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LIGHT CURVE STUDIES OF SN 1993J AND SN 1994I

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ABSTRACT

Numerical light curve calculations have been carried out to constrain the light-curve parameters of the recent SNs 1993J and 1994I. For SN 1993J the radius of the progenitor star is constrained to be in the range 2–4 $\times 10^{13}$ cm which is consistent with the candidate progenitor star. The ejected mass is constrained to be in the range 1.9–3.5 $M_{\odot}$; equating the ejected mass to the helium core mass of the progenitor implies a main-sequence mass in the range 12–17 $M_{\odot}$. Using the new Cepheid distance to M81, the ejected ^{56}Ni mass is found to be in the range 0.10–0.14 $M_{\odot}$. For SN 1994I the ejected mass is in the range 0.9–1.3 $M_{\odot}$; equating the ejected mass to the carbon-oxygen core mass of the progenitor implies a main-sequence mass in the range 13–20 $M_{\odot}$. For a distance of 7 Mpc and an extinction $A_V = 1.4$ mag, the ejected ^{56}Ni mass is found to be 0.07 $M_{\odot}$. Recent studies of galactic chemical evolution have suggested that the main-sequence masses and ejected ^{56}Ni masses of core collapse SNs may be inversely correlated. We examine this effect for 1993J, 1994I, and 1987A, but the small number of known nickel mass–main-sequence mass systems makes it too early to draw definitive conclusions.

Subject headings: stars: evolution — supernovae: general — supernovae: individual (SN 1993J, SN 1994I)

1. INTRODUCTION

Because it showed strong hydrogen lines in its early optical spectra, SN 1993J was a Type II supernova. The helium lines and the somewhat weak hydrogen lines of its later spectra caused it to be classified Type IIb (Filippenko, Matheson, & Ho 1993; Nomoto et al. 1993; Woosley et al. 1994) or Type IIpec (Baron et al. 1995c) and indicated that most of the hydrogen envelope of the progenitor star had been lost before the explosion. The light curve of SN 1993J, like that of SN 1987A, showed an initial decline followed by a rise to a second peak, but the SN 1993J light curve evolved much faster. Most studies of the early light curve of SN 1993J, up to 90 days after explosion, concluded that the ejected mass was low, 1.6 to 3.0 $M_{\odot}$, and that the ejected hydrogen mass was only 0.1 to 0.3 $M_{\odot}$ (Podsiadlowski et al. 1993; Ray, Singh, & Sutaria 1993; Nomoto et al. 1993; Bartunov et al. 1994; Utrobin 1994; Woosley et al. 1994; Shigeyama et al. 1994). These studies were based on various values of the interstellar extinction of SN 1993J, and on an assumed distance of 3.3 Mpc.

Because it lacked conspicuous lines of hydrogen, He I, and Si II in its early optical spectra, SN 1994I was a Type Ic supernova. The light curve showed a quick rise to a single narrow peak followed by a rapidly declining tail, indicating that the ejected mass was low and that the entire light curve was powered by the radioactive decay of ^{56}Ni and ^{56}Co. The early light curve (the first 60 days), together with the lack of conspicuous He I lines in the optical spectrum, indicated that the immediate progenitor of SN 1994I was the carbon-oxygen core of a massive star (Nomoto et al. 1994; Iwamoto et al. 1994; Woosley, Langer, & Weaver 1995).

In this Letter we study the light curve of SN 1993J to 300 days, using the most recent estimate of the extinction, $A_V = 0.6$ (Lewis et al. 1994), and the recent Cepheid-based distance of 3.63 ± 0.4 Mpc (Freedman et al. 1994). We also study the light curve of SN 1994I to 90 days. The objective is to constrain the following light curve parameters: progenitor radius, ejected mass, kinetic energy, ejected hydrogen mass, ejected ^{56}Ni mass, and the extent of ^{56}Ni mixing. Because SN 1993J still retained a small portion of its hydrogen envelope when it exploded, the ejected mass inferred from the light curve can be used to estimate the helium core mass and therefore the main sequence mass of its stellar progenitor. Similarly, because SN 1994I still retained a small portion of its helium (as indicated by the probable detection [Filippenko 1994] of the He I λ10830 line), the ejected mass of SN 1994I can be used to estimate the C—O core mass and then the main sequence mass of its progenitor. The main sequence masses and ejected ^{56}Ni masses of SN 1993J and 1994I, together with known values for SN 1987A, allow us to begin to look for a relation between main-sequence mass and ejected ^{56}Ni mass for massive stars.

2. DATA AND MODELS

For SN 1993J we use the bolometric light curves as constructed by Lewis et al. (1994) and Richmond et al. (1994). Because our calculated light curves assume that the radiation is distributed as a blackbody, we use the bolometric light curves that were constructed by fitting blackbodies, rather than by spline fitting, to the broad band photometry. We have scaled the bolometric light curves to the Cepheid-based distance of 3.63 ± 0.4 Mpc (Freedman et al. 1994). We note that distances based on spectral fitting (Baron et al. 1993, 1995a, Baron, Hauschildt, & Branch 1994) and radio observations (Bartel et al. 1994) of SN 1993J tend to give somewhat longer distances, near 4.0 Mpc. The extinction is taken to be $A_V = 0.6$ (Lewis et al. 1994). Clocchiatti et al. (1995) have suggested that the extinction should be higher $A_V = 0.74 \pm 0.05$, but for now we adopt the lower value and take the uncertainty into account in our errors.

For SN 1994I we use the bolometric light curve as constructed by Schmidt & Kirshner (1994). Also following Schmidt & Kirshner (1994) the distance to M51 is assumed to be 7.0 Mpc. The extinction is taken to be $A_V = 1.4$ mag (Baron et al. 1995b; Schmidt & Kirshner 1994).

We calculated light curves for presupernova models based on evolved stellar models with main sequence masses in the

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TABLE 1

LIGHT CURVE PARAMETERS FOR SN 1993J

Radius (10^{13} cm)	M_{ej} ($M_\odot$)	E (10^{51} ergs)	M_{ej}(H) ($M_\odot$)	M(He Core) ($M_\odot$)	M(MS) ($M_\odot$)	M_{ej}(^{56}Ni) ($M_\odot$)
3	1.9	1.0	0.4	3.1	12	0.14
3	2.6	1.0	0.2	4.0	15	0.1
3	3.5	1.35	0.1	5.0	17	0.1

range 13–20 $M_\odot$, from Nomoto & Hashimoto (1988) and Weaver & Woosley (1993). For SN 1993J we replaced the hydrogen envelope of the precollapse models with a smaller hydrogen atmosphere of 0.1–0.5 $M_\odot$ by means of homology transformations, and the radius of the atmosphere was also varied homologously (Young 1994). Similarly, for SN 1994I the hydrogen and helium envelopes were replaced by a small helium atmosphere. Explosions were produced by artificially placing kinetic and thermal energy above a mass cut of 1.6 $M_\odot$ in the amounts required to give the ejecta the desired final kinetic energies. The calculations were carried out with a spherically symmetric, LTE, flux limited diffusion hydrodynamical code, with Cox-Stewart opacities and variable floor opacities to account for the effects of lines and nonthermal ionization. We used a simple description of gamma-ray deposition (Young 1994), a modified version of the method of Sutherland & Wheeler (1984).

3. SN 1993J

The light curve of SN 1993J can be fit with a range of models, because the effects of the light-curve parameters are correlated. For example, a decrease in the ejected mass can be compensated for by a decrease in the kinetic energy and increases in the hydrogen envelope mass and the ^{56}Ni mass. Our favored set of parameters, with an ejected mass of 2.6 $M_\odot$, as well as the parameters for the minimum (1.9 $M_\odot$) and maximum (3.5 $M_\odot$) ejected masses for which we obtain reasonable fits, are given in Table 1. In all three models ^{56}Ni was mixed uniformly throughout the helium core, which we have found to well reproduce the light curve shape. Due to the low ejecta mass the light curve parameters are relatively insensitive to the amount of mixing assumed. The fit of the favored model to the SN 1993J light curve is shown in Figure 1.

Figure 1 also illustrates how we estimate the ^{56}Ni mass. The initial peak is powered by the diffusive release of shock energy from the outer layers of the ejecta. The secondary peak is produced by radiation that was heated after the explosion by ^{56}Ni and ^{56}Co radioactivity. After the photosphere recedes, the light curve "tail" is powered only by the spontaneous deposition of energy from radioactivity. For SN 1987A, which ejected a much greater mass, the transition from the secondary peak to the tail was easily identified. For SN 1993J the transition is not so obvious but a reasonable estimate is at about 40 days; this is indicated by an arrow in Figure 1. Before that time the luminosity can exceed the instantaneous radioactivity luminosity, but after that time, a decreasing fraction of the spontaneous radioactivity luminosity is thermalized and the luminosity must be less than the radioactivity luminosity. The radioactivity luminosities for ^{56}Ni masses of 0.14, 0.1, 0.07 $M_\odot$ are shown in Figure 1. On this basis we estimate the ^{56}Ni mass to be 0.1 $M_\odot$ for our favored model for SN 1993J.

The radius of the SN 1993J progenitor star affects only the initial peak of the light curve. The larger the radius, the

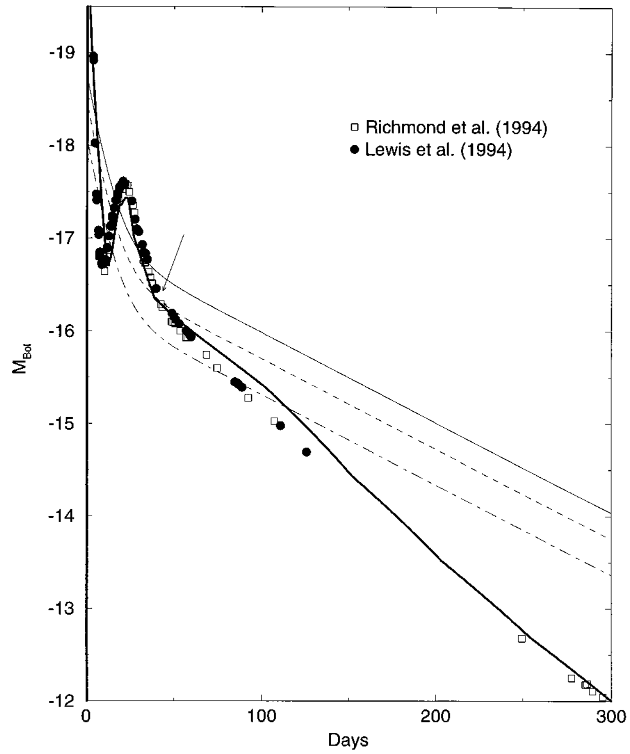

FIG. 1.—Light curve of our favored model (see Table 1) for SN 1993J (*thick solid line*) is fit to the observed bolometric light curve. The transition from the secondary peak to the tail (see text) is indicated by an arrow. The radioactivity luminosities, for ^{56}Ni masses = 0.14, 0.10, and 0.07 $M_\odot$, are indicated by the solid, dashed, and dot-dashed lines, respectively.

brighter and broader the initial peak. In Figure 2 pre-maximum observations are used to constrain the radius. In order to fit the first bolometric point plotted at 5 days, and to avoid violating the upper limit plotted at 2 days, the progenitor radius is constrained to be in the range 2–4 $\times 10^{13}$ cm.

Is the progenitor radius deduced from the light curve consistent with the radius of the candidate progenitor star? The latter, according to Podsiadlowski et al. (1993) and Aldering et al. (1994), is a G to early K supergiant with $-6 < M_{bol} < -8$, which confines it to the rectangle shown in Figure 3. The dashed lines correspond to our limits on the radius from the light curve and are consistent with the candidate progenitor star.

4. SN 1994I

For SN 1994I we considered two models, the parameters of which are listed in Table 2. In both models the ^{56}Ni was mixed uniformly throughout the C—O core, i.e., essentially throughout the entire ejecta. The two models have the same ratio of kinetic energy to ejected mass and, as shown in Figure 4, both models can account for the width of the peak of the bolometric light curve although for our adopted distance the higher mass model is somewhat favored. While our ejected mass is in general agreement with the results of Iwamoto et al. (1994) and Woosley et al. (1995), Iwamoto et al. (1994) prefer lower ejected masses and Woosley et al. (1995) prefer higher ejected masses. Without more detailed models we can only constrain the main sequence mass of the progenitor to the broad range 13–20 $M_\odot$.

The possibility of producing the C—O progenitor star by

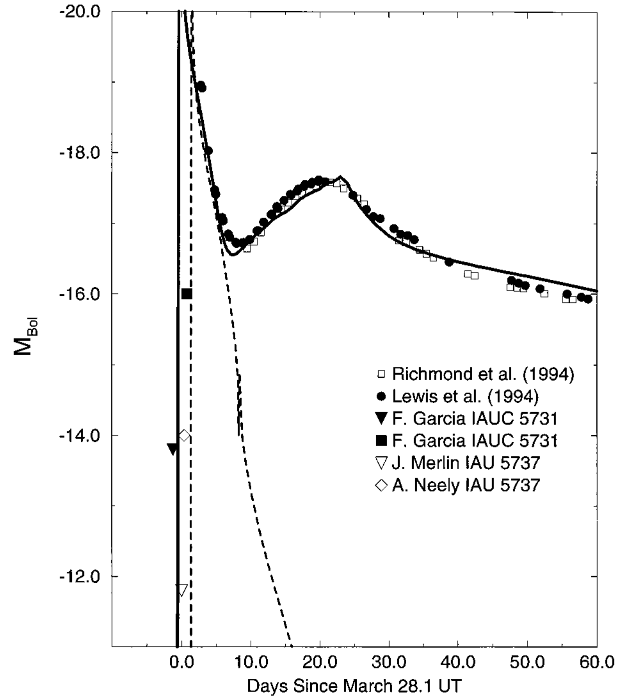

FIG. 2.—Earliest observations taken together with the bolometric light curve provide constraints on the initial radius of the progenitor star. The model calculations have initial progenitor radii, $R = 2.0 \times 10^{13}$ cm (*dashed line*) and $R = 4.0 \times 10^{13}$ cm (*solid line*). The triangles are upper limits and no bolometric corrections have been applied to the early observations of Ripero & Garcia (1993), Neeley (1993), and Merlin (1993).

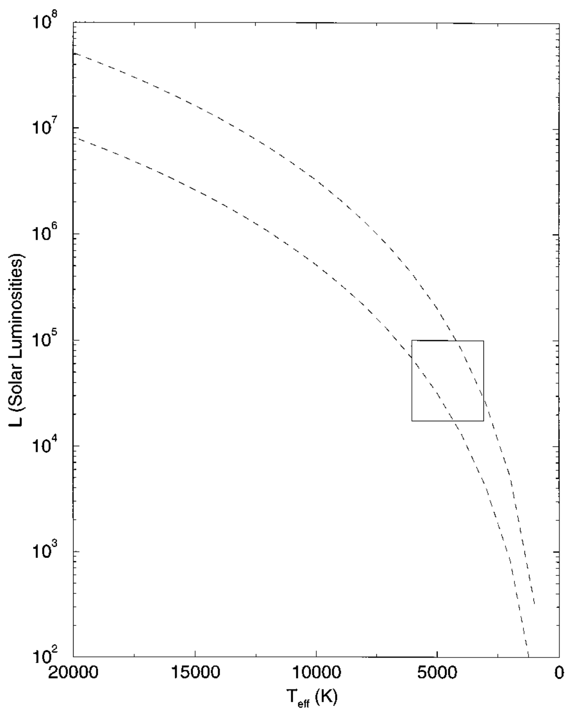

FIG. 3.—SN 1993J progenitor on HR diagram. The rectangle shows the position of the candidate progenitor star of SN 1993J. The dashed lines correspond to the maximum and minimum radii of the progenitor star according to our analysis of the light curve.

TABLE 2

LIGHT CURVE PARAMETERS FOR SN 1994I

M_{ej} ($M_\odot$)	E (10^{51} ergs)	M_{ej}(He) ($M_\odot$)	M(C—O Core) ($M_\odot$)	M(MS) ($M_\odot$)	$M_{ej}(^{56}Ni)$ ($M_\odot$)
0.9	1.0	0.05	<1.5	<15	0.07
1.3	1.4	0.05	<2.4	<20	0.07

means of two Roche overflow episodes has been discussed by Nomoto et al. (1994), and by means of one Roche overflow followed by a stellar wind by Woosley et al. (1995). Because the whole light curve of SN 1994I is powered by radioactivity, the inferred ^{56}Ni mass depends on the adopted extinction and distance. For an extinction $A_V = 1.4$ and a distance of 7 Mpc we determine a ^{56}Ni mass of 0.07 $M_\odot$. Our models do not fit the light curve as well if we assume a smaller extinction. This is due to the fact that when a lower extinction is assumed, the difference between peak and tail is significantly reduced in the reconstructed light curve (Schmidt & Kirshner 1994).

5. DISCUSSION

The ^{56}Ni masses and the main sequence masses of SNs 1993J, 1994I, and 1987A (Arnett et al. 1989) are plotted in Figure 5. For SN 1993J the plotted nickel mass includes uncertainties in distance (0.4 Mpc), extinction (0.2 mag), and the nickel mass obtained from our models (0.015 $M_\odot$). For SN 1994I we take the uncertainties to be 0.5 mag in extinction and a 20% distance uncertainty.

The ejected ^{56}Ni mass as a function of main-sequence progenitor mass is an important input to models of galactic chemical evolution. It has been suggested that more nickel may be ejected from lower mass progenitor stars (Nomoto et al. 1991). It has also been argued that such a trend is helpful to account for the Fe abundances found in halo stars and in

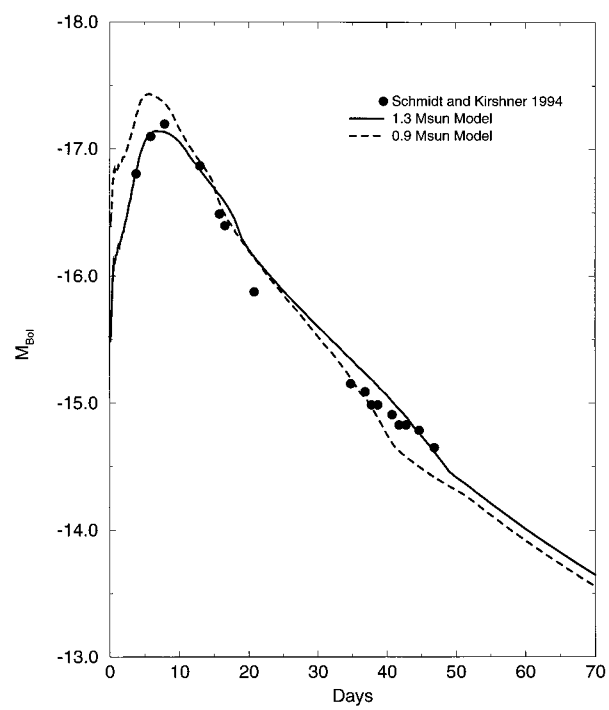

FIG. 4.—Light curves calculated for the parameters listed in Table 2 are compared to the bolometric light curve of SN 1994I.

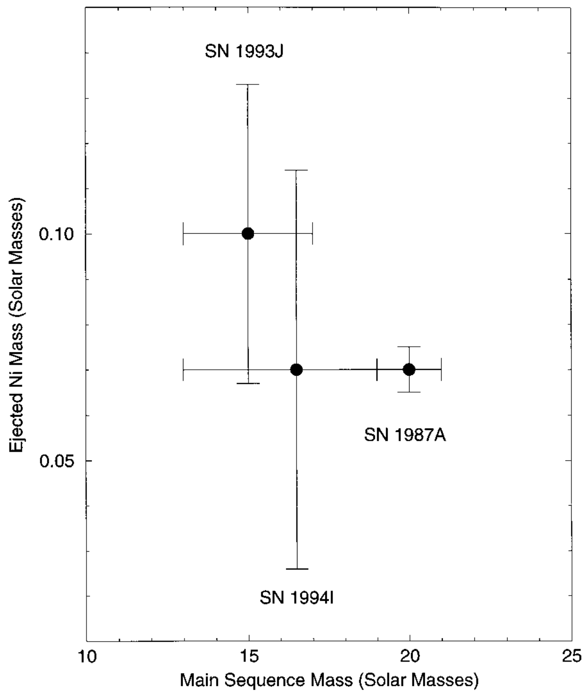

FIG. 5.—Ejected ^{56}Ni mass is plotted against main sequence mass, for SNs 1993J, 1994I, and 1987A.

models of galactic chemical evolution (Thielemann et al. 1993, 1995; Tsujimoto et al. 1993). It seems plausible that the nickel mass ejected depends to zero-order on the core mass at the time of explosion, so that one would expect a different relation for the ejected nickel mass and the ZAMS mass between single stars and those in binaries. If the ejected nickel mass also depends on fallback, the relation may also depend on envelope size at the time of core collapse. Detailed chemical evolution models will need to include statistical averages over the realization frequencies, and binary histories of such systems. Therefore, continued observations and analyses of supernova rates and binary frequencies are quite important. Examining Figure 5, it is apparent that for the core collapse supernovae where the nickel mass and progenitor main-sequence mass are known, the errors make any attempt to discern a trend premature. The largest error in extracting a nickel mass is due to the distance uncertainty, which can be overcome when a detailed analysis of spectra is available. Thus, while a light curve analysis is crucial for obtaining information about the progenitor and nucleosynthesis, spectra are also important.

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