RADIO SUPERNOVAE AS DISTANCE INDICATORS

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ABSTRACT

Long-term monitoring of the radio emission from supernovae with the Very Large Array (VLA) shows that the radio "light curves" evolve in a systematic fashion with a distinct peak flux density (and thus, in combination with a distance, a peak spectral luminosity) at each frequency and with a well-defined time from explosion to that peak. Studying these two quantities at 6 cm wavelength, peak spectral luminosity ($L_{6\text{ cm peak}}$), and time after explosion date ($t_0$) to reach that peak ($t_{6\text{ cm peak}} - t_0$), we find that they appear related. In particular, based on two objects, Type Ib supernovae may be approximate radio "standard candles" with a 6 cm peak luminosity of $L_{6\text{ cm peak}} \approx 19.9 \times 10^{26}$ ergs s$^{-1}$ Hz$^{-1}$; also, based on two objects, Type Ic supernovae may be approximate radio standard candles with a 6 cm peak luminosity of $L_{6\text{ cm peak}} \approx 6.5 \times 10^{26}$ ergs s$^{-1}$ Hz$^{-1}$; and, based on 12 objects, Type II supernovae appear to obey a relation $L_{6\text{ cm peak}} \approx 5.5 \times 10^{23}(t_{6\text{ cm peak}} - t_0)^{1.4}$ ergs s$^{-1}$ Hz$^{-1}$, time measured in days. If these relations are supported by further observations, they provide a means for determining distances to supernovae, and thus to their parent galaxies, from purely radio continuum observations. With currently available sensitivity of the VLA, it is possible to employ these relations for objects further than the Virgo Cluster out to $\sim 100$ Mpc. With planned improvements to the VLA and the possible construction of more sensitive radio telescopes, these techniques could be extended to $z \sim 1$ for some classes of bright radio supernovae.

Subject headings: galaxies: distances and redshifts — radio continuum: stars — stars: distances — supernovae: general

1. INTRODUCTION

A series of papers published over the past 15 years on radio supernovae (RSNe) (see references to Table 2) have established the radio evolution for 16 objects: two Type Ib supernovae (SN 1983N and SN 1984L), two Type Ic supernovae (SN 1990B and SN 1994I), and 12 Type II supernovae (SN 1970G, SN 1978K, SN 1979C, SN 1980K, SN 1981K, SN 1985L, SN 1986E, SN 1986J, SN 1987A, SN 1987B, SN 1988Z, SN 1993J, and SN 1996cb). In this extensive study of the radio emission from supernovae (SNe), in most cases using the Very Large Array (VLA)$^4$ radio telescope, two effects have been noticed: (1) Type Ib and Type Ic SNe have roughly constant 6 cm radio luminosities at peak with only slight differences between the two types, and (2) Type II SNe appear to have a higher 6 cm radio luminosity at peak if they take longer to reach that peak. These two effects are also consistent with the tenets of the SN shock/circumstellar medium interaction model of Chevalier (1982a, 1982b, 1984) for the origin of the radio emission if (1) the radio emission for the rather homogeneous classes of Type Ib/c SNe arises in similar circumstellar environments, and (2) the radio emission for the more inhomogeneous class of Type II SNe arises in diverse circumstellar environments, but the denser the circumstellar medium, the longer it takes for the material to become optically thin to the radio emission and the brighter the radio emission. If these effects can be quantified, they can provide a purely radio-based secondary distance indicator for SNe and, by association, for their parent galaxies. The RSNe available for study and some relevant properties of their parent galaxies are listed in Table 1.

2. MODELS

While the relations to be described are empirical, there is some support from theoretical modeling. All known RSNe appear to share common properties of (1) nonthermal synchrotron emission with high brightness temperature; (2) a decrease in absorption with time, resulting in a smooth, rapid turn-on first at shorter wavelengths and later at longer wavelengths; (3) a power-law decline of the emission flux density with time at each wavelength after maximum flux density (absorption $\tau \approx 1$) is reached at that wave-
length; and, (4) a final, asymptotic approach of spectral index α to an optically thin, nonthermal, constant negative value (Weiler et al. 1986; Weiler, Panagia, & Sramek 1990). Chevalier (1982a, 1982b) has proposed that the relativistic electrons and enhanced magnetic field necessary for synchrotron radio emission are generated by the outgoing shock wave from the SN explosion interacting with a relatively high-density envelope of ionized circumstellar material surrounding the presupernova star. This dense cocoon is presumed to arise from mass loss in a stellar wind from a red supergiant SN precursor, or a companion, which has been ionized and heated by the initial UV/X-ray flash of the SN explosion. This circumstellar material (CSM) is also the source of the initial absorption. A rapid rise in the observed radio flux density results from the shock overtaking more and more of the wind material, leaving progressively less of it along the line of sight to the observer to absorb the slowly decreasing synchrotron emission from the shock region.

The radio light curve that results from these two competing effects of rapidly declining absorption and more slowly declining emission is shown schematically for one frequency in Figure 1.

2.1. Parameterized Radio Light Curves

It has been shown by Weiler et al. (1986) that the radio emission from RSNes can be described, for simple cases, by

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

(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 and uniform external absorption, respectively, at 5 GHz (6 cm wavelength) 1 day after the date of explosion, $t_0$. The term $e^{-\tau}$ represents the attenuation of a medium that completely and uniformly covers the emitting source (i.e., a uniform external absorption), and the absorption is assumed to be due to purely thermal, ionized hydrogen with frequency dependence $\nu^{-2.1}$. The parameter $\delta$ describes the time dependence of the optical depth for the uniform exter-

### Table 1

| Radio Supernova | Optical Type | Parent Galaxy | Hubble Type | Systemic Velocity (km s$^{-1}$) | Assumed Distance (Mpc) | Distance Reference |
|-----------------|--------------|---------------|-------------|---------------------------------|------------------------|-------------------|
| Type Ib/c:      |              |               |             |                                 |                        |                   |
| SN 1983N ...... | Ib           | NGC 5236 (M83)| Scd–II      | 337                             | 5.4 ± 0.8              | 1                 |
| SN 1984L ...... | Ib           | NGC 991       | ScI         | 1541                            | 21.7 ± 3.3             | 2                 |
| SN 1990B ...... | Ic           | NGC 4568      | Sbc         | 2168                            | 19.4 ± 2.9             | 3                 |
| SN 1994I ...... | Ic           | NGC 5194 (M51)| Sbc         | 573                             | 8.9 ± 1.3              | 4                 |
| Type II:        |              |               |             |                                 |                        |                   |
| SN 1970G ...... | II            | NGC 5457 (M101)| Scd         | 379                             | 7.4 ± 0.6              | 1                 |
| SN 1978K ...... | II            | NGC 1313      | Sd          | 254                             | 4.5 ± 0.7              | 2                 |
| SN 1979C ...... | III           | NGC 4321 (M100)| Sbc        | 1522                            | 17.1 ± 1.8             | 3                 |
| SN 1980K ...... | III           | NGC 946       | Scd         | 338                             | 6.3 ± 1.0              | 4                 |
| SN 1981K ...... | II            | NGC 4258 (M106)| Sbc        | 521                             | 5.9 ± 1.1              | 5                 |
| SN 1985L ...... | III           | NGC 5033      | Sc          | 931                             | 21.6 ± 3.2             | 6                 |
| SN 1986E ...... | III           | NGC 4302      | Sc          | 1044                            | 19.4 ± 2.9             | 7                 |
| SN 1986J ...... | II            | NGC 891       | Sb          | 712                             | 11.1 ± 1.7             | 8                 |
| SN 1987A ...... | Ipec          | LMC           | Irr         | 3.9                              | 0.051 ± 0.002          | 9                 |
| SN 1988Z ...... | In            | MCG + 03-28-022| S          | 6670                            | 102.6 ± 15.4           | 10                |
| SN 1993J ...... | Iib           | NGC 3031 (M81)| Sab         | 96                              | 3.6 ± 0.3              | 11                |
| SN 1996b......  | Iib           | NGC 3510      | SBm         | 770                             | 9.1 ± 1.4              | 12                |

*From Tully 1988; heliocentric velocity of the parent galaxy is corrected for Galactic rotation of 300 km s$^{-1}$ toward $l = 90^\circ$, $b = 0^\circ$. Unless otherwise referenced, the distance is from Tully 1988 and is based on systemic velocity, corrected by a model which assumes the Milky Way is retarded by 300 km s$^{-1}$ from universal expansion by the mass of the Virgo Cluster, and on an assumed Hubble constant of $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ (Tully 1988 uses $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). Unless otherwise referenced, errors are conservatively taken to be ±15%, a value that is large enough to encompass both $H_0 = 55$ and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ within 1σ.

References.—(1) Kelson et al. 1996; (2) Freedman et al. 1994a; (3) average of VLBI H$2$O maser dynamical distances from Greenhill et al. 1995 (5.4 ± 1.3 Mpc) and from Miyoshi et al. 1995 (6.4 ± 0.9 Mpc); (4) Panagia et al. 1991; (5) Stathakis & Sadler 1991 (systemic velocity; distance derived from this velocity and an assumed $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$); (6) Freedman et al. 1994b.
nal absorbing medium. The emission from the RSN is assumed to be nonthermal synchrotron radiation with spectral index $\alpha$ and to be decreasing with time with index $\beta$.

2.2. Model Interpretation and Predictions

The parameters of equations (1) and (2) can be interpreted in terms of the Chevalier (1982a, 1982b, 1984) model if the dense, external cocoon of material is established by a constant mass-loss rate ($\dot{M}$), constant velocity ($w$) wind from a red supergiant progenitor. The time dependence, $\beta$, of the flux density decline is derived by assuming equipartition between the magnetic and relativistic particle energies, a constant ratio of those energies to the thermal postshock particle energy, a power-law density distribution for the unshocked circumstellar material (CSM) of $\rho_{\text{CSM}} \propto r^{-m}$, and a density distribution for the unshocked ejecta of $\rho_{\text{ej}} \propto r^{-n}$. The time dependence, $\delta$, of the external uniform optical depth is clearly a function of both the shock expansion index, $m$ ($R_{\text{shock}} \propto t^m$), and the radial distribution of the CSM [$\delta = -3m = -3(n-3)/(n-s)$].

The Chevalier model then interprets the parameters of equation (1) at any given frequency $\nu$ as

$$K_1 \propto (\dot{M}/w)^{\gamma - 7 + 12m/4} \quad \text{or} \quad K_1 \propto (\dot{M}/w)^a,$$

where

$$a = (\gamma - 7 + 12m)/4,$$

and

$$\beta = -(\gamma + 5 - 6m)/2.$$

and of equation (2) as

$$K_2 \propto (\dot{M}/w)^{5 - 3m} \quad \text{or} \quad K_2 \propto (\dot{M}/w)^c,$$

where

$$c = 5 - 3m,$$

and

$$\delta = -3m.$$

The term $\gamma$ is the index of the energy spectrum of the relativistic synchrotron electrons (which is related to the radio spectral index $x$ by $\gamma = -2x + 1$), and $m$ is the shock expansion index described above.

Substituting these relations into equation (1) and including the distance to the SN to convert observed flux density ($S_\nu$) into spectral luminosity ($L_\nu$), we can write

$$L_\nu \propto (\dot{M}/w)^{\gamma}(t - t_0)^\delta \exp \left[\frac{(\dot{M}/w)^{\gamma}(t - t_0)^\delta}{L_\nu}\right].$$

This is a function which has a single peak when the optical depth approaches unity, so that we can obtain a value for the mass-loss rate/presupernova wind velocity ratio ($\dot{M}/w$) from setting the first derivative equal to zero [i.e., $dL_\nu/d(t - t_0) \equiv 0$], which gives

$$(\dot{M}/w)^{\gamma} \propto \tau_{\text{peak}} = \beta/\delta$$

or

$$\dot{M}/w \propto (\beta/\delta)^{1/\gamma}(t_{\text{peak}} - t_0)^{-\delta/\gamma}.$$

Substituting this back into equation (9) yields a luminosity for frequency $\nu$ at time $t_{\text{peak}}$

$$L_{\nu, \text{peak}} \propto (\dot{M}/w)^{\gamma}(t_{\text{peak}} - t_0)^\delta e^{-\nu(t_{\text{peak}} - t_0)^\delta},$$

or

$$L_{\nu, \text{peak}} \propto (\beta/\delta)^{1/\gamma}e^{-\nu(t_{\text{peak}} - t_0)^\delta},$$

where

$$\eta = -(a\delta - \beta c)/c.$$

Equation (13) implies that the peak luminosity at any frequency is related to the time interval after explosion required for the radio emission to reach that peak. This is illustrated schematically in Figure 2.

In principle, the index, $\eta$, in this simplified modeling treatment is fully determined by only two physical parameters, the index of the electron energy spectrum, $\gamma$ (where $\gamma = -2x + 1$), and the index of the shock expansion, $m$ (i.e., $R_{\text{shock}} \propto t^m$). In practice, we do not expect to be able to describe the evolution of a SN explosion so simply and will employ an empirical fit to the available data. However, it is interesting to note that, although there is considerable scatter, the simple model prediction for the four Type Ib/c SNe gives, on average, relatively little variation of spectral luminosity with turn-on delay [$L_{\nu, \text{peak}} \propto (t_{\text{peak}} - t_0)^\eta$, $\eta \approx -0.2$], and for the 12 Type II SNe, a much stronger dependence of spectral luminosity with turn-on delay ($\eta \approx +1.4$). For the Type II SNe, it is quite surprising that this is the same index value as is obtained from the actual fit to the data in equation (17). However, since the scatter in $\eta$ values is quite large, this exact agreement is certainly fortuitous, even though the indication of a steep slope is supported.

2.3. Type II Peculiar SNe

It should be noted that fitting the so-called Type II "peculiar" (Type IIpec), or Type IIn, radio supernovae SN
1986J (Weiler et al. 1990) and SN 1988Z (Van Dyk et al. 1993b) and Type IIb radio supernova SN 1993J (Van Dyk et al. 1994) radio light curves requires additional absorption terms beyond those given by equations (1) and (2). In particular, an additional term describing an “internal” or “clumpy external” component of the absorption, which is not included in the standard Chevalier model, must be used and could imply that some Type II RSNe must be considered separately. However, since our results are empirically determined, and since the radio supernovae SN 1986J, SN 1988Z, and SN 1993J appear to obey the same relation as their more normal brethren, they are included along with other Type II SNe for the present discussion.

2.4. SN 1987A

One of the major peculiarities of SN 1987A is that its explosion occurred when its progenitor was a blue supergiant (BSG) rather than being a red supergiant (RSG). Because of the much higher wind velocity of a BSG than that of a RSG, the density of the CSM, i.e., the density of the presupernova stellar wind \( \rho \) around SN 1987A was considerably lower than around “normal” Type II SNe and, therefore, its early radio emission was intrinsically much weaker and evolved much more quickly than normal. In particular, the flux density at 6 cm reached a peak only 1 day after the explosion and fell below detection limits only a few days later. As a consequence, despite the efforts of Australian radio astronomers, the radio light curve of SN 1987A is poorly defined.

This fact, and the large difference in circumstellar environment (much lower density, much higher velocity) as compared with normal Type II SNe, makes it uncertain whether a quantitative comparison of SN 1987A with the other Type II SNe can be made. However, it is apparent in Figure 3 that SN 1987A agrees reasonably well with an extrapolation of the relation determined for the remaining Type II SNe, which have much greater peak 6 cm radio luminosities and much longer times from explosion to 6 cm peak flux density. This may imply that the relation is indeed valid for all Type II RSNe and that the gap between radio supernovae SN 1996cb and SN 1987A is due to selection effects against fast turn-on, low-radio luminosity RSNe. Thus, since we are dealing with an empirical relation, we have included SN 1987A in our discussion.

3. DATA

3.1. Peak Luminosity and Time to Peak

In order to quantify possible relations between SN type, peak radio luminosity, and time from explosion to radio peak, it is necessary to establish these quantities in a systematic fashion. The data sets available for the various RSNe are of quite variable quality, and most RSNe show some deviation from smooth radio light curves. Thus, even when
### TABLE 2
**Radio Supernova Properties**

| Radio Supernova | Optical Type | Peak 6 cm Flux Density\(^a\) \((S_{6\text{ cm peak}})\) \((\text{mJy})\) | Time from Explosion to 6 cm Peak\(^a\) \((t_{6\text{ cm peak}} - t_0)\) \((\text{days})\) | Peak 6 cm Luminosity\(^a, b\) \((L_{6\text{ cm peak}})\) \((10^{26} \text{ ergs s}^{-1} \text{ Hz}^{-1})\) | Radio Supernova References |
|-----------------|--------------|-------------------------------------------------|---------------------------------|-------------------------------------------------|--------------------------|
| **Type Ib/c:**  |              |                                                 |                                 |                                                 |                          |
| SN 1983N ...... | Ib           | 40.1\(^\pm\)0.1 \(^a\)                         | 11.6\(^\pm\)1.0               | 14.1\(^\pm\)4.2 \(^a\)                        | 1, 2                     |
| SN 1984L ...... | Ib           | 4.6\(^\pm\)0.1 \(^b\)                          | 11.0\(^\pm\)9.0               | 25.7\(^\pm\)23.7 \(^b\)                       | 1, 3                     |
| SN 1990B ...... | Ic           | 1.3\(^\pm\)0.1 \(^a\)                          | 37.5\(^\pm\)1.7               | 5.6\(^\pm\)1.8 \(^a\)                        | 4                       |
| SN 1994I ...... | Ic           | 14.6\(^\pm\)1.0 \(^b\)                         | 35.8\(^\pm\)2.2               | 13.7\(^\pm\)4.1 \(^b\)                       | 5                       |
| **Type II:**    |              |                                                 |                                 |                                                 |                          |
| SN 1970G ...... | II           | 21.5\(^\pm\)1.4 \(^a\)                         | 307.0\(^\pm\)0.0              | 14.0\(^\pm\)5.3 \(^a\)                        | 1, 6, 7, 8               |
| SN 1978K ...... | II           | 229.0\(^\pm\)4.0 \(^b\)                        | 685.0\(^\pm\)8.0              | 55.3\(^\pm\)19.7 \(^b\)                       | 9, 10                    |
| SN 1979C ...... | II           | 7.3\(^\pm\)0.2 \(^a\)                          | 605.0\(^\pm\)15.0             | 25.3\(^\pm\)5.4 \(^a\)                        | 1, 11, 12                |
| SN 1980K ...... | II           | 2.5\(^\pm\)0.1 \(^a\)                          | 140.0\(^\pm\)29.3             | 1.2\(^\pm\)0.4 \(^a\)                        | 1, 13                    |
| SN 1981K ...... | II           | 5.1\(^\pm\)1.0 \(^b\)                          | 338.0\(^\pm\)36.4             | 2.1\(^\pm\)1.2 \(^b\)                        | 1, 14, 15                |
| SN 1985L ...... | II           | 0.7\(^\pm\)0.1 \(^a\)                          | 309.0\(^\pm\)30.0             | 3.6\(^\pm\)1.4 \(^a\)                        | 16                      |
| SN 1986E ...... | II           | 0.3\(^\pm\)0.1 \(^b\)                          | 224.0\(^\pm\)32.0             | 1.4\(^\pm\)0.5 \(^b\)                        | 17                      |
| SN 1986F ...... | II           | 136.0\(^\pm\)4.4 \(^b\)                        | 1150.0\(^\pm\)50.0            | 199.0\(^\pm\)60.0 \(^b\)                      | 18                      |
| SN 1987A ...... | IIpec        | 91.4\(^\pm\)133.5 \(^b\)                       | 1.0\(^\pm\)2.2                | 0.003\(^\pm\)32.0 \(^b\)                      | 19                      |
| SN 1988Z ...... | II           | 1.9\(^\pm\)0.1 \(^a\)                          | 1420.0\(^\pm\)990.0           | 237.0\(^\pm\)71.4 \(^a\)                      | 20                      |
| SN 1993J ...... | Ib           | 95.2\(^\pm\)1.8 \(^b\)                         | 180.0\(^\pm\)61               | 15.0\(^\pm\)2.8 \(^b\)                        | 21                      |
| SN 1996cb ......| Ib           | 1.8\(^\pm\)0.2 \(^a\)                          | 19.4\(^\pm\)4.9               | 1.8\(^\pm\)0.6 \(^a\)                        | 22, 23                   |

\(^a\) See § 3.2 for discussion of errors.
\(^b\) Distances are from Table 1, and peak flux densities are from the third column.

**REFERENCES**—(1) Weiler et al. 1986; (2) Sramek, Panagia, & Weiler 1984; (3) Panagia, Sramek, & Weiler 1986; (4) Van Dyk et al. 1993a; (5) Rupen et al. 1998; (6) Allen et al. 1976; (7) Marscher & Brown 1978; (8) Cowan, Goss, & Sramek 1991; (9) Ryder et al. 1993; (10) Montes, Weiler, & Panagia 1997; (11) Weiler et al. 1981; (12) Weiler et al. 1991; (13) Weiler et al. 1992; (14) van der Hulst et al. 1983; (15) Van Dyk et al. 1992; (16) Van Dyk et al. 1998a; (17) Montes et al. 1997; (18) Weiler, Panagia, & Sramek 1990; (19) Turtle et al. 1987; (20) Van Dyk et al. 1993b; (21) Van Dyk et al. 1994; (22) Van Dyk et al. 1996; (23) K. W. Weiler 1997, private communication.

### TABLE 3
**Distances**

| Radio Supernova | Optical Type | Assumed Distance\(^a\) \((\text{Mpc})\) | Radio Distance\(^b\) \((\text{Mpc})\) |
|-----------------|--------------|---------------------------------|---------------------------------|
| **Type Ib/c:**  |              |                                 |                                 |
| SN 1983N ...... | Ib           | 5.4 \(\pm\) 0.8                  | 6.5 \(\pm\) 1.9                 |
| SN 1984L ...... | Ib           | 21.7 \(\pm\) 3.3                | 19.1 \(\pm\) 1.1                 |
| SN 1990B ...... | Ic           | 19.4 \(\pm\) 2.9                | 20.7 \(\pm\) 3.2                 |
| SN 1994I ...... | Ic           | 8.9 \(\pm\) 1.3                 | 6.1 \(\pm\) 1.0                  |
| **Type II:**    |              |                                 |                                 |
| SN 1970G ...... | II           | 7.4 \(\pm\) 0.6                 | 7.4 \(\pm\) 0.7                  |
| SN 1978K ...... | II           | 4.5 \(\pm\) 0.7                 | 3.9 \(\pm\) 0.8                  |
| SN 1979C ...... | II           | 17.1 \(\pm\) 1.8                | 20.1 \(\pm\) 2.1                 |
| SN 1980K ...... | II           | 6.3 \(\pm\) 1.0                 | 12.7 \(\pm\) 2.0                 |
| SN 1981K ...... | II           | 5.9 \(\pm\) 1.1                 | 3.3 \(\pm\) 1.1                  |
| SN 1985L ...... | II           | 21.6 \(\pm\) 3.2                | 42.5 \(\pm\) 9.8                 |
| SN 1986E ...... | II           | 19.4 \(\pm\) 2.9                | 49.0 \(\pm\) 8.3                 |
| SN 1986F ...... | II           | 11.1 \(\pm\) 1.7                | 7.2 \(\pm\) 1.1                  |
| SN 1987A ...... | IIpec        | 0.051 \(\pm\) 0.002             | 0.071 \(\pm\) 0.01              |
| SN 1988Z ...... | II           | 102.6 \(\pm\) 15.4              | 70.7 \(\pm\) 10.7               |
| SN 1993J ...... | Iib          | 3.6 \(\pm\) 0.3                 | 2.4 \(\pm\) 0.2                 |
| SN 1996cb ......| Iib          | 9.1 \(\pm\) 1.4                 | 3.8 \(\pm\) 0.6                 |

\(^a\) From Table 1.
\(^b\) Distance that the RSN would have if (1) for Type Ib/c RSNe, the peak observed 6 cm flux density originates from a standard candle radio source with peak luminosity given, respectively, by eqs. (15) and (16) or (2) for Type II RSNe, the peak observed 6 cm flux density originates from a source with peak luminosity given by eq. (17), with time in days.
observations are available at 6 cm wavelength near the time of peak flux density, the smoother best-fit model values have been used in all cases to determine the two quantities of interest: peak 6 cm flux density, \(S_{6\text{ cm peak}}\) (from which the peak 6 cm spectral luminosity, \(L_{6\text{ cm peak}}\) is calculated using the distances given in Table 1), and the time in days \((t_{6\text{ cm peak}} - t_0)\) from explosion, \(t_0\), to 6 cm peak luminosity, \(t_{6\text{ cm peak}}\). These values, along with associated errors, are given in Table 2 for each of the 16 RSNe under consideration.

Two caveats should be kept in mind. First, new fits have been performed for all available data sets and, due to revisions or the inclusion of new data, some fitting parameters may differ slightly from previously published values. Second, these results are from preliminary fits to some of the data sets, and more data may somewhat alter the parameter values in future treatments.

### 3.2. Errors

Because of the very diverse nature of the data, missing data at critical (usually early) times, and variations in the assumptions for the modeling of different RSNe, it is extremely difficult to assign errors to the basic quantities of \(S_{6\text{ cm peak}}\) and \((t_{6\text{ cm peak}} - t_0)\), including, in many cases, large uncertainty in determining or assigning a date of explosion, \(t_0\). Additionally, the conversion of \(S_{6\text{ cm peak}}\) into \(L_{6\text{ cm peak}}\) introduces the uncertainty of poor distance estimates to many of the parent galaxies of the SNe.

However, to try to provide some indication of the relative quality of the different points, we have attempted to assign reasonable error estimates to all values. For the distances listed in Table 1, we have tried to find the best value and error estimate available in the literature and, when successful, have listed the appropriate reference. For galaxies for which no estimate is available, we have taken the value from Tully (1988), accepting all of his corrections but adjusting his distance value obtained with his assumed \(H_0 = 75\, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}\) to what appears to be a more recently preferred value of \(H_0 = 65\, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}\) (see, e.g., Saha et al. 1997 and references therein; Riess, Press, & Kirshner 1996; Hamuy et al. 1996). Since Tully (1988) assigns no distance error to his values, we have assumed that \(\pm 15\%\), to roughly cover the range of \(H_0\) from 55 to 75 \(\text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}\) within 1 \(\sigma\), is a reasonable estimate.

For the other two critical parameters, \(S_{6\text{ cm peak}}\) and \((t_{6\text{ cm peak}} - t_0)\), we have used several methods to obtain rough error estimates.

Where enough data are available and the radio light curves are well determined (e.g., SN 1993J with hundreds of measurements), we were able to use the bootstrap method\(^5\) to obtain direct estimates of the 1 \(\sigma\) deviation for both quantities. However, in the cases in which the data were very sparse (e.g., SN 1986E with only one detection at one frequency), we had to rely on a qualitative estimate of the error by adjusting fitting parameters by hand to obtain a range of values for \(S_{6\text{ cm peak}}\) and \((t_{6\text{ cm peak}} - t_0)\) that appeared consistent with the data. In extreme cases where one or both parameters were effectively indeterminate, that has been indicated in Table 2 by the superscript "ind." and, in Figure 3, by a missing limit for that side of the range of uncertainty.

Once error estimates were established for \(S_{6\text{ cm peak}}\) and the distance, determination of error estimates for the \(L_{6\text{ cm peak}}\) followed standard error propagation procedures.

Finally, error estimates for the "radio distances" in Table 3 were obtained for Type Ib and Type Ic SNe from propagation of the flux density error from Table 2 and the deviation from the average luminosity (eq. [15] for Type Ib and eq. [16] for Type Ic) for each SN type. For Type II SNe, errors were estimated from the flux density error from Table 2 and the standard deviation of the luminosities from the straight line shown in Figure 3. While it is felt that these error estimates are reasonable for the quality of the data available, they cannot be rigorously justified.

### 4. Discussion

#### 4.1. Type Ib/c Peak Radio Luminosities and Distances

The model discussion presented in § 2 suggests that Type Ib/c SNe may have relatively little variation in their peak spectral luminosities, even if there are variations in the measured time from explosion to peak. Unfortunately, there are only four Type Ib/c RSNe that have been studied at radio wavelengths, and even these four examples are diverse, with two being Type Ib and two being Type Ic. Additionally, SN 1984L has very limited data available, and SN 1990B was quite distant and therefore studied with poor a signal-to-noise ratio. Within these limitations, however, examination of Table 2 shows that Type Ib RSNe, based on data for only two objects, may be approximate standard candles with peak 6 cm luminosities ranging only from 14.1 to 25.7 \(\times 10^{26}\) ergs \text{s}^{-1} \text{Hz}^{-1}\), and, similarly, Type Ic RSNe, again based on data for only two objects, may be approximate standard candles with peak 6 cm luminosities ranging only from 5.6 to 13.7 \(\times 10^{26}\) ergs \text{s}^{-1} \text{Hz}^{-1}\). These are consistent to within the errors for Type Ib SNe having an average peak 6 cm luminosity of

\[
L_{6\text{ cm peak}} \approx 19.9 \times 10^{26}\text{ ergs \text{s}^{-1} \text{Hz}^{-1}} \tag{15}
\]

and Type Ic SNe having an average peak 6 cm luminosity of

\[
L_{6\text{ cm peak}} \approx 6.5 \times 10^{26}\text{ ergs \text{s}^{-1} \text{Hz}^{-1}} \tag{16}
\]

If we assume that Type Ib and Type Ic RSNe are, in fact, standard candles in their peak 6 cm radio emission and that, on average, the assumed distances listed for the objects in Table 1 are correct, we can determine a "radio distance" to each RSN, such that its measured peak 6 cm flux density would yield the average peak 6 cm spectral luminosity for its particular type. These distances are listed in Table 3 along with an error. The "assumed distances" and errors from Table 1 are reprinted in Table 3 for the reader’s convenience.

While it should be kept in mind that the two sets of distance estimates are not completely independent, with the assumed "independent" distances de facto setting the scale...
for the radio distances, it is apparent that the data are consistent, to within the errors, with an assumption of constant 6 cm peak luminosity. Thus, the distance to any Type Ib or Type Ic RSN can be estimated simply by measuring its 6 cm peak flux density and comparing this observed value with the luminosity predicted by equations (15) and (16). Clearly, more objects of both subtypes must be identified and studied in the radio to better test and define these two equations.

4.2. Type II Peak Radio Luminosities and Distances

There are 12 examples of Type II RSNe that have a sufficient number of radio observations available for detailed study. While Type II RSNe are far more heterogeneous in their radio (as well as in their optical) properties than Type Ib/c RSNe, inspection of and shows that the longer it takes a Type II RSN to reach 6 cm peak flux density, the higher its 6 cm luminosity at that peak. This is also supported by the model discussion in §2, which implies a relatively steep power-law relation between the two quantities. However, as with the Type Ib/c SNe, we are considering here an empirical test and therefore will determine a best-fit power law to the available turn-on time versus peak 6 cm luminosity data.

Performing an unweighted least-squares fit to the data for the 12 available Type II RSNe, we obtain the relation (formal fitting errors given) of

\[ L_{6\,\text{cm\,peak}} \approx 5.5^{+8.2}_{-3.4} \times 10^{23}(t_{6\,\text{cm\,peak}} - t_0)^{1.4 \pm 0.2} \text{ ergs \, s}^{-1} \, \text{Hz}^{-1}, \]  

with time in days. This relation is shown as the dashed line in Figure 3. We note that the empirically derived slope of the \( L_{6\,\text{cm\,peak}} \) versus \( (t_{6\,\text{cm\,peak}} - t_0) \) relationship agrees well with the value inferred from model estimates (see eq. [14]). This result suggests that the Chevalier (1982a, 1982b) model is valid, at least for interpreting the origin of the radio emission.

If we assume that Type II RSNe obey this relation and that, on average, the independent distances listed for the objects in Table 1 are correct, we can determine a radio distance to each RSN, such that its measured peak 6 cm flux density would yield the “best-fit” 6 cm spectral luminosity predicted by equation (17). These radio distances are listed in the fourth column of Table 3, along with errors, while the assumed distances and errors from Table 1 are reprinted in Table 3 for the reader’s convenience.

Again, while it should be kept in mind that the two sets of distance estimates are not completely independent, with the assumed distances de facto setting the scale for the radio distances, it is apparent that the data are consistent, to within the errors, with the results of equation (17). Thus, the distance to any Type II RSN can be estimated simply by measuring its time from explosion to 6 cm peak flux density and comparing the observed 6 cm peak flux density with the predicted luminosity.

5. DEVIATIONS

Examination of the distances determined from the relations of equations (15), (16), and (17) for Type Ib, Type Ic, and Type II, respectively, in Table 3 shows that they are generally in good agreement to within the estimated errors.

However, several cases show relatively large disagreement that is inconsistent with the error estimates.

5.1. SN 1985L, SN 1986E, and SN 1996cb

Perhaps too easily, large deviations for these three SNe can be explained, if not dismissed. SN 1985L was faint (\( S_{6\,\text{cm\,peak}} \approx 0.65 \text{ mJy, estimated} \) and had only two clear detections of radio emission (Van Dyk et al. 1988a). While reasonable estimates of RSN parameters can be obtained for SN 1985L through the use of a number of upper limits, the quality of the \( L_{6\,\text{cm\,peak}} \) and \( (t_{6\,\text{cm\,peak}} - t_0) \) must remain suspect.

SN 1986E (Montes et al. 1997) has the same difficulties as SN 1985L but is even more extreme. Only one clear radio detection at one frequency exists, and the rest of the parameter fitting has to rely on the use of upper limits. It was also quite faint, with a peak 6 cm flux density of only \( S_{6\,\text{cm\,peak}} \approx 0.31 \text{ mJy} \).

SN 1996cb (Van Dyk et al. 1998b), while relatively bright with a 6 cm peak flux density of \( S_{6\,\text{cm\,peak}} \approx 1.8 \text{ mJy} \), exhibited the most rapid turn-on of any Type II RSN except for SN 1987A. In fact, many of its radio properties resemble those of the Type Ib/c RSNe. This, unfortunately, meant that the turn-on at wavelengths shorter than 20 cm was completely missed, and estimates of \( S_{6\,\text{cm\,peak}} \) and \( (t_{6\,\text{cm\,peak}} - t_0) \) are rather uncertain.

5.2. SN 1980K in NGC 6946

Radio supernova SN 1980K (Weiler et al. 1986, 1992) has a very large deviation from equation (17) (Fig. 3, dashed line). Also, it is possibly the most interesting deviation in that it is not easily explained away. SN 1980K was a reasonably strong, well-studied, normal Type II RSN, where there can be little doubt as to its characteristics and model parameters. Thus, it may well serve as a test case.

If the relation of equation (17) for Type II SNe is valid, and SN 1980K is indeed a normal Type II RSN, then the distance estimate of 6.3 Mpc from Tully (1988) (converted to \( H_0 = 65 \text{ km \, s}^{-1} \text{ Mpc}^{-1} \)) for the parent galaxy, NGC 6946, must be too short. A significantly larger distance of \( \geq 10 \text{ Mpc} \) is implied by the radio results.

NGC 6946 is a large (11.5 \times 9.8\,\text{arcmin}) spiral galaxy, which has been a prolific producer of SNe in the last century (SN 1917A, SN 1939C, SN 1948B, SN 1968D, SN 1969P, and SN 1980K). However, it is at a low galactic latitude and\( (b = 11\deg, \, v_\text{galactic} = 65 \text{ km \, s}^{-1}) \) located along the direction of rotation of the Milky Way\( (l = 95\deg) \), requiring large corrections to obtain an intrinsic radial velocity with respect to the galactic rest frame. Because it is so close, peculiar motions within the Local Group of galaxies may also disturb the Hubble flow and yield an inaccurate distance estimate from corrected radial velocity measurements.

Recent work on the expanding photosphere method (EPM) by Schmidt, Kirshner, & Eastman (1992) yields a distance to SN 1980K (and thus, NGC 6946) of 8.1 \pm 1.5 Mpc from IR observations and 7.2^{+0.7}_{-1.0} \text{ Mpc} from optical observations, both of which are somewhat closer than our radio estimate of 12.3 \pm 1.9 Mpc. Furthermore, a revision of the EPM results by Schmidt et al. (1994) yields a distance of 5.7 \pm 0.7 Mpc, which is in much closer agreement with the Tully (1988) distance than with our radio distance.

We have circumstantial evidence that NGC 6946 may be more distant than commonly assumed. The fact that NGC
6946 is the galaxy with the largest number of SN events ever recorded suggests a high blue luminosity, which should be at least as high as that of another prolific SN producer, NGC 4321 (M100), in which four SNe have been discovered (with only one, SN 1979C, being a bona fide Type II SN). If we assume that NGC 6946 has the same blue luminosity, \( M_B \), as NGC 4321 and establish the difference in their total apparent magnitudes as \( m_B(NGC 4321) - m_B(NGC 6946) = 0.47 \) (Tully 1988), accepting that the difference of their reddening corrections is \( \pm 0.1 \) mag (as indicated by optical and UV observations of SN 1979C and SN 1980K; Panagia 1982), we find that the distance to NGC 6946 is no less than 0.51 times the distance to NGC 4321 (\( d = 17.1 \pm 1.3 \) Mpc; Freedman et al. 1994a). Thus, this implies a distance to NGC 6946 of \( d > 8.7 \) Mpc.

In any case, it appears that the distance to NGC 6946 is sufficiently uncertain that it may be in error by the factor of \( \sim 2 \) that the radio data for SN 1980K imply. Clearly, a measurement of the distance to NGC 6946 with more accurate techniques (e.g., Cepheids) is called for and could provide an important test of the \( L_6 \) cm peak versus \( (t_6 \) cm peak \( - t_0) \) hypothesis.

6. CONCLUSIONS

We have presented evidence that the radio emission from SNe may have quantifiable properties that allow for distance determinations. Type Ib RSNe, based on a statistically very small sample of only two objects, may be approximate radio standard candles, with a 6 cm peak luminosity of \( \sim 19.9 \times 10^{26} \) erg s\(^{-1}\) Hz\(^{-1}\); Type Ic RSNe, also on a very small sample of only two objects, may be approximate radio standard candles with a 6 cm peak luminosity of \( \sim 6.5 \times 10^{26} \) erg s\(^{-1}\) Hz\(^{-1}\); and Type II RSNe, based on a sample of 12 objects, appear to obey a relation \( L_6 \) cm peak \( \sim 5.5 \times 10^{23} (t_6 \) cm peak \( - t_0)^{1.4} \) ergs s\(^{-1}\) Hz\(^{-1}\) (with time in days). Thus, measurement of the radio turn-on time \( (t_6 \) cm peak \( - t_0) \) and peak flux density \( S_6 \) cm peak can yield a luminosity estimate and therefore a distance.

The reality of the "standard radio candle" hypothesis for Type Ib and Type Ic RSNe may be tested simply through the study of more objects. For Type II RSNe, the large deviation of the well-observed SN 1980K in NGC 6946 from the distance predictions of this hypothesis could serve as a useful test. Whereas the presently accepted distance is \( \sim 6 \) Mpc to NGC 6946 (Tully 1988), the radio results predict a significantly larger distance of \( \geq 10 \) Mpc. A new, accurate determination of the distance to NGC 6946 is certainly called for and, in general, improved distances to all host galaxies of RSNe would be valuable.

Although there are still relatively few objects to which these techniques can be applied, RSNe may eventually provide a powerful and independent technique for investigating the long-standing problem of distance estimates in astronomy. With such intrinsically bright Type II RSNe as SN 1988Z and SN 1986J could be detected up to a redshift of \( \sim 1 \), while a more normal Type II SN, such as SN 1980K, could be studied accurately up to a redshift of \( \geq 0.1 \).\(^6\)

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\(^6\) Additional information and data on radio supernovae can be found on http://rsd-www.nrl.navy.mil/7214/weiler/ and linked pages. The information contained therein has not been refereed, and none of these web pages is maintained by the Astrophysical Journal.