MAXIMUM BRIGHTNESS AND POSTMAXIMUM DECLINE OF LIGHT CURVES OF TYPE SUPERNOVAE Ia: A COMPARISON OF THEORY AND OBSERVATIONS

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ABSTRACT

We compare the observed correlations between the maximum brightness, postmaximum decline rate, and color at maximum light of Type Ia supernovae (SNs Ia) with model predictions.

The observations are based on a total of 40 SNs Ia, including 29 SN of the Calan Tololo Supernova Search and 11 local SNs which cover a range of ≈ 2 mag in the absolute visual brightness. The observed correlations are not tight, one dimensional relations. Supernovae with the same postmaximum decline or the same color have a spread in visual magnitude of ≈ 0.7 mag. The dispersion in the color-magnitude relation may result from uncertainties in the distance determinations or the interstellar reddening within the host galaxy. The dispersion in the decline rate–magnitude relation suggests that an intrinsic spread in the supernova properties exists that cannot be accounted for by any single relation between visual brightness and postmaximum decline.

Theoretical correlations are derived from a grid of models which encompasses delayed detonations, pulsating delayed detonations, the merging scenario, and helium detonations. We find that the observed correlations can be understood in terms of explosions of Chandrasekhar mass white dwarfs. Our models show an intrinsic spread in the relations of about 0.5 mag in the maximum brightness and ≈ 0.1 mag in the $B - V$ color. Our study provides strong evidence against the mechanism of helium detonation for subluminous, red SNs Ia.

Subject headings: cosmology: observations — cosmology: theory — distance scale — supernovae: general

1. INTRODUCTION

Supernovae of Type Ia are the most luminous stellar objects and, in principle, can be used to determine extragalactic distances and the cosmological parameters. Their use as standard candles is based on the assumption that they form a homogeneous group. However, Type Ia supernovae (SNs Ia) have long been suspected to not be perfectly homogeneous, from both their light curves and their spectra (Pskovskii 1970, 1977; Barbon, Ciatti, & Rosino 1973; Barbon et al. 1990; Branch 1981; Elias et al. 1985; Frogel et al. 1987; Phillips et al. 1987; Cristiani et al. 1992). The discovery of the strongly subluminous supernova SN 1991BG established the existence of a wide range of luminosities among SNs Ia (Filippenko et al. 1992; Leibundgut et al. 1993). New, uniform data sets of high quality confirm this diversity (Hamuy et al. 1993; Maza et al. 1994; Suntzeff 1995; Hamuy et al. 1996). From these data, the existence of a correlation between the maximum brightness and the shape of the light curves was established, used to correct for the variations in the absolute brightness, and used

to determine H_0 (Phillips 1993; Hamuy et al. 1995; Riess, Press, & Kirshner 1995).

It is widely accepted that SNs Ia are thermonuclear explosions of carbon-oxygen white dwarfs (Hoyle & Fowler 1960). The three main scenarios are the explosion (1) of a Chandrasekhar mass white dwarf (Arnett 1969; Nomoto, Sugimoto, & Neo 1976; Nomoto, Thielemann, & Yokoi 1984; Khokhlov 1991), (2) of merging white dwarfs (Tutukov & Yungelson 1983; Iben & Tutukov 1984; Webbink 1984), and (3) of a low-mass white dwarf triggered by a helium detonation at its surface as suggested by Nomoto (1981) and Woosley, Taam, & Weaver (1980). Within each scenario different amounts of ^{56}Ni can be produced depending on details of the progenitor evolution, presupernova structure, and flame propagation. Because Ni is the main energy source for the light curve, the brightness of the models must be expected to vary. Detailed modeling of the light curves shows that they differ in both their brightness and their shape, but their physical correlation differs depending on the scenario (Höflich, Khokhlov, & Müller 1993). Therefore, a comparison between theory and
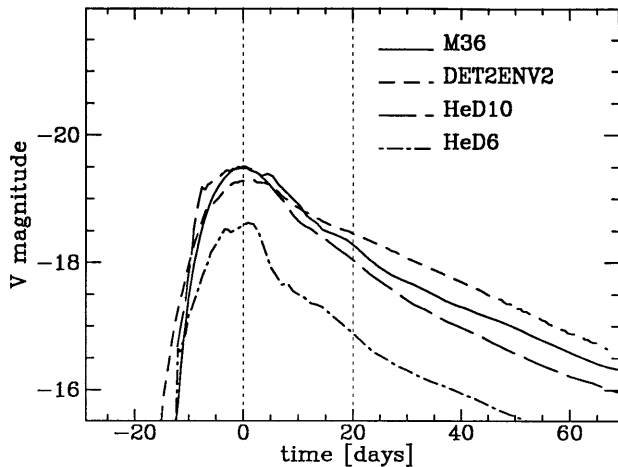
FIG. 1.—Visual light curves for the delayed detonation model M36, the envelope models DET2ENV2, and the helium detonations HeD 6 and 10 (from Khokhlov et al. 1993; Höflich 1995; Höflich & Khokhlov 1996). The two vertical lines mark the time of maximum light and 20 days later. Note that for HeD 6, $\Delta M_V(20)$ does not provide a good measurement for the postmaximum decline.

observations can be used to discriminate among explosion scenarios. The theoretical relation can be further used to determine H_0 independent of secondary distance indicators needed in purely empirical determination (Müller & Höflich 1994; Höflich & Khokhlov 1996, and references therein).

In this Letter, we compare the observed correlations between maximum brightness, the postmaximum decline, and colors of the visual light curves of SNs Ia with theory. The postmaximum decline is characterized by the parameter $\Delta M_V(t)$ defined as the difference between the brightness at maximum light and that t days later. The comparison is based on 40 well-observed supernovae and our light-curve calculations of a set of 42 models. The list of supernovae includes the uniform set of 29 supernovae obtained with the Calan Tololo Supernova Search (SNs 1990O, 1990T, 1990Y, 1990af, 1991S, 1991U, 1991ag, 1992J, 1992K, 1992P, 1992ae, 1992ag, 1992al, 1992aq, 1992au, 1992bc, 1992bg, 1992BH, 1992BL, 1992BO, 1992BP, 1992BR, 1992BS, 1993B, 1993H, 1993O, 1993ag, and

1993ah) and 11 nearby supernovae (SNs 1937C, 1972E, 1980N, 1981B, 1986G, 1989B, 1990N, 1991T, 1991bg, 1992A, and 1994D) (see Hamuy et al. 1996).

2. OBSERVATIONS VERSUS THEORY

To illustrate the nature of $\Delta M_V(t)$, we show in Figure 1 four theoretical V light curves based on different explosion scenarios. The function $\Delta M_V(t)$ provides a particular measure of postmaximum decline rate. The color (V) in which the comparison is made and the value of the time base t must be chosen carefully. We use the visual wavelength range because, past maximum light, most of the energy is emitted in V and, consequently, the theoretical light curves are most accurate in V. Moreover, the spectral variation of the flux across the V filter is smaller than in other bands, e.g., B or R. Consequently, differences induced by the assumed transmission of filters and those actually used during the observations will be smallest (Höflich 1995). We have found that a time base of 15 days, previously used in B by Phillips (1993), does not permit a clear distinction between different visual light waves, because the decline rate in V is much smaller than in B. Moreover, a value of $\Delta M_V(15)$ is not that sensitive to the postmaximum decline but is strongly influenced by the broadness of the maximum. On the other hand, a very long base will measure predominantly the exponential decay at late times. We find that $t = 20$ days is a better choice in order to differentiate the various light curves in V.

In Figure 2, the observed absolute visual brightness M_V is plotted as a function of $\Delta M_V(20)$ based on the light curves observed at Cerro Tolo Inter-American Observatory (CTIO) (Hamuy et al. 1996). The errors are estimated as follows: In M_V, uncertainties are due to uncertainty in the apparent magnitude. For those SNs which were observed at maximum, we estimate an uncertainty of 0.05 mag. For those not observed at maximum light, M_V is determined by fitting template curves to *extrapolate* to a peak magnitude.

In so doing we are essentially comparing the brightnesses at maximum light given by the various templates employed. This technique provides a way to estimate our uncertainty in guessing a quantity that was not observed. For instance, if the
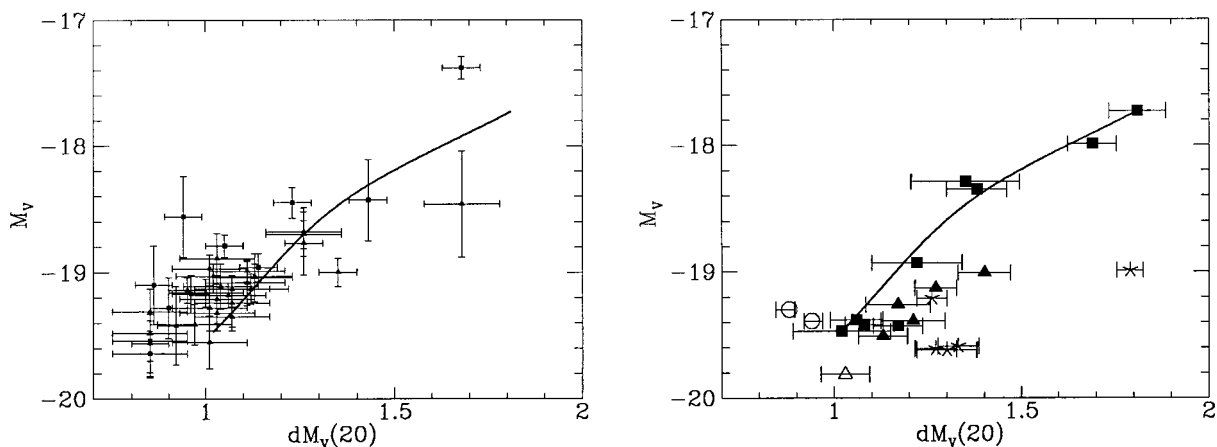

FIG. 2.—Observed M_V as a function $\Delta M_V(20)$ (*left plot*) normalized to $H_0 = 65$ km Mpc^{-1} s^{-1} (Hamuy et al. 1996; Höflich & Khokhlov 1996). In the right plot, the theoretical models are shown for the delayed detonation (*open triangles*: N-series, Khokhlov 1991; *filled triangles*: M-series, Höflich 1995), pulsating delayed detonations (*filled circles*), and merging scenarios (*open circles*) (Khokhlov, Müller, & Höflich 1993; Höflich, Khokhlov, & Wheeler 1995; Höflich & Khokhlov 1996), and for the helium detonations (*asterisks*, Höflich & Khokhlov 1996). The correlation between M_V and $\Delta M_V(20)$ within each set of models is evident. Note that the models of the M- and N-series do produce different relations. Although both are based on the delayed detonation mechanism, the flame velocities and presupernova structures are different. The curve represents the theoretical relations for pulsating delayed detonations given in both plots for orientation.
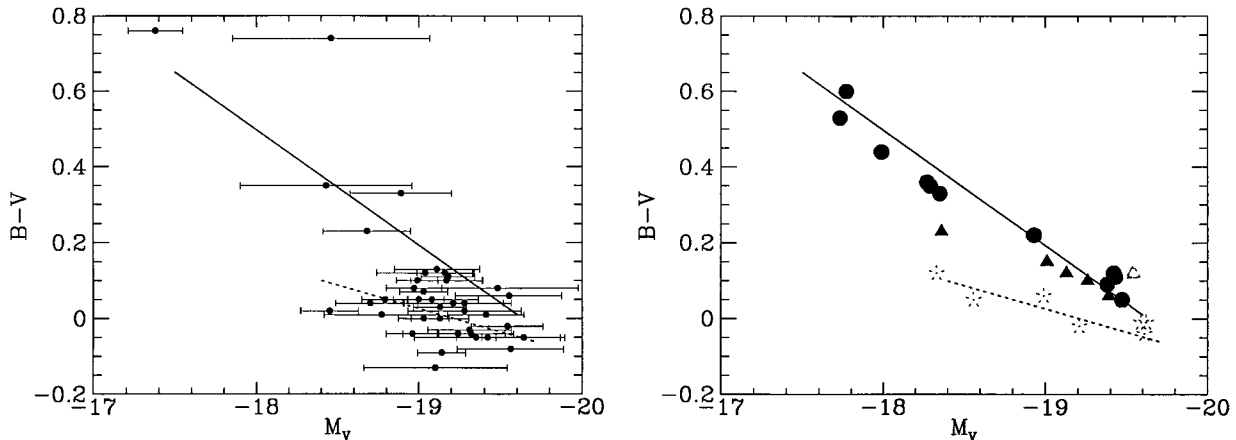
Fig. 3.—Observed (*left*, normalized to $H_0 = 65$ km Mpc^{-1} s^{-1}) and theoretical (*right*) plot of $B - V$ as a function of M_V for the same supernovae and models as in Fig. 2. The observational errors in $B - V$ are of the order of a few hundredths of a magnitude. The lines show the approximate relation for delayed detonations (*solid lines*) of the M-series and helium detonations (*dashed lines*).

best fit yields $V_{\max} = 15.00$ mag and the next-best fit yields 15.25, we quote $V_{\max} = 15.00 \pm 0.25$. Therefore, our error estimates for the peak luminosities are larger than 1 σ, since they cover a range of confidence larger than 67%. Given this uncertainty in the peak apparent magnitude, we add in quadrature an estimate of the foreground extinction correction (0.045 mag), an estimate in the K-term correction (0.02 mag), and the uncertainty of 600 km s^{-1} in the velocity of the cosmological expansion due to the correction for peculiar motions. Another source of error, not included in the error bars (see below), is due to the distance determinations of the host galaxies which are based on the Tully-Fisher (Tully & Fisher 1977) and the surface brightness fluctuations (Tonry & Schneider 1988). For $\Delta M_V(20)$, we adopt an error of 0.05 mag for those SNs whose light curves were observed from maximum light through day 20, and 0.10 mag for others.

The correlation between M_V and $\Delta M_V(20)$ can be clearly seen in Figure 2. With decreasing brightness at maximum light, supernovae decline faster. There is, however, a spread in M_V of about 0.7 mag within the relation. This spread is larger than the estimated error. It may be explained either by the error in the individual distance determinations, by reddening in the host galaxy, by an intrinsic spread among SNs Ia with the same $\Delta M_V(20)$, or by a combination of all these effects. In the first case, this would imply an uncertainty of $\approx 40\%$ in the distance determinations. This is much larger than the relative uncertainties of the Tully-Fisher and the surface brightness fluctuations, which are 12% and 10%, respectively (Jacoby et al. 1992). The error in E_{B-V} of the host galaxy of less than 0.1 mag is probably realistic. Taking the latter error estimates, we are forced to assume an intrinsic spread of M_V of ≈ 0.3 to -0.6 mag of SNs Ia at a given $\Delta M_V(20)$.

The theoretical relation between M_V and $\Delta M_V(20)$ is shown in the right panel of Figure 2. The models do provide a spread in M_V within each explosion scenario, and $\Delta M_V(20)$ decreases with M_V. The largest variation is among delayed and pulsating delayed detonations. Both scenarios show qualitative agreement with the observations within the error bars. For normal bright delayed detonations, however, the postmaximum decline is somewhat steeper than observed. If this systematic tendency is real, models postulating lower central densities of the exploding white dwarfs may be preferred, or expanding envelopes with a more pronounced shell-like structure may be

favored. Helium detonations fall well outside the observed range. They decline much too fast.

In Figure 3, we give $B - V$ as function of M_V for observed supernovae and our models. With decreasing maximum brightness, supernovae become redder (Fig. 3). The color relation again shows a substantial scatter. The reasons may be interstellar reddening (Branch & Miller 1994), errors in the distance determination (see above), or errors intrinsic to the observations, or may reflect an intrinsic spread of properties of SNs Ia, or some combination of the above. Qualitatively, models for the explosion of Chandrasekhar mass white dwarfs follow, within the uncertainties, the same $(B - V)$-M_V relation as the observations. For these models, the intrinsic spread of the $B - V$ relation is apparently of the order of 0.1 mag. Given the intrinsic uncertainties and approximations used for the light-curve calculations, the discrepancies are well within the expected errors. Non-LTE effects, for instance, tend to produce slightly bluer colors (≈ 0.02 to -0.05 mag) at maximum light compared to our light-curve colors (Höflich 1995). Another possible source of systematic errors entering the comparison is connected to the filter response functions of the observations and those used for the theoretical light curves. For dim supernovae, the models are slightly bluer. This can be explained by interstellar reddening, but is more likely due to selective line blanketing (D. Branch 1995, private communication) or dust formation (Dominick, Höflich, & Khokhlov 1995; Höflich & Khokhlov 1996).

Helium detonations show a rather blue, even if somewhat subluminous, color. Their color is clearly in agreement with bright SNs Ia. A very large reddening would be required in order to reproduce the observed extremely subluminous SNs Ia1. For SN 1992K, for instance, E_{B-V} must be as large as 0.7 mag (Hamuy et al. 1994). This would mean an intrinsic brightness of -20.7 mag assuming $A_V = 3.1\, E_{B-V}$, which is inconsistent with the helium models and is out of the reach of even pure detonation models of Chandrasekhar mass white dwarfs ($M_V = -20$ mag; Khokhlov, Müller, & Höflich 1993).

3. CONCLUSIONS AND DISCUSSION

The observed correlations between the absolute brightness and the postmaximum decline rates and $B - V$ color can be understood in terms of explosions of Chandrasekhar mass

white dwarfs. In these models, the variation in brightness is due to different amounts of ^{56}Ni produced in the central region. If little Ni is produced, the envelope stays cooler. This has two effects: the color is redder and the photosphere recedes faster at maximum light, which results in a fast postmaximum decline (Höflich & Khokhlov 1996 and references therein).

For the very same reason, helium detonations show different behavior. In those models, a significant amount of Ni is present in the outer layers. This heats up the photosphere and keeps it hot even in subluminous explosions. The color remains blue. This implies that the red color observed in subluminous SNs Ia must be attributed to interstellar reddening. This, in turn, is incompatible with the maximum brightness (see above). In addition, the postmaximum decline of helium detonations is always steep because, near maximum light, the outer region with substantial ^{56}Ni becomes transparent to γ-rays. This results in a rapid increase of the escape probability and, consequently, in a rapidly declining light curve even for bright SNs Ia. Note that, for normal bright supernovae, early-time spectra indicate expansion velocities of Si-rich layers in excess of 19,000 km s^{-1} (e.g., SN 1990N, Leibundgut et al. 1991; SN1994D, Höflich 1995; SN1995E, A. G. Riess 1995, private communication). In contrast, both one-dimensional and two-dimensional model calculations for helium detonations predict velocities smaller than 14,000 km s^{-1} for these layers (Woosley & Weaver 1994; Livne & Arnett 1995; Höflich & Khokhlov 1996). The restriction of Si to low velocities must be regarded as a generic feature of helium detonations. Within this scenario, a minimum of $0.15–0.2\,M_{\odot}$ of He atop the carbon-oxygen white dwarf is required. Explosive burning of helium at low densities produces mainly ^{56}Ni. To make helium detonations consistent with the limits from early spectra with respect to both the appearance of strong Si lines and the absence of strong Ni lines, the burning products of the outer, former He shell ($M_{He} \approx 0.1–0.2\,M_{\odot}$) must be accelerated to velocities well above $\approx 16,000–18,000$ km s^{-1}. The energy required would be well in excess of the total energy

of a thermonuclear explosion. For more details see Höflich & Khokhlov (1996).

Models do not give one-parameter relations for M_V-$\Delta M_V(20)$ and $(B - V)$-M_V. If a single monotonic relation is used (see Figs. 2 and 3), then a spread exists around this relation of 0.5 mag in M_V and 0.1 mag in $B - V$. Thus, even within a given explosion scenario, models with different flame velocities and presupernova structures do produce the same M_V, but produce different colors and light-curve shapes as a comparison of the models of the N- and M- series reveals (Figs. 2 and 3).

The observations show an even larger spread in both the M_V-$\Delta M_V(20)$ and the $(B - V)$-M_V relation. This may be partially attributed to uncertainties in the distances and interstellar reddening. Within these uncertainties, the observed $(B - V)$-M_V relation may be consistent with a one-parameter relation because the reddening correction enters both $B - V$ and M_V. For the $\Delta M_V(20)$-M_V relation, however, the reddening correction enters M_V only. To attribute the observed spread in $\Delta M_V(20)$-M_V to the reddening alone would require a mean E_{B-V} of at least 0.2 mag. Based on the statistical studies of Branch & Miller (1994) and our individual fits of SN Ia light curves, we regard the implied mean reddening as rather unlikely. This unacceptably high value indicates that at least a part of the variation is intrinsic to SNs Ia. To distangle the different causes of the spread, detailed analyses of the entire light curves and spectra and deeper understanding of the physics of the stellar evolution and explosion is required.

REFERENCES

Arnett, W. D. 1969, Ap&SS, 5, 280
Barbon, R., Benetti, S., Cappellaro, E., Rosino, L., & Turatto, M. 1990, A&A, 237, 79
Barbon, R., Ciatti, F., & Rosino, L. 1973, A&A, 29, 57
Branch, D. 1981, ApJ, 248, 1076
Branch, D., & Miller, D. L. 1993, ApJ, 405, L5
Cristiani, S., et al. 1992, A&A, 259, 63
Dominick, C., Höflich, P., & Khokhlov, A. 1996, ApJ, in preparation
Elias, J. H., Mathews, K., Neugebauer, G., & Persson, S. E. 1985, ApJ, 296, 379
Faber, S. M., & Jackson, R. E. 1976, ApJ, 204, 668
Filippenko, A. V., et al. 1992, AJ, 104, 1543
Frogel, J. A., Gregory, B., Kawara, K., Laney, D., Phillips, M. M., Terndrup, D., Vrba, F., & Whitford, A. E. 1987, ApJ, 315, L129
Hamuy, M., et al. 1993, AJ, 106, 2392
———. 1994, AJ, 108, 2226
Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., & Aviles, A. 1995, AJ, 109, 1
———. 1996, AJ, submitted
Höflich, P. 1995, ApJ, 443, 533
Höflich, P., & Khokhlov, A. P. 1996, ApJ, 457, 500
Höflich, P., Khokhlov, A. P., & Müller, E. 1993, A&A, 268, 570
Höflich, P., Khokhlov, A. P., & Wheeler, J. C. 1995, ApJ, 444, 831
Höflich, P., Khokhlov, A., Wheeler, J. C., Nomoto, K., & Thielemann, F.-K. 1995, in Thermonuclear Supernovae, ed. R. Canal et al. (Dordrecht: Kluwer), in press
Hoyle, F., & Fowler, W. A. 1960, ApJ, 132, 565
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Jacoby, G. H., et al. 1992, PASP, 104, 599

Khokhlov, A. 1991, A&A, 245, 114
Khokhlov, A., Müller, E., & Höflich, P. 1993, A&A, 270, 223
Leibundgut, B., et al. 1991, ApJ, 371, L23
———. 1993, AJ, 105, 301
Livne, E., & Arnett, D. 1995, ApJ, 452, 62
Maza, J., Hamuy, M., Phillips, M. M., Suntzeff, N. B., & Aviles, R. 1994, ApJ, 424, L107
Müller, E., & Höflich, P. 1994, A&A, 281, 51
Nomoto, K. 1981, in IAU Symp. 93, Fundamental Problems in the Theory of Stellar Evolution, ed. D. Sugimoto, D. Q. Lamb, & D. Schramm (Dordrecht: Reidel), 295
Nomoto, K., Sugimoto, D., & Neo, S. 1976, Ap&SS, 39, 137
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M., et al. 1987, PASP, 90, 592
Pskovskii, Y. P. 1970, AZh, 47, 994
Pskovskii, Y. P. 1977, Soviet Astron., 21, 675
Riess, A. G., Press, W. H., & Kirshner, R. P. 1995, ApJ, 438, L17
Suntzeff, N. B. 1995, Workshop on Supernovae, ed. D. McCray (Chicago: Univ. Chicago) in press
Tonry, J. L., & Schneider, D. P. 1988, AJ, 96, 807
Tully, R. B., & Fisher, J. R. 1977, A&A, 54, 661
Tutukov, A. V., & Yungelson, L. R. 1982, in IAU Colloq. 70, Nature of Symbiotic Stars, ed. M. Friedjung & R. Viotti (Dordrecht: Reidel), 283
Webbink, R. F. 1984, ApJ, 277, 355
Woosley, S. E., Taam, R. E., & Weaver, T. A. 1980, in Type I Supernovae, ed. C. Wheeler (Austin: Univ. Texas)
Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371