion (taking $t_0 =$ 2011 May 31.8 UTC) and continuing through day 92 (Program 11A-277: PI: Soderberg). These observations comprise seven epochs with roughly logarithmic spacing, matching the expected evolution of the SN light curves. The second through final epochs covered 1.0–36.5 GHz, utilizing the L- (1–2 GHz), S- (2-4 GHz), C- (4-8 GHz), X- (8-8.8 GHz), Ku- (12-18 GHz), K- (18-26.5 GHz), and Ka-band (26.5-40 GHz) receivers (see Perley et al. 2011 for a description of new observing capabilities with the EVLA). Within each observing band (except the X band),⁸ each of two basebands was tuned to a different frequency in order to maximize spectral coverage. We took data with the maximum available 1 GHz of bandwidth per baseband at all bands during the first five epochs, and 128 MHz for the final two. Each epoch was 3 hr in duration. All observations were performed while the EVLA was in its most extended A configuration, giving the highest available spatial resolution. EVLA observations were not continued in the subsequent (most compact) D configuration, due to concerns about confusion with other sources of radio emission in M51 at lower frequencies, to which the spectral peak of SN 2011dh had shifted by this time.

Phase reference calibration was carried out using J1335+4542 (1°.7 away; 8–40 GHz) or J1327+4326 (3°.8 away; 1–8 GHz). At the highest frequencies (>20 GHz), rapid switching (2 minute cadence) between SN 2011dhand J1335+4542 was done to enable optimal correction for atmospheric phase variations, and referenced pointing was used to correct for antenna pointing

offsets. Each observation included data at all bands for the standard flux density calibration source 3C286. Processing was performed with NRAO's Common Astronomy Software Applications (McMullin et al. 2007) or Astronomical Image Processing System (Greisen 2003), using the same procedure in each.

Bad data identified by the EVLA online system were deleted, as were pure zeros (sometimes generated by the correlator as a result of failure); further editing out of radio-frequency interference and poorly performing antennas was done by hand. Frequency-dependent atmospheric opacity was accounted for using the average of a seasonal model and observationspecific information from the weather station (Marvil 2010). At frequencies higher than 5 GHz, where elevation-dependent antenna gain effects become important ($\gtrsim 1\%$ variance from zenith values), gain curve information was applied at relevant points in the calibration process.

To calibrate the data, a bandpass solution was derived using 3C286; applying this solution, we solved for the complex gains of the calibration sources. We scaled the amplitude gains of the phase calibrator according to the values derived for 3C286 using the "Perley-Butler 2010" flux density standard, and applied these solutions to SN 2011dh.⁹ When there was sufficient signal, we performed phase-only self-calibration, and natural weighting was used during the imaging process. We fit an elliptical Gaussian model at each frequency to derive integrated flux density values. To estimate the uncertainties on our measured flux densities, we added (in quadrature) uncertainties from the Gaussian fitting with the rms noise of the images, as well as 1%systematic errors at low frequencies (<20 GHz) and 3% at high frequencies (>20 GHz). The integrated flux density values and associated 1σ uncertainties, as well as mean rms image noises for each frequency, are reported in Tables 1 and 2.

3. MODELING AND RESULTS

Radio emission from SNe arises when the expanding ejecta interact with pre-existing circumstellar material, which for

⁹ Due to a problem with data acquisition, the flux density calibrator was not present at the Ku band for epoch 3. We characterized the variability of J1335+4542 over the other epochs and found it to be small (rms of

approximately 1% at both 13.5 and 16.0 GHz). We fit its average spectrum and used this model to flux calibrate the data for SN 2011dh, adding the additional source of error from J1335+4542's variability in quadrature with the image noise and fit errors to determine the total uncertainty on flux density.

 Table 2

 8–37 GHz Radio Flux Densities (mJy)^a

| Date | MJD | D Day ^b | Frequency (GHz) | | | | | | |
|------------------------|---------|--------------------|-------------------|-------------------|-------------------|-------------------|-----------------|-------------------|-------------------|
| | | | 8.4 | 13.5 | 16.0 | 20.5 | 25.0 | 29.0 | 36.0 |
| Image rms ^c | | | 0.015 | 0.026 | 0.029 | 0.034 | 0.036 | 0.028 | 0.037 |
| Jun 17 | 55729.2 | 16.4 | 5.535 ± 0.057 | 6.970 ± 0.074 | 6.790 ± 0.073 | 6.50 ± 0.20 | 5.13 ± 0.16 | 4.60 ± 0.14 | 3.47 ± 0.11 |
| Jun 21 | 55733.2 | 20.4 | 5.870 ± 0.060 | 5.940 ± 0.064 | 5.313 ± 0.057 | 4.56 ± 0.14 | 3.61 ± 0.12 | 3.117 ± 0.097 | 2.190 ± 0.074 |
| Jun 26 | 55738.2 | 25.4 | 6.935 ± 0.071 | 5.574 ± 0.080 | 4.744 ± 0.096 | 3.70 ± 0.13 | 2.88 ± 0.11 | 2.349 ± 0.077 | 1.644 ± 0.064 |
| Jul 6 | 55748.1 | 35.3 | 6.820 ± 0.071 | 4.334 ± 0.068 | 3.917 ± 0.073 | 2.92 ± 0.11 | 2.53 ± 0.10 | 2.063 ± 0.073 | 1.772 ± 0.074 |
| Jul 16 | 55758.1 | 45.3 | 6.082 ± 0.064 | 3.790 ± 0.063 | 2.960 ± 0.067 | 2.493 ± 0.097 | 1.819 ± 0.080 | 1.549 ± 0.053 | 1.159 ± 0.051 |
| Jul 29 | 55771.0 | 58.2 | 5.097 ± 0.057 | 2.83 ± 0.14 | 2.32 ± 0.14 | 2.35 ± 0.15 | 1.53 ± 0.16 | 1.32 ± 0.15 | < 0.69 |
| Sep 1 | 55805.7 | 92.9 | 2.891 ± 0.043 | 1.627 ± 0.064 | 1.321 ± 0.072 | 1.28 ± 0.15 | 0.71 ± 0.10 | 0.60 ± 0.11 | < 0.42 |

Notes.

^a Quoted upper limits are 3σ .

^b Days from 2011 June 1 (MJD 55712.8).

^c Mean image rms for the first five epochs. The final two epochs have rms values $\approx \sqrt{8}$ times higher, since the available bandwidth was 1/8 that of previous observations.

SN IIb is provided by the progenitor's stellar wind. The interaction of the SN blast wave with the circumstellar environment probes recent stellar mass loss (Chevalier & Fransson 2006). Here, we model the radio emission from SN 2011dh using the standard circumstellar interaction model ("model 1" in Chevalier 1996): as the expanding shock moves into the circumstellar medium, the magnetic field strength in the interaction zone increases via turbulence generated in the shocked region. Electrons that have been accelerated to relativistic energies interact with this enhanced magnetic field, producing synchrotron emission. This emission is subject to selfabsorption, as further explored by Chevalier (1998); we employ this form of the synchrotron self-absorption (SSA) model to provide an analytic description of the observed radio spectra.

3.1. SSA Model Fits and Derived Parameters

For each given epoch, we fit the radio spectrum using the parameterization

$$S(\nu) = 1.582 S_{\nu_{\tau}} \left(\frac{\nu}{\nu_{\tau}}\right)^{5/2} \left\{ 1 - \exp\left[-\left(\frac{\nu}{\nu_{\tau}}\right)^{-(p+4)/2}\right] \right\},$$
(1)

where $S_{\nu_{\tau}}$ is the flux density at ν_{τ} , the frequency at which the optical depth is unity, and *p* is the electron power-law index (Chevalier 1998). We do not see any evidence of external free–free absorption, as was found for SN 1993J (Weiler et al. 2007). Including free–free absorption in our fits did not reduce the resulting χ^2 values; the fitting minimized its effect to an insignificant contribution. This is not surprising, since the spectra often show excess emission relative to the SSA model at low frequencies—the opposite of what is expected if free–free absorption were significant.

Allowing *p* to vary did not significantly improve the resulting reduced χ^2 values, so we froze this parameter to its average fitted value of p = 2.8 to limit the number of free parameters. For p = 2.8, the observed peak radio flux $S_{\nu_{op}}$ occurs at $\nu_{op} = 1.17 \nu_{\tau}$.

Although the SSA model likely represents an oversimplification of the actual source geometry and physics, it provides reasonable fits to the observations (see Figure 1). Despite some systematic deviations, the model matches the peaks in the

| Table 3 SSA Model Fits | | | | | | | |
|----------------------------------|--------------------------------------|-------------------------|------------------------------------|------------------------------|-------------|--|--|
| Day ^a | $S_{\nu_{\overline{\tau}}}$ (mJy) | ν _τ (GHz) | $\frac{R_s}{(10^{15} \text{ cm})}$ | <i>B</i> _s (G) | $A_*{}^{b}$ | | |
| 16.4 | 7.03 ± 0.25 | 10.01 ± 0.29 | 3.2 ± 0.4 | 1.21 ± 0.06 | 3.2 ± 0.3 | | |
| 20.4 | 6.19 ± 0.15 | 8.13 ± 0.18 | 3.7 ± 0.4 | 1.00 ± 0.04 | 3.4 ± 0.3 | | |
| 25.4 | 6.52 ± 0.22 | 6.18 ± 0.21 | 5.0 ± 0.6 | 0.76 ± 0.04 | 3.0 ± 0.3 | | |
| 35.3 | 7.28 ± 0.15 | 4.72 ± 0.10 | 6.9 ± 0.7 | 0.57 ± 0.02 | 3.3 ± 0.2 | | |
| 45.3 | 7.36 ± 0.19 | 3.91 ± 0.11 | 8.4 ± 0.9 | 0.47 ± 0.02 | 3.8 ± 0.3 | | |
| 58.2 | 7.69 ± 0.20 | 3.184 ± 0.088 | 11 ± 1 | 0.38 ± 0.02 | 4.1 ± 0.4 | | |
| 92.9 | 6.44 ± 0.21 | 2.235 ± 0.076 | 14 ± 2 | 0.27 ± 0.01 | 5.3 ± 0.6 | | |

Notes.

^a Days from 2011 June 1 (MJD 55712.8).

^b $5 \times 10^{-11} \text{ g cm}^{-2}$.

spectra well; large variations of the true average radii from the ones implied by the models therefore seem unlikely.

However, the formal errors described in Section 2 are small relative to deviations from the fits, resulting in large values of χ^2 and unacceptably small uncertainties on the fitted values of $S_{\nu_{\tau}}$ and ν_{τ} . This is probably due to a combination of underestimated formal errors (the EVLA was still in its commissioning phase at the time of the observations), as well as unaccounted for physics that is beyond the scope of this paper. To better estimate the errors on the fitted parameters, we scaled the fitted uncertainties for each epoch so that the reduced χ^2 values were unity, equivalent to increasing the errors by a factor of 3–7. These uncertainties were propagated throughout subsequent calculations. Values for $S_{\nu_{\tau}}$ and ν_{τ} , as well as the parameters derived below, are presented in Table 3.

We find that the SSA-derived peak frequencies are systematically $\approx 10\%$ lower than the apparent peaks, but since this trend is consistent over the course of the observations, it will not affect the time dependence of the derived parameters. We also note that for the final three epochs (days 45, 58, and 92), the high-frequency data trend below the model. This is likely due to the fact that for these epochs, there was insufficient flux to perform self-calibration above 20 GHz (K or Ka bands), resulting in possible underestimation of the flux densities due to phase decoherence.

The fitted spectra can be used as observational tracers of the outer shock radius (R_s), strength of the magnetic field (B_s), and density of the progenitor's wind (ρ_{wind}), given a minimal set of



Figure 1. Panels (a)–(g): spectra of SN 2011dh. Dashed curves show corresponding SSA model fits. In addition to errors derived from Gaussian source fitting and image rms, we include 1% and 3% systematic errors at low (<20 GHz) and high (>20 GHz) frequencies; these are generally smaller than the plotted symbols. Panel (h): light curves of SN 2011dh. Data are averaged for each receiver band and color coded as in the preceding spectral plots. (A color version of this figure is available in the online journal.)

assumptions (Chevalier 1998; Chevalier & Fransson 2006):

$$R_{s} = 3.9 \times 10^{14} \,\alpha^{-1/19} \left(\frac{f}{0.5}\right)^{-1/19} \left(\frac{D}{\text{Mpc}}\right)^{18/19} \\ \times \left(\frac{S_{\nu_{\text{op}}}}{\text{mJy}}\right)^{9/19} \times \left(\frac{\nu_{\text{op}}}{5 \,\text{GHz}}\right)^{-1} \text{cm},$$
(2)

$$B_{s} = 1.0 \,\alpha^{-4/19} \left(\frac{f}{0.5}\right)^{-4/19} \left(\frac{D}{\text{Mpc}}\right)^{-4/19} \\ \times \left(\frac{S_{\nu_{\text{op}}}}{\text{mJy}}\right)^{-2/19} \left(\frac{\nu_{\text{op}}}{5 \,\text{GHz}}\right) \text{G}, \tag{3}$$

and

$$\rho_{\rm wind} = Ar^{-2}\,\mathrm{g\,cm}^{-3},\tag{4}$$

where the circumstellar density is parameterized as $A_* = A/(5 \times 10^{11} \text{ g cm}^{-1})$, and

$$A_{*} = 0.82 \,\alpha^{-8/19} \left(\frac{\epsilon_{B}}{0.1}\right)^{-1} \left(\frac{f}{0.5}\right)^{-8/19} \left(\frac{D}{\text{Mpc}}\right)^{-8/19} \\ \times \left(\frac{S_{\nu_{\text{op}}}}{\text{mJy}}\right)^{-4/19} \left(\frac{\nu_{\text{op}}}{5 \,\text{GHz}}\right)^{2} \left(\frac{t}{10 \,\text{d}}\right)^{2}.$$
(5)

Here, α is the ratio of electron to magnetic energy densities (u_e/u_B) , f is the filling fraction of emitting material, D is the distance, t is the age, and ϵ_B is the converted fraction of kinetic to magnetic energy density ($\epsilon_B = u_B/\rho_{wind} v_s$). We assume equipartition ($\alpha = 1$) and take p = 2.8 (as fitted). In addition, we assume a filling factor f = 0.5 (approximately as was found for SN 1993J; Bartel et al. 2002) and a distance $D = 8.4 \pm 0.6$ Mpc (Feldmeier et al. 1997; Vinkó et al. 2012). The time evolution of the shock radius is consistent with

 $R_s \propto t^{0.9}$ (see also Bietenholz et al. 2012), and the magnetic field strength with $B_s \propto t^{-1}$ (top and center panels of Figure 2). The expectation of $\rho_{\text{wind}} \propto r^{-2}$ may be questionable at large radii, but it is reasonable to approximate the immediate circumstellar environment by assuming a constant progenitor wind (Dwarkadas & Gruszko 2012). These observations probe a region extending to ~1000 AU, corresponding to ~5 yr for a 1000 km s⁻¹ wind—much shorter than necessary for substantial wind variability. Given these constraints, and taking $\epsilon_B = 0.1$, we find $A_* \approx 3.5$. There is no strong evidence for time variability, suggesting that our assumption of a constant progenitor wind was reasonable (bottom panel of Figure 2).

In Paper I, joint radio and X-ray model fits pointed to deviations from equipartition, $\alpha \approx 30$ and $\epsilon_B \approx 0.01$, under the assumption that inverse Compton emission dominates the X-ray signal. With these values, our radius estimates are smaller by a factor of 0.8, magnetic field values smaller by a factor of 0.5, and A_* larger by a factor of 2.

3.2. Physical Interpretation

The derived outer shock radii imply an average shock velocity of $dR_s/dt \approx 25,000 \text{ km s}^{-1}$, or $\approx 0.1c$, in agreement with Paper I. As noted there, the shockwave is traveling a factor of ~ 1.5 faster than material at the optical photosphere ($\approx 17,000 \text{ km s}^{-1}$ at $\Delta t \approx 3$ days; Silverman et al. 2011).

Assuming that the SN ejecta and progenitor wind have powerlaw density profiles, the time evolution of the shock radius can be expressed as $R_s \propto t^m$. For the expected circumstellar density $\rho_{\text{wind}} \propto r^{-2}$, m = (n - 3)/(n - 2), where *n* is the power-law index of the outer SN density profile. We find $m = 0.87 \pm 0.07$, corresponding to $n = 9.7^{+12}_{-3.7}$, and reasonable for a fast blast wave from a compact progenitor (canonical value of m = 0.9; Chevalier 1992). This value of *m* is also consistent with joint EVLA very long baseline interferometry fits reported in our companion paper (Bietenholz et al. 2012).



Figure 2. Upper panel: shock radius, center panel: magnetic field strength, and lower panel: circumstellar density parameter derived from the per-epoch SSA fits. The expected time behavior from the standard model of Chevalier (1996) is shown with dashed lines.

(A color version of this figure is available in the online journal.)

The measured decrease in magnetic field strength agrees with the standard model for the hydrodynamic evolution of a selfsimilar shock. The magnetic field generation is thought to arise via turbulence in the shocked region, so it is proportional to the total post-shock energy density ($\propto t^{-2}$; Chevalier 1998); therefore, $B_s \propto t^{-1}$, as observed.

We find that the scaling factor for the circumstellar density is consistent with a constant value, $A_* \approx 3.5$, over the course of our observations. This implies a constant mass-loss rate of $\approx 3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, assuming a wind velocity of 1000 km s^{-1} . These values are in the expected range for a Wolf-Rayet progenitor (Crowther 2007), and agree with our analysis of the early-time radio data (Paper I). Since the implied mass-loss rate scales linearly with wind velocity ($\dot{M} \propto A v_{\text{wind}}$), a wind velocity of 20 km s⁻¹ gives a mass-loss rate of $\approx 7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, reasonable for a YSG progenitor (Georgy 2012).

However, the high shock velocity, as well as the rapid cooling observed in early-time optical spectra, suggests a compact progenitor star for SN 2011dh and a Type cIIb classification (Arcavi et al. 2011; Paper I). Furthermore, the fitted electron power-law index of p = 2.8 is close to what is typically found for observations of SNe Ibc ($p \approx 3$; Chevalier & Fransson 2006), which are presumed to have compact progenitors.

One further observational characteristic of Type cIIb SNe is that they often display late-time radio variability, as was seen in SN 2001ig and SN 2003bg (Ryder et al. 2004; Soderberg et al. 2006). We do not yet see evidence of variability in SN 2011dh, but note that our observations only cover the first \sim 100 days of evolution, around the time that variability was discovered in other SNe cIIb.

4. CONCLUSIONS

The radio spectra of SN 2011dh are well characterized by an SSA model without any need for additional free–free absorption. This is in contrast with SN 1993J, which required both, and also had a substantially higher derived mass-loss rate ($A_* \approx 500$, compared with ≈ 4 for SN 2011dh; Fransson & Björnsson 1998). SN 1993J was classified as an SN eIIb because of its extended progenitor (Chevalier & Soderberg 2010; Woosley et al. 1994): the observed differences in absorption and circumstellar density could be characteristic of these two classes of IIb SNe.

However, pre-SN images of M51 show a YSG co-located with the explosion site, which was suggested as a potential progenitor or binary companion (Maund et al. 2011; Van Dyk et al. 2011; Murphy et al. 2011). As we have mentioned, it seems unlikely that the YSG is in fact the progenitor. If it were, this would require a process to enable the escape of fast shockwaves from YSGs, either through steep ejecta density profiles or ejecta asymmetries.

If the YSG was a binary companion, then some interaction of the shock and the YSG might be expected. The observational agreement of the radio measurements with the standard model suggests that this did not occur within ~ 1000 AU of the explosion site. In this scenario, then, the orbit must have been quite wide, with an orbital period of 6000 yr, so any interaction between the YSG and the SN progenitor would have been limited. For comparison, the binary progenitor of SN 1993J likely had an orbital period of ~2000 days (Stancliffe & Eldridge 2009), allowing substantial mass transfer to occur and stripping the pre-SN star of its H-rich envelope (Woosley et al. 1994). This would not have been possible for SN 2011dh. Alternatively, if the blast wave were highly asymmetric, interaction with a more nearby companion could have been minimized. We consider this unlikely, since the radio data agree quite well with the standard, spherical ejecta model. Furthermore, the YSG phase is estimated to last only \sim 3000 yr (Drout et al. 2009), making it improbable that the companion would happen to be a YSG at the time of the SN.

Finally, it may be that the YSG is unrelated to the SN, and is only coincidentally along the same line of sight. Future observations, including optical imaging of the field after SN 2011dh has faded, will help determine any association with the YSG and the true nature of the progenitor system.

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