

LONG-TERM RADIO MONITORING OF SN 1993J

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Received 2007 March 6; accepted 2007 September 7

ABSTRACT

We present our extensive observations of the radio emission from supernova (SN) 1993J, in M81 (NGC 3031), made with the Very Large Array, at 90, 20, 6, 3.6, 2, 1.2, and 0.7 cm, as well as numerous measurements from other telescopes and at other wavelengths. The combined data set constitutes probably the most detailed set of measurements ever established for any SN outside of the Local Group in any wavelength range. The radio emission evolves regularly in both time and frequency, and the usual interpretation in terms of shock interaction with a circumstellar medium (CSM) formed by a pre-supernova stellar wind describes the observations rather well. However, (1) The highest frequency measurements at 85–110 GHz at early times (<40 days) are not well fitted by the parameterization which describes the centimeter wavelength measurements. (2) At midcentimeter wavelengths there is often deviation from the fitted radio light curves. (3) At a time ~ 3100 days after shock breakout, the decline rate of the radio emission steepens from $(t^{+\beta}) \beta \sim -0.7$ to -2.7 without change in the spectral index ($\nu^{+\alpha}$; $\alpha \sim -0.81$); however, this decline is best described not as a power-law, but as an exponential decay with an e -folding time of ~ 1100 days. (4) The best overall fit to all of the data is a model including both nonthermal synchrotron self-absorption (SSA) and thermal free-free absorbing (FFA) components at early times, evolving to a constant spectral index, optically thin decline rate until the break. (5) The radio and X-ray light curves display quite similar behavior and both suggest a sudden increase in the supernova progenitor mass-loss rate occurred at ~ 8000 yr prior to shock breakout.

Subject headings: galaxies: individual (NGC 3031, M81) — radio continuum: stars — stars: mass loss — supernovae: general — supernovae: individual (SN 1993J)

1. INTRODUCTION

SN 1993J [R.A. (J2000.0) = $9^{\text{h}}55^{\text{m}}24.7740^{\text{s}} \pm 0.0006^{\text{s}}$, decl. (J2000.0) = $+69^{\circ}01'13.700'' \pm 0.003''$; Marcaide et al. 1993a] in M81 (NGC 3031) was discovered at magnitude $V \sim 11.8'$ mag on 1993 March 28.91 (Ripero et al. 1993) and by March 30, at maximum optical magnitude $V = 10.7'$ mag, had become the brightest supernova (SN) in the northern hemisphere since SN 1954A. Hydrogen was soon identified in its optical spectrum, classifying it as a Type II SN (SNII; see, e.g., Gomez 1993; Andriolat et al. 1993; Filippenko et al. 1993b).

From the outset, SN 1993J displayed unusual characteristics for a SNII. The visual light curve was markedly different from

both the SNIIL (linear) and SNIIP (plateau) subtypes in that it exhibited a second maximum ~ 17 days after the first one (van Driel et al. 1993). Its unusual light curve and spectrum were quickly interpreted by Podsiadlowski et al. (1993), Nomoto et al. (1993), and Swartz et al. (1993) as implying a red supergiant progenitor with a thin hydrogen envelope which would spectrally evolve from resembling a SNII to resembling a SNIb, thereby suggesting a SNIb classification for SN 1993J. Continuing observations of visual spectra by Filippenko et al. (1993a) confirmed this transition.

Due to its proximity (3.63 ± 0.34 Mpc; Freedman et al. 1994) and the fact that SNeII are expected to be strong radio emitters (Weiler et al. 1989, Sramek et al. (1993) made very early attempts with the Very Large Array (VLA)⁴ to detect the SN. After establishing upper limits at 3.6 and 20 cm on UT 1993 March 31.07

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⁴ The VLA telescope of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

TABLE 1
FLUX DENSITY MEASUREMENTS FOR SN 1993J

Observation Date	Days from Reference Date	Telescope/VLA Configuration ^a	$S(20 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(6 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(3.6 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(2 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(1.2 \text{ cm}) \pm \text{Error}^b$ (mJy)
1993 Mar 28	=0.00	...	...	...	...	...	...
1993 Mar 30	2.90	Camb	...	...	...	<0.6	...
1993 Mar 31	3.10	VLA B	...	...	<0.090	...	...
	3.10	VLA B	<0.180	...	...	...	...
1993 Apr 01.....	4.91	Camb	...	...	...	<2.4	...
1993 Apr 02.....	5.29	VLA B	...	...	...	<0.348	...
	5.30	VLA B	...	...	<0.120	...	...
	5.34	VLA B	...	...	...	...	0.740 ± 0.195
	5.77	Camb	...	...	...	<0.3	...
1993 Apr 03.....	6.91	Camb	...	...	...	<0.6	...
1993 Apr 04.....	7.72	Camb	...	...	...	1.1 ± 0.11	...
1993 Apr 05.....	8.83	Camb	...	...	...	3.8 ± 0.38	...
1993 Apr 06.....	9.88	Camb	...	...	...	5.0 ± 0.5	...
1993 Apr 07.....	10.68	Camb	...	...	...	5.8 ± 0.58	...
	10.81	Camb	...	...	...	6.4 ± 0.64	...
	10.93	Camb	...	...	...	6.9 ± 0.69	...
1993 Apr 08.....	11.08	Camb	...	...	...	7.9 ± 0.79	...
	11.37	VLA B	...	...	0.750 ± 0.063	8.040 ± 0.629	18.940 ± 1.905
	11.69	Camb	...	...	...	8.0 ± 0.8	...
1993 Apr 09.....	12.08	Camb	...	...	...	8.7 ± 0.87	...
	12.33	VLA B	...	...	...	10.569 ± 0.828	22.487 ± 2.261
	12.99	Camb	...	...	...	11.1 ± 1.11	...
1993 Apr 10.....	13.04	VLA B	...	...	1.330 ± 0.097	...	25.753 ± 2.576
	13.46	VLA B	...	...	...	11.586 ± 0.934	25.550 ± 2.578
	13.73	Camb	...	...	...	11.1 ± 1.11	...
1993 Apr 11.....	14.25	VLA B	<0.180	...	1.890 ± 0.107	14.610 ± 1.122	28.640 ± 2.875
	14.88	Camb	...	...	...	12.4 ± 1.24	...
1993 Apr 12.....	15.73	Camb	...	...	...	16.0 ± 1.60	...
1993 Apr 13.....	16.02	VLA B	...	...	2.980 ± 0.169	...	31.600 ± 5.336
	16.53	VLA B	...	0.327 ± 0.080	3.140 ± 0.172	17.680 ± 1.428	33.200 ± 3.491
	16.85	Camb	...	...	...	16.4 ± 1.64	...
1993 Apr 14.....	17.07	VLA B	...	0.280 ± 0.052	3.590 ± 0.189	20.140 ± 1.525	35.250 ± 3.540
	17.65	Camb	...	...	...	19.4 ± 1.94	...
1993 Apr 16.....	19.02	VLA B	...	0.360 ± 0.063	...	...	39.860 ± 4.078
	19.06	Camb	...	...	...	24.1 ± 2.41	...
1993 Apr 17.....	20.07	Camb	...	...	...	26.0 ± 2.60	...
1993 Apr 18.....	21.73	Camb	...	...	...	29.3 ± 2.93	...
1993 Apr 19.....	22.25	VLA B	...	0.880 ± 0.074	7.860 ± 0.396	31.440 ± 2.372	39.140 ± 3.933
	22.62	Camb	...	...	...	31.6 ± 3.16	...
	22.97	VLA B	...	0.870 ± 0.066	8.990 ± 0.453	34.910 ± 2.638	...
1993 Apr 20.....	23.83	Camb	...	...	...	35.8 ± 3.58	...
1993 Apr 21.....	24.51	VLA B	...	1.290 ± 0.095	9.710 ± 0.491	34.770 ± 2.631	38.420 ± 3.892
	24.78	Camb	...	...	...	36.1 ± 3.61	...
1993 Apr 22.....	25.48	VLA B	...	1.700 ± 0.110	11.770 ± 0.592	37.350 ± 2.822	39.940 ± 4.029
1993 Apr 23.....	26.67	Camb	...	...	...	39.7 ± 3.97	...
	26.88	VLA B	<0.330	1.930 ± 0.113	14.610 ± 0.735	37.920 ± 2.865	40.020 ± 4.150
1993 Apr 24.....	27.71	Camb	...	...	...	42.2 ± 4.22	...
	27.87	VLA B	...	2.050 ± 0.130	15.170 ± 0.763	...	48.810 ± 5.062
1993 Apr 25.....	28.71	Camb	...	...	...	46.0 ± 4.60	...
	28.99	VLA B	...	2.640 ± 0.149	16.710 ± 0.839	...	45.450 ± 4.626
1993 Apr 26.....	29.70	Camb	...	...	...	46.0 ± 4.60	...
	29.85	VLA B	...	3.260 ± 0.182	18.580 ± 0.932	47.200 ± 3.594	...
1993 Apr 27.....	30.84	VLA B	...	3.180 ± 0.178	19.730 ± 0.991	...	51.260 ± 5.272
1993 Apr 28.....	31.05	Camb	...	...	...	49.8 ± 4.98	...
	31.52	VLA B	...	3.630 ± 0.195	20.550 ± 1.031	51.450 ± 3.883	55.380 ± 5.598
	31.63	Camb	...	...	...	50.4 ± 5.04	...
1993 Apr 29.....	32.50	VLA B	...	4.110 ± 0.238	21.930 ± 1.103	...	45.010 ± 4.528
	32.61	Camb	...	...	...	48.1 ± 4.81	...
1993 Apr 30.....	33.71	Camb	...	...	...	56.6 ± 5.66	...
1993 May 01.....	34.37	VLA B	...	5.820 ± 0.299	26.000 ± 1.302	...	55.780 ± 5.639
	34.93	VLA B	<0.660	6.290 ± 0.327	29.630 ± 1.484	61.090 ± 4.585	52.810 ± 5.288
1993 May 02.....	35.63	Camb	...	...	...	60.4 ± 6.04	...
	35.71	VLA B	...	6.000 ± 0.310	30.310 ± 1.518	55.950 ± 4.205	...
1993 May 03.....	36.66	Camb	...	...	...	60.4 ± 6.04	...

TABLE 1—Continued

Observation Date	Days from Reference Date	Telescope/VLA Configuration ^a	$S(20\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(6\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(3.6\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(2\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(1.2\text{ cm}) \pm \text{Error}^b$ (mJy)
1993 May 04.....	37.27	VLA B	...	8.060 ± 0.406	33.320 ± 1.668	67.320 ± 5.066	62.900 ± 6.327
	37.78	Camb	...	...	...	65.4 ± 6.54	...
1993 May 05.....	38.79	Camb	...	...	...	63.1 ± 6.31	...
1993 May 06.....	39.79	Camb	...	...	...	65.7 ± 6.57	...
1993 May 07.....	40.11	VLA B	...	10.510 ± 0.529	37.070 ± 1.854	67.440 ± 5.074	53.640 ± 5.396
	40.79	Camb	...	...	...	65.7 ± 6.57	...
1993 May 09.....	42.78	Camb	...	...	...	64.0 ± 6.40	...
1993 May 11.....	44.74	VLA B/C	...	15.550 ± 0.785	52.100 ± 2.611	69.900 ± 5.249	46.700 ± 4.691
1993 May 12.....	45.71	Camb	...	...	...	70.4 ± 7.04	...
1993 May 13.....	46.74	Camb	...	...	...	70.9 ± 7.09	...
1993 May 14.....	47.20	VLA B/C	...	18.170 ± 0.915	59.030 ± 2.960	77.150 ± 5.805	61.070 ± 6.169
	47.73	Camb	...	...	...	73.5 ± 7.35	...
1993 May 16.....	49.70	Camb	...	...	...	71.0 ± 7.10	...
	49.86	VLA B/C	<1.903	22.100 ± 1.110	...	...	...
1993 May 17.....	50.00	VLA ^c	...	...	63.0 ± 3.2	...	...
	50.13	VLA B/C	...	...	61.910 ± 3.099	74.400 ± 5.582	54.610 ± 5.470
	50.69	Camb	...	...	...	70.2 ± 7.02	...
1993 May 19.....	52.76	Camb	...	...	...	71.4 ± 7.14	...
1993 May 20.....	53.17	VLA B/C	<1.045	25.819 ± 1.298	63.900 ± 3.201	72.698 ± 5.474	54.749 ± 5.502
1993 May 21.....	54.68	Camb	...	...	...	72.0 ± 7.20	...
1993 May 22.....	55.65	Camb	...	...	...	72.6 ± 7.26	...
1993 May 23.....	56.65	Camb	...	...	...	73.7 ± 7.37	...
1993 May 24.....	57.68	Camb	...	...	...	76.7 ± 7.67	...
1993 May 25.....	58.67	Camb	...	...	...	71.2 ± 7.12	...
	58.99	VLA B/C	<0.613	34.560 ± 1.734	77.920 ± 3.898	79.480 ± 5.979	67.480 ± 6.810
1993 May 26.....	59.66	Camb	...	...	...	74.1 ± 7.41	...
1993 May 30.....	63.04	VLA B/C	...	40.000 ± 2.007	81.500 ± 4.080	76.2 ± 5.726	53.000 ± 5.342
1993 Jun 01.....	65.72	Camb	...	...	...	77.2 ± 7.72	...
1993 Jun 02.....	66.62	Camb	...	...	...	77.9 ± 7.79	...
1993 Jun 03.....	67.57	Camb	...	...	...	75.9 ± 7.59	...
1993 Jun 04.....	68.06	VLA B/C	<1.035	43.970 ± 2.220	...	65.593 ± 4.960	47.200 ± 4.759
1993 Jun 06.....	70.71	Camb	...	...	...	76.9 ± 7.69	...
1993 Jun 07.....	71.85	Camb	...	...	...	76.4 ± 7.64	...
1993 Jun 09.....	73.71	Camb	...	...	...	78.2 ± 7.82	...
1993 Jun 10.....	74.70	Camb	...	...	...	78.0 ± 7.80	...
1993 Jun 11.....	75.06	VLA C	0.650 ± 0.103	56.330 ± 2.820	90.740 ± 4.538	77.270 ± 5.808	51.140 ± 5.157
1993 Jun 13.....	77.69	Camb	...	...	...	72.9 ± 7.29	...
1993 Jun 18.....	82.92	VLA C	1.220 ± 0.141	70.740 ± 3.572	108.980 ± 5.472	74.920 ± 5.641	...
1993 Jun 20.....	84.59	Camb	...	...	...	67.9 ± 6.79	...
1993 Jun 21.....	85.57	Camb	...	...	...	70.9 ± 7.09	...
1993 Jun 22.....	86.60	Camb	...	...	...	71.3 ± 7.13	...
1993 Jun 23.....	87.46	Camb	...	...	...	72.0 ± 7.20	...
1993 Jun 24.....	88.77	Camb	...	...	...	72.2 ± 7.22	...
1993 Jun 25.....	89.75	VLA C	2.850 ± 0.314	79.780 ± 4.018	101.370 ± 5.094	75.860 ± 5.695	51.820 ± 5.212
1993 Jul 01.....	95.22	VLA C	2.940 ± 0.330	87.200 ± 4.379	102.730 ± 5.138	73.660 ± 5.539	44.850 ± 4.552
	95.64	Camb	...	...	...	75.0 ± 7.50	...
1993 Jul 07.....	101.82	Camb	...	...	...	69.1 ± 6.91	...
1993 Jul 08.....	102.66	Camb	...	...	...	70.0 ± 7.00	...
	102.76	VLA C	4.090 ± 0.436	102.670 ± 5.142	129.360 ± 6.472	...	...
1993 Jul 13.....	107.77	VLA C	6.840 ± 0.694	111.420 ± 5.583	134.220 ± 6.716	89.190 ± 6.718	...
1993 Jul 19.....	113.02	VLA C	6.520 ± 0.657	104.370 ± 5.223	108.630 ± 5.434	72.960 ± 5.488	47.630 ± 4.820
1993 Jul 20.....	114.55	Camb	...	...	...	70.9 ± 7.09	...
1993 Jul 30.....	124.38	Camb	...	...	...	64.9 ± 6.49	...
	124.88	VLA C	9.770 ± 0.982	110.540 ± 5.539	103.430 ± 5.179	62.920 ± 4.761	41.680 ± 4.457
1993 Aug 02.....	127.74	Camb	...	...	...	56.7 ± 5.67	...
1993 Aug 04.....	129.75	Camb	...	...	...	56.8 ± 5.68	...
1993 Aug 05.....	130.34	Camb	...	...	...	61.3 ± 6.13	...
1993 Aug 06.....	131.95	VLA C	11.720 ± 1.430	116.930 ± 6.236	115.980 ± 6.075	58.860 ± 4.513	...
1993 Aug 10.....	135.94	VLA C/D	16.747 ± 1.752	112.510 ± 5.660	84.150 ± 4.223	37.856 ± 2.884	19.540 ± 2.223
1993 Aug 12.....	137.93	VLA C/D	17.193 ± 1.964	110.230 ± 5.523	...	42.091 ± 3.219	26.270 ± 2.859
1993 Aug 13.....	138.32	Camb	...	...	...	54.7 ± 5.47	...
1993 Aug 14.....	139.73	Camb	...	...	...	56.2 ± 5.62	...
1993 Aug 16.....	141.72	Camb	...	...	...	56.6 ± 5.66	...
1993 Aug 17.....	142.79	VLA C	15.180 ± 1.583	114.720 ± 5.971	92.280 ± 4.904	...	31.360 ± 3.651
1993 Aug 20.....	145.45	Camb	...	...	...	60.6 ± 6.06	...

TABLE 1—Continued

Observation Date	Days from Reference Date	Telescope/VLA Configuration ^a	$S(20\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(6\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(3.6\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(2\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(1.2\text{ cm}) \pm \text{Error}^b$ (mJy)
1993 Aug 21.....	146.41	Camb	...	...	...	54.8 ± 5.48	...
1993 Aug 22.....	147.71	Camb	...	...	...	57.4 ± 5.74	...
1993 Aug 23.....	148.54	VLA C	15.137 ± 1.576	112.250 ± 5.925	88.740 ± 4.574	59.740 ± 4.502	36.350 ± 3.716
1993 Aug 25.....	150.49	Camb	...	...	...	56.1 ± 5.61	...
1993 Aug 26.....	151.93	VLA C	17.560 ± 1.906	120.120 ± 6.057	102.840 ± 5.334	...	35.540 ± 4.317
1993 Aug 29.....	154.69	Camb	...	...	...	49.7 ± 4.97	...
1993 Aug 31.....	156.78	VLA C/D	...	111.520 ± 5.620	92.185 ± 4.688	47.432 ± 3.618	27.964 ± 2.990
1993 Sep 02.....	158.39	Camb	...	...	...	50.2 ± 5.02	...
1993 Sep 03.....	159.33	Camb	...	...	...	50.6 ± 5.06	...
1993 Sep 05.....	161.35	Camb	...	...	...	47.8 ± 4.78	...
1993 Sep 06.....	162.48	Camb	...	...	...	48.5 ± 4.85	...
1993 Sep 09.....	165.59	Camb	...	...	...	48.3 ± 4.83	...
1993 Sep 11.....	167.91	VLA C/D	22.790 ± 2.751	103.650 ± 5.202	...	...	...
1993 Sep 13.....	169.59	Camb	...	...	...	48.1 ± 4.81	...
1993 Sep 15.....	171.49	Camb	...	...	...	45.1 ± 4.51	...
1993 Sep 18.....	174.33	Camb	...	...	...	43.5 ± 4.35	...
1993 Sep 19.....	174.72	VLA C/D	...	...	78.700 ± 3.984	49.500 ± 3.732	39.100 ± 3.918
	175.00	VLA ^c	...	...	78.7 ± 4.0	49.5 ± 3.0	...
	175.75	VLA C/D	26.870 ± 3.148	103.990 ± 5.211	61.341 ± 3.207	37.243 ± 2.810	22.630 ± 2.302
1993 Sep 25.....	181.34	Camb	...	...	...	44.8 ± 4.48	...
1993 Sep 26.....	182.75	VLA C/D	30.940 ± 3.488	104.930 ± 5.268	70.460 ± 3.594	43.950 ± 3.324	28.000 ± 2.864
1993 Sep 27.....	183.30	Camb	...	...	...	43.4 ± 4.34	...
1993 Sep 29.....	185.62	Camb	...	...	...	42.7 ± 4.27	...
1993 Oct 04.....	190.50	Camb	...	...	...	39.8 ± 3.98	...
	190.66	VLA C/D	28.303 ± 3.098	100.050 ± 5.013	68.947 ± 3.491	39.930 ± 3.006	24.152 ± 2.437
1993 Oct 08.....	194.31	Camb	...	...	...	43.7 ± 4.37	...
1993 Oct 09.....	195.27	Camb	...	...	...	42.7 ± 4.27	...
1993 Oct 16.....	202.26	Camb	...	...	...	44.1 ± 4.41	...
1993 Oct 17.....	203.80	VLA C/D	35.770 ± 3.982	99.880 ± 5.012	65.150 ± 3.791	24.650 ± 2.003	15.970 ± 1.939
1993 Oct 25.....	211.56	Camb	...	...	...	37.9 ± 3.79	...
	211.61	VLA C/D	33.220 ± 3.662	97.260 ± 4.905	...	37.320 ± 2.830	23.640 ± 2.486
1993 Nov 01.....	218.58	VLA D	24.590 ± 2.478	105.560 ± 5.474	67.210 ± 3.471	38.930 ± 2.954	30.360 ± 3.101
1993 Nov 05.....	222.26	Camb	...	...	...	37.8 ± 3.78	...
1993 Nov 06.....	223.00	VLA ^c	61.5 ± 5.8	97.6 ± 4.9	64.7 ± 3.2	39.6 ± 2.0	25.7 ± 3.9
	223.21	Camb	...	...	...	38.4 ± 3.84	...
1993 Nov 10.....	227.23	Camb	...	...	...	39.7 ± 3.97	...
1993 Nov 11.....	228.22	Camb	...	...	...	36.4 ± 3.64	...
1993 Nov 16.....	233.40	Camb	...	...	...	37.1 ± 3.71	...
1993 Nov 19.....	236.58	VLA D	34.510 ± 3.466	97.110 ± 4.924	64.320 ± 3.252	38.610 ± 2.921	25.790 ± 2.643
1993 Nov 20.....	237.17	Camb	...	...	...	35.4 ± 3.54	...
1993 Nov 23.....	240.06	Camb	...	...	...	36.1 ± 3.61	...
1993 Nov 28.....	245.56	VLA D	47.020 ± 5.230	94.940 ± 4.758	61.470 ± 3.083	36.840 ± 2.813	26.140 ± 2.701
1993 Nov 29.....	246.45	Camb	...	...	...	32.2 ± 3.22	...
1993 Dec 01.....	248.26	Camb	...	...	...	35.5 ± 3.55	...
1993 Dec 02.....	249.14	Camb	...	...	...	32.7 ± 3.27	...
1993 Dec 03.....	250.14	Camb	...	...	...	32.6 ± 3.26	...
1993 Dec 05.....	252.14	Camb	...	...	...	33.5 ± 3.35	...
	252.58	VLA D	59.100 ± 6.118	91.660 ± 4.674	59.630 ± 2.994	32.290 ± 2.440	23.720 ± 2.468
1993 Dec 06.....	253.13	Camb	...	...	...	32.6 ± 3.26	...
1993 Dec 17.....	264.00	VLA ^c	86.3 ± 4.7	93.3 ± 4.7	57.1 ± 2.9	33.2 ± 1.7	27.4 ± 2.0
1993 Dec 19.....	266.58	VLA D	63.110 ± 6.642	89.160 ± 4.517	56.880 ± 2.873	34.300 ± 2.625	22.260 ± 2.365
1993 Dec 20.....	267.15	Camb	...	...	...	34.0 ± 3.40	...
1993 Dec 22.....	269.10	Camb	...	...	...	32.9 ± 3.29	...
1993 Dec 25.....	272.09	Camb	...	...	...	32.5 ± 3.25	...
1993 Dec 26.....	273.93	Camb	...	...	...	33.3 ± 3.33	...
1993 Dec 27.....	274.56	VLA D	63.590 ± 6.522	87.350 ± 4.396	55.750 ± 3.156	33.280 ± 2.525	23.520 ± 2.472
1993 Dec 28.....	275.93	Camb	...	...	...	34.5 ± 3.45	...
1994 Jan 03.....	281.07	Camb	...	...	...	33.2 ± 3.32	...
1994 Jan 07.....	285.37	VLA D	58.780 ± 5.965	84.470 ± 4.238	55.740 ± 2.817	33.740 ± 2.547	23.080 ± 2.357
1994 Jan 10.....	288.12	Camb	...	...	...	34.0 ± 3.40	...
1994 Jan 13.....	291.51	VLA D	58.900 ± 5.957	84.850 ± 4.267	54.640 ± 2.804	32.480 ± 2.449	23.420 ± 2.373
1994 Jan 27.....	305.30	VLA D	50.400 ± 5.125	80.860 ± 4.052	55.430 ± 2.832	32.260 ± 2.443	22.140 ± 2.302
1994 Jan 28.....	306.00	VLA ^c	...	80.4 ± 4.000	52.2 ± 2.6	29.2 ± 2.9	...
	306.86	Camb	...	...	...	29.9 ± 2.99	...
1994 Feb 07.....	316.82	Camb	...	...	...	30.2 ± 3.02	...

TABLE 1—Continued

Observation Date	Days from Reference Date	Telescope/VLA Configuration ^a	$S(20\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(6\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(3.6\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(2\text{ cm}) \pm \text{Error}^b$ (mJy)	$S(1.2\text{ cm}) \pm \text{Error}^b$ (mJy)
1994 Feb 08.....	317.22	VLA D	60.830 ± 6.472	94.640 ± 4.804	60.240 ± 3.106	31.230 ± 2.395	24.950 ± 2.614
1994 Feb 15.....	324.80	Camb	...	...	...	27.8 ± 2.78	...
1994 Feb 17.....	326.90	Camb	...	...	...	26.6 ± 2.66	...
1994 Feb 18.....	327.30	VLA A	78.700 ± 7.882	79.720 ± 4.031	49.420 ± 2.490	34.350 ± 2.610	17.980 ± 2.057
1994 Feb 19.....	328.96	Camb	...	...	...	26.1 ± 2.61	...
1994 Feb 20.....	329.96	Camb	...	...	...	25.700 ± 2.570	...
1994 Mar 08.....	345.18	Camb	...	...	...	27.4 ± 2.74	...
	345.80	Camb	...	...	...	26.5 ± 2.65	...
1994 Mar 15.....	352.00	VLA ^c	99.1 ± 5.0	71.4 ± 3.6	45.7 ± 2.3	...	...
1994 Mar 20.....	357.36	VLA A	91.217 ± 9.123	74.070 ± 3.762	43.370 ± 2.282	29.717 ± 2.276	15.540 ± 1.929
1994 Mar 22.....	359.00	Camb	...	...	...	28.4 ± 2.84	...
1994 Apr 07.....	375.70	Camb	...	...	...	21.3 ± 2.13	...
1994 Apr 12.....	380.16	VLA A	86.830 ± 8.684	...	...	...	...
1994 Apr 22.....	390.00	VLA ^c	102.7 ± 5.1	...	...	...	...
	390.10	VLA A	...	65.820 ± 3.291	42.210 ± 2.111	...	...
1994 Apr 25.....	393.18	VLA A	87.470 ± 8.772	64.490 ± 3.274	39.820 ± 2.009	17.950 ± 1.447	10.390 ± 1.247
1994 May 14.....	412.57	Camb	...	...	...	21.8 ± 2.18	...
1994 May 26.....	424.16	VLA A/B	96.810 ± 9.707	73.280 ± 3.757	40.290 ± 2.071	26.790 ± 2.061	12.320 ± 1.407
1994 Jun 20.....	449.60	Camb	...	...	...	23.3 ± 2.33	...
1994 Jun 22.....	451.00	VLA ^c	...	59.3 ± 3.0	39.0 ± 2.0	...	...
1994 Jun 23.....	452.98	VLA B	104.520 ± 10.534	53.820 ± 2.919	30.550 ± 1.627	...	7.196 ± 0.896
1994 Sep 01.....	522.69	VLA B	101.940 ± 10.297	57.430 ± 3.041	30.770 ± 1.674	15.710 ± 1.313	9.080 ± 1.442
1994 Oct 13.....	564.64	VLA C	101.290 ± 10.215	51.060 ± 3.135	29.260 ± 2.183	14.440 ± 1.248	9.960 ± 1.622
1994 Oct 31.....	582.00	VLA ^c	...	53.0 ± 2.6	33.0 ± 1.7	...	...
1994 Nov 07.....	589.47	VLA C	112.280 ± 11.291	42.450 ± 2.188	31.480 ± 1.584	...	...
1994 Dec 23.....	635.00	VLA ^c	...	49.0 ± 2.5	31.9 ± 1.6	...	...
1995 Jan 05.....	648.39	VLA C/D	107.010 ± 10.736	45.210 ± 2.764	23.210 ± 1.920	16.220 ± 1.667	15.290 ± 2.638
1995 Feb 12.....	686.00	VLA ^c	120.0 ± 10.0	46.4 ± 2.3	29.2 ± 1.5	...	...
1995 Apr 06.....	739.14	VLA D	118.840 ± 12.205	44.230 ± 2.242	28.200 ± 1.468	9.670 ± 0.864	14.800 ± 1.593
1995 May 11.....	774.00	VLA ^c	...	...	25.6 ± 1.5	...	...
1995 Jun 16.....	810.05	VLA D/A	101.760 ± 10.247	34.960 ± 1.939	16.480 ± 0.877	6.490 ± 0.727	...
1995 Aug 18.....	873.00	VLA ^c	...	37.7 ± 1.9	24.5 ± 1.2	...	...
1995 Oct 06.....	922.69	VLA B	99.910 ± 9.992	35.810 ± 1.965	23.300 ± 1.425	14.300 ± 1.152	9.360 ± 1.086
1995 Dec 19.....	996.00	VLA ^c	...	33.9 ± 1.7	22.1 ± 1.1	...	...
1996 Jan 12.....	1020.00	VLA B/C	84.007 ± 8.415	33.770 ± 1.696	21.062 ± 1.061	13.345 ± 1.030	9.393 ± 0.983
1996 Apr 08.....	1107.00	VLA ^c	...	31.4 ± 1.6	20.2 ± 1.1	...	10.3 ± 0.7
1996 Sep 01.....	1253.00	VLA ^c	...	29.0 ± 1.4	19.1 ± 1.0	...	...
1996 Oct 05.....	1287.57	VLA D/A	70.860 ± 7.132	26.950 ± 1.434	16.310 ± 2.013	10.370 ± 1.672	9.160 ± 2.899
1996 Dec 13.....	1356.00	VLA ^c	70.8 ± 3.7	28.6 ± 1.4	18.7 ± 0.9	...	...
1997 Jan 23.....	1397.21	VLA A/B	71.910 ± 7.297	26.340 ± 1.573	16.750 ± 0.965	10.700 ± 0.915	7.340 ± 0.974
1997 Jun 07.....	1532.00	VLA ^c	...	26.3 ± 1.3	17.2 ± 0.9	...	...
1997 Aug 14.....	1600.99	VLA C/D	61.631 ± 6.176	...	...	...	...
1997 Nov 15.....	1693.00	VLA ^c	60.6 ± 3.3	24.3 ± 1.3	17.2 ± 0.9	14.0 ± 2.6	10.4 ± 1.3
1998 Jun 03.....	1893.00	VLA ^c	...	22.8 ± 1.3	16.0 ± 1.0	...	...
1998 Jun 09.....	1899.85	VLA A/B	52.165 ± 5.356	20.803 ± 1.136	9.632 ± 0.610	4.735 ± 0.435	3.927 ± 0.762
1998 Nov 20.....	2063.00	VLA ^c	48.2 ± 2.8	20.5 ± 1.1	13.9 ± 0.7	12.3 ± 1.0	7.7 ± 0.9
1998 Dec 07.....	2080.00	VLA ^c	47.9 ± 2.8	20.7 ± 1.0	14.3 ± 0.8	12.3 ± 1.3	5.1 ± 1.0
1999 Jun 06.....	2261.00	VLA ^c	39.6 ± 2.1	...	12.8 ± 0.8	8.4 ± 0.8	5.5 ± 1.0
1999 Jun 13.....	2268.96	VLA D/A	37.770 ± 3.799	12.155 ± 0.927	...	...	...
1999 Jun 16.....	2271.00	VLA ^c	...	20.9 ± 1.2	...	...	...
1999 Nov 24.....	2432.00	VLA ^c	38.8 ± 2.3	17.5 ± 0.9	12.5 ± 0.7	...	...
2000 Feb 25.....	2525.00	VLA ^c	...	...	12.0 ± 0.8	9.0 ± 4.0	...
2000 Nov 08.....	2782.00	GMRT ^d	35.1 ± 3.5	...	...	...	...
2000 Nov 13.....	2787.00	VLA ^c	33.8 ± 1.7	...	10.9 ± 0.6	8.3 ± 0.8	...
2000 Dec 16.....	2820.00	GMRT ^d	36.1 ± 3.6	...	...	...	...
2000 Dec 19.....	2823.00	VLA A ^e	30.5 ± 0.4 ^f	...	...	...	...
	2823.00	VLA A ^e	33.7 ± 0.4 ^f	...	...	...	...
2000 Dec 21.....	2825.00	VLA A ^e	...	14.7 ± 0.4	10.4 ± 0.2	6.7 ± 0.1	...
2001 Jan 23.....	2858.00	VLA ^c	...	...	9.7 ± 0.7	...	...
2001 Jun 02.....	2988.00	GMRT ^d	32.7 ± 3.3	...	...	...	...
2001 Jun 10.....	2996.00	VLA ^c	28.8 ± 1.6	14.4 ± 0.7	9.4 ± 0.5	...	...
2001 Oct 15.....	3123.00	GMRT ^d	33.9 ± 3.3	...	...	...	...
2001 Nov 25.....	3164.00	VLA A ^e	24.4 ± 1.5	...	8.4 ± 0.5	...	...
2002 Jan 13.....	3213.38	VLA D/A	31.440 ± 4.278	15.000 ± 0.774	7.880 ± 0.459	4.490 ± 0.479	2.495 ± 0.282
2002 Apr 07.....	3297.00	GMRT ^d	24.6 ± 3.7	...	...	...	...

TABLE 1—Continued

Observation Date	Days from Reference Date	Telescope/VLA Configuration ^a	$S(20 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(6 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(3.6 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(2 \text{ cm}) \pm \text{Error}^b$ (mJy)	$S(1.2 \text{ cm}) \pm \text{Error}^b$ (mJy)
2002 Jun 24	3375.00	GMRT ^d	23.4 ± 2.5	...	...	...	...
2002 Sep 21	3464.00	GMRT ^d	24.2 ± 2.4	...	...	...	...
2003 May 23	3708.93	VLA A	17.377 ± 1.968	6.962 ± 0.429	3.943 ± 0.207	...	1.928 ± 0.237
2003 Jun 13	3729.00	GMRT ^d	20.2 ± 2.1	...	...	...	...
2003 Jun 26	3742.91	VLA A	...	8.349 ± 0.424	...	≤ 0.975	≤ 0.816
2004 Jan 29	3959.47	VLA B/C	14.359 ± 1.469	6.973 ± 0.376	4.513 ± 0.241	2.492 ± 0.215	1.792 ± 0.191
2004 Sep 10	4184.57	VLA A	11.309 ± 1.142	5.526 ± 0.304	3.220 ± 0.257	2.470 ± 0.323	0.967 ± 0.217
2005 Jun 13	4460.90	VLA B/C	8.893 ± 0.894	3.906 ± 0.276	2.562 ± 0.136	0.990 ± 0.152	0.897 ± 0.139
2006 Jan 24	4685.17	VLA D	...	3.880 ± 0.480	1.307 ± 0.371	≤ 1.440	...
2006 Jun 28	4840.05	VLA B	5.303 ± 0.469	...	...	...	...
2006 Sep 25	4929.64	VLA B/C	...	≤ 1.800	≤ 0.957	...	...

^a The “Camb” data are all from the Ryle Telescope (Pooley et al. 1993; Pooley & Green 1993; G. G. Pooley & D. A. Green 1994, private communication). For a discussion of why 10% errors were assumed for the Cambridge data, see § 2.

^b All upper limits are three times the map rms (3σ).

^c Bartel et al. 2002.

^d Chandra et al. 2004.

^e Pérez-Torres et al. 2002.

^f Pérez-Torres et al. 2002 give two measurements of SN 1993J in the 20 cm band, a value of 30.5 ± 0.4 at 1.67 GHz and 33.7 ± 0.4 at 1.34 GHz. We include both measurements here.

(Sramek et al. 1993), radio emission was detected with the VLA on UT 1993 April 02.30, with a flux density of 0.8 ± 0.2 mJy at 1.3 cm (Weiler et al. 1993; see also Van Dyk et al. 1993a, 1993c) and with the Ryle Telescope in Cambridge, UK, on UT 1993 April 5.7 at 2 cm (15.3 GHz) by Pooley et al. (1993). By UT 1993 April 25, the rapidly expanding SN already had a measurable size of 0.25 ± 0.1 milliarcseconds (mas) with Very Long Baseline Interferometry (VLBI) techniques (Marcaide et al. 1993a, 1993b).

High angular resolution VLBI size measurements of the expanding SN were conducted very early by Marcaide et al. (1994) and Bartel et al. (1994) and VLBI monitoring continues to the present at multiple wavelengths (see, e.g., Marcaide et al. 1995a, 1995b, 1997, 2005, 2008; Bartel et al. 2000, 2002; Bietenholz et al. 2001, 2003).

Extensive radio monitoring of the integrated flux density of SN 1993J has been conducted by the VLA at 20 cm (1.4 GHz), 6 cm (4.9 GHz), 3.6 cm (8.4 GHz), 2 cm (14.9 GHz), and 1.2 cm (22.5 GHz) by Van Dyk et al. (1994) and with the Ryle Telescope at 2 cm (15.3 GHz) by Pooley & Green (1993). Additional observations were also conducted at 0.3 cm (85–110 GHz) with the Institut de Radioastronomie Millimétrique (IRAM) telescope (Radford et al. 1993) and at the Caltech Owens Valley Radio Observatory (OVRO; Phillips et al. 1993a, 1993b), and at 0.9 cm with the Effelsberg 100 m telescope of MPIfR (W. Reich 1993, private communication). More recently, Chandra et al. (2001) have conducted observations with the Giant Metrewave Radio Telescope (GMRT) in India at 49 cm (0.6 GHz) and 20 cm (1.4 GHz), and we have added new measurements with the VLA at 90 cm (0.3 GHz) and 0.7 cm (43 GHz).

In this paper we consider the integrated flux density measurements and their physical interpretation.

2. RADIO OBSERVATIONS

Almost a decade and a half has passed since the explosion of SN 1993J, and this is an appropriate interval to consider the extensive set of radio observations which are now available from 90 cm at the longest wavelength to 0.3 cm at the shortest. In addition to previously published VLA results (Van Dyk et al. 1994), we present here almost 200 new VLA observations of SN 1993J at 90, 20, 6, 3.6, 2, 1.2, and 0.7 cm along with all published results which could be found in the literature or have

been provided to us as private communications at 49, 20, 0.9, and 0.3 cm.

All of the available data are presented in Tables 1 and 2 and the data at the best sampled wavelengths of 90, 49, 20, 6, 3.6, 2, 1.2 and 0.3 cm, principally from the VLA and the Cambridge Ryle telescope, along with contributions from the IRAM and OVRO millimeter telescopes and the GMRT, are plotted in and Figures 1 and 2 (see also Figs. 8, 11, and 13). The previously published results from Van Dyk et al. (1994) are also included in Tables 1 and 2 and plotted in the figures for completeness and ease of reference. However, to reduce the size and complexity of Figures 1 and 2 (and also Figs. 8, 11, and 13), the sparse measurements at 32 and 43 GHz are not plotted, even though they were used in the fitting procedure.

The techniques of observation, editing, calibration, and error estimation are described in previous publications on the radio emission from SNe (see, e.g., Weiler, et al. 1986, 1990). The “primary” calibrator was 3C 286, which is assumed to be constant in time with flux densities of 25.84, 14.45, 7.42, 5.20, 3.45, and 2.52 Jy at 90, 20, 6, 3.6, 2, and 1.2 cm, respectively. The “secondary” calibrator⁵ was normally J1048+717,⁶ with a defined position of R.A. (J2000.0) = $10^{\text{h}}48^{\text{m}}27.619917^{\text{s}}$, decl. (J2000.0) = $+71^{\circ}43'35.938280''$. After flux density calibration by 3C 286, it served as the actual gain and phase calibrator for SN 1993J. As expected for secondary calibrators, the flux density of J1048+717 has been varying over the years, as can be seen in Table 3 and Figure 3.

The flux density measurement errors for SN 1993J are a combination of the rms map error, which measures the contribution of small unresolved fluctuations in the background emission and random map fluctuations due to receiver noise, and a basic fractional error ϵ , included to account for the normal inaccuracy of

⁵ Secondary calibrators are chosen to be compact and unresolved by the longest VLA baselines. While compact and serving as good phase references, such objects are usually variable, so that their flux density must be recalibrated regularly from the primary calibrators.

⁶ Several of the early observations at 90 cm used J0834+555, with a position of R.A. (J2000.0) = $08^{\text{h}}34^{\text{m}}54.904117^{\text{s}}$, decl. (J2000.0) = $+55^{\circ}34'21.070980''$ as a secondary calibrator. Also, between 1993 September 11 and 1994 February 8, J0949+662 [R.A. (J2000.0) = $09^{\text{h}}49^{\text{m}}12.2100^{\text{s}}$, decl. (J2000.0) = $+66^{\circ}14'59.321''$] was used as a secondary calibrator at 20 cm.

TABLE 2
OTHER FLUX DENSITY MEASUREMENTS FOR SN 1993J

Observation Date	Days from Reference Date	Telescope	Flux Density \pm Error (mJy)	Frequency (GHz)	Reference
1993 Mar 28	=0.00	...	...	...	...
1993 Apr 09	12.00	IRAM	11.0 ± 3.0	87	1
1993 Apr 11	14.00	IRAM	11.0 ± 3.0	87	1
	14.39	OVRO	18 ± 4	99.4	2
1993 Apr 12	15.00	IRAM	13.5 ± 3.4	87	1
1993 Apr 14	17.39	OVRO	17 ± 4	99.4	2
1993 Apr 15	18.00	IRAM	12.5 ± 3.2	87	1
1993 Apr 16	19.00	IRAM	10.0 ± 2.8	110	1
1993 Apr 21	24.00	IRAM	14.3 ± 3.5	86.2	3
	24.38	OVRO	20 ± 4	99.4	2
1993 Apr 30	33.28	OVRO	17.0 ± 3.5	99.4	3
	33.65	Bonn	59.1 ± 16.8	32	4
1993 May 10	43.00	Bonn	65.8 ± 17.8	32	4
	43.39	OVRO	23.0 ± 4.8	99.4	3
1993 May 11	44.00	Bonn	64.8 ± 17.7	32	4
1993 May 17	50.00	Bonn	62.0 ± 19.5	32	4
1993 May 24	57.00	Bonn	63.9 ± 17.5	32	4
1993 May 25	58.00	Bonn	67.7 ± 24.2	32	4
1993 May 30	63.32	OVRO	19.0 ± 3.8	99.4	3
1993 Jun 02	66.33	OVRO	22.0 ± 4.5	99.4	3
1993 Jun 18	82.23	OVRO	14.0 ± 2.8	99.4	3
1993 Jul 03	97.17	OVRO	16.0 ± 3.2	99.4	3
1993 Sep 12	168.80	OVRO	13 ± 3	99.4	5
1993 Oct 09	195.61	OVRO	8 ± 2	99.4	5
1993 Nov 14	231.67	OVRO	8.0 ± 1.7	99.4	3
1994 Jul 28	487.93	VLA B	<31.662	0.330 ^a	6
1995 Jun 16	810.10	VLA D/A	<27.386	0.330	6
1995 Oct 06	922.74	VLA B	15.500 ± 3.161	0.330 ^a	6
1995 Dec 12	989.49	VLA B	<33.513	0.330 ^a	6
1996 Jan 12	1020.41	VLA B/C	<65.100	0.330 ^a	6
1997 Jan 23	1397.17	VLA A/B	83.700 ± 21.195	0.330	6
1998 Jun 09	1899.89	VLA A/B	63.690 ± 24.758	0.330	6
1999 Nov 24	2432.00	VLA	108 ± 20	0.330	7
2000 Dec 19	2823.00	VLA A	71.1 ± 3.4	0.324	8
2001 Mar 24	2918.00	GMRT	56.1 ± 5.5	0.610	9
2001 Jul 05	3021.00	GMRT	69.2 ± 15.8	0.325	9
2001 Aug 24	3071.00	GMRT	55.8 ± 5.7	0.610	9
2001 Dec 30	3199.00	GMRT	47.8 ± 5.5	0.610	9
2001 Dec 31	3200.00	GMRT	57.8 ± 7.6	0.239	9
2002 Jan 19	3219.49	VLA A	61.501 ± 10.136	0.330	6
2002 Mar 07	3266.00	GMRT	56.2 ± 7.4	0.325	9
2002 Mar 08	3267.00	GMRT	60.9 ± 10.8	0.243	9
	3267.00	GMRT	44.4 ± 4.5	0.610	9
2002 May 19	3339.00	GMRT	44.6 ± 4.5	0.610	9
2002 Aug 16	3428.00	GMRT	61.8 ± 8.8	0.325	9
2002 Sep 16	3459.00	GMRT	56.7 ± 8.7	0.243	9
	3459.00	GMRT	37.5 ± 3.8	0.610	9
2003 May 23	3708.89	VLA A	62.673 ± 13.793	0.330	6
	3708.99	VLA A	<0.667	43.315	6
2003 Jun 17	3733.00	GMRT	58.2 ± 11.8	0.243	9
	3733.00	GMRT	33.4 ± 4.3	0.610	9
2004 Sep 10	4184.55	VLA A	35.500 ± 8.480	0.330	6

^a Calibrator is J1331+305 (3C 286).

REFERENCES.—(1) Radford et al. 1993; (2) Phillips et al. 1993a; (3) S. Radford 1993, private communication; (4) W. Reich 1993, private communication; (5) Phillips & Kulkarni 1993; (6) this paper; (7) Bartel et al. 2002; (8) Pérez-Torres et al. 2001; (9) Chandra et al. (2004).

VLA flux density calibration (see, e.g., Weiler et al. 1986) and possible deviations of the primary calibrator from an absolute flux density scale. The final errors (σ_f) given for the measurements of SN 1993J are taken as

$$\sigma_f^2 = (\epsilon S_0)^2 + \sigma_0^2, \quad (1)$$

where S_0 is the measured flux density, σ_0 is the map rms for each observation, and $\epsilon = 0.15$ for 90 cm, 0.10 for 20 cm, 0.05 for 6 and 3.6 cm, 0.075 for 2 cm, and 0.10 for 1.2 cm. All upper limits are listed as three sigma (3σ).

The appropriate errors to use for the Cambridge measurements at 2 cm are difficult to determine. The authors (Pooley & Green 1993) mention that the variable nucleus of M81 is not fully

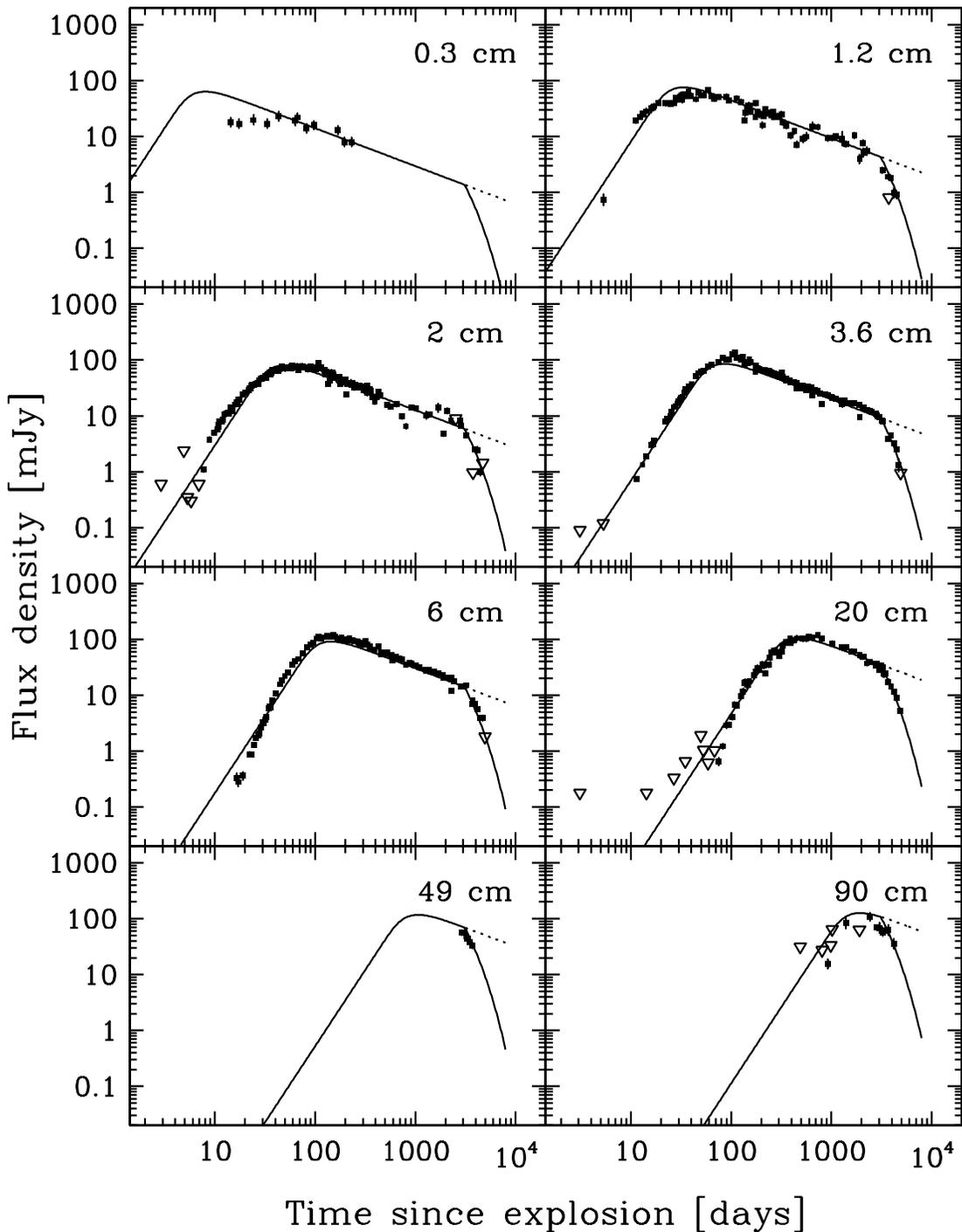


FIG. 1.—Radio light curves for SN 1993J, plotted from left to right and top to bottom at 0.3, 1.2, 2, 3.6, 6, 20, 49, and 90 cm. The solid lines represent the best-fit “pure” synchrotron self-absorption (SSA) model as described in the text with the parameters listed in Table 4, col. (2), and an exponential flux density decline after day 3100 with an e -folding time of 1100 days. The extrapolation of the best-fit model curves without the exponential roll-off is shown as the dotted lines. Upper limits (3σ) are shown as open inverted triangles.

resolved from SN 1993J, and that their calibrator B0954+658 is clearly variable. However, they have done their best to remove such effects and estimate that 5% “is a good estimate of the uncertainty in the observations.” Because of our knowledge of the uncertainties of observations with the VLA at 2 cm wavelength, and our decision to use a standard minimum error of 7.5% in equation (1) at that wavelength, we have chosen to assign a 10% error to all Cambridge data to additionally account for possible systematic effects between the two telescopes and the two different secondary calibrators. Such a value may well be too conservative

but because of the large number of multifrequency points in the data set, the assumption of possibly too large errors for the Cambridge data does not affect any of our fits or conclusions.

3. RADIO SUPERNOVA MODELS

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 turn-on first at shorter wavelengths and later at longer wavelengths; (3) a power-law decline of the flux density with time at

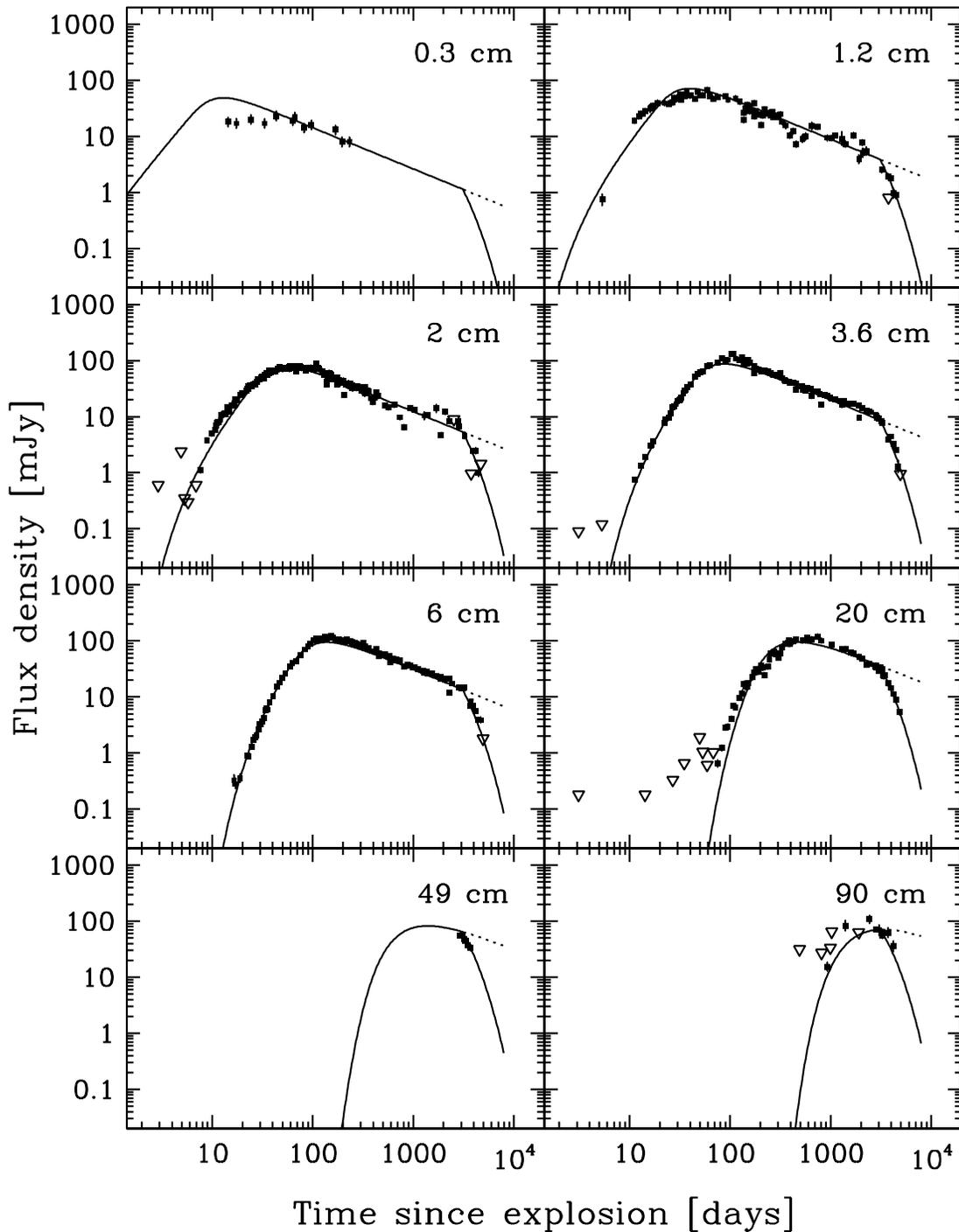


FIG. 2.—Radio light curves for SN 1993J, plotted from left to right and top to bottom at 0.3, 1.2, 2, 3.6, 6, 20, 49, and 90 cm. The solid lines represent the best-fit “pure” thermal, free-free absorption (FFA) model as described in the text with the parameters listed in Table 4, col. (3), and an exponential flux density decline after day 3100 with an e -folding time of 1100 days. The extrapolation of the best-fit model curves without the exponential roll-off is shown as the dotted lines. Upper limits (3σ) are shown as open inverted triangles.

each wavelength after the source becomes optically thin at that wavelength; and (4) a final, asymptotic approach of spectral index α ($S \propto \nu^{+\alpha}$) to an optically thin, nonthermal, constant negative value (Weiler et al. 1986, 1990).

Chevalier (1982a, 1982b) proposed that the relativistic electrons and enhanced magnetic field necessary for synchrotron emission arise from the SN blast wave interacting with a relatively high density CSM which has been ionized and heated by the initial UV/X-ray flash. This CSM is presumed to have been established by a constant mass-loss (\dot{M}) rate, constant velocity (w_{wind}) wind

[i.e., $\rho \propto \dot{M}/(w_{\text{wind}} r^2)$] from a massive stellar progenitor or a companion. This ionized CSM is the source of some or all of the initial free-free absorption (FFA), although more recently Chevalier (1998) has proposed that synchrotron self-absorption (SSA) may play a role at some times and in some objects.

A rapid rise in the observed radio flux density results from a decrease in these absorption processes as the radio emitting region expands and the absorption processes, either internal or along the line of sight, decrease. Weiler et al. (1990) have suggested that this CSM can be “clumpy” or “filamentary,” leading to a slower radio

TABLE 3
FLUX DENSITY MEASUREMENTS FOR THE VLA SECONDARY CALIBRATOR J1048+717

Observation Date	Days from Reference Date	Telescope/VLA Configuration	S(20 cm) (mJy)	S(6 cm) (mJy)	S(3.6 cm) (mJy)	S(2 cm) (mJy)	S(1.2 cm) (mJy)
1993 Mar 31	3.10	VLA B	...	...	0.566	...	...
	3.10	VLA B	0.754	...	...	...	...
1993 Apr 02	5.29	VLA B	...	...	...	0.577	...
	5.30	VLA B	...	...	0.583	...	...
	5.34	VLA B	...	...	...	...	0.596
1993 Apr 08	11.37	VLA B	...	...	0.582	0.583	0.611
1993 Apr 09	12.33	VLA B	...	...	...	0.591 ^a	0.616 ^a
1993 Apr 10	13.04	VLA B	...	...	0.585 ^a	...	0.619 ^a
	13.46	VLA B	...	...	...	0.602 ^a	0.621 ^a
1993 Apr 11	14.25	VLA B	0.715	...	0.588	0.609	0.624
1993 Apr 13	16.02	VLA B	...	...	0.581 ^a	...	0.613 ^a
	16.53	VLA B	...	0.601 ^a	0.581 ^a	0.593 ^a	0.613 ^a
1993 Apr 14	17.07	VLA B	...	0.599	0.574	0.577	0.602
1993 Apr 16	19.02	VLA B	...	0.598 ^a	...	...	0.596 ^a
1993 Apr 19	22.25	VLA B	...	0.597	0.563	0.577	0.591
	22.97	VLA B	...	0.593 ^a	0.565 ^a	0.568 ^a	...
1993 Apr 21	24.51	VLA B	...	0.593 ^a	0.565 ^a	0.568 ^a	0.563 ^a
1993 Apr 22	25.48	VLA B	...	0.589	0.567	0.559	0.535
1993 Apr 23	26.88	VLA B	0.710 ^a	0.589 ^a	0.566 ^a	0.569 ^a	0.570 ^a
1993 Apr 24	27.87	VLA B	...	0.589 ^a	0.566 ^a	...	0.570 ^a
1993 Apr 25	28.99	VLA B	...	0.589 ^a	0.566 ^a	...	0.570 ^a
1993 Apr 26	29.85	VLA B	...	0.589 ^a	0.566 ^a	0.569 ^a	...
1993 Apr 27	30.84	VLA B	...	0.589 ^a	0.566 ^a	...	0.570 ^a
1993 Apr 28	31.52	VLA B	...	0.589 ^a	0.566 ^a	0.569 ^a	0.570 ^a
1993 Apr 29	32.50	VLA B	...	0.589 ^a	0.566 ^a	...	0.570 ^a
1993 May 01	34.37	VLA B	...	0.589	0.564	...	0.604
	34.93	VLA B	0.692	0.589 ^a	0.565 ^a	0.573 ^a	0.596 ^a
1993 May 02	35.71	VLA B	...	0.590 ^a	0.565 ^a	0.573 ^a	...
1993 May 04	37.27	VLA B	...	0.591	0.566	0.567	0.587
1993 May 07	40.11	VLA B	...	0.595	0.574	0.582	0.535
1993 May 11	44.74	VLA B/C	...	0.595	0.573	0.582	0.535
1993 May 14	47.20	VLA B/C	...	0.586	0.577	0.599	0.566
1993 May 16	49.86	VLA B/C	0.754 ^a	0.595	...	...	...
1993 May 17	50.13	VLA B/C	...	...	0.579	0.604	0.618
1993 May 20	53.17	VLA B/C	0.754 ^a	0.595 ^a	0.585 ^a	0.613 ^a	0.688 ^a
1993 May 25	58.99	VLA B/C	0.637	0.604	0.596	0.627	0.734
1993 May 30	63.04	VLA B/C	...	0.595	0.576	0.581	0.596
1993 Jun 04	68.06	VLA B/C	0.711	0.594	...	0.566	0.604
1993 Jun 11	75.06	VLA C	0.754	0.610	0.593	0.615	0.622
1993 Jun 18	82.92	VLA C	...	0.597	...	0.596 ^a	...
1993 Jun 25	89.75	VLA C	0.747 ^a	0.603 ^a	0.582 ^a	0.596 ^a	0.580 ^a
1993 Jul 01	95.22	VLA C	0.740	0.597	0.571	0.578	0.539
1993 Jul 08	102.76	VLA C	0.737 ^a	0.629 ^a	0.615 ^a	...	...
1993 Jul 13	107.77	VLA C	0.734	0.662	0.659	0.600	...
1993 Jul 19	113.02	VLA C	0.739	0.614	0.592	0.611	0.603
1993 Jul 30	124.88	VLA C	0.765	0.601	0.589	0.605	0.623
1993 Aug 06	131.95	VLA C	0.744	0.568	0.677	0.506	...
1993 Aug 10	135.94	VLA C/D	0.818 ^a	0.607 ^a	0.568 ^a	0.608 ^a	0.618 ^a
1993 Aug 12	137.93	VLA C/D	0.828 ^a	0.608 ^a	...	0.609 ^a	0.616 ^a
1993 Aug 17	142.79	VLA C	0.758	0.636	0.628	...	0.664
1993 Aug 23	148.54	VLA C	0.760	0.618	0.602	0.620	0.568
1993 Aug 26	151.93	VLA C	0.811	0.650	0.684	...	0.914
1993 Aug 31	156.78	VLA C/D	...	0.604	0.671 ^a	0.634 ^a	0.651 ^a
1993 Sep 11	167.91	VLA C/D	2.238	0.616	...	...	...
1993 Sep 18	174.72	VLA C/D	...	...	0.863	0.889	0.996
1993 Sep 19	175.75	VLA C/D	2.200	0.626	0.620	0.654	0.660
1993 Sep 26	182.75	VLA C/D	2.231	0.624	0.618	0.640	0.638
1993 Oct 04	190.66	VLA C/D	2.200	0.636	0.625	0.624	0.591
1993 Oct 17	203.80	VLA C/D	2.236	0.631	0.616	0.588	0.489
1993 Oct 25	211.61	VLA C/D	2.260	0.637	...	0.620	0.582
1993 Nov 01	218.58	VLA D	2.205	0.649	0.637	0.620	0.590
1993 Nov 19	236.58	VLA D	2.230	0.633	0.617	0.601	0.563
1993 Nov 28	245.56	VLA D	2.237	0.636	0.623	0.604	0.581
1993 Dec 05	252.58	VLA D	2.230	0.640	0.624	0.595	0.561

TABLE 3—Continued

Observation Date	Days from Reference Date	Telescope/VLA Configuration	$S(20\text{ cm})$ (mJy)	$S(6\text{ cm})$ (mJy)	$S(3.6\text{ cm})$ (mJy)	$S(2\text{ cm})$ (mJy)	$S(1.2\text{ cm})$ (mJy)
1993 Dec 19	266.58	VLA D	2.226	0.650	0.641	0.625	0.600
1993 Dec 27	274.56	VLA D	2.234	0.646	0.646	0.649	0.631
1994 Jan 07	285.37	VLA D	2.226	0.658	0.653	0.628	0.590
1994 Jan 13	291.51	VLA D	2.230	0.671	0.659	0.644	0.600
1994 Jan 27	305.30	VLA D	2.226	0.647	0.658	0.664	0.620
1994 Feb 08	317.22	VLA D	2.236	0.652	0.673	0.705	0.754
1994 Feb 18	327.30	VLA A	0.698	0.671	0.670	0.744	0.767
1994 Mar 20	357.36	VLA A	0.688	0.727	0.842	1.160	1.159
1994 Apr 25	393.18	VLA A	0.698	0.816	0.836	0.742	0.668
1994 May 26	424.16	VLA A/B	0.713	0.937	0.965	0.905	0.845
1994 Jun 23	452.98	VLA B	0.733	0.968	0.979	...	0.874
1994 Nov 07	589.47	VLA C	0.786	1.102	1.091	...	...
1995 Jan 05	648.39	VLA C/D	0.788	1.129	1.098	0.973	0.934
1995 Apr 06	739.14	VLA D	0.790	1.156	1.103	1.029	0.941
1995 Jun 16	810.05	VLA D/A	0.837	1.113	0.989	0.763	...
1995 Oct 06	922.69	VLA B	0.786	1.029	0.986	0.939	1.110
1996 Jan 12	1020.00	VLA B/C	0.821	1.066	1.069	1.094	1.100
1996 Oct 05	1287.57	VLA D/A	0.978	1.578	1.489	1.157	1.145
1997 Jan 23	1397.21	VLA A/B	1.096	1.719	1.711	1.691	1.570
1997 Aug 14	1600.99	VLA C/D	1.256	...	...	...	...
1998 Jun 09	1899.85	VLA A/B	1.335	1.647	1.411	1.209	1.125
1999 Jun 13	2268.96	VLA D/A	1.299	1.117	...	...	...
2002 Jan 13	3213.38	VLA D/A	1.610	1.774	1.181	1.307	1.295
2003 May 23	3708.93	VLA A	1.397	1.347	1.249	...	1.383
2003 Jun 26	3742.91	VLA A	...	1.358 ^a	...	1.406	1.55
2004 Jan 29	3959.47	VLA B/C	1.464	1.353	1.247	1.181	1.102
2004 Sep 10	4184.57	VLA A	1.312	1.323	1.445	1.734	1.830
2005 Jun 13	4460.90	VLA B/C	1.277	1.825	2.008	2.117	2.102
2006 Jan 24	4685.17	VLA D	...	2.178	2.418	2.768	...
2006 Jun 28	4840.05	VLA B	1.556	...	...	...	...
2006 Sep 25	4929.64	VLA B/C	...	3.058	1.182	...	...

NOTES.—For the measurements from 1993 September 11 through 1994 February 8, the secondary calibrator at 20 cm was J0949+662.

^a A primary calibrator was not measured, so the flux density for the secondary calibrator was determined from earlier observations.

turn-on, and Montes et al. (1997) have found at least one example for the presence of a distant ionized medium along the line of sight which is time independent and can cause a spectral turnover at low radio frequencies. In addition to clumps or filaments, the CSM may be structured with significant density irregularities such as rings, disks, shells, or gradients and many, if not most, well-studied RSNs appear to show a transition to a significantly less dense CSM after a number of years (several thousand years in the time frame of the presupernova wind; see, e.g., SN 1980K, Montes et al. 1998; SN 1988Z, Van Dyk et al. 1993b; Williams et al. 2002; and SN 2001gd, Stockdale et al. 2007).

3.1. Radio Light Curves

Following the most recent RSN modeling discussion of Weiler et al. (2002) and Sramek & Weiler (2003) we adopt a parameterized model:

$$S(\text{mJy}) = K_1 \left(\frac{\nu}{5\text{ GHz}} \right)^\alpha \left(\frac{t-t_0}{1\text{ day}} \right)^\beta \times e^{-\tau_{\text{ext}}} \left(\frac{1 - e^{-\tau_{\text{CSM}_{\text{cl}}}}}{\tau_{\text{CSM}_{\text{cl}}}} \right) \left(\frac{1 - e^{-\tau_{\text{int}}}}{\tau_{\text{int}}} \right), \quad (2)$$

with

$$\tau_{\text{ext}} = \tau_{\text{CSM}_{\text{hom}}} + \tau_{\text{dist}}, \quad (3)$$

where

$$\tau_{\text{CSM}_{\text{hom}}} = K_2 \left(\frac{\nu}{5\text{ GHz}} \right)^{-2.1} \left(\frac{t-t_0}{1\text{ day}} \right)^\delta, \quad (4)$$

$$\tau_{\text{dist}} = K_4 \left(\frac{\nu}{5\text{ GHz}} \right)^{-2.1}, \quad (5)$$

$$\tau_{\text{CSM}_{\text{cl}}} = K_3 \left(\frac{\nu}{5\text{ GHz}} \right)^{-2.1} \left(\frac{t-t_0}{1\text{ day}} \right)^{\delta'}, \quad (6)$$

with K_1 , K_2 , K_3 , and K_4 determined from fits to the data and corresponding, formally, to the flux density (K_1), homogeneous (K_2 , K_4), and clumpy or filamentary (K_3) FFA at 5 GHz 1 day after the explosion date t_0 . The terms $\tau_{\text{CSM}_{\text{hom}}}$ and $\tau_{\text{CSM}_{\text{cl}}}$ describe the attenuation of local, homogeneous free-free absorption CSM and clumpy or filamentary free-free absorbing CSM, respectively, that are near enough to the SN progenitor that they are altered by the rapidly expanding SN blast wave. The $\tau_{\text{CSM}_{\text{hom}}}$ FFA is produced by an ionized medium that completely covers the emitting source (“homogeneous external absorption”), and the $(1 - e^{-\tau_{\text{CSM}_{\text{cl}}}})\tau_{\text{CSM}_{\text{cl}}}^{-1}$ term describes the attenuation produced by an inhomogeneous FFA medium (“clumpy absorption”; see Natta & Panagia 1984 for a more detailed discussion of attenuation in inhomogeneous media). The τ_{dist} term describes the attenuation produced by a homogeneous FFA medium which completely covers the source but is so distant from the SN progenitor that it is not affected by the expanding SN blast wave and is consequently

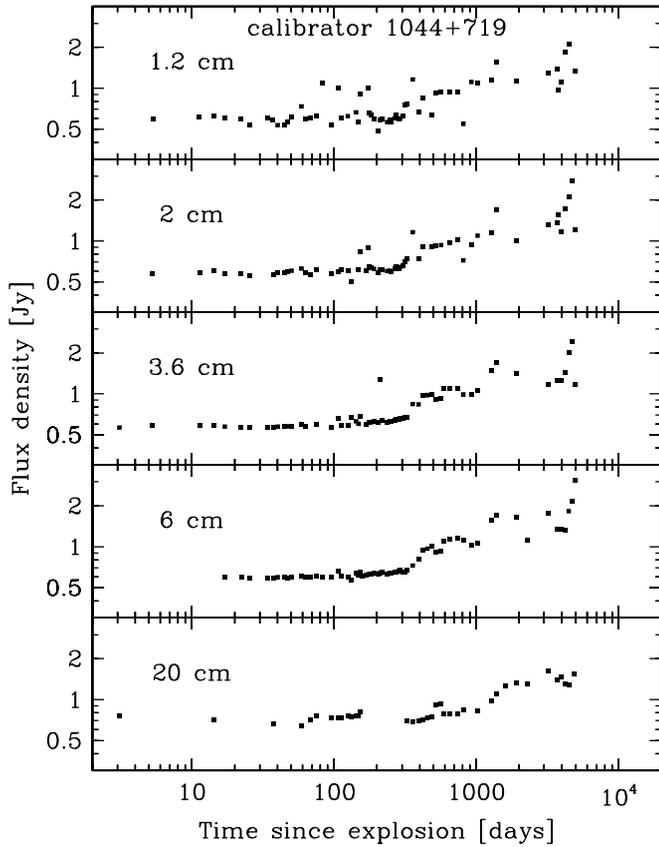


FIG. 3.—Flux density measurements for the VLA secondary calibrator J1048+717 at wavelengths of 1.2, 2, 3.6, 6, and 20 cm. Calibration measurements at other observing bands were too sparse to show any trends.

constant in time. All external and clumpy absorbing media are assumed to be purely thermal, singly ionized gas which absorbs via free-free absorption (FFA) with frequency dependence $\nu^{-2.1}$ in the radio. The parameters δ and δ' describe the time dependence of the optical depths for the local homogeneous and clumpy or filamentary media, respectively.

Since it is physically realistic and may be needed in some RSNs where radio observations have been obtained at early times and high frequencies, equation (2) also includes the possibility for an internal absorption term.⁷ This internal absorption (τ_{int}) term may consist of two parts: synchrotron self-absorption (SSA; τ_{intSSA}), and mixed, thermal FFA/nonthermal emission (τ_{intFFA}):

$$\tau_{\text{int}} = \tau_{\text{intSSA}} + \tau_{\text{intFFA}}, \quad (7)$$

$$\tau_{\text{intSSA}} = K_5 \left(\frac{\nu}{5 \text{ GHz}} \right)^{\alpha-2.5} \left(\frac{t-t_0}{1 \text{ day}} \right)^{\delta''}, \quad (8)$$

$$\tau_{\text{intFFA}} = K_6 \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left(\frac{t-t_0}{1 \text{ day}} \right)^{\delta'''}, \quad (9)$$

with K_5 corresponding, formally, to the internal, nonthermal ($\nu^{\alpha-2.5}$) SSA and K_6 , corresponding, formally, to the internal thermal ($\nu^{-2.1}$) free-free absorption mixed with nonthermal emission, at 5 GHz 1 day after the explosion date t_0 . The parameters δ'' and δ''' describe the time dependence of the optical depths for the SSA and FFA internal absorption components, respectively.

⁷ Note that for simplicity an internal absorber attenuation of the form $(1 - e^{-\tau_{\text{int}}})/\tau_{\text{int}}$, which is appropriate for a plane-parallel geometry, is used instead of the more complicated expression (e.g., Osterbrock 1974, p. 82) valid for the spherical case. The assumption does not affect the quality of the analysis, because, to within 5% accuracy, the optical depth obtained with the spherical case formula is simply three-fourths of that obtained with the plane-parallel slab formula.

TABLE 4
MODEL FITTING RESULTS FOR SN 1993J

PARAMETER ^a	EARLY DATA ^b		
	SSA Only Fit (2)	FFA Only Fit (3)	SSA+FFA “Best” Fit (4)
K_1	3.3×10^3	4.9×10^3	4.8×10^3
α	-0.77	-0.82	-0.81
β	-0.68	-0.73	-0.73
K_2	0 ^c	1.7×10^2	1.6×10^2
δ .....	...	-1.42	-1.88
K_3	0 ^c	4.3×10^5	4.6×10^5
δ' .....	...	-2.84	-2.83
K_4	0 ^c	0 ^c	0 ^c
K_5	9.2×10^6	0 ^c	2.62×10^3
δ''	-3.41	...	-2.05
χ^2	12.8	8.8	8.1
Shock breakout ^d	1993 March 28.0	1993 March 28.0	1993 March 28.0
Distance ^e .....	...	...	3.63 ± 0.34 Mpc
\dot{M} ($M_{\odot} \text{ yr}^{-1}$) ^f .....	...	...	$(0.5-5.9) \times 10^{-6}$
t_{max} (6 cm peak) .....	...	...	133 days
S_{max} (6 cm peak) .....	...	...	96.9 mJy
L_{max} (6 cm peak) .....	...	...	$1.5 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$

^a See the text for an explanation of the model fitting parameters.

^b Using data from the first radio detection to day 3100.

^c Defined fixed for the fit.

^d From Wheeler et al. 1993.

^e From Freedman et al. 1994.

^f Assuming $w_{\text{wind}} = 10 \text{ km s}^{-1}$, $t_i = 45 \text{ days}$, $v_i = 15,000 \text{ km s}^{-1}$, $T = 20,000 \text{ K}$, and $m = 0.845$ (see eq. [12]).

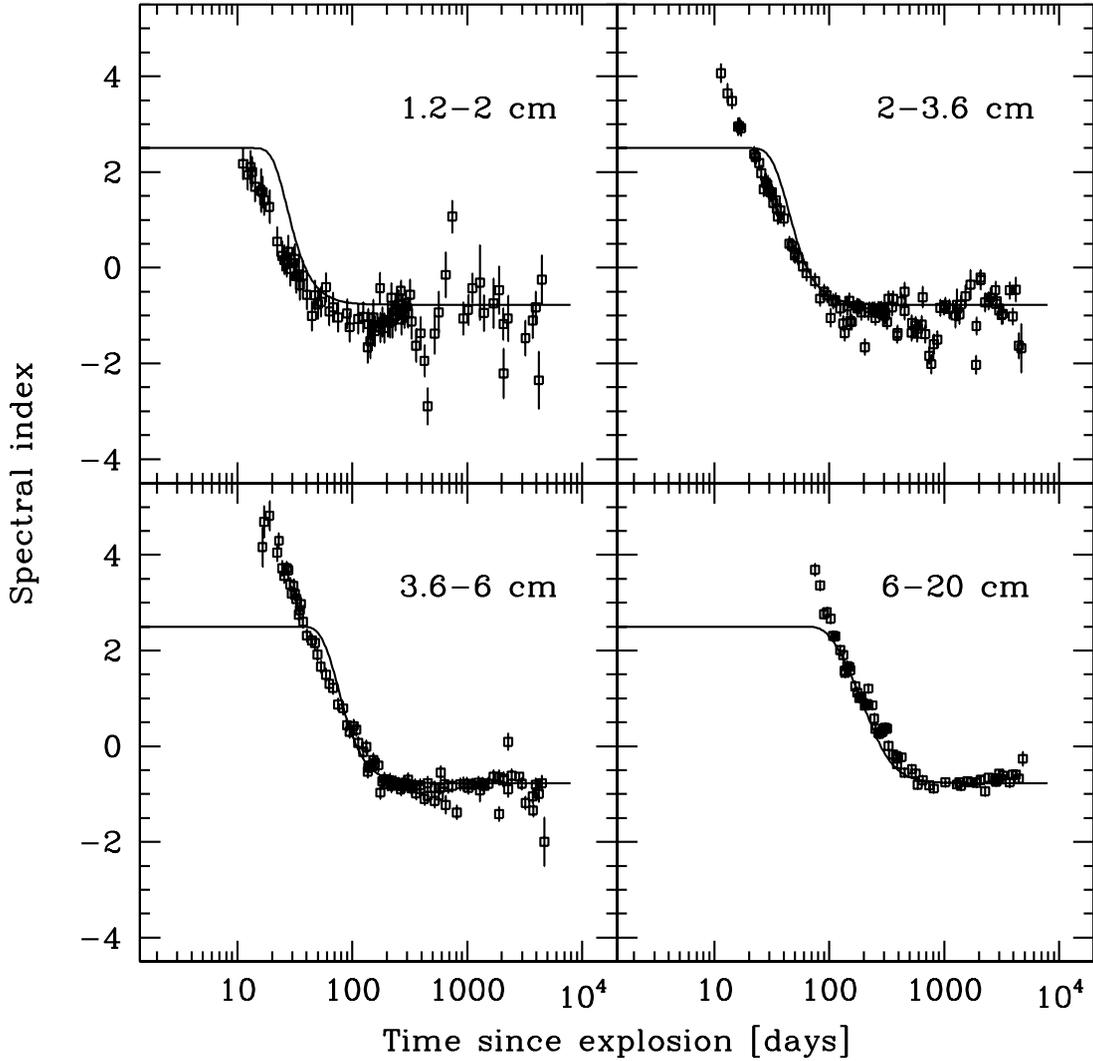


FIG. 4.— Spectral index (α ; $S \propto \nu^{+\alpha}$) evolution for SN 1993J between 1.2 and 2 cm (*top left*), between 2 and 3.6 cm (*top right*), between 3.6 and 6 cm (*bottom left*), and between 6 and 20 cm (*bottom right*). As in Fig. 1 the lines represent the best-fit pure synchrotron self-absorption (SSA) model as described in the text with the parameters listed in Table 4, col. (2). Note that the observed spectral index values at early times are much in excess of the asymptotic SSA value of $\alpha = +2.5$.

Application of this basic parameterization has been shown to be effective in describing the physical characteristics of the pre-supernova system, its CSM, and its final stages of evolution before explosion for objects ranging from the two decades of monitoring the complex radio emission from SN 1979C (Montes et al. 2000) through the unusual SN 1998bw (GRB 980425; Weiler et al. 2001) and most recent γ -ray bursters (Weiler et al. 2002, 2003).

3.2. Brightness Temperature

Given the measured fluxes, we can compute the corresponding brightness temperatures if the angular size of the radio region is known. Marcaide et al. (1995a, 1995b, 1997, 2005, 2008) have measured the apparent expansion of SN 1993J in the radio with a series of VLBI experiments, starting as early as day 182 and extending up to day 3858. Marcaide et al. (2008) find that a power law of the form $r \propto t^m$ can provide a good, frequency-independent fit to all observations of the angular diameter at 3.6, 6, and 18 cm with $m = 0.845 \pm 0.005$ through day 1500. Although there are no measurements at early epochs, the remarkably good quality of the fit up to day 1500 justifies our assuming $m = 0.845$, since

the epoch of the SN shock breakout. Under this assumption we can express the angular expansion of SN 1993J as

$$r = 6.2(t/1 \text{ day})^{0.845} \mu\text{as}, \quad (10)$$

which gives the radius r of the circle in microarcseconds (μas) that encompasses half of the total radio flux density to better than 20%, assuming isotropic radio emission. Adopting this expansion rate, the brightness temperature turns out to be

$$T_B = 1.30 \times 10^{10} [S_\nu(\text{corr})/2] \lambda^2 t^{-1.69} \text{ K}, \quad (11)$$

where the radio flux density $S_\nu(\text{corr})$ is the observed flux density, corrected for model estimated external free-free absorption, expressed in mJy, the wavelength (λ) in cm, and the time (t) in days. The term $S_\nu/2$ accounts for the fact that the circular area inside r is defined to include only half of the total flux density.

4. FITTING RESULTS

Note that even approximate fitting of the data with our standard models requires splitting it into two parts: an “early” data set from

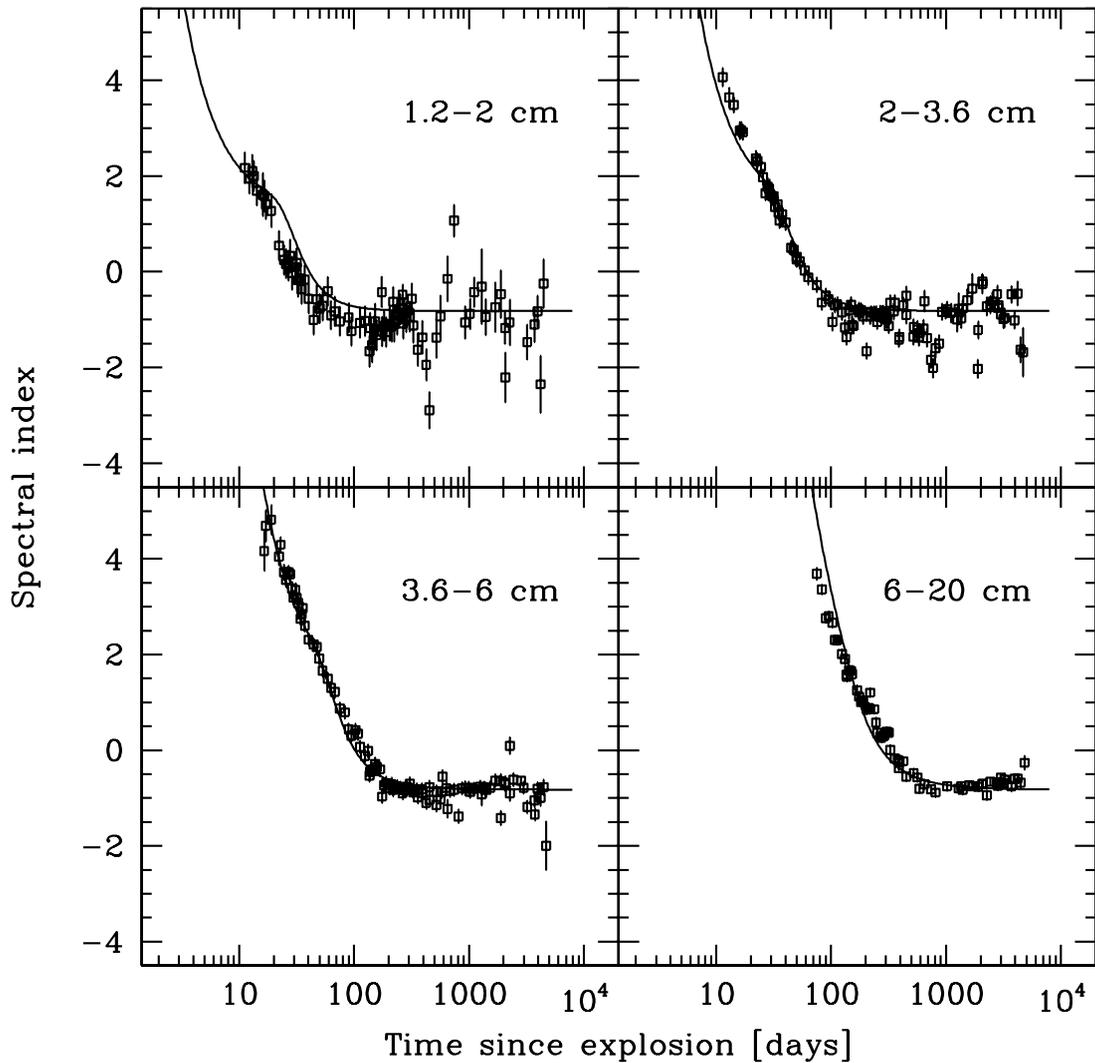


FIG. 5.— Spectral index (α ; $S \propto \nu^{+\alpha}$) evolution for SN 1993J between 1.2 and 2 cm (*top left*), between 2 and 3.6 cm (*top right*), between 3.6 and 6 cm (*bottom left*), and between 6 and 20 cm (*bottom right*). As in Fig. 2 the lines represent the best-fit pure thermal, free-free absorption (FFA) model as described in the text with the parameters listed in Table 4, col. (3).

the first radio detection through day ~ 3100 and a “late” data set for the period from day ~ 3100 through the final measurements on day 4930. The reason for this splitting of the data set is that the decline rate β is clearly much steeper after day ~ 3100 , which, for illustrative purposes, we have shown in Figures 1 and 2 (see also Figs. 8, 11, and 13) as an exponential with e -folding time of 1100 days. Of course, the transition interval is gradual, but in order to maintain model simplicity, we have taken day 3100 as marking the break between the early and late fitting procedures.

4.1. Early Data Fitting

The early (day < 3100) data were first fitted with two possible “pure” absorption models, namely, pure SSA (i.e., negligible FFA at all times) and pure FFA (i.e., negligible SSA at all times). The parameters derived from these fits are listed in Table 4, columns (2) and (3), respectively, and the resulting curves are plotted with the data in Figures 1 and 2, respectively. We also show the spectral index evolution calculated for pairs of frequencies in Figures 4 and 5. The lines in this case are derived from exactly the same models (pure SSA for Fig. 4 and pure FFA for Fig. 5) as were derived for Figures 1 and 2. We see that both models are able to represent the light curves as well as the spectral index evolution fairly well. However, there are some features that are systemat-

ically misrepresented by these “pure” models, which we discuss below.

We also calculate the apparent brightness temperature evolution from equation (11) for both the pure SSA and pure FFA models and plot them in Figures 6 and 7, respectively. Note that, for Figures 6 and 7, we have applied a correction derived from our models for the presumed external thermal absorption for the early data to obtain a “true” flux density, and thus a “true” brightness temperature, as if no thermal absorption were present.

For the pure SSA model (Fig. 1), the rising branch of the light curve at early times tends to be “too straight” in that it cannot reproduce the apparent curvature in the flux density turn-on that is most noticeable at frequencies lower than 5 GHz. Also, the spectral index evolution at early times (Fig. 4) is clearly inadequate to represent the observations. This is to be expected because with pure SSA the asymptotic spectral index cannot exceed $\alpha = +2.5$ ($S \propto \nu^{+\alpha}$), clearly at variance with values of $\alpha = 4-5$ observed at early epochs. Moreover, the corresponding brightness temperature evolution seen in Figure 6 is rather strange in that the temperature appears to peak at later times for lower frequencies.

For the pure FFA model the rising branch of the light curves appears to provide a better fit for both the light curves (Fig. 2)

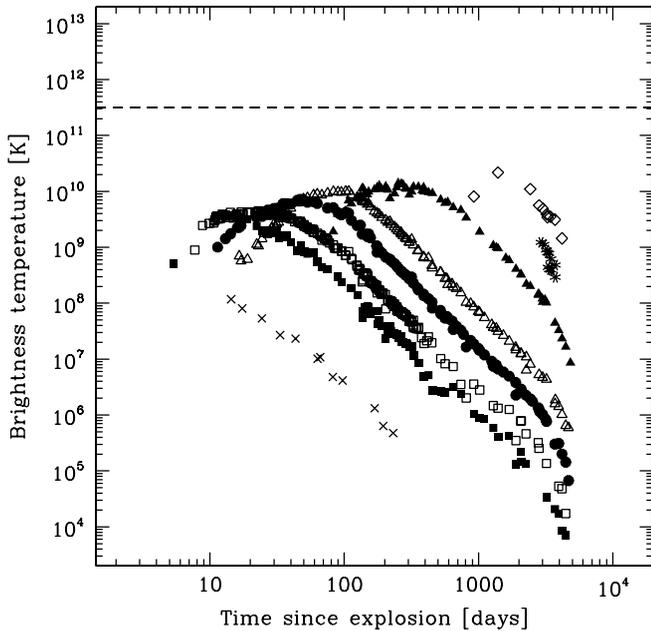


FIG. 6.—Brightness temperature (T_B) evolution for SN 1993J for, from left to right, 0.3 cm (*crosses*), 1.2 cm (*filled squares*), 2 cm (*open squares*), 3.6 cm (*filled circles*), 6 cm (*open triangles*), 20 cm (*filled triangles*), 49 cm (*stars*), and 90 cm (*open diamonds*) for the case of a pure synchrotron self-absorption (SSA) model as described in the text with the parameters listed in Table 4, col. (2). The horizontal dashed line denotes the limiting value of $T_B \simeq 3 \times 10^{11}$ K (Kellermann & Pauliny-Toth 1969; Readhead 1994), which is not reached at any frequency. Note that the brightness temperature is low at early times, reaches a peak which always falls well below 3×10^{11} K, and occurs at later times for lower frequencies.

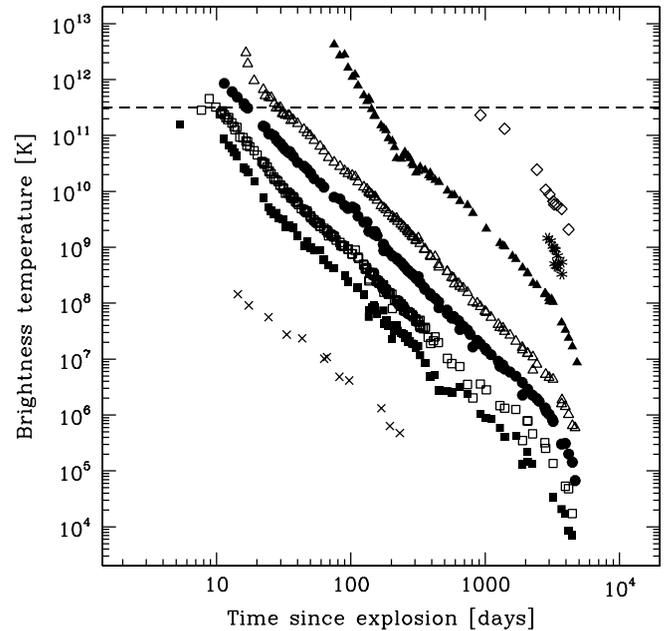


FIG. 7.—Brightness temperature (T_B) evolution for SN 1993J for, from left to right, 0.3 cm (*crosses*), 1.2 cm (*filled squares*), 2 cm (*open squares*), 3.6 cm (*filled circles*), 6 cm (*open triangles*), 20 cm (*filled triangles*), 49 cm (*stars*), and 90 cm (*open diamonds*) for the case of a pure thermal, free-free absorption (FFA) model as described in the text with the parameters listed in Table 4, col. (3). To obtain the “true” brightness temperature at early times, the measured flux densities have been corrected for the model estimated external, thermal, free-free absorption. The horizontal dashed line denotes the limiting value of $T_B \simeq 3 \times 10^{11}$ K (Kellermann & Pauliny-Toth 1969; Readhead 1994), which is greatly exceeded for most frequencies at early times.

and the spectral index (Fig. 5), but it fails the test of the brightness temperature (Fig. 7). After flux density correction for the external, thermal absorption, the implied brightness temperature at early times, for several frequencies, exceeds the physical limit of $T_B \simeq 3 \times 10^{11}$ K (see, e.g., Kellermann & Pauliny-Toth 1969; Readhead 1994).

Thus, it is clear that no “simple” model, either pure SSA or pure FFA, can account for all observational aspects of the data and a combination of the two absorption mechanisms must be at work. The best results are achieved with a model that comprises both SSA and FFA; the best-fit parameters are given in Table 4, column (4) and the corresponding fits are displayed in Figures 8, 9, and 10, which show the light curves, the spectral index evolution, and the brightness temperature evolution, respectively. As before, after day ~ 3100 we have shown, for illustrative purposes, an exponential with an e -folding time of 1100 days for the plotted curve. These results are discussed further in § 5.

4.2. Late-Time Data Fitting

Even though the data are well described after day ~ 3100 by an exponential decay with an e -folding time of 1100 days, to show the increasing decline rate of the flux density at all wavelengths, it is perhaps worthwhile to describe the decline after day 3100 in terms of our standard model parameters. Since all of the absorption processes are negligible by the time of the steepening flux density decline around day ~ 3100 , the “late” radio light curves are essentially the same for both thermal, free-free absorption (FFA) and nonthermal synchrotron self-absorption (SSA) models. Therefore, the only two remaining parameters to be determined are the spectral index (α) and the decline rate (β). Least-squares fitting reveals that the “late” data are consistent with a constant spectral

index equal to that derived for the early data ($\alpha = -0.8$) but with a much faster rate of decline with β steepening from -0.7 to -2.7 . However, examination of Figure 11 shows that such a fit (*dotted lines*) does not describe the data well, and an exponential decline with an e -folding time of 1100 days (Fig. 11, *solid lines*) provides a much better fit. Chandra et al. (2004) have proposed a steepening of the spectral index after day 3200, but Figures 9 and 11, both of which use constant spectral index models, do not appear to confirm their suggestion (see also § 5.4).

5. DISCUSSION

5.1. Synchrotron Self-Absorption versus Thermal Free-Free Absorption

Chevalier (1998) proposed that nonthermal synchrotron self-absorption (SSA) could play a significant role in the early turn-on, absorption-dominated phase of the radio emission from supernovae. While the possibility is included in the parameterization of the radio emission discussed above in equations (2) and (8), actual observational evidence for the difference in turn-on rate expected between thermal free-free absorption (FFA) and SSA has been difficult to establish. Certainly there are valid physical arguments for expecting SSA to play a role in the radio emission from RSNE which are radio luminous at early times.

The source brightness temperature (T_B) is simply proportional to the source flux density (S), corrected where appropriate for suppression of the flux density by external free-free absorption, divided by the source angular size ($\sim \theta^2$). The temperature T_B cannot exceed 3×10^{11} K (Kellermann & Pauliny-Toth 1969; Readhead 1994) without being quenched by inverse Compton scattering and the consequent SSA. The problems in determining

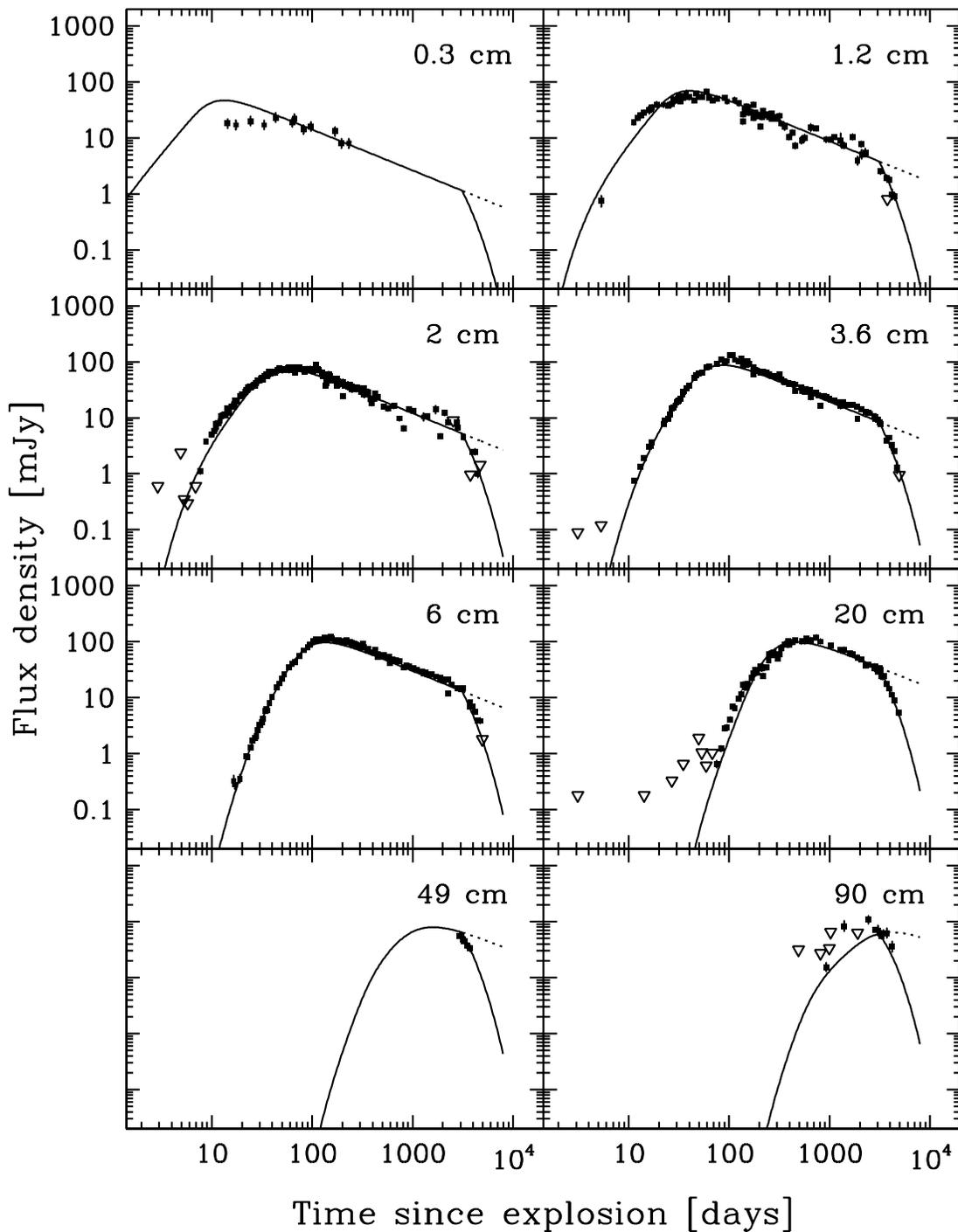


FIG. 8.—Radio light curves for SN 1993J, plotted from left to right and top to bottom at 0.3, 1.2, 2, 3.6, 6, 20, 49, and 90 cm. The solid lines represent the best-fit combined synchrotron self-absorption (SSA) and thermal, free-free absorption (FFA) model as described in the text with the parameters listed in Table 4, col. (4), and an exponential flux density decline after day 3100 with an e -folding time of 1100 days. The extrapolation of the best-fit model curves without the exponential roll-off is shown as the dotted lines. Upper limits (3σ) are shown as open inverted triangles.

this relatively straightforward quantity are that the source angular size at very early times cannot be directly observed, even with VLBI techniques; there is likely to be some thermal, ionized, absorbing material surrounding these massive exploding stellar systems giving some level of initial thermal absorption; current models do not include a start-up engine to predict what the flux density would be without any absorption present; and the velocity of expansion of the radio emitting region may well change during the very early phases of the radio supernova phenomenon.

All of these factors could lead to a false estimate of the source size and source flux density at early times and to an incorrect estimate of the source brightness temperature and the likelihood of SSA dominating.

In some objects such as GRBs, where there is evidence for very little external material to give rise to thermal absorption, and the objects are very compact and very radio luminous, the case for SSA seems clear. For example, the nearby GRB 980425 (SN 1998bw), although somewhat ambiguous with Kulkarni et al.

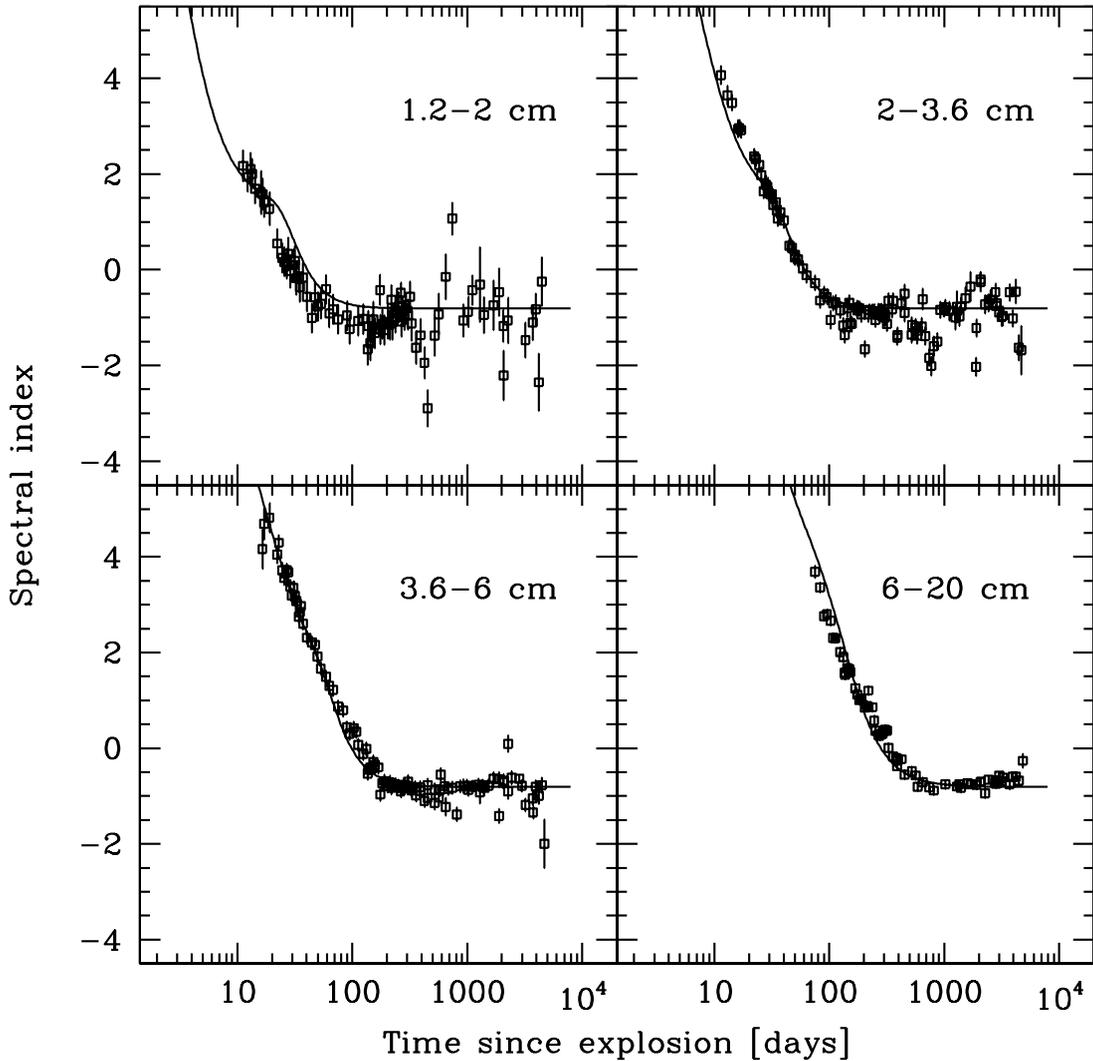


FIG. 9.— Spectral index (α ; $S \propto \nu^{\alpha}$) evolution for SN 1993J between 1.2 and 2 cm (*top left*), between 2 and 3.6 cm (*top right*), between 3.6 and 6 cm (*bottom left*), and between 6 and 20 cm (*bottom right*). As in Fig. 8 the lines represent the best-fit combined synchrotron self-absorption (SSA) and thermal, free-free absorption (FFA) model as described in the text with the parameters listed in Table 4, col. (4).

(1998) claiming evidence for SSA while Weiler et al. (2001) showed that FFA gives a fit to the data of equal quality, is probably a good example where SSA is dominant, at least early on.

Several authors have discussed the possibility of SSA being a prominent absorption mechanism for SN 1993J (Fransson & Björnsson 1998; Pérez-Torres et al. 2001; Bartel et al. 2002), whereas Van Dyk et al. (1994) were able to describe the early absorption effects entirely through FFA in a circumstellar medium with a density profile flatter ($\rho_{\text{CSM}} \propto r^{-1.5}$) than the $\rho_{\text{CSM}} \propto r^{-2}$ expected for a constant mass-loss rate, constant velocity, pre-supernova stellar wind. We have investigated the fitting of both pure SSA (Figs. 1 and 4) and pure FFA (Figs. 2 and 5) to the extensive data for SN 1993J and find that both models are acceptable from light curve fitting considerations alone ($\chi_{\text{SSA}}^2 = 12.8$, $\chi_{\text{FFA}}^2 = 8.8$) with each fitting some parts of the light curves slightly better, and some parts of the data slightly worse, than the other. However, when the additional parameters of the spectral index evolution (Figs. 4 and 5) and the brightness temperature evolution (Figs. 6 and 7) are considered, neither the pure SSA nor the pure FFA models can satisfy all physical conditions, i.e., to reproduce simultaneously the light curves, the spectral index evolution, and the brightness temperature limit. However, a model which includes both SSA and FFA can account rather well ($\chi_{\text{SSA+FFA}}^2 = 8.1$) for

the observed radio emission from SN 1993J without violating the brightness temperature limit and provides a good description of the spectral index evolution (see Figs. 8, 9, and 10).

5.2. Evidence for a “Flutter” Circumstellar Density Profile

When Van Dyk et al. (1994) presented multifrequency radio observations of SN 1993J for the first eight months of monitoring, they concluded that the CSM surrounding the supernova, which was likely established by the SN progenitor in the last stages of evolution, consists of (1) a homogeneous medium (K_2) with embedded clumpy or filamentary components (K_3), and (2) a CSM with a density profile that is significantly flatter ($\rho_{\text{CSM}} \propto r^{-1.5}$) than the $\rho_{\text{CSM}} \propto r^{-2}$ expected for a constant mass-loss rate, constant velocity presupernova stellar wind. Since the density, and therefore the radio emission, is proportional to the ratio of the mass-loss rate (\dot{M}) to the wind speed (w), i.e., \dot{M}/w , and since the wind speed is unlikely to vary on relatively short timescales, Van Dyk et al. (1994) estimated that the mass-loss rate from the SN 1993J progenitor system decreased from $\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$ to $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ during the last 1000 yr before explosion. This conclusion was later supported by Immler et al. (2001), who found a similarly flat CSM density profile from X-ray observations, and accepted by other modeling work (Fransson et al. 1996). However,

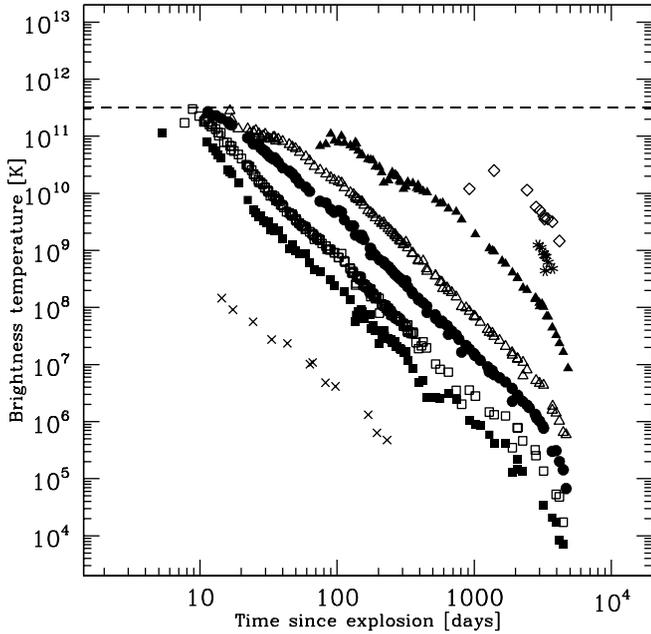


FIG. 10.—Brightness temperature (T_B) evolution for SN 1993J for, from left to right, 0.3 cm (crosses), 1.2 cm (filled squares), 2 cm (open squares), 3.6 cm (filled circles), 6 cm (open triangles), 20 cm (filled triangles), 49 cm (stars), and 90 cm (open diamonds) for the case of both synchrotron self-absorption (SSA) and thermal free-free absorption (FFA) present in the model as described in the text, with the parameters listed in Table 4, col. (4). The horizontal dashed line denotes the limiting value of $T_B \simeq 3 \times 10^{11}$ K (Kellermann & Pauliny-Toth 1969; Readhead 1994), which is not exceeded at any frequency.

Fransson & Björnsson (1998) later concluded that the flatter CSM density profile is not necessary and the results can be interpreted in terms of SSA with an r^{-2} density profile and an electron cooling mechanism. Nevertheless, because the X-ray emission arises from the thermal component of the CSM, rather than the nonthermal component which gives rise to the radio emission, the support for a “flatter” CSM density profile from both radio and X-ray observations appears strong.

With a model that includes both SSA and FFA, the radio data alone are not able to constrain the CSM profile efficiently, because fits with steep δ slopes and high values of the K_2 can provide comparable accuracy to shallow δ slopes and low K_2 values. Therefore, to calculate our best model, which includes both SSA and FFA and satisfies all observational and physical constraints, we adopted a CSM density profile of $\rho_{\text{CSM}} \propto r^{-1.61}$, which is close to the behavior determined from the evolution of the X-ray luminosity (Immler et al. 2001; Zimmermann & Aschenbach 2003; see also § 5.5).

With these assumptions, the mass-loss rate giving rise to uniform, external thermal absorption is given by a straightforward modification of equation (16) of Weiler et al. (1986), which becomes

$$\frac{\dot{M} (M_{\odot} \text{ yr}^{-1})}{(w_{\text{wind}}/10 \text{ km s}^{-1})} = 3.0 \times 10^{-6} \phi \tau^{0.5} m^{-1.5} \times \left(\frac{v_i}{10^4 \text{ km s}^{-1}} \right)^{1.5} \left(\frac{t_i}{45 \text{ days}} \right)^{1.5} \left(\frac{t}{t_i} \right)^{1.5m} \left(\frac{T}{10^4 \text{ K}} \right)^{0.68}, \quad (12)$$

where the extra factor ϕ is a small correction that takes into account the fact that, in this case, the CSM density behaves like $\rho_{\text{CSM}} \propto r^{-1.61}$ instead of r^{-2} as it does under the usual constant

mass-loss rate assumption. The factor ϕ is given by the square root of the ratio of the integration constant for τ in the case of $\rho_{\text{CSM}} \propto r^{-1.61}$ to the one appropriate for $\rho_{\text{CSM}} \propto r^{-2}$, i.e.,

$$\phi = \left(\frac{2 \times 1.61 - 1}{2 \times 2 - 1} \right)^{0.5} = 0.86. \quad (13)$$

For equation (12) we assume $v_i = 15,000 \text{ km s}^{-1}$ at $t_i = 45$ days, which is a value consistent with the results of Marcaide et al. (2008), and we adopt values of $T = 20,000 \text{ K}$, $w_{\text{wind}} = 10 \text{ km s}^{-1}$ (which is appropriate for a RSG wind), and $m = 0.845$, as measured by Marcaide et al. (2008). With the assumptions for the blast wave and CSM properties discussed above, and the results for the best-fit parameters listed in Table 4, column (4), our estimated presupernova mass-loss rate is $\dot{M} = 5.4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ at the time of shock breakout.

In addition, we have to take into account the shallow slope of the CSM. The CSM density behaves like $\rho_{\text{CSM}} \propto r^{-1.61}$, indicating that the mass-loss rate was not constant but was higher in the years leading up to the explosion, i.e., $\dot{M} \propto r^2 \rho w_{\text{wind}} \propto r^{0.39}$ for a constant w_{wind} . Thus, we calculate that when the abrupt change in the radio light curves occurred around day ~ 3100 ($\sim 8000 \text{ yr}$ before explosion) the mass-loss rate was as high as $5.9 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. Integrating the mass-loss rate over the last $\sim 8000 \text{ yr}$, we find that during that time the progenitor star shed $\sim 0.04 M_{\odot}$ in a massive stellar wind.

At earlier epochs of the progenitor’s evolution, more than 8000 yr before explosion, the mass-loss rate was considerably lower, as indicated by the radio light curve “break” discussed above and the transition of the blast wave to a lower density CSM at that time. One has to keep in mind that these values are derived for an adopted pre-SN stellar wind speed of 10 km s^{-1} and blast wave speed of $15,000 \text{ km s}^{-1}$. If the wind speed was appreciably higher than 10 km s^{-1} , then the mass-loss rates were proportionally higher.

Thus, our current analysis of this larger data set of radio observations of SN 1993J is consistent with the early predictions of Van Dyk et al. (1994), Immler et al. (2001), and Zimmermann & Aschenbach (2003) of a flatter CSM density profile and a changing mass-loss rate in the millennia before explosion and inconsistent with a $\rho_{\text{CSM}} \propto r^{-2}$ density profile with electron cooling proposed by Fransson & Björnsson (1998).

5.3. Increased Flux Density Decline Rate

A noteworthy aspect of the radio emission from SN 1993J is that after day ~ 3100 , its decline rate significantly steepens. In Figures 1, 2, 8, and 11 (see also Fig. 13) this has been illustrated by multiplying the curve fitted to the early data by an exponential decay term that affects the emission after day 3100 and has an e -folding time of 1100 days, i.e., $\exp[-(t - t_0 - 3100)/1100]$ for $t - t_0 > 3100$.

While the visual description of the data is greatly enhanced by these curves, another way of describing this change in evolution is shown as the dotted lines in Figure 11 where the data after day 3100 are fitted with the best-fit “early” spectral index (the emission is optically thin at that time, so whether an SSA or FFA model is used at early times is of no consequence) and a new decline rate $\beta = -2.7$ determined. Nevertheless, it should be noted that the exponential decay (Fig. 11, solid lines) give a better description of the data than a power-law decline (Fig. 11, dotted lines).

Although our exponential decay is a purely empirical assumption, the fact that it is so successful in fitting all light curves at all

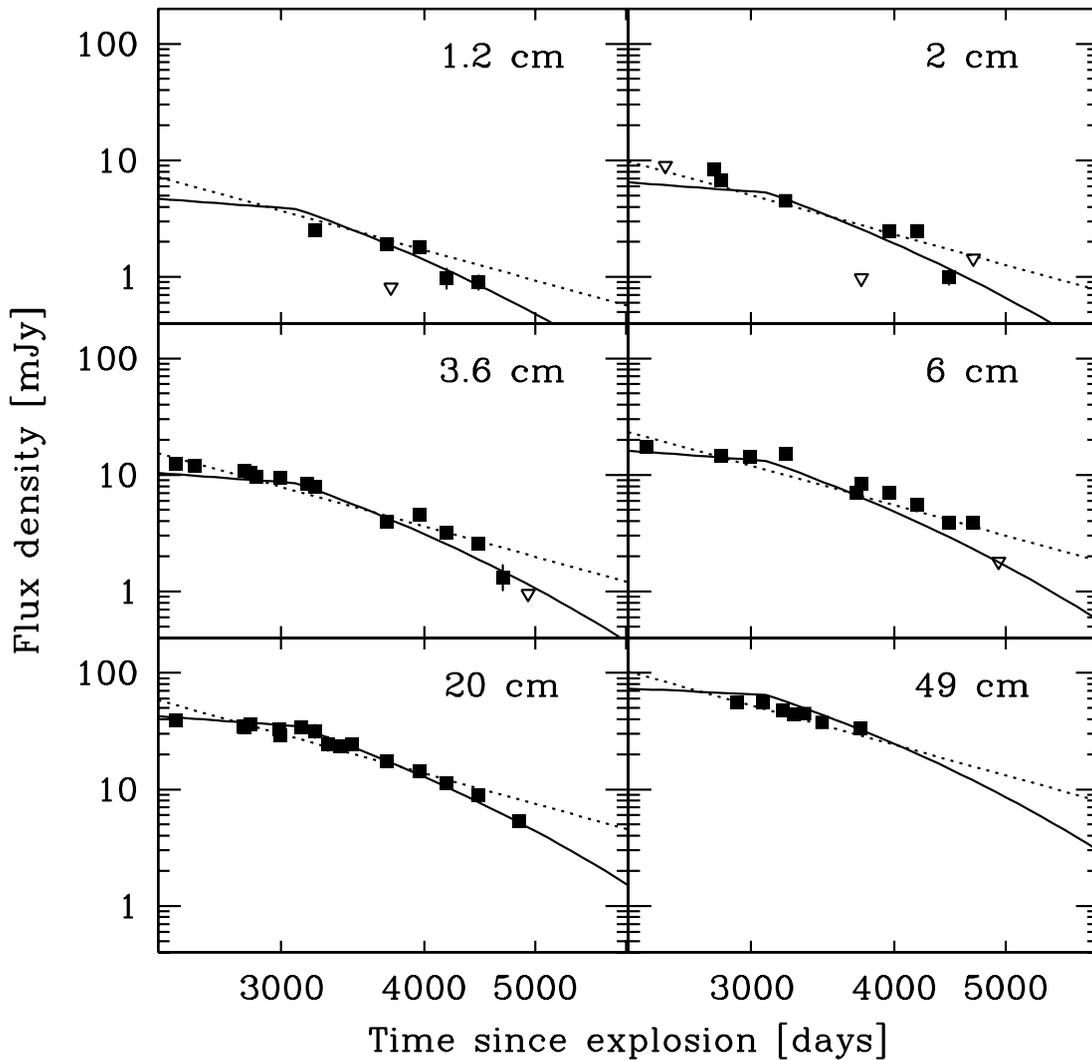


FIG. 11.—“Late” (after day 3100) radio light curves, plotted from left to right and top to bottom at 1.2, 2, 3.6, 6, 20, and 49 cm. Since all absorption processes are negligible, the best model consists of a constant spectral index α fixed from the best-fit “early” light curve model, a decline rate β , and a normalization K_1 . Whereas the “early” data before day 3100 were described by a decline rate of $\beta = -0.7$, the “late” data require a decline rate of $\beta = -2.7$, shown as the dotted lines. However, a constant decline rate β is clearly not the best description of the data and an exponential decline with an e -folding time of 1100 days (solid lines) is a better description. Upper limits (3σ) are shown as open inverted triangles.

frequencies simultaneously indicates that the decay is the result of a phenomenon whose e -folding time at all frequencies is very short. In other words, the observed decay appears to be dominated by the decline of a synchrotron emission energy supply, such as that derived from the blast wave-CSM interaction, implying a sudden variation in the circumstellar density (and, therefore, in the mass-loss rate) rather than an energy loss reflecting the cooling times at individual frequencies.

Interpreting this exponential decay in terms of a sudden decrease of the CSM density leads to a presupernova density distribution that decreases like $r^{-1.61}$ up a distance of 2.4×10^{17} cm, and has a sudden drop by a factor of ~ 3 by a radius of $\sim 4 \times 10^{17}$ cm. To cause this, the mass-loss rate had to have a steep enhancement by at least a factor of 3 around 8000 yr before the supernova explosion and to decrease afterward at a rate proportional to $t^{-0.39}$. This scenario is illustrated in Figure 12, that shows the mass-loss rate as function of the time before explosion (*left*) and the H number density as a function of radius (*right*). The heavy solid curves correspond to behaviors actually constrained by the radio observations, whereas the dashed curves are extrapolations as a simple power law very near to the star and as

an exponential cutoff plus a constant mass-loss rate at large times (radii) before explosion. This last, an assumed constant mass-loss rate at large times before explosion, is simply notional, since our observations provide no constraints at such times (radii). The dotted lines are power-law extrapolations of the density for larger radii, or the mass-loss rate at earlier epochs, which are drawn just to guide the eye to better appreciate the variations.

In astrophysical terms our empirical result suggests that the progenitor star underwent a shell ejection that, ~ 8000 yr before the supernova explosion, increased the effective mass-loss rate from the star by possibly an order of magnitude, which then slowly decreased with time. This phenomenon is reminiscent of the recurrent shell ejections considered by Panagia & Bono (2001) for stars of masses around $12\text{--}14 M_{\odot}$ that become pulsationally unstable in their red supergiant phases.

5.4. Spectral Index Evolution

In addition to the radio light curves and their comparison with models, it is also possible to examine the spectral index evolution and its comparison with pure SSA (Fig. 4) and pure FFA (Fig. 5) model predictions. Examination of both figures shows

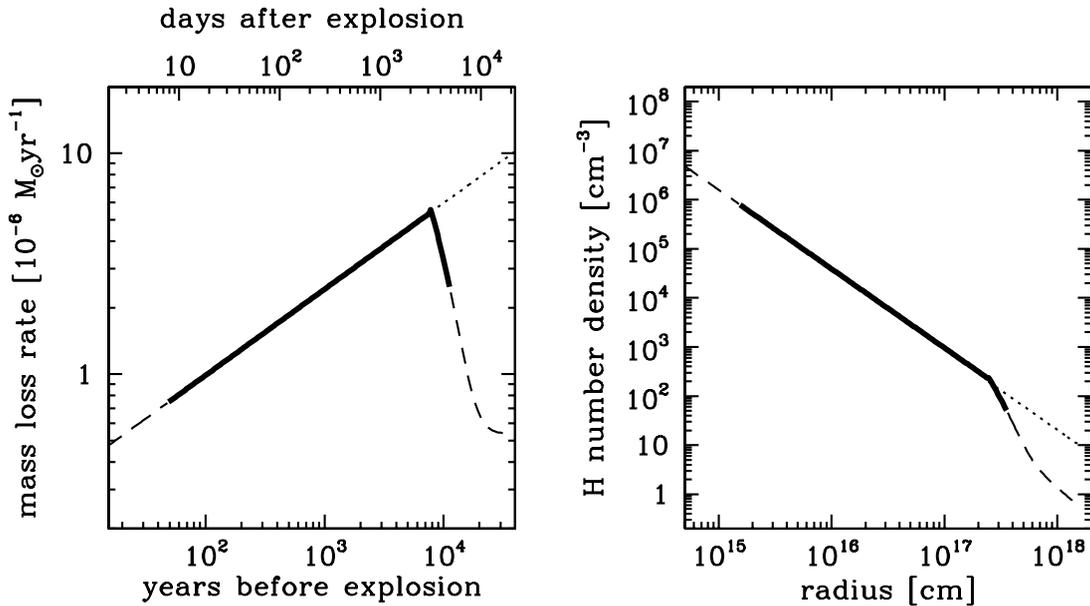


FIG. 12.—*Left*: Presupernova mass-loss rate as function of the time before explosion. *Right*: CSM hydrogen number density as a function of radius. The heavy solid curves correspond to behaviors actually constrained by the radio observations, whereas the dashed curves are extrapolations as a simple power law very near to the star and an exponential cutoff plus a constant mass-loss rate at large times (radii) before explosion. This last—an assumed constant mass-loss rate at large times before explosion—is simply notional since our observations provide no constraints at such times (radii). The dotted lines are power-law extrapolations of the density for larger radii or the mass-loss rate at earlier epochs, which are drawn just to guide the eye to better appreciate the variations.

that the spectral index evolution is reasonably well described only by the FFA model. However, as discussed earlier, the pure FFA model appears unrealistic when brightness temperature considerations (Fig. 7) are included. Our best model, a combination of both SSA and FFA processes (Fig. 8), fits the spectral index evolution (Fig. 9) quite well and satisfies the brightness temperature limitations (Fig. 10). Nevertheless, deviations can still be noticed in the light curves and in the spectral index evolution because, as mentioned earlier, we cannot expect simple models to describe such a complex phenomenon as a supernova explosion in detail.

Particular note should be made of the late time spectral index evolution. Chandra et al. (2004) suggest a break in the spectrum around day ~ 3200 , with higher frequency flux densities declining faster than lower frequency ones, leading to a steepening of the spectral index. From this they were able to calculate a number of physical properties of the radio emitting region. With data now extending to day ~ 5000 it is possible to check for such a break. Examination of the agreement between our constant spectral index model curves and the data, particularly in Figure 11, does not appear to confirm this suggestion.

5.5. Radio and X-Ray Evolution

A comparison of the radio and X-ray light curves reveals features that can help to understand the SN 1993J phenomenon. The top panel of Figure 13 shows the X-ray light curve as summarized by Zimmermann & Aschenbach (2003) plus two recent measurements obtained with the *Swift* satellite (S. Immler 2007, private communication). We have calculated a fit to the upper envelope of the X-ray data that gives $L_X \propto t^{-0.22}$, i.e., a slope that is a little flatter than the Zimmermann & Aschenbach (2003) value of -0.30 , and that implies a density behavior of $\rho_{\text{CSM}} \propto r^{-1.61}$, again marginally flatter than Zimmermann & Aschenbach (2003) estimate of $\rho_{\text{CSM}} \propto r^{-1.65}$.

The other five panels display the observed radio data (without showing upper limits) at 1.2, 2, 3.6, 6, and 20 cm and their best-

fit curves as already shown in Figure 8 and given in Table 4, column (4). The two vertical dashed lines are meant to guide the eye to two particular events, the rightmost being the already discussed steepening of the flux density decline rate of the radio emission after day ~ 3100 , and the leftmost being an apparent “dip” of the X-ray luminosity around day ~ 460 . Even if the X-ray coverage at late times is rather sparse, the two most recent measurements appear to confirm a steepening seen in the radio decay rate after day 3100, consistent with the same e -folding time of 1100 days. Also, it is intriguing that the radio light curve at 1.2 cm appears to “dip” in a manner similar to the X-ray luminosity around day ~ 460 . Both the X-ray and the 1.2 cm light curves are well enough sampled to provide rough timescales for this event, i.e., the dip has ~ 70 days half-power width at 1.2 cm and ~ 280 days half-power width at X-ray wavelengths.

Since radio emission is due to synchrotron processes, whereas the X-ray emission is accounted for by reverse shock heating, these coincidences in the overall evolution suggest that the observed variations are the result of a change in the efficiency of the energy supply, i.e., most likely due to anomalies in the circumstellar medium density distribution. On the other hand, it is not clear why a significant variation is observed in the 1.2 cm flux density at the time of the X-ray dip around 460 days, but no appreciable changes are recorded at other equally well sampled radio frequencies.

6. CONCLUSIONS

We present detailed radio observations of SN 1993J at multiple wavelengths for ~ 13 yr after explosion. This data collection arguably represents the most detailed set of observations of any supernova at any wavelength except for the nearby and spectacular SN 1987A.

The radio emission evolves regularly in both time and frequency, and the usual interpretation in terms of shock interaction with a complex circumstellar medium (CSM) formed by a presupernova structured stellar wind, with the inclusion of both

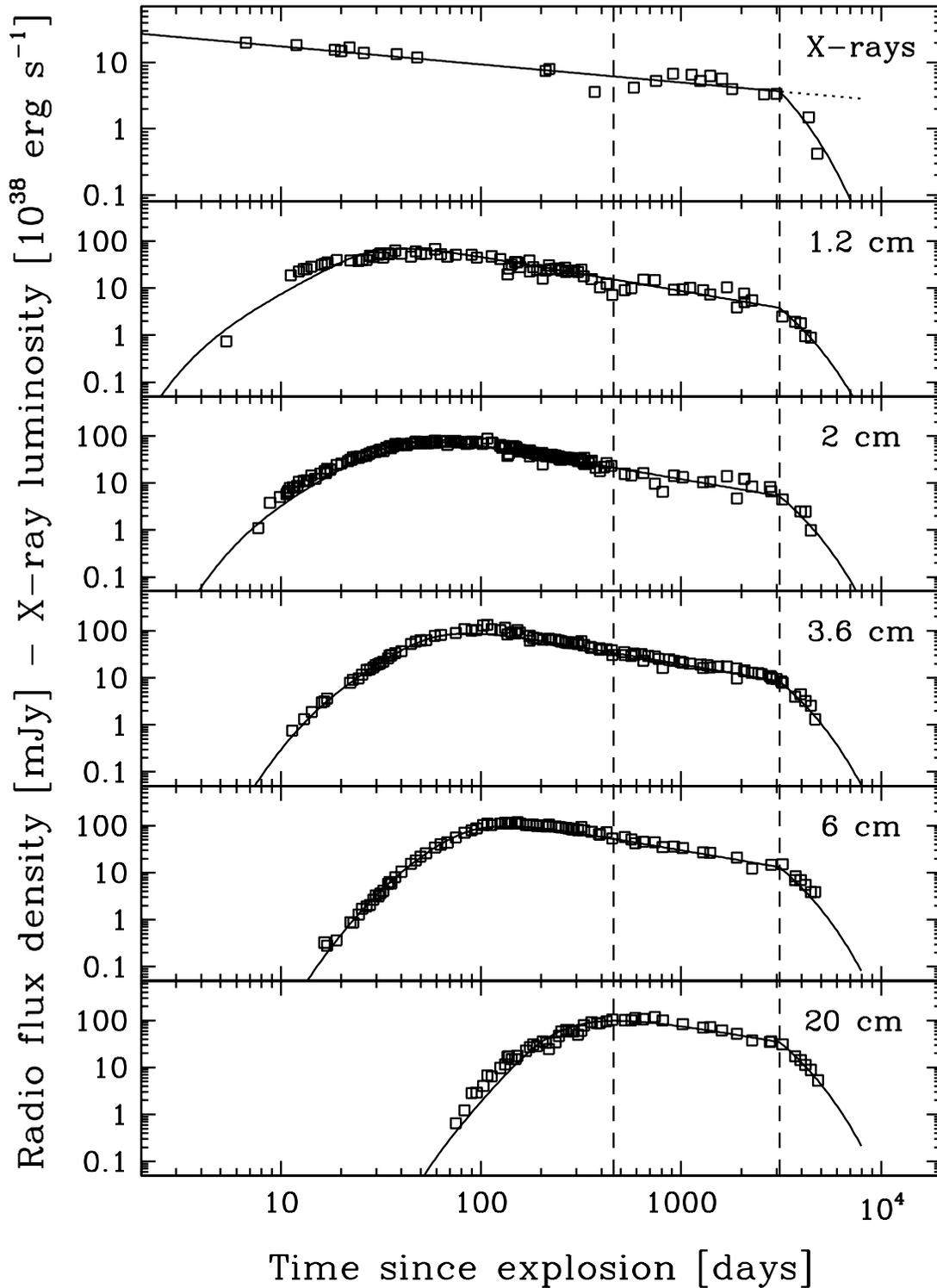


FIG. 13.—X-ray and best-populated radio data sets (no upper limits are shown) plotted on the same timescale for comparison. Each panel is labeled with the wavelength of the observations. The vertical dashed lines denote the epoch of a prominent dip in the X-ray light curve (around day ~ 460) and the beginning of the overall decay at all frequencies (around day ~ 3100). Note that the first X-ray dip corresponds to a similar dip in the 1.2 cm radio light curve that is not prominent at longer radio wavelengths.

synchrotron self-absorption (SSA) and thermal free-free absorption (FFA) at early times, describes the observations rather well considering the complexity of the phenomenon. However, there are some notable characteristics peculiar to SN 1993J: (1) At a time around day ~ 3100 after shock breakout the decline rate of the radio emission steepens from $(t^{+\beta}) \beta \sim -0.7$ to -2.7 without change in the spectral index ($\nu^{+\alpha}; \alpha \sim -0.81$); this variation, however, can better be described in terms of an exponential decay start-

ing at day ~ 3100 with an e -folding time of ~ 1100 days. (2) The spectral index appears constant throughout our measurement era. (3) The best overall fit to all of the “early” (i.e., before day 3100) data is a model including both SSA and FFA components, evolving to a constant decline rate until the break at day ~ 3100 ; in particular, neither a pure SSA nor a pure FFA absorbing model can provide a fit that simultaneously reproduces the light curves and the spectral index evolution and provides a physically realistic

brightness temperature evolution. (4) The radio and X-ray light curves display quite similar behavior and their comparison suggests the presence of at least two episodes of change in the supernova progenitor mass-loss rate in the last several thousand years before explosion.

We are indebted to the VLA TAC and schedulers for permitting and arranging our numerous observations over many years and to observers who have contributed data at other radio wave-

lengths, sometimes unpublished. K. W. W. wishes to thank the Office of Naval Research (ONR) for the 6.1 funding supporting his research. C. J. S. is a Cottrell Scholar of Research Corporation and work on this project has been supported by the NASA Wisconsin Space Grant Consortium. N. P. is Astronomer Emeritus at the Space Telescope Science Institute (STScI) that kindly provided research facilities and partial support for this work. J. M. M. acknowledges support from grant AYA2006-14986-C02-02. Additional information and data on radio supernovae can be found on <http://rsd-www.nrl.navy.mil/7213/weiler/sne-home.html> and linked pages.

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