Modulations in the radio light curve of the Type IIb supernova 2001ig: evidence for a Wolf–Rayet binary progenitor?

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ABSTRACT
We describe the radio evolution of supernova (SN) 2001ig in NGC 7424, from 700 d of multifrequency monitoring with the Australia Telescope Compact Array (ATCA) and the Very Large Array (VLA). We find that deviations of the radio light curves at each frequency from the standard ‘minishell’ model are consistent with density modulations in the circumstellar medium (CSM), which seem to recur with a period near 150 d. One possibility is that these are due to enhanced mass loss from thermal pulses in an asymptotic giant branch star progenitor. A more likely scenario, however, is that the progenitor was a Wolf–Rayet (WR) star, whose stellar wind collided with that from a massive hot companion on an eccentric 100-d orbit, leading to a regular build-up of CSM material on the required time and spatial scales. Recent observations of ‘dusty pinwheels’ in WR binary systems lend credibility to this model. Since such binary systems are also thought to provide the necessary conditions for envelope stripping which would cause the WR star to appear as a Type Ib/c SN event rather than a Type II, these radio observations of SN 2001ig may provide the key to linking Type Ib/c SNe to Type IIb events, and even to some types of gamma-ray bursts.

Key words: binaries: general – circumstellar matter – supernovae: individual: SN 2001ig – stars: Wolf–Rayet – galaxies: individual: NGC 7424 – gamma-rays: bursts.

1 INTRODUCTION

Radio studies of supernovae (SNe) can provide valuable information about the density structure of the circumstellar medium (CSM), the late stages of stellar mass loss, and independent distance estimates for host galaxies (Weiler et al. 2002). Furthermore, with the growing realization that some gamma-ray bursts (GRBs) may be intimately linked with SNe [e.g. GRB 980425 and SN 1998bw (Kulkarni et al. 1998); GRB 011121 and SN 2001ke (Garnavich et al. 2003); GRB 030329 and SN 2003dh (Stanek et al. 2003)], such studies are crucial to understanding GRB environments. To date, radio emission has only ever been detected from core-collapse Type II and Type Ib/c SNe [for a recent review of SN taxonomy, see Turatto (2003)], and not at all from thermonuclear Type Ia SNe.

SN 2001ig was discovered visually by Evans (2001) on 2001 December 10.43 UT in the outskirts of the nearby late-type spiral galaxy NGC 7424 (D = 11.5 Mpc; Tully 1988). No SNe have been recorded previously in this galaxy. Initial optical spectroscopy of SN 2001ig from Las Campanas Observatory (Matheson & Jha 2001) revealed similarities to the Type IIb SN 1987K (Filippenko 1988), while spectra from the European Southern Observatory over the following month (Clocchiatti & Prieto 2001; Clocchiatti 2002) showed a similar behaviour to that of the Type IIb SN 1993J, by transitioning from Type II to Type Ib/c as the H recombination lines weakened. By 2002 October, the transition to a Type Ib/c SN in the nebular phase was well and truly complete (Filippenko & Chornock 2002). SN 2001ig was also detected by the Advanced CCD Imaging Spectrometer-S (ACIS-S) instrument on board the Chandra X-ray Observatory on 2002 May 22 UT with a 0.2–10.0-keV luminosity of ∼1038 erg s–1 (Schlegel & Ryder 2002). A second observation 3 weeks later showed that the X-ray luminosity had halved in that time (Schlegel, private communication).

Radio monitoring of SN 2001ig with the Australia Telescope Compact Array (ATCA) commenced within a week of its discovery, and has continued on a regular basis. In Section 2, we present...
2 RADIO MONITORING

Table 1 contains the complete log of radio flux measurements from the ATCA. Column 2 lists the days elapsed since explosion, which is derived from the model fitting in Section 4. Total time on-source ranged from as little as 2 h, up to a full 12-h synthesis, but was typically 4–6 h. As the ATCA is capable of observing on two frequency bands simultaneously, determining fluxes in four frequency bands on the same day required time-sharing. Dual-frequency observations centred on 18.75 and 18.88 GHz and bandwidths of 128 MHz were carried out using a prototype receiver system on just three ATCA antennas. The central frequencies of the other bands are 8.640, 4.790, 2.496 and 1.376 GHz, and the bandwidth is 128 MHz. From 2002 July 11 onwards, the S-band central frequency was changed from 2.496 to 2.368 GHz, to reduce the amount of in-band interference. The ATCA primary flux calibrator, PKS B1934–638, has been observed once per run, while observations of the nearby source PKS B2310–417 allow us to monitor and correct for variations in gain and phase during each run.

Table 1. SN 2001ig radio flux measurements with the ATCA.

| Date (UT) | Days since 2001 December 3 UT | $S_{18.8 \text{ GHz}}$ (mJy) | $S_{8.6 \text{ GHz}}$ (mJy) | $S_{4.8 \text{ GHz}}$ (mJy) | $S_{2.4 \text{ GHz}}$ (mJy) | $S_{1.4 \text{ GHz}}$ (mJy) |
|-----------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 15/12/01  | 12                            | 2.1 ± 0.3                   | 0.6 ± 0.3                   |                            |                            | 0.8                         |
| 18/12/01  | 15                            | 3.9 ± 1.6                   | 1.6 ± 0.2                   |                            |                            |                             |
| 22/12/01  | 19                            | 8.7 ± 0.8                   | 2.7 ± 0.3                   |                            |                            |                             |
| 26/12/01  | 23                            | 15.0 ± 3.0                  | 4.8 ± 0.3                   |                            |                            |                             |
| 31/12/01  | 28                            | 43 ± 4                      |                            | 6.3 ± 0.3                   |                            | 1.8                         |
| 07/01/02  | 35                            |                            |                            | 10.6 ± 0.3                  |                            |                             |
| 10/01/02  | 38                            | 22 ± 3                      | 23.6 ± 4.1                  | 14.2 ± 0.9                  |                            |                             |
| 15/01/02  | 43                            | 11 ± 4                      | 18.9 ± 5.6                  | 15.1 ± 0.7                  |                            |                             |
| 20/01/02  | 48                            |                            |                            |                            | 5.3 ± 0.3                   |                             |
| 02/02/02  | 61                            | 9.9 ± 2.2                   | 18.4 ± 4.4                  |                            |                            |                             |
| 17/02/02  | 76                            |                            | 7.0 ± 1.1                   | 11.0 ± 0.5                  |                            |                             |
| 26/02/02  | 85                            |                            |                            |                            | 11.5 ± 0.3                  | 7.0 ± 0.5                   |
| 17/03/02  | 104                           | 10.7 ± 2.0                  | 18.1 ± 1.3                  |                            |                            |                             |
| 19/03/02  | 106                           |                            |                            |                            | 25.1 ± 1.3                  | 13.8 ± 1.5                  |
| 28/03/02  | 115                           | 11.1 ± 2.0                  | 21.9 ± 1.0                  | 23.5 ± 0.3                  | 14.2 ± 0.6                  |
| 09/04/02  | 127                           | 12.6 ± 0.7                  | 21.2 ± 0.6                  |                            |                            |                             |
| 22/04/02  | 140                           | 12.7 ± 0.9                  | 21.6 ± 0.7                  |                            |                            |                             |
| 12/05/02  | 160                           | 12.4 ± 0.5                  | 21.7 ± 0.4                  | 30.3 ± 1.6                  | 21.8 ± 1.0                  |
| 27/05/02  | 175                           | 8.0 ± 1.7                   | 15.6 ± 1.3                  | 24.4 ± 0.3                  | 21.5 ± 0.7                  |
| 09/06/02  | 188                           | 6.2 ± 1.7                   | 11.9 ± 1.2                  | 19.7 ± 1.0                  | 19.5 ± 0.6                  |
| 30/06/02  | 209                           | 4.6 ± 1.4                   | 8.9 ± 1.0                   | 14.4 ± 0.6                  | 19.5 ± 0.8                  |
| 11/07/02  | 220                           | 4.0 ± 1.2                   | 7.6 ± 0.9                   | 14.9 ± 0.4                  | 19.8 ± 1.2                  |
| 28/07/02  | 237                           | 3.6 ± 0.9                   | 7.1 ± 0.7                   | 13.0 ± 0.3                  | 18.2 ± 0.5                  |
| 11/08/02  | 251                           | 3.3 ± 1.0                   | 6.4 ± 0.8                   | 12.7 ± 0.3                  | 18.1 ± 1.0                  |
| 23/08/02  | 263                           | 3.8 ± 0.5                   | 6.7 ± 0.3                   | 12.5 ± 0.2                  | 17.8 ± 0.9                  |
| 31/08/02  | 271                           | 3.7 ± 0.3                   | 6.7 ± 0.2                   | 12.5 ± 0.2                  | 17.4 ± 0.9                  |
| 17/09/02  | 288                           | 3.2 ± 1.0                   | 6.6 ± 0.7                   | 12.3 ± 0.3                  | 16.4 ± 0.6                  |
| 12/10/02  | 313                           | 2.7 ± 0.9                   | 6.7 ± 0.4                   | 10.2 ± 0.6                  | 15.4 ± 0.8                  |
| 22/11/02  | 354                           | 2.5 ± 0.3                   | 4.5 ± 0.3                   | 8.0 ± 0.3                   | 11.7 ± 0.5                  |
| 17/12/02  | 379                           | 1.3 ± 0.3                   | 3.6 ± 0.3                   | 6.5 ± 0.5                   | 11.5 ± 1.1                  |
| 05/02/03  | 429                           | 1.8 ± 0.4                   | 2.2 ± 0.2                   | 6.1 ± 0.5                   | 10.0 ± 1.3                  |
| 16/03/03  | 468                           | 1.5 ± 0.4                   | 2.6 ± 0.3                   | 5.5 ± 0.4                   | 8.8 ± 0.4                   |
| 20/05/03  | 533                           | 1.2 ± 0.5                   | 2.4 ± 0.2                   | 4.5 ± 0.2                   | 7.7 ± 0.7                   |
| 03/08/03  | 608                           | 0.9 ± 0.4                   | 2.0 ± 0.2                   | 3.8 ± 0.3                   | 6.3 ± 0.4                   |
| 07/11/03  | 704                           | 0.8 ± 0.3                   | 1.6 ± 0.2                   | 3.1 ± 0.3                   | 5.1 ± 0.5                   |

*Chandra & Ray (2002) reported a flux at 1.4 GHz of $11.7 \pm 1.5$ mJy for SN 2001ig on 2002 September 25.8 UT with the Giant Meterwave Radio Telescope (GMRT). The source of this discrepancy has since been traced to an elevation-dependent gain error in the GMRT data (Chandra & Ray, private communication).
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Figure 1. Contours of 4.790-GHz radio emission, on a V-band image of NGC 7424. The radio observations were made with the ATCA on 2002 February 17 UT, and have a synthesized beamwidth of 3.8 arcsec × 1.5 arcsec. SN 2001ig is the upper-left of the two (unresolved) sources. The optical image is 3.5 arcmin on a side, obtained with the DFOSC instrument on the Danish 1.54-m telescope on La Silla (Larsen & Richtler 1999), and made available through the NASA/IPAC Extragalactic Database.

Table 2. SN 2001ig radio flux measurements with the VLA.

| Date (UT) | Days since 2001 December 3 UT | S(22.5 GHz) (mJy) | S(15.0 GHz) (mJy) | S(8.5 GHz) (mJy) | S(4.9 GHz) (mJy) | S(1.4 GHz) (mJy) |
|-----------|------------------------------|------------------|------------------|------------------|------------------|------------------|
| 28/12/01  | 25                           | 37.2 ± 5.6       | 36.5 ± 3.7       | –                | –                | –                |
| 07/01/02  | 35                           | 22.3 ± 3.4       | 30.9 ± 3.1       | –                | –                | –                |
| 10/01/02  | 38                           | 16.6 ± 2.5       | 25.1 ± 2.6       | –                | –                | –                |
| 13/01/02  | 41                           | 15.8 ± 2.4       | 20.5 ± 2.1       | 23.5 ± 1.8       | –                | –                |
| 17/01/02  | 45                           | –                | –                | –                | –                | –                |
| 21/03/02  | 108                          | 10.5 ± 0.5       | 18.6 ± 0.9       | 12.6 ± 0.8       | –                | –                |

adjacent source, was crucial to recovering valid flux measurements from observations with poor phase stability and/or limited hour-angle coverage.

The ATCA observations have been supplemented by a few early observations with the Very Large Array (VLA). The observing and data analysis procedure follows that described in Weiler et al. (1986), and the results are listed separately in Table 2. Owing to the low elevation of SN 2001ig as observed from the VLA, and the compact configuration of the VLA at the time, both the sensitivity and the resolution are relatively poor. Nevertheless, these data prove to be important in constraining the early evolution of SN 2001ig, particularly at the very highest frequencies.

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Figure 2. SN 2001ig at radio frequencies of 22.5/18.8 GHz (circles, thick solid line), 8.6/8.5 GHz (crosses, dashed line), 4.9/4.8 GHz (squares, dash-dotted line), 2.4 GHz (triangles, dotted line), and 1.4 GHz (diamonds, dash-triple dotted line). The curves are a model fitting to the data, as described in the text.

3 RADIO LIGHT CURVES

The ATCA and VLA radio data are plotted in Fig. 2. The data at 15.0 GHz are not shown here, to reduce confusion with the other high-frequency points, but are incorporated in the model fitting of Section 4. The time evolution of the spectral index $\alpha$ (where flux $S \propto \nu^\alpha$) between simultaneous positive detections at 1.4 and 4.8/4.9 GHz and between 4.8/4.9 and 8.6 GHz is plotted in Fig. 3.

The radio ‘light curve’ of a Type II SN can be broadly divided into three phases: first, there is a rapid turn-on with a steep spectral index ($\alpha > 2$, so the SN is brightest at the higher frequencies), due to a decrease in the line-of-sight absorption. After some weeks or months have elapsed, the flux reaches a peak, turning over first at the highest frequencies. Eventually, the SN begins to fade steadily, and at the same rate at all frequencies, in the optically thin phase.

Although broadly consistent with this picture, the radio light curve of SN 2001ig displays significant departures from a smooth turnover and decline, which are most pronounced at 8.64 and 4.79 GHz. At around day 80, the flux at these frequencies reversed its initial decline, and by day 130 had almost doubled. The flux remained almost constant for a period of $\sim$50 d, before resuming its decline at close to the original rate. Near day 250, the decline was again temporarily interrupted for another 50 d. There are indications of perhaps one more bump after day 450, but by this stage the SN has faded to the millijansky level where any variations are comparable to the measurement uncertainties. The deviations are less pronounced, but still evident at 2.50 and 1.38 GHz.

4 MODEL FITTING

The general properties of SN radio light curves as outlined in Section 3 are well represented by a modified version of the ‘minishell’ model of Chevalier (1982), and have been successfully parametrized for more than a dozen radio supernovae (RSNe) (see table 2 of Weiler et al. 2002). Radio synchrotron emission is produced when the SN shock wave ploughs into an unusually dense CSM. Following the notation of Weiler et al. (2002) and Sramek & Weiler (2003), we model the multifrequency evolution as

$$S(\text{mJy}) = K_i \left(\frac{\nu}{5 \text{ GHz}}\right)^\alpha \left(\frac{t - t_0}{1 \text{ d}}\right)^\beta e^{-\tau_{\text{external}}} \times \left(\frac{1 - e^{-\tau_{\text{CSMclumps}}}}{\tau_{\text{CSMclumps}}} \right) \left(\frac{1 - e^{-\tau_{\text{external}}}}{\tau_{\text{internal}}}\right)$$

(1)

with

$$\tau_{\text{external}} = \tau_{\text{CSMclumps}} + \tau_{\text{distant+}}$$

(2)
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where

$$\tau_{\text{CSM, homog}} = K_2 \left( \frac{v}{5 \, \text{GHz}} \right)^{-2.1} \left( \frac{t - t_0}{1 \, \text{d}} \right)^{\delta},$$  \hspace{1cm} (3)

$$\tau_{\text{distant}} = K_4 \left( \frac{v}{5 \, \text{GHz}} \right)^{-2.1}$$  \hspace{1cm} (4)

and

$$\tau_{\text{CSM, clumps}} = K_3 \left( \frac{v}{5 \, \text{GHz}} \right)^{-2.1} \left( \frac{t - t_0}{1 \, \text{d}} \right)^{\delta'},$$  \hspace{1cm} (5)

with the various $K$ terms representing the flux density ($K_1$), the attenuation by a homogeneous absorbing medium ($K_2$, $K_3$), and the attenuation by a clumpy/filamentary medium ($K_4$), at a frequency of 5 GHz 1 d after the explosion date, $t_0$. The $\tau_{\text{CSM, homog}}$ and $\tau_{\text{CSM, clumps}}$ absorption arises in the CSM external to the blast wave, while $\tau_{\text{distant}}$ is a time-independent absorption produced by, for example, a foreground H II region or more distant parts of the CSM unaffected by the shock wave. The spectral index is $\alpha$: $\beta$ gives the rate of decline in the optically thin phase; and $\delta$ and $\delta'$ describe the time dependence of the optical depths in the local homogeneous and clumpy/filamentary CSM, respectively [see Weiler et al. (2002) and Sramek & Weiler (2003) for detailed accounts of how these parameters are related.] For lack of sufficient high-frequency data prior to the turnover to constrain it, we adopt $\tau_{\text{turnoff}} = 0$.

In order to assess the gross properties of SN 2001ig in comparison with other Type IIb RSNe, we have fitted this standard model to the data in Tables 1 and 2, but excluding days 48–70 and 110–190. Thus, the model fit is constrained primarily by the rise at early times, by the region of the high-frequency turnover, and by the late-time decay. The actual date of explosion, $t_0$, is found to be 2001 December 3 UT, 1 week prior to discovery. The full set of model parameters that yields the minimum reduced $\chi^2$ value is given in Table 3 and the model curves are plotted in Fig. 2. For comparison, we show in Table 3 the equivalent parameters for two other well-sampled Type IIb RSNe: SN 1993J (Van Dyk et al., in preparation) in M81 and SN 2001gd (Stockdale et al. 2003) in NGC 5033. Note that we have fixed the value of $\delta$ to be ($\alpha - \beta - 3$), as in the Chevalier (1982) model for expansion into a CSM with density decreasing as $r^{-2}$.

The spectral index, $\alpha$, of SN 2001ig is virtually identical to SN 1993J, but less steep than SN 2001gd. However, the rate of decline $\beta$ is much steeper in SN 2001ig than in either of the other Type IIb SNe, and the time to reach the peak 5-GHz flux is also much shorter. In this respect, SN 2001ig has behaved more like a Type Ib/c SN than most ‘normal’ Type II SNe. The interpolated peak 5-GHz luminosity would be about twice that attained by SN 1993J, although in practice SN 2001ig was near a local minimum in the flux at that time, and the actual peak was not reached for another 40 d.

Using the methodology outlined in Weiler et al. (2002) and Sramek & Weiler (2003), we can derive an estimate of mass-loss rate of the progenitor, based on its radio absorption properties. Substituting our model fit results above into their equation (11), and assuming that both $\tau_{\text{CSM, homog}}$ and $\tau_{\text{CSM, clumps}}$ contribute to the absorption, we find that

$$\frac{\dot{M}}{(\text{M}_\odot \text{yr}^{-1})} = \left(2.2 \pm 0.5\right) \times 10^{-5},$$

where $w$ is the mass-loss wind velocity, and the ejecta velocity as measured from the earliest optical spectra (Clocchiatti & Prieto 2001; Clocchiatti 2002) is in the range 15 000–20 000 km s$^{-1}$. Clearly, this is only an average value, subject to major variations discussed in the next section, but is in the same domain as the mass-loss rates derived similarly for SN 1993J and SN 2001gd (Table 3). Although generally less well constrained, mass-loss rates may also be estimated directly from the radio emission properties, relying only on the peak 5-GHz luminosity, and the time taken to reach that peak. Equations (17) and (18) of Weiler et al. (2002) give $\dot{M}/w = 1.5 \times 10^{-5}$ and $3.5 \times 10^{-5}$ for the average Type Ib/c and Type II SNe, respectively. Thus, the mass-loss rate calculations are in good agreement, with SN 2001ig being intermediate between the expected rates for Type Ib/c and Type II SNe, consistent with its Type IIb classification.

5 DISCUSSION

In Fig. 4 we have plotted the deviations of the observed flux density, from the best-fitting model curves as shown in Fig. 2. The solid line in this figure is a four-point boxcar average of the mean deviation

![Figure 4](https://academic.oup.com/mnras/article-abstract/349/3/1093/1027078/1097)

Table 3. Comparison of the radio light-curve model parameters.

| Parameter          | SN 2001ig   | SN 1993J   | SN 2001gd |
|--------------------|-------------|------------|-----------|
| $K_1$              | $2.71 \times 10^4$ | $1.36 \times 10^4$ | $1.49 \times 10^3$ |
| $\alpha$           | $-1.06$     | $-1.05$    | $-1.38$   |
| $\beta$            | $-1.50$     | $-0.88$    | $-0.96$   |
| $K_2$              | $1.38 \times 10^3$ | $9.14 \times 10^2$ | $3.25 \times 10^6$ |
| $\delta$           | $-2.56$     | $-1.88$    | $-1$      |
| $K_3$              | $1.47 \times 10^3$ | $8.33 \times 10^4$ | $1.05 \times 10^3$ |
| $\delta'$          | $-2.69$     | $-2.26$    | $-1.27$   |
| $K_4$              | $0.0$       | $2.76 \times 10^{-3}$ | $173$ |
| Time to $L_{5\text{GHz, peak}}$ (days) | 74 | 167 | 173 |
| $L_{5\text{GHz, peak}}$ (erg s$^{-1}$ Hz$^{-1}$) | $3.5 \times 10^{27}$ | $1.4 \times 10^{27}$ | $2.9 \times 10^{27}$ |
| Mass-loss rate (M$\odot$ yr$^{-1}$) | $(2.2 \pm 0.5) \times 10^{-5}$ | $2.1 \times 10^{-5}$ | $3.0 \times 10^{-5}$ |

$^1$ Case 2 in the notation of Weiler et al. (2002). Note that there is a misprint in that section, namely that in the limit of $\tau_{\text{CSM, clumps}} \rightarrow 0$, then $(\delta')^5 \rightarrow \tau_{\text{CSM, homog}}^{0.5}$ in equation (13), and not $\tau_{\text{CSM, homog}}$. We prefer the term ‘homogeneous’ here over ‘uniform’, as the latter could give the misleading impression of no density gradient at all, whereas an $r^{-2}$ dependence of density is implicit.
over all frequencies at each epoch, which serves to emphasize the quasi-damped harmonic nature of the deviations, having a period near 150 d, and peak intensity declining with time (i.e. with increasing distance from the star). The rms deviation of the actual data from the smoothed interpolation is less than one third of the amplitude of the observed modulation. As the fractional amplitude of these deviations is virtually identical at each frequency, the evolution of the spectral index (Fig. 3) in the optically thin phase appears relatively unaffected. We take this as evidence that the bumps and dips in the radio light curve primarily reflect abrupt modulations in the CSM density structure, rather than optical depth effects (although optical depth is tied to CSM density to some degree). We now consider ways in which such a structured CSM may have been laid down late in the life of the progenitor of SN 2001ig.

Before doing so, we need to examine the effects of a change in CSM density on the velocity of the expansion, as well as on the radio emission. The blast-wave radius increases with time as \( r \propto t^m \), where \( m = 1 \) for no deceleration. As \( m = -\delta / 3 \) in the Chevalier (1982) model, then \( m = 0.85 \) for SN 2001ig, implying significant deceleration in the surrounding CSM. The radio luminosity is related to the average CSM density (\( \rho_{\text{CSM}} \propto \dot{M}/w \)) via

\[
L \propto \left( \frac{\dot{M}}{w} \right)^{\gamma-7+12w/4} \tag{6}
\]

(Chevalier 1982) so that, for SN 2001ig, \( L \propto (\dot{M}/w)^{1.6} \). Consequently, a doubling in the CSM density will cause the radio emission to rise by a factor of 3.

5.1 Episodic mass loss from a single progenitor

The observed transition in SN 2001ig from a Type II optical spectrum with H lines to a Type Ib/c spectrum without H lines argues for the ejection of a significant fraction of the red giant envelope. Fig. 4 indicates strong excesses in observed flux at \( r \sim 150 \) and \( \sim 300 \) d (with a net flux excess still at 500–600 d), hinting at a possible periodicity of 150 d in CSM density enhancements. If these density enhancements (by factors of 30 and 15 per cent, respectively) correspond to discrete shells of material expelled by the red supergiant, then the spacing between these shells is given by

\[
R_{\text{sh}} = \frac{\dot{M}}{\rho_{\text{CSM}} w} \propto \left( \frac{\dot{M}}{w} \right)^{\gamma-7+12w/4} \tag{6}
\]

(1982) model, then

\[
R_{\text{sh}} = \frac{\dot{M}}{\rho_{\text{CSM}} w} \propto \left( \frac{\dot{M}}{w} \right)^{1.6} \tag{6}
\]

(Chevalier 1982) so that, for SN 2001ig, \( L \propto (\dot{M}/w)^{1.6} \). Consequently, a doubling in the CSM density will cause the radio emission to rise by a factor of 3.

5.2 Binary model

Among the other RSNe studied to date, only SN 1979C shows anywhere near as much systematic variation in its optically thin decline phase as SN 2001ig. Indeed, for the first decade or so, the late-time radio light curve of SN 1979C could be well represented by a sinusoidal modulation of the flux, with a period of 1575 d (Weiler et al. 1992). More recently, however, these regular variations in SN 1979C have ceased, and the light curve has flattened out (Montes et al. 2000). The implied modulation period of the mass-loss rate is \( T \sim 4000 \) yr, a factor of 100 longer than that computed above for SN 2001ig. On the basis of evidence that the progenitor of SN 1979C had an initial mass of at least 16 M\(_{\odot}\), Weiler et al. (1992) argued against the thermal-pulse scenario described in Section 5.1, as the interperiod for such a massive star and its resulting core would be \( \ll 4000 \) yr. Instead, they proposed modulation of the progenitor wind due to eccentric orbital motion about a massive binary companion as the cause of the periodicity in the radio light curve of SN 1979C.

The particular binary scenario presented by Weiler et al. (1992) had a red supergiant progenitor and a 10-M\(_{\odot}\) B1 dwarf orbiting their common barycentre, with a 4000-yr period. For a purely circular orbit, the orbital motion of the progenitor is a sizable fraction of the wind velocity, resulting in a spiral (or pinwheel-like) density structure being imprinted on the otherwise uniform mass-loss CSM in the orbital plane. This by itself would not lead to any periodic variation in the CSM density swept up by the SN shock wave. If instead the orbit were eccentric (\( e = 0.5 \) say), the acceleration of the progenitor near periastron every 4000 yr would cause an additional pile-up of wind material which may then account for the observed periodicity in the radio emission. Schwarz & Pringle (1996) performed full hydrodynamical simulations of this, taking into account shocks generated in the wind, the gravitational influence of the companion on the wind, and light-travel time effects. Their simulations produced pronounced, but asymmetric, spiral shock patterns, particularly when a polytropic equation of state is assumed. They also demonstrated that the amplitude of the modulations in the radio light curve tends to decrease as our view of the orbital plane goes from edge-on, to face-on. This may partly explain why such periodic variations as seen in SN 1979C and SN 2001ig are comparatively rare, as not only must the mass-loss rate be modulated by the right kind of binary orbit parameters, but we must also then be fortunate enough to view it from close to edge-on.

Similar hydrodynamical simulations, but in three dimensions, of detached binary systems comprising a 1.5-M\(_{\odot}\) AGB star and a secondary star of 2.0–4.0 M\(_{\odot}\) were presented by Mastrodemos & Morris (1999), specifically targeted at reproducing the observed structures in IRC +10216, CRL 2688, etc., mentioned in Section 5.1. Interestingly, for sufficiently large binary separations (>10 au) and wind velocities (\( w > 15 \) km s\(^{-1}\)), the spiral shock structure extends to high latitudes, and the resulting ‘spiral onion shell’ structure seen in cross-section could resemble the shells seen in protoplanetary...
nebulae (PPNe), and implied in SN 2001ig. In an alternative binary scenario, Harpaz, Rappaport & Soker (1997) postulate that it is the close passage of the secondary star effectively ‘choking off’ uniform mass loss from an AGB star having an extended atmosphere, rather than any enhancements in the mass-loss rate itself, which gives rise to these shells.

Perhaps the best direct evidence for the existence of binary-generated spiral shocks comes from high-resolution observations of dusty Wolf–Rayet (WR) stars. Tuthill, Monnier & Danchi (1999) and Monnier, Tuthill & Danchi (1999) used the technique of aperture-masking interferometry on the Keck I telescope to image structures at better than 50-mas resolution in the K-band around WR 104 and WR 98a. In both cases, they found pinwheel-shaped nebulae wrapping almost entirely around the central source out to distances of 150–300 au. Their model has an OB-type companion orbiting the WR star, with dust formation taking place in the wake of the interface region between their colliding stellar winds. The combination of orbital motion and wind-driven radial motion results in a ‘lawn sprinkler’ effect, and the resultant dusty spirals. Hydrodynamic models in three dimensions of these colliding wind binary systems by Walder & Folini (2003) show the effects of varying the orbital eccentricity.

Remarkably, the characteristic radial scale for density enhancements implied by the radio light curve of SN 2001ig ($R_{\text{sh}} = 0.0006$ pc; Section 5.1) is an almost perfect match to the typical scale of one full rotation of these pinwheel nebulae: 50–100 mas at $D \sim 2$ kpc $\rightarrow R = 0.0005-0.001$ pc. Thus, SN 2001ig may represent the obliteration of just such a pinwheel nebula. Further support for this scenario comes from the flux excess (at least 60 per cent, although this is a lower limit due to optical depth effects) in the first 50 d over that expected from a simple $r^{-2}$ CSM density profile, as shown in Fig. 4. Coupled with the deceleration mentioned previously, this would tend to favour a centrally condensed additional CSM component such as a pinwheel nebula, rather than concentric mass-loss shells.

5.3 SN 2001ig and the link between Type II and Type Ib/c SNe

It is interesting to note that the apparent requirements to produce such a pinwheel nebula, i.e. a close binary system composed of two massive stars in which the primary is a WR star, are similar to those invoked by stellar evolution theory to explain the origin of Type Ib/c SNe. The peculiar spectral evolution and optical light-curve behaviour of SN 1993J and SN 1997K (Section 5.1) have been attributed to the explosion of a H-poor, He-rich progenitor (Swartz et al. 1993). A large fraction of the original H envelope of the progenitor must have been shed prior to core collapse, either through a strong stellar wind from a single massive (25–30 $M_\odot$) star (Höflich, Langer & Duschinger 1993); or, more likely, via mass transfer from an intermediate-mass (10–15 $M_\odot$) star in a binary system (Nomoto et al. 1993; Podsiadlowski et al. 1993; Utrobin 1994; Van Dyk et al. 1996). Models for the evolution of massive stars in close binaries (e.g. Podsiadlowski, Joss & Hsu 1992; Woosley, Langer & Weaver 1995) produce He stars. The suggestion is that stars that have lost some or all of their H would be the WN class of WR stars, and explode as Type Ib SNe; while those that also lose their He layer would be WC or WO classes of WR stars, and explode as Type Ic SNe (Harkness et al. 1987; Filippenko, Matheson & Ho 1993).

At least 40 per cent of solar neighbourhood WR stars are in binary systems with hot companions (Moffat et al. 1986; van der Hucht et al. 1988), and the fraction may be even higher in low-metallicity environments (Dalton & Sarazin 1995), such as the outskirts of NGC 7424. The extent of mass transfer, and thus the end-products of the binary system, depends on the evolutionary stage of the primary at the time mass transfer commences. As shown by Podsiadlowski et al. (1992) and Pols & Nomoto (1997), Case C mass transfer (which takes place after the core He-burning phase) in systems with large eccentricity and orbital periods of a few years can be episodic, occurring mainly near periastron, just as outlined in Section 5.2. We propose that SN 2001ig may well have undergone just such a phase, without actually sharing a common envelope with a companion. The implied orbital period is given by one complete winding of the pinwheel nebula, which is simply the ratio of $R_{\text{sh}} \sim 0.0006$ pc divided by the terminal wind velocity of a WN star ($\sim$2000 km s$^{-1}$; Abbott & Conti 1987), or $T \sim 100$ d, consistent with this scenario.

In this context, the highly modulated radio light curves for SN 2001ig may represent some of the best evidence yet for a link between Type IIb and Type Ib/c SNe, in that SN 2001ig evolved optically like a Type IIb, but has the radio characteristics that should be expected for a Type Ib/c SN originating in a WR + OB binary system viewed nearly edge-on. A testable prediction from this scenario is that the companion star (which by virtue of mass accretion may be even brighter than the WR progenitor of SN 2001ig) should eventually become visible against the fading optical remnant, as has recently been demonstrated for the case of SN 1993J by Maund et al. (2004).

In addition to its apparent association with GRB 980425, SN 1998bw is also notable for showing bumps and dips in its radio light curves not dissimilar to those seen in SN 2001ig (Weiler, Panagia & Montes 2001). These deviations, while exhibiting no clear periodicity in the first 1000 d, were less conspicuous at low frequencies, just as in SN 2001ig. This kind of behaviour is likely due to the CSM still being optically thick to low frequencies at relatively late times, and therefore only emission originating in the near-side of the CSM can be seen; whereas at high frequencies, emission from the entire CSM is visible. SN 1998bw had the spectral characteristics primarily of a Type Ic event, with a probable WR progenitor (Iwamoto et al. 1998). Unfortunately, barely half a dozen Type Ib/c SNe have been detected or studied in the radio, so it is too early to tell whether such modulated radio light curves may be clues to a common massive binary origin for Type IIb and Type Ib/c SNe, and possibly some GRBs.

6 CONCLUSIONS

By compiling one of the most complete multifrequency radio data sets ever collected for any SN, we have been fortunate to witness regular modulations in the radio light curves of the Type IIb SN 2001ig. The time taken to reach the peak 5-GHz luminosity, the rate of decline since then, and the derived mass-loss rates prior to explosion are all intermediate between those of Type Ib/c and ‘normal’ Type II SNe. We find that the light-curve modulations to recur on a time-scale of $\sim$150 d, and have shown them to be true density modulations in the CSM, and not optical depth effects. Allowing for the deceleration of the ejecta, these density enhancements are spaced 0.6 mpc (or 130 au) apart.

While we cannot totally exclude the possibility that these density enhancements represent mass-loss shells from the thermal-pulsing phase of a single AGB star progenitor, we find that the weight of evidence supports a stellar wind, modulated by motion in an eccentric binary system, as their source. As had been suggested previously for SN 1979C, the combination of a massive binary companion causing a pile-up of mass loss during periastron,
and a favourable viewing angle, can result in just the kind of periodic density variations observed in SN 2001ig. Recent near-infrared interferometric observations of the anticipated ‘pinwheel’ dust nebulae in systems comprising a WR star and a hot massive companion lend weight to this scenario, especially as the observed size scales match those required for SN 2001ig. Finally, as optical spectroscopy has recently been leading to the conclusion that Type Ib/c SNe are the product of a core-collapse event in the WR component of such systems (and Type Ib SNe being those caught early enough to reveal the final traces of their lost H envelope), we believe that these radio observations of SN 2001ig provide the ‘missing link’ between the pinwheel nebulae observed in Galactic WR binary systems, and their eventual fate in Type Ib or Type Ib/c SNe.

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REFERENCES

Abbott D. C., Comti P. S., 1987, ARA&A, 25, 113
Becker S. A., Iben I., 1979, ApJ, 232, 831
Becker S. A., Iben I., 1980, ApJ, 237, 111
Chandra P., Ray A., 2002, IAU Circ. 7994
Chevalier R., 1982, ApJ, 259, 302
Clocchiatti A., 2002, IAU Circ. 7793
Clocchiatti A., Prieto J. L., 2001, IAU Circ. 7781
Dalton W. W., Sarazin C. L., 1995, ApJ, 448, 369
Evans R. O., 2001, IAU Circ. 7772
Filippenko A. V., 1988, AJ, 96, 1941
Filippenko A. V., Chornock R., 2002, IAU Circ. 7988
Filippenko A. V., Matheson T., Ho L. C., 1993, ApJ, 415, L103
Garnavich P. M. et al., 2003, ApJ, 582, 924
Harkness R. P. et al., 1987, ApJ, 317, 355
Harpaz A., Rappaport S., Soker N., 1997, ApJ, 487, 809
Höflich P., Langer N., Duschinger M., 1993, A&A, 275, L29
Iben I., Renzini A., 1983, ARA&A, 21, 271
Iwamoto K. et al., 1998, Nat, 395, 672
Kulkarni S. R. et al., 1998, Nat, 395, 663
Kwok S., Su K. Y. L., Hrivnak B. J., 1998, ApJ, 501, L117
Larsen S. S., Richtler T., 1999, A&A, 345, 59
Mastromenos N., Morris M., 1999, ApJ, 523, 357
Matheson T., Jha S., 2001, IAU Circ. 7772
Maund J. R., Smartt S. J., Kudritzki R. P., Podsiadlowski P., Gilmore G. F., 2004, Nat, 427, 129
Mauron N., Huggins P. J., 2000, A&A, 359, 707
Moffat A. F. J., Lamontagne R., Shara M. M., McAlister H. A., 1986, AJ, 91, 1392
Monnier J. D., Tuthill P. G., Danchi W. C., 1999, ApJ, 525, L97
Montes M. J., Weiler K. W., Van Dyk S. D., Panagia N., Lacey C. K., Sramek R. A., Park R., 2000, ApJ, 532, 1124
Nomoto K., Suzuki T., Shigeyama T., Kumagai S., Yamaoka H., Saio H., 1993, Nat, 364, 507
Paczyński B., 1975, ApJ, 202, 558
Podsiadlowski Ph., Joss P. C., Hsu J. J. L., 1992, ApJ, 391, 246
Podsiadlowski Ph., Hsu J. J. L., Joss P. C., Ross R. R., 1993, Nat, 364, 509
Pols O. R., Nomoto K., 1997, in Leung K. C., ed., ASP Conf. Ser. Vol. 130, The Third Pacific Rim Conference on Recent Development of Binary Star Research. Astron. Soc. Pac., San Francisco, p. 153
Sahai R. et al., 1998, ApJ, 493, 301
Schlegel E. M., Ryder S. D., 2002, IAU Circ. 7913
Schwarz D. H., Pringle J. E., 1996, MNRAS, 282, 1018
Sramek R. A., Weiler K. W., 2003, in Weiler K. W., ed., Supernovae and Gamma-Ray Bursters. Springer-Verlag, Berlin, p. 145
Stanek K. Z. et al., 2003, ApJ, 591, L17
Stockdale C., Weiler K. W., Van Dyk S. D., Montes M. J., Panagia N., Sramek R. A., Perez-Torres M. A., Marcaide J. M., 2003, ApJ, 592, 900
Swartz D. A., Clocchiatti A., Benjamin R., Lester D. F., Wheeler J. C., 1993, Nat, 365, 232
Tully R. B., 1988, Nearby Galaxies Catalog. Cambridge Univ. Press
Turatto M., 2003, in Weiler K. W., ed., Supernovae and Gamma-Ray Bursters. Springer-Verlag, Berlin, p. 21
Tuthill P. G., Monnier J. D., Danchi W. C., 1999, Nat, 398, 487
Utrobin V., 1994, A&A, 281, L89
van der Hucht K. A., Hidayat B., Admiranto A. G., Supelli K. R., 1988, A&A, 199, 217
Van Dyk S. D., Hanumy M., Filippenko A. V., 1996, AJ, 111, 2017
Walder R., Folini D., 2003, in van der Hucht K. A., Herrero A., Esteban C. eds, Proc. IAU Symp. 212, A Massive Star Odyssey, from Main Sequence to Supernova. Astron. Soc. Pac., San Francisco, p. 139
Weiler K. W., Sramek R. A., Panagia N., van der Hulst J. M., Salvati M., 1986, ApJ, 301, 790
Weiler K. W., Van Dyk S. D., Pringle J. E., Panagia N., 1992, ApJ, 399, 672
Weiler K. W., Panagia N., Montes M. J., 2001, ApJ, 562, 670
Weiler K. W., Panagia N., Montes M., Sramek R. A., 2002, ARA&A, 40, 387
Woosley S. E., Langer N., Weaver T. A., 1995, ApJ, 448, 315

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