MONITORING OF THE PROMPT RADIO EMISSION FROM THE UNUSUAL SUPERNOVA SN 2004dj IN NGC 2403

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ABSTRACT

Supernova SN 2004dj in the nearby spiral galaxy NGC 2403 was detected optically in 2004 July. Peaking at a magnitude of 11.2, this is the brightest supernova detected for several years. Here we present Multi-Element Radio Linked Interferometer Network (MERLIN) observations of this source, made over a 4 month period, that give a position of R.A. = 07h37m 17s.044, decl. = +65°35'57"84 (J2000.0). We also present a well-sampled 5 GHz light curve covering the period from 2004 August 5 to December 2. With the exception of the unusual and very close SN 1987A, these observations represent the first detailed radio light curve for the prompt emission from a Type II-P supernova.

Subject headings: galaxies: starburst — radio continuum: stars — supernovae: individual (SN 2004dj)

On-line material: color figure

1. INTRODUCTION

We are currently using MERLIN4 (Multi-Element Radio Linked Interferometer Network) and NRAO’s VLA5 (Very Large Array) to monitor the radio emission associated with a sample of nearby starburst galaxies (Argo et al. 2004b), with the objective of determining their radio supernova rates. As the active star-forming regions of these galaxies contain large numbers of massive stars, it is likely that most of the radio supernovae will be associated with core-collapse supernovae (Type Ib/c and Type II). In addition to regular monitoring of the galaxies in our sample, we plan to use MERLIN to monitor the radio flux density of other nearby supernova events where possible (e.g., Beswick et al. 2004a, 2004b), particularly when the VLA is in compact configurations.

The detection of SN 2004dj, visually on 2004 July 31 (Nakano et al. 2004) and in the radio using the VLA at 8.4 GHz on August 2 (Stockdale et al. 2004), provided an ideal opportunity to study a nearby supernova and its evolution at radio wavelengths. The high declination of NGC 2403, the host galaxy (+65°), makes it an ideal source for high-resolution MERLIN observations.

Peaking at a magnitude of 11.2, SN 2004dj was the brightest optical supernova for several years. Shortly after the initial detection, it was reported that the spectrum of SN 2004dj showed features typical of Type II-P supernovae (Papat et al. 2004). Type II-P supernovae are believed to originate via core collapse in hydrogen-rich, massive stars. The main characteristic of Type II-P supernovae is that their optical luminosity, unlike other Type II supernovae, does not decay rapidly after peaking but remains approximately constant for 2–3 months before decaying exponentially. The physics of supernovae are discussed in detail in Woosley & Weaver (1986) and references therein.

Despite the fact that Type II-P supernovae are relatively common optically, few have been detected in the radio. As far as we are aware, only two Type II-P supernovae have been detected at radio wavelengths: SN 1987A (Ball et al. 1995; Kirk et al. 1994; Turtle et al. 1987 and references therein) and SN 1999em (Pooley et al. 2002). A further possibility is SN 1923A, although this is arguably a supernova remnant rather than a radio supernova (Eck et al. 1998).

The only detailed radio study of a Type II-P radio supernova is SN 1987A (see § 3.3), whereas the radio observations of SN 1999em are rather limited with relatively few detections between day 34 and day 70, despite extensive monitoring between 8.4 and 1.4 GHz. Consequently, no well-sampled radio light curve of SN 1999em was established.

SN 2004dj occurred in NGC 2403, a nearby (3.2 Mpc; Karachentsev et al. 2004) spiral galaxy located within the M81 group. As this is approximately half the distance of SN 1999em, this offered us an excellent opportunity to establish a Type II-P radio light curve, so using a subset of the MERLIN array, we began monitoring this source frequently at 5 GHz on August 5 and continued through to 2004 December 2.

2. OBSERVATIONS

Monitoring observations at 4994 MHz with a bandwidth of 14.75 MHz were made with a subset of the MERLIN array (Thomasson 1986) between 2004 August 5 and October 6. These employed a single 218 km baseline between the Cambridge and Defford antennas. The primary flux calibration was performed using the strong source 3C 84 assuming a flux density of 14.53 Jy, which was derived via a comparison with 3C 286. The nearby point source 0733+646 was used for primary phase calibration and for secondary flux calibration assuming a flux density of 0.3566 Jy. Two additional secondary phase calibration sources (0713+669 and 0752+639) were also observed in order to establish the precision to which point-source positions could be derived from single baseline data. Tests using all three phase calibration sources have shown that we are able to derive the position of SN 2004dj to better than 50 mas.

The single-baseline “maps,” shown in Figure 1, illustrate that SN 2004dj is detected at greater than 3 σ in each of our 2.5 day integrations and that we are able to measure its position
Fig. 1.—Radio light curve of SN 2004dj from MERLIN data. Day 0 of the radio light curve is 2004 July 31. The three upper panels show contoured images of SN 2004dj at different stages of its evolution. Observations up until October were performed using a single 217 km baseline; following this the entire MERLIN array was used. Each image is contoured with multiples of $2 \times 165, 63, \text{and } 32 \mu\text{Jy beam}^{-1}$, from left to right, respectively. The convolved beam size in each image is $45 \times 45$ mas, $45 \times 45$ mas, and $58 \times 57$ mas, respectively. The peak flux of the source at each epoch is shown in the bottom left-hand corner of each image. The date shown in each image represents the start date for each of the imaged epochs. [See the electronic edition of the Journal for a color version of this figure.]

from such images. It should be noted that, although these single-baseline maps can only provide limited structural information regarding the source, its position and flux density can be obtained. The light curve from August to early October (Fig. 1) is derived from 2.5 day vector-averaged points after rotating the data from the nominal pointing position to the measured position for SN 2004dj. Additional points on the light curve (November onward) are derived from observations made using the full MERLIN array and were calibrated and imaged using standard methods.

3. RESULTS AND DISCUSSION

3.1. Position and Progenitor

From these MERLIN observations, the position of SN 2004dj is found to be R.A. = $07^h37^m17.044$, decl. = $+65^\circ35'57".84$ (J2000.0), with an absolute error of $<50$ mas. No proper motion is detected between any of our epochs. This position is within 0\'4 of the optical position reported by Nakano et al. (2004) and agrees with the Chandra X-ray position reported by Pooley & Lewin (2004). However, the VLA D-configuration position reported by Stockdale et al. (2004; R.A. = $7^h37^m16.916$, decl. = $+65^\circ35'56".97$) is $\sim1\"$ away from the MERLIN, Chandra, and optical positions. The error in this radio position is almost certainly the result of confusion from the extended radio emission from NGC 2403 (Filippenko et al. 2004, S. D. Van Dyk 2004, private communication).

This position measurement puts the supernova near to n2403-2866 (R.A. = $07h37m16.93$, decl. = $+65^\circ35.577$; Larsen & Richtler 1999), a cluster also known as Sandage 96, and the luminous blue variable (LBV) candidate 7-3909 (R.A. =
was undetectable above the noise (mJy beam
decaying slowly from this radio plateau level. By December (day variation from mJy over the following month before0.9
of August before reaching an approximately constant flux value 2004dj was observed to decrease during the second half of
et al. 2004a). Following this initial detection, the flux of SN
was detected with a flux density of 1.8 mJy at 5 GHz (Argo
vations, is shown in Figure 1.
At each epoch, SN 2004dj was detected and imaged. The radio
light curve for SN 2004dj, derived from the MERLIN obser-
Based on radio observations of several Type II supernovae, Weiler et al. (2002) derive an empirical relationship between the peak luminosity and the time delay from explosion to its
peak such that

\[ L_{6 \text{ cm peak}} \approx 5.5^{+8.7}_{-3.4} \times 10^{34} (t_{6 \text{ cm peak}} - t_0)^{1.4 \pm 0.2} \text{ W Hz}^{-1}, \]  

where \( t_{6 \text{ cm peak}} - t_0 \) is the number of days between the supernova detonation and the peak of the prompt radio emission at 6 cm. Assuming that the peak luminosity of SN 2004dj at 6 cm is \( 2.45 \times 10^{34} (\pm 10\%) \) W Hz\(^{-1}\), this implies \( t_{6 \text{ cm peak}} - t_0 = 15^{+42}_{-10} \) days, placing the detonation date between July 11 and the first detection of SN 2004dj, July 31. This is broadly consistent with spectroscopic observations of SN 2004dj, obtained on August 3 (Patat et al. 2004), which report SN 2004dj to have a spectrum similar to that of SN 1999em about 3 weeks after explosion (i.e., around July 13). SN 2004dj is a Type II-P supernova and only the second of this type for which a well-
sampled radio light curve exists. Thus, although these observations appear to be approximately consistent with equation (1), more observations of the prompt radio emission from Type
II-P supernovae are required to make conclusions regarding the whole of this class of supernovae, if their radio emission is to be used as a reliable luminosity distance indicator.

3.3. Comparison with SN 1987A and SN 1999em

The only other Type II-P supernova to have been extensively monitored and imaged at radio wavelengths in its early evolution is the supernova 1987A (Ball et al. 1995; Kirk et al. 1994; Turtle et al. 1987, and references therein). By virtue of the proximity of SN 1987A, situated in the LMC at a distance of \( \sim 50 \) kpc, the prompt radio emission from this supernova was detected a couple of days after its optical detection and has been monitored at various frequencies ever since (Turtle et al. 1987).

The peak luminosity of the prompt radio emission from SN 1987A at gigahertz frequencies was \( 4 \times 10^{34} \) W Hz\(^{-1}\) (Turtle et al. 1987), approximately 2 orders of magnitude lower than the peak luminosity at 5 GHz recorded for SN 2004dj (\( \gtrsim 2.6 \times 10^{34} \) W Hz\(^{-1}\)). However, the 5 GHz peak luminosity of SN 2004dj is comparable to that of the Type II-P supernova 1999em, which was estimated to have a \( L_{6 \text{ cm peak}} \approx 2.2 \times 10^{34} \) W Hz\(^{-1}\) (Pooley et al. 2002). The X-ray luminosity of SN 2004dj is approximately 3 times greater than that of SN 1999em (Pooley & Lewin 2004).

Our estimate of \( t_{6 \text{ cm peak}} - t_0 = 15^{+42}_{-10} \) days and the spectroscopically based estimates of \( \sim 30 \) days of Patat et al. (2004) are comparable to the estimates for SN 1999em (\( \sim 34 \) days; Pooley et al. 2002). In both of these cases, the time delay before the peak of the supernova’s gigahertz radio emission is an order of magnitude longer than that observed for the Type II-P supernova 1987A.

Along with the detection of prompt radio emission from supernovae 1987A, 1999em, and 2004dj, all three of these sources have also been detected at X-ray wavelengths (Masai et al. 1987; Dotani et al. 1987; Rodin et al. 1987; Pooley et al. 2002; Pooley & Lewin 2004). This is often true for core-collapse supernovae (see Fig. 1 of Immler & Lewin 2003) and is unsurprising since both types of emission arise from the shocked circumstellar medium. Consequently, it appears that an X-ray detection of a Type II-P supernova may be an indicator that it can also be detected at radio wavelengths, or vice versa. However, to date very few supernovae of this type have been detected in either of these wave bands.

Interestingly, in the only other case where a Type II-P supernova has been extensively monitored at radio wavelengths, SN 1987A, the radio flux was found to evolve and brighten after \( \sim 1400 \) days (Manchester et al. 2002 and references therein), signifying the birth of a radio remnant. In fact, since this redetection of SN 1987A, its radio emission has continued to increase at an approximately monotonic rate and now far exceeds the radio brightness of its initial prompt radio emission phase. This increase in the observed radio luminosity of SN 1987A occurred as the expanding shock front from the supernova encountered a large increase in the density of the circumstellar medium. Coincidently, this second phase of emission was also observable at X-ray wavelengths. Uniquely, SN 2004dj’s proximity may provide a second opportunity to study the transition of a radio supernova into a supernova remnant, although this will be dependent on the density of the surrounding circumstellar medium, and thus the nature of the progenitor. Additionally, if, in a few years time, SN 2004dj does significantly brighten, it may be detectable and resolvable using high-
sensitivity VLBI observations. As such, it is essential that continued radio monitoring observations of this source are made.

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REFERENCES

Argo, M. K., Muxlow, T. W. B., Beswick, R. J., Pedlar, A., & Marcaide, J. M. 2004a, IAU Circ. 8399
Argo, M. K., Muxlow, T. W. B., Pedlar, A., Beswick, R. J., & Strong, M. 2004b, MNRAS, 351, L66
Ball, L., Campbell-Wilson, D., Crawford, D. F., & Turtle, A. J. 1995, ApJ, 453, 864
Beswick, R. J., Muxlow, T. W. B., Argo, M. K., & Pedlar, A. 2004a, IAU Circ. 8332
Beswick, R. J., Muxlow, T. W. B., Argo, M. K., Pedlar, A., & Marcaide, J. M. 2004b, IAU Circ. 8435
Dotani, T., Hayashida, K., Inoue, H., Itoh, M., & Koyama, K. 1987, Nature, 330, 230
Eck, C. R., Roberts, D. A., Cowan, J. J., & Branch, D. 1998, ApJ, 508, 664
Filippenko, A. V., Li, W., Challis, P., & Van Dyk, S. D. 2004, IAU Circ. 8391
Immler, S., & Lewin, W. H. G. 2003, in Supernovae and Gamma-Ray Bursters, ed. K. W. Weiler (Lecture Notes in Phys. 598; New York: Springer), 91
Karachentsev, I. D., Karachentseva, V. E., Huchtmeier, W. K., & Makarov, D. I. 2004, AJ, 127, 203
Kirk, J. G., Duffy, P., & Ball, L. 1994, ApJS, 90, 807
Larsen, S. S., & Richtler, T. 1999, A& A, 345, 59
Maíz-Apellániz, J., Bond, H. E., Siegel, M. H., Lipkin, Y., Maoz, D., Ofek, E. O., & Poznanski, D. 2004, ApJ, 615, L113
Manchester, R. N., Gaensler, B. M., Wheaton, V. C., Staveley-Smith, L., Tzioumis, A. K., Bizunok, N. S., Kesteven, M. J., & Reynolds, J. E. 2002, Publ. Astron. Soc. Australia, 19, 207
Masai, K., Hayakawa, S., Itoh, H., & Nomoto, K. 1987, Nature, 330, 235
Nakano, S., Itagaki, K., Bouma, R. J., Lehky, M., & Hornoch, K. 2004, IAU Circ. 8377
Patat, F., Benetti, S., Pastorello, A., Filippenko, A. V., & Aceituno, J. 2004, IAU Circ. 8378
Pooley, D., & Lewin, W. H. G. 2004, IAU Circ. 8390
Pooley, D., et al. 2002, ApJ, 572, 932
Rodin, V., et al. 1987, Nature, 330, 227
Stockdale, C. J., Sramek, R. A., Weiler, K. W., Van Dyk, S. D., Panagia, N., Pooley, D., Lewin, W., & Marcaide, J. M. 2004, IAU Circ. 8379
Thomasson, P. 1986, QJRAS, 27, 413
Turtle, A. J., Campbell-Wilson, D., Bunton, J. D., Jauncey, D. L., & Kesteven, M. J. 1987, Nature, 327, 38
Weiler, K. W., Pangia, N., Montes, M. J., & Sramek, R. A. 2002, ARA&A, 40, 387
Weis, K., Bomans, D. J., Klose, K., & Spiller, F. 2004, IAU Circ. 8384
Woosley, S. E., & Weaver, T. A. 1986, ARA&A, 24, 205