Observing Application

Date : Mar, 03 2009
Proposal ID : VLA/09A-192
Legacy ID : AS988
PI : Christopher Stockdale
Type : Rapid Response - Target of Opportunity
Category : Extragalactic
Total Time : 24.0

Monitoring Late-Time Radio Emission from Two Nearby Core-Collapse Supernovae

Abstract:

We propose new VLA observations to monitor supernovae (SNe) 1996aq and 2004dk, two type Ib/Ic SNe with detected late-time radio emission. The systematic radio studies of SNe beginning with Weiler et al (1981, 1986) recognized synchrotron emission as the mechanism responsible for their radio emission, which the classic model of Chevalier (1982) interpreted as arising from an interaction between the SN blastwave and the circumstellar material (CSM) shed by a massive progenitor in the 1,000's of years prior to explosion. Over the last 30 years, >50 SNe have been detected in the radio, typically within one year after explosion. Two notable exceptions are SNe 2001em and 1996cr. SN 2001em was detected in a search of older type Ib/c SNe (later reclassified as a type IIn SN). SN 1996cr was discovered via serendipitous archival observations, and exhibited a radio turn-on ~2 yrs after explosion. Both are examples of the SN-blastwave hitting a distant and dense CSM. We now have detected two new radio SNe, originally classified type Ic, emitting more than 5 years after optical discovery. New VLA observations to monitor these SNe will explore the properties of this new subclass of radio SNe.

Authors:

Name	Institution	Email	Status
Christopher Stockdale	Marquette University	christopher.stockdale@mu.edu	
Franz Bauer	Columbia University	feb@astro.columbia.edu	
Schuyler Van Dyk	Spitzer Science Center/Caltech	vandyk@ipac.caltech.edu	
Kurt Weiler	Naval Research Laboratory	Kurt.Weiler@nrl.navy.mil	
David Pooley	Wisconsin at Madison, University of	dave@astro.wisc.edu	
Stefan Immler	Goddard Space Flight Center	stefan.immler@nasa.gov	
Nino Panagia	Space Telescope Science Institute	panagia@stsci.edu	
Vikram Dwarkadas	Chicago, University of	vikram@oddjob.uchicago.edu	
Richard Sramek	National Radio Astronomy Observatory/ALMA Chile	dsramek@aoc.nrao.edu	

Principal Investigator:	Christopher Stockdale
Contact:	Christopher Stockdale
Telephone:	414-288-3989
Email:	christopher.stockdale@mu.edu

Related proposals:

AB1321

Joint:

Not a Joint Proposal

Observing type(s):

Continuum

VLA Resources

Name	Conf.	Frontend & Backend	Setup
L BAND - B Config	B	L Band 20 cm 1000 - 2000 MHz VLA Correlator - Single Channel Continuum	Rest frequencies: 1464.9,1385.1 MHz Bandwidth: 50 MHz
X BAND - B Config	B	X Band 3.6 cm 8080 - 8750 MHz VLA Correlator - Single Channel Continuum	Rest frequencies: 8435.1,8485.1 MHz Bandwidth: 50 MHz
C BAND - B Config	B	C Band 6 cm 4000-8000 MHz VLA Correlator - Single Channel Continuum	Rest frequencies: 4885.1,4835.1 MHz Bandwidth: 50 MHz
L BAND - C Config	C	L Band 20 cm 1000 - 2000 MHz VLA Correlator - Single Channel Continuum	Rest frequencies: 1464.9,1385.1 MHz Bandwidth: 50 MHz
X BAND - C Config	C	X Band 3.6 cm 8080 - 8750 MHz VLA Correlator - Single Channel Continuum	Rest frequencies: 8435.1,8485.1 MHz Bandwidth: 50 MHz
C BAND - C Config	C	C Band 6 cm 4000-8000 MHz VLA Correlator - Single Channel Continuum	Rest frequencies: 4885.1,4835.1 MHz Bandwidth: 50 MHz

Sources:

Name	RA / RA Range	Dec / Dec Range	Epoch	Velocity / z	Group
SN1996aq	14:22:22.7 00:00:00.0	-00:23:24 00:00:00	J2000	Velocity : 1638	New Late Time SNe
SN2004dk	16:21:48.9 00:00:00.0	-2:16:17 00:00:00	J2000	Velocity : 1573	New Late Time SNe

Sessions:

Name	Session Time (hours)	Repeat	Separation	LST minimum	LST maximum	Elevation Minimum
Bi-monthly monitoring	6.00	2	60 day	09:30:00	18:00:00	10
Monthly monitoring	6.00	2	30 day	09:30:00	18:00:00	10

Session Constraints:

Name	Constraints	Comments
Bi-monthly monitoring	To run in C config	2 separate searches for each SNe at X C and L at 1 hour on source each.
Monthly monitoring	To run in B config	Three separate searches for each SNe at X C and L at 1 hour on source each.

Session Source/Resource Pairs:

Session Name	Source	Resource	Time	Figure of Merit	Subarray
Monthly monitoring	SN1996aq SN2004dk	L BAND - B Config	2.0 hour	0.08 mJy/bm	
Monthly monitoring	SN1996aq SN2004dk	X BAND - B Config	2.0 hour	0.03 mJy/bm	
Monthly monitoring	SN1996aq SN2004dk	C BAND - B Config	2.0 hour	0.03 mJy/bm	
Bi-monthly monitoring	SN1996aq SN2004dk	L BAND - C Config	2.0 hour	0.08 mJy/bm	
Bi-monthly monitoring	SN1996aq SN2004dk	C BAND - C Config	2.0 hour	0.03 mJy/bm	
Bi-monthly monitoring	SN1996aq SN2004dk	X BAND - C Config	2.0 hour	0.03 mJy/bm	

Present for observation: no

Staff support: None

Plan of Dissertation: no

Background

Among the ∼850 core-collapse SNe that have exploded in the last few decades within 100 Mpc, only ≈50 have been detected as radio supernovae (RSNe) within the first year (e.g., Weiler et al. 1989; Weiler et al. 2002; Soderberg et al. 2006). Systematic radio studies of supernovae (SNe), beginning with Weiler et al (1981, 1986), recognized synchrotron emission as the mechanism responsible for their radio emission, which the classic model of Chevalier (1982) interpreted as arising from an interaction between the SN blastwave and the circumstellar material (CSM) shed by its massive progenitor in the 1,000's years prior to explosion. Such radio emission, which is often accompanied by detectable X-ray emission (e.g., Stockdale et al. 2002, 2006; Immler & Kuntz 2005), is linked to the interaction between the SN blast-wave and the progenitor wind-established CSM, which must be relatively dense (i.e., $\dot{M} \gtrsim 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ for v_{wind}∼10 km s^{-1}) to be observed at all even in these nearby objects. When well-constrained, these young RSNe generally follow a standard evolution (e.g., Chevalier 1982, Chevalier & Fransson 1994) wherein their light curves show a frequency-dependent "turn-on" due either to free-free absorption, synchrotron self-absorption, or both in the ionized circumstellar medium, followed by a $\sim t^{-1.0\pm0.5}$ decline (e.g., SN 1993J Weiler et al. 2007). Likewise, X-ray emission, when detected, can be seen as early as 10 days after explosion, with a similar $\sim t^{-1.0\pm0.5}$ decline from the onset (e.g., Fig. 1 and Fig. 2 of Immler & Kuntz 2005).

Enter SN 1996cr

In 2007, SN 1996cr was discovered ∼11 years after it was believed to explode (Bauer 2007; Bauer & Matilla 2007) in the nearby Circinus Galaxy, only 3.8±0.6 Mpc away (Freeman et al. 1977). The type IIn SN 1996cr is comparable to several well-known core-collapse SNe interacting with dense circumstellar material (CSM) such as SN 1978K, SN 1979C, SN 1986J, SN 1988Z, SN 1993J, and SN 1998S (e.g., Weiler et al. 2002; Immler & Lewin 2003). What makes SN 1996cr so remarkable is not only its proximity, but also its unique radio and X-ray light curves (Fig. 1), which are both quite faint for the first 1–2 yrs (only upper limits) and then rise in a dramatic manner (Bauer 2007, Bauer et al. 2008). SN 1996cr shows evidence for a frequency-dependent free-free "turn-on" typical for most RSNe, but it additionally requires a luminosity jump of >1000 to adequately explain the full radio light curve (Bauer et al. 2008). A similarly unusual evolution is seen in the X-ray light curve. As the radio and X-ray emission both trace the underlying CSM structure of the SN progenitor, these temporal features demonstrate that the density of the CSM within $\lesssim 10^{16}$ cm was relatively sparse, while beyond this radius it must have jumped at least a few orders of magnitude to perhaps $\sim 10^{-5}$–$10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$, depending on the assumed progenitor wind velocity.

The only viable scenarios for such behavior are ones in which the progenitor either ejected a shell of material at some late evolutionary stage [e.g., a pulsationally unstable red supergiant (RSG), Panagia & Bono 2001, or a Luminous Blue Variable eruption, Smith et al. 2007a] or changed evolutionary wind states such that it generated a wind-blown bubble (e.g. perhaps from a RSG to a Wolf-Rayet star; Weaver et al. 1977; Dwarkadas 2005, 2007). Such SNe as SN 1996cr, or a more luminous SN 1987A, would be missed by traditional RSNe searches because they took so long to develop; most RSNe programs have typically only observed SNe up to 1 yr before giving up. **Could such "late-blooming" RSNe be more common than we think?**

While the best-studied RSNe cannot match the dramatic changes seen in SN 1996cr, many do in fact show evidence for moderate-scale variations in their CSMs. One of the most prominent in this regard is SN 1986J, a type IIn SN at ∼9.5 Mpc (van Gorkom et al. 1986). Radio observations by Weiler et al. (1990) measured a mass-loss rate of $2.4 \times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ and peak 6 cm flux density of ∼155 mJy for SN 1986J, making it roughly twice as intrinsically luminous as SN 1996cr. Early data for SN 1986J are not well fit by a standard model, and hint at a potentially large density

Table 1: Radio and X-ray Constraints for SN1996aq and SN2004dk

SN	Date (UT)	1.2 cm mJy	2 cm mJy	3.5 cm mJy	6 cm mJy	20 cm mJy	0.5–10.0 keV 10^{-15} erg s^{-1} cm^{-2}
1996aq	1996 Oct 05	—	—	<0.36	<0.62	—	—
	1997 Jan 23	—	—	<0.24	<0.30	—	—
	1998 Feb 09	—	—	<0.17	—	—	—
	2003 Oct 17	—	—	<0.14	—	—	—
	2007 Mar–Jul	—	—	—	—	—	<5.7
	2009 Feb 11.50	—	—	—	0.30 ± 0.05	—	—
	2009 Feb 23.35	—	—	0.13 ± 0.03	0.30 ± 0.03	0.88 ± 0.08	—
2004dk	1990 Jul 30	—	—	—	<0.22	—	—
	2004 Aug 12	—	—	—	—	—	2.0 ± 0.5
	2004 Oct 4.05	<0.70	<0.66	0.41 ± 0.07	0.53 ± 0.08	—	—
	2004 Oct 17.93	—	<0.66	0.29 ± 0.06	0.47 ± 0.06	—	—
	2005 Feb 12.30	—	—	<0.18	<0.70	—	—
	2006 Jan 21–24	—	—	—	—	—	<56
	2009 Feb 12.58	—	—	—	0.22 ± 0.06	—	—
	2009 Feb 24.51	—	—	0.19 ± 0.03	0.21 ± 0.03	0.39 ± 0.08	—

Limits are 3σ.

enhancement between days 600–1000, as well as several smaller enhancements later on (Fig. 1). Likewise, SN 2001em, initially classified as a type Ic, was only detected in the radio ~2 years later (Stockdale et al. 2003) and has since undergone an unusual optical evolution into a type IIn (Fig. 1). Chugai & Chevalier (2006) suggest that the blast-wave from SN 200lem is currently overrunning a dense circumstellar shell, which they postulate was likely ejected a few 10^3 years prior to explosion with a mass loss rate $\sim (2\text{–}10) \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. Finally, we note that SN 1978K, a third nearby type IIn SN, currently has a strong, flat X-ray light curve and arguably exhibited an early, rising X-ray light curve (Schlegel et al. 2004), evocative of SN 1996cr. Unfortunately, SN 1978K has no early radio constraints, although it has recently shown 20–30% fluctuations on an otherwise standard late-time decline (Smith et al. 2007b).

A Systematic Survey for More SN 1996cr's Yields SNe 1996aq and 2004dk

So how common are strong evolutionary changes in massive stars, just prior to explosion? Three key past studies have weighed in on this issue with sufficient sensitivity. Weiler et al. (1989), van Dyk et al (1996) and Soderberg et al. (2006) studied the late-time emission from samples of general SNe, type IIn, and type Ib/c SNe, respectively, all of which were closer than ≈120 Mpc with ages of 1–30 yrs. Only one type Ib/c (SN 2001em) was detected above $f_{3cm}<0.2$ mJy (Stockdale et al. 2004), implying that objects like SN 1996cr are quite rare. A fourth study recently completed by our team, however, re-observed 40 nearby core-collapse SNe at 4–20 yrs, many of which had been the subjects of previous unsuccessful early-time radio searches. Surprisingly, our survey yielded two new detections from optically identified type Ib/Ic SNe SNe 2004dk and 1996aq (both at ≈27 Mpc; NED); see Table 1 for full radio and X-ray constraints. Further study SN 1996aq and 2004dk will place 1996cr-like objects on a sounder statistical footing. We critically require VLA follow-up observations to constrain their CSM histories.

RSNe Within the Broader Picture

SNe such as SNe 1996cr, 1996aq, 1986J, 2001em, and 2004dk provide valuable insight into the very late evolutionary stages of the most massive stars, a period which has traditionally been difficult to study by other means. There is still much debate, for instance, over the number, duration, and sequence of various phases of stellar evolution (e.g., Lamers et al. 1991; Stothers & Chin 1996; Maeder & Meynet 2000). For these particular sources, their radio emission should stem from an interaction with a distant and dense CSM, possibly established by the progenitor star the last

0.1% of the progenitor star's existence in some combination of a RSG wind and a Wolf-Rayet wind (Dwarkardas 2005; 2007) or an LBV-ejection (Smith et al. 2007a). Our understanding of the evolution of massive stars has made enough progress over the last two decades, however, to at least provide us with testable (albeit model-dependent) predictions about the mass-loss history of SN progenitors (e.g. Langer et al. 1994, Heger et al. 2003). The ultimate test of these models is the radio probing of the CSM structure by objects like SNe 1996aq, 1996cr, and 2004dk.

The key to interpreting the RSNe observations in the framework of stellar evolution is the comparison with hydrodynamical simulations of the CSM formation and its interaction with the blastwave. As a first step, it should be possible to constrain portions of parameter space by comparing the results of simple shock fits (like those shown in Fig. 1) to analytical calculations of the CSM structure (Weaver et al. 1977; Koo & McKee 1992a, b) or existing 1D and 2D hydro models (Dwarkadas 2005, 2007). Eventually with enough effort, specific models tailored to these exceptional RSNe should reveal the details of the mass-loss processes in their progenitors. In observations such as these, it is crucial that the data acquisition be followed by a realistic and coordinated effort to interpret the data, firmly anchored by theoretical models produced in concert with the data analysis. Our assembled team has the necessary experience to provide this. Finally, it is important that we reevaluate the basic RSNe observing strategy that has been employed for the past 20 years, in light of the many new radio instruments which will come online in the next decade (eVLA, ALMA, LOFAR, ASKAP, etc.).

Technical Feasibility

SNe 1996cr and 2001em represent two extremes in our expectations. After a long epoch of a constant non-thermal radio emission, SN 1996cr is now beginning to decline at $\gtrsim$1–2% per month. SN 2001em has been evolving more akin to traditional RSNe, declining in time with a shallow log-log linear slope ($\beta \sim -0.5$, $S_\nu \sim t^\beta$) when compared to typical core collapse SNe with log-log linear slope typically ($-0.5 < \beta < -1.5$; Fig. 1).

As such, we request four sets of measurements for each SN to establish a baseline for their radio evolution, with each epoch composed of three one hour observations at 3.5 cm, 6 cm, and 20 cm. Such exposures will reach limits of ~0.01–0.03 mJy/beam, which are necessary to detect our sources even if they are declining. This is the same strategy for our confirmation observations made with the VLA in late February. The first two epochs would be one month apart, scheduled during March and April in the current B configuration. Assuming each source is not rapidly varying, we would extend the monitoring to a bimonthly cadence as the VLA transitions into the C config. with observations in late May/June and again in August. If either source does show more rapid signs of variation, we would appreciate some latitude in the scheduling the latter two observations to properly sample a more rapid evolution of the radio emission. We will use these observations to prepare a long-term monitoring strategy to begin in the next A config.; note that D config. will be severely compromised by diffuse host galaxy emission at ≈1–2 mJy/beam at long wavelengths.

It is important to monitor the spectral evolution of these non-thermal sources to determine the source of the radio emission, either from the SN shock or contamination from a newly formed compact object. A regular cadence for an "ordinary" RSN is 8–12 months at late times, but observations of SN 1996cr indicate more frequent monitoring roughly proportional to the expected ~1 month light-crossing time are required to chart an abrupt changes in evolution. Weiler et al. (2007) observed an abrupt drop in the radio emission of SN 1993J, which was interpreted as a transition in the mass-loss rate of the SN progenitor prior to explosion. With so few late-time RSNe known, it is critical to explore the mass-loss history for each object carefully. We are seeking new, deep *Swift* observations of SNe 1996aq and 2004dk to determine if there is detectable X-ray

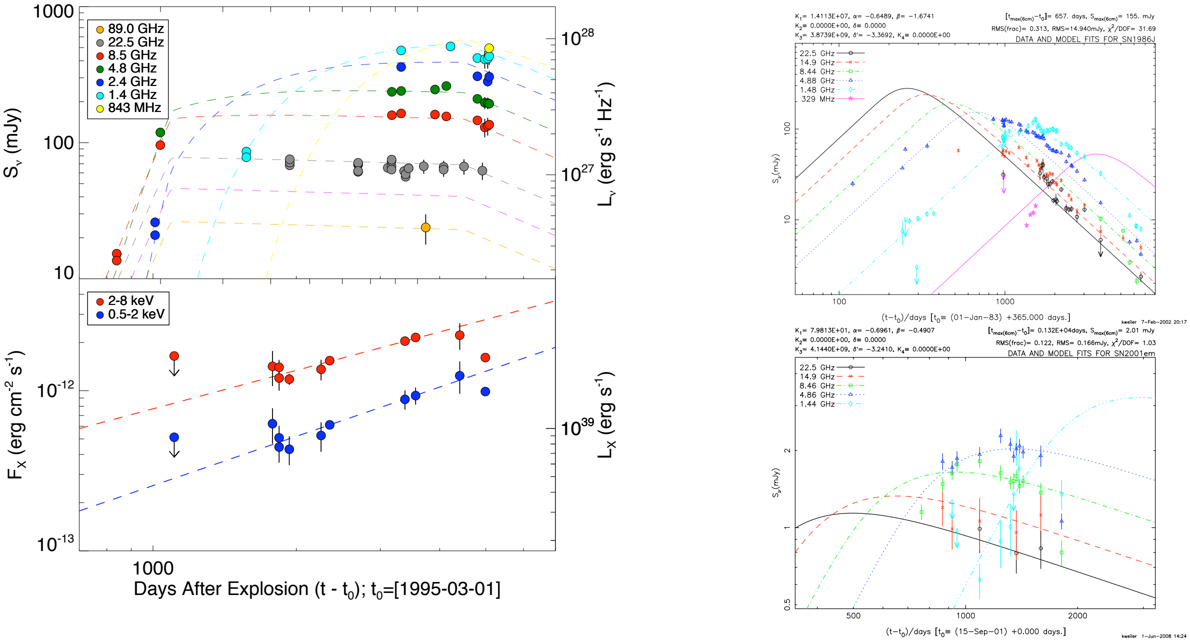

Figure 1: *Left:* Radio and X-ray light curves with best-fit empirical models for SN 1996cr (Bauer et al. 2008). The achromatic rise of SN 1996cr's light curves is atypical, indicating that the blast-wave impacted with a dense wind-swept shell ∼1–2 yrs after explosion, a picture similar to SN 1987A's expansion into its circumstellar ring, albeit 5× more compact and $> 10^3\times$ more luminous. We note the apparent decline that has been observed within the last year. *Right:* Radio light curves with poorly-fit empirical models for SNe 1986J (*above*) and 2001em (*below*). SN 1986J was only coarsely-sampled during its initial years. It is unclear whether the initial data show hints of an early turn-on/rollover around day ∼300, followed by a subsequent jump between days 600–1000 and subsequent small-scale variations, or just a standard rollover at day ∼1000 with small-scale variations throughout the light curve. SN 2001em looks similar to SN 1996cr near peak, but was perhaps too faint to catch the initial rise and may have had a thinner or clumpier shell, since we observe a significant dip in all bands around day ∼1700.

emission from the shock-heated CSM and will plan further X-ray experiments based on future VLA and *Swift* results.

References

Bauer, F. E., et al. 2001, AJ, 122, 182
Bauer, F. 2007, CBET, 879, 1
Bauer, F. E. et al. 2008, ApJ, 688, 1210
Chevalier, R. A. 1982, ApJ, 259, 302
Chevalier, R. A. & Fransson, C. al. 1994, ApJ, 420, 258
Chugai, N. N. & Chevalier, R. A. 2006, ApJ, 641, 1051
Dwarkadas, V. V. 2005, ApJ, 630, 892
Dwarkadas, V. V. 2007, ApJ, 667, 226
Freeman, K. C., et al. 1977, A&A, 55, 445
Heger, A., et al. ApJ, 591, 288
Immler, S., & Lewin, W. 2003, LNP v598: SNe & GRBs, 91
Immler, S., & Kuntz, K. D. 2005, ApJL, 632, 99
Koo, B.-C., & McKee, C. F. 1992a, ApJ, 388, 93
Koo, B.-C., & McKee, C. F. 1992b, ApJ, 388, 103
Lamers, H. J. G. L. M. et al. 1991, ApJ, 368, 538
Maeder, A. & Meynet, G. 2000, ARA&A, 38, 143
Langer, N., et al. 1994, A&A, 290, 819
Panagia, N., & Bono, G. 2001, STScI Symp. v13: SNe & GRBs, 184
Schlegel, E. M., et al. 2004, ApJ, 603, 644
Smith, N., et al. 2007a, ApJ, 666, 1116
Smith, I. A., et al. 2007b, ApJ, 669, 1130
Soderberg, A. M., et al. 2006, ApJ, 638, 930
Stockdale, C. J., et al. 2002, ApJL, 559, L139
Stockdale, C. J., et al. 2004, IAUC, 8282, 2
Stockdale, C. J., et al. 2006, AJ, 131, 889
Stothers, R. B. & Chin, C.-W. 1996, ApJ, 468, 842
van Dyk, S. D., et al. 1996, AJ, 111, 1271
van Gorkom, J., et al. 1986, IAUC, 4248, 1
Weaver, R., et al. 1977, ApJ, 218, 377
Weiler, K.W., et al. 1981, ApJ, 243, L151
Weiler, K.W., et al. 1986, ApJ, 301, 790
Weiler, K. W., et al. 1989, ApJ, 336, 421
Weiler, K. W., et al. 2002, ARA&A, 40, 387
Weiler, K. W., et al. 2007, ApJ, 671, 1959