THE ASTROPHYSICAL JOURNAL, 306:L77–L80, 1986 July 15

TYPE Ib SUPERNOVAE 1983n AND 1985f: OXYGEN-RICH LATE TIME SPECTRA

C. M. GASKELL, E. CAPPELLARO, H. L. DINERSTEIN, D. R. GARNETT, R. P. HARKNESS, AND J. C. WHEELER
Department of Astronomy and McDonald Observatory, University of Texas at Austin
Received 1986 February 10; accepted 1986 April 23

ABSTRACT

Spectra of the Type Ib supernova 1983n in M83 8 months after maximum light show distinct broad emission lines of [O I] λλ6300,6364, [Ca II] λλ7291,7324, Na I λ5890,5896, and Mg I] λ4562. These spectra are very similar to spectra of supernova 1985f discovered by Filippenko and Sargent in NGC 4618, establishing that the latter event was also a Type Ib supernova. The physical conditions in the ejecta and the possible progenitor stars are discussed.

Subject heading: stars: supernovae

I. INTRODUCTION

SN 1983n is the modern prototype of the class of peculiar Type I supernovae SN Ib (Bertola 1964; Bertola, Mammano, and Perinotto 1965; Panagia *et al.* 1986; Elias *et al.* 1985; Wheeler and Levreault 1985; Uomoto and Kirshner 1986; Branch 1986). These events are apparently hydrogen deficient at maximum light, and there is evidence for substantial amounts of helium (Wheeler and Harkness 1986; Harkness *et al.* 1986) although a quantitative interpretation of the spectrum has not yet been presented. They are dimmer than ordinary Type I supernovae (SN Ia) by about 1.5 mag, and hence comparable to Type II (plateau) events. The shape of the optical light curve is similar to that of SN Ia near peak light, with the rise perhaps somewhat slower. Wheeler and Levreault used the latter two facts and a presumption of similar velocities and opacities to SN Ia to argue that core collapse is the driving mechanism for SN Ib rather than the thermonuclear explosion suspected for SN Ia (Sutherland and Wheeler 1984; Nomoto, Thielemann, and Yokoi 1984; Woosley, Axelrod, and Weaver 1984). SN 1983n is slightly off center from a large H II region complex in M83 (Richter and Rosa 1983) and SN 1984l, another SN Ib, is coincident with an H II region in NGC 991 (Levreault 1985).

Infrared light curves clearly distinguish between SN Ia and SN Ib (Elias *et al.* 1985) with SN Ia displaying an absorption dip in J and H at about 20 days and a subsequent secondary peak at 30 days past maximum whereas SN Ib fall monotonically from maximum light. Detection of the 1.644 μm line of [Fe II] 360 days after optical maximum in SN 1983n suggests the presence of $\sim 0.3\ M_\odot$ of iron which might plausibly have resulted from decay of a similar quantity of radioactive ^{56}Ni produced in the explosion (Graham *et al.* 1986). The two recent SN Ib events SN 1983n and SN 1984l have been detected in the radio (Sramek, Panagia, and Weiler 1984; Panagia, Sramek, and Weiler 1986) suggesting the presence of a circumstellar nebula, presumably produced by a wind (Chevalier 1984).

Filippenko and Sargent (1985) reported the discovery of an object of unprecedented observational properties in the galaxy NGC 4618. The spectrum is composed of strong emission lines possibly superposed on a continuum. The most distinctive feature is a blend of the very strong [O I] λλ6300,6364 lines. The stronger λ6300 line is about 90 Å wide [FWHM] corresponding to a Doppler velocity of order 4000 km s^{-1}. Filippenko and Sargent concluded that this object is likely to have resulted from a stellar explosion, and the object has been designated SN 1985f. Other lines identified were Na I D λλ5890,5896 and probably Mg I] λ4562. SN 1985f is projected onto and presumably spatially near to an H II region. Narrow features of this H II region are also observed in the spectrum. Filippenko and Sargent speculate that SN 1985f is related to Cas A and other supernova remnants which show oxygen-rich high velocity filaments.

We present here McDonald Observatory spectra of SN 1983n obtained 8 months after maximum light and of SN 1985f 1 month after discovery. We argue on the basis of these spectra that the event in NGC 4618 must be similar to SN 1983n and discuss the importance of these late time spectra to this class of supernovae.

II. OBSERVATIONS

Spectra of the supernova SN 1983n were obtained by Gaskell using the IDS spectrograph of the 2.7 m telescope at McDonald Observatory on the nights of 1984 February 28 and March 1. SN 1983n fell from $V \approx 11.5$ at peak light to $V \geq 14.6$ at 170$^{\rm d}$ past maximum, the latter point contaminated with Galaxy background (Panagia *et al.* 1986). At the time of the McDonald observations it was estimated to be at $m \approx 15$, approximately 8 months (236 ± 2 days) after optical maximum (Panagia *et al.* 1986). A 4″ square slit was used with seeing of 3″ (FWHM). The wavelength calibration and quartz flatfield lamps were taken at the same declination as M83 with the telescope backed to the mid-hour angle of the observations. The standard star CD $-32°$9927 was used for flux calibration (Stone and Baldwin 1983). Several spectra on two nights showed an rms scatter at 5000 Å of about 0.4 mag, representing the uncertainty in the flux calibration. The uncertainty in the continuum slope in the blue is particularly large because of the high air mass of the observations at approximately $-20°$. A composite of these spectra is pre-

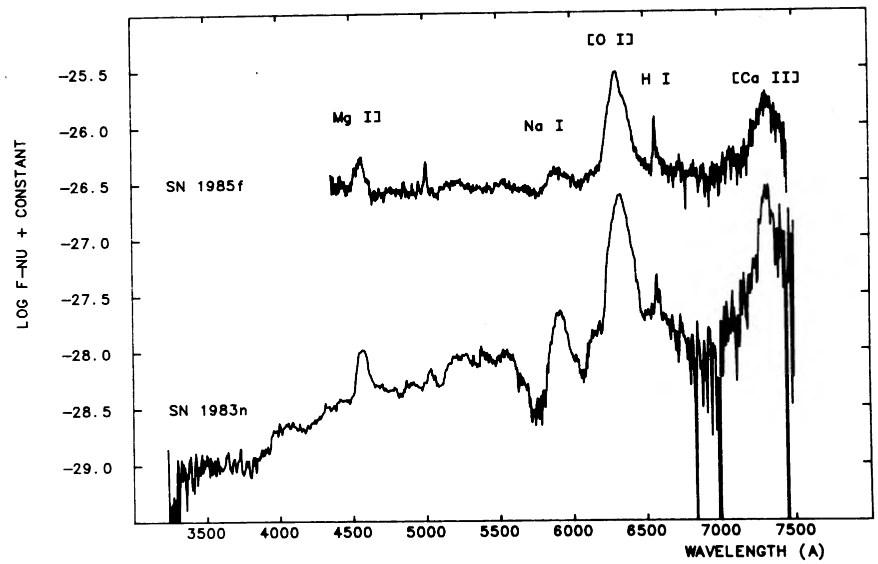

FIG. 1.—The spectrum of SN 1985f in NGC 4618 (*top*) obtained on 1985 March 25, 25 days after discovery is shown in comparison with a composite spectrum from the nights of February 28, 1984 March 1 of SN 1983n in M83 (NGC 5236) (*bottom*). Both spectra are presented in the rest frame of the host galaxy. The flux scale applies to SN 1985f. The spectrum of SN 1983n has been shifted down by a factor 10^2. SN 1983n is a known member of the class of peculiar Type I supernovae SN Ib and the spectral similarity argues that SN 1985f must be a member of this class as well.

sented in Figure 1. Also shown in Figure 1 is the spectrum of SN 1985f obtained by Dinerstein and Garnett using the same equipment on 1985 March 25, 25 days after the Filippenko-Sargent discovery. Clouds may have affected the absolute flux calibration and continuum slope. Other spectra of SN 1985f will be published elsewhere. The strong similarity of the spectra of SN 1983n and SN 1985f shown in Figure 1 argues that these events are of the same class.

In the 25 days between the Filippenko and Sargent (1985) and McDonald observations of SN 1985f, the line ratios seem to have changed little suggesting no rapid change in the spectrum at this epoch although there are discernible changes over a 4 month time scale (Filippenko and Sargent 1986). Figure 1 shows a strong [Ca II] $\lambda\lambda$7291,7324 feature which falls too red for the original Filippenko and Sargent observations but shows clearly in Filippenko and Sargent (1986). In the SN 1983n spectrum the broad emission lines are stronger compared to the continuum and the nebular Hα line. Other nebular lines are difficult to discern. The [O I] λ6300 line seems enhanced compared to the λ6364 line, and the [Ca II] λ7291,7324 feature is stronger with respect to both the [O I] lines than in SN 1985f. The Na D λ5893 and Mg I] λ4562 lines are relatively more distinct compared to the continuum, but weaker with respect to the [O I] lines. Note that there is no obvious evidence in these spectra for [O II] λ3727, [O I] λ5577, or [S II] $\lambda\lambda$4068–4076. Nor is there a sign of helium which is revealed by He I lines for 2 months after maximum in spectra of SN 1983n and SN 1984l (Harkness *et al.* 1986).

The integrated flux of the [O I] $\lambda\lambda$6300,6364 feature in SN 1983n is $f = 5.1 \times 10^{-12}$ ergs s^{-1} cm^{-2} with $A_v = 1$ mag. This yields $L(6300, 6364) = 4.2 \times 10^{40}$ ergs s^{-1} $(d/8.3$ Mpc$)^2$, quite comparable to the value determined for SN 1985f by Begelman and Sarazin (1986) of 5.1×10^{40} ergs s^{-1} $(d/10.6$ Mpc$)^2$ (both on the long scale corresponding approximately to $H_0 = 50$ km s^{-1} Mpc^{-1}). The limit on the flux of λ5577 $L(5577)/L(6300, 6364) < 0.04$ is also very similar to that for SN 1985f (< 0.05). These observations constrain n_e and T and set limits on the oxygen mass. The spectrum of SN 1983n does not include O I λ7774 by which Begelman and Sarazin constrain the amount of O^+ (presuming λ7774 to arise in recombination), so by this means we can only determine that the mass of O^0 exceeds $\sim 0.5\ M_\odot$.

A preliminary numerical collisional ionization analysis suggests that the observed line strengths of [O I] $\lambda\lambda$6300,6364, [Ca II] $\lambda\lambda$7291,7724, Na I $\lambda\lambda$5890,5896, and Mg I] λ4562 can be reproduced by conditions with $n_e \approx 2 \times 10^8$ cm^{-3} and $T \approx 3900$ K. These results suggest that Mg/O may slightly exceed the solar ratio, that Fe/O is approximately solar, and that the upper limit on S/O is consistent with the solar value. Hydrogen may be deficient by as much as a factor of 1000. The mass of oxygen derived in this manner is $\sim 15\ M_\odot$ $(d/8.3$ Mpc$)^{-2}$, a value in agreement with Begelman and Sarazin (1986) but in conflict with other observations of SN Ib (see below). A more extensive quantitative analysis of these spectra will be presented elsewhere.

The spectrum of SN 1983n shows distinct minima at $\sim$ 5700 Å and $\sim$ 6100 Å, spanning the Na D feature. Filippenko and Sargent (1985, 1986) show that these minima were present (though not so deep) at discovery on 1985 February 28 for SN 1985f. The minima were filled in by March 25 (Fig. 1) and continued to be so on June 27 (Filippenko and Sargent 1986). If one adopts the evolution of these minima as a chronometer, then at discovery SN 1985f was at a phase comparable to, or slightly later than, that corresponding to the spectra of SN 1983n in Figure 1, of order 8 months. Filippenko and Sargent (1986) show that the emission lines in SN 1985f shrink with respect to the continuum over a 4 month period, with the [O I] lines dropping more rapidly than Mg I] λ4562. The relatively large ratio of the [O I] to Mg I] features displayed for SN 1983n in Figure 1 again might suggest that SN 1985f was discovered slightly later, $\gtrsim$ 8 months after maximum.

III. DISCUSSION

The hydrogen deficiency, the presence of a circumstellar nebula, and the correlation with H II regions all serve to argue that SN Ib represent the explosion of Wolf-Rayet stars. Near maximum light SN Ib show spectra with some qualitative similarities to SN Ia, and the lines presumably consist of broad overlapping P Cygni lines. Figure 1 shows that by 8 months the spectrum of SN 1983n has changed drastically. At 8 months the spectrum of SN 1983n comprises broad emission lines with perhaps a faint continuum. The apparent large abundance of oxygen in SN 1983n and SN 1985f is further evidence that the progenitors of these supernovae were massive stars. This reinforces the notion that immediately prior to explosion, the progenitor was in a state strongly reminiscent of a Wolf-Rayet star.

Wheeler and Levreault (1985) argued against this interpretation because with approximately constant opacity, the diffusion time through the mass normally associated with Wolf-Rayet stars $\gtrsim 10\ M_\odot$, the light curve would be too broad. This conclusion was simplistic because it neglected the effects of recombination in the expanding material (Cahen, Schaeffer, and Cassé 1986), but not necessarily incorrect. There is apparently a major conflict between the mass derived from the line strength analysis and the constraint from the width of the light curve.

If estimates of their peak brightness have not been overly biased by uncertain extinction corrections, SN Ib are dimmer than SN Ia by ~ 1.5 mag at maximum light. On the other hand, SN Ib may decline more slowly after the initial peak than do SN Ia (Panagia *et al.* 1986). The net result is that on the long distance scale adopted by Filippenko and Sargent an SN Ib event would have an absolute magnitude ~ -18.5 at maximum light and would be ~ -15 mag about 250 days later, extrapolating the light curve of Panagia *et al.* This age estimate is roughly consistent with the estimated luminosity evolution for SN 1983n and with the suggestions from the spectra that SN 1985f at discovery was at about the same age as SN 1983n 8 months after maximum. If these estimates are correct then SN 1985f would have been at maximum in 1984 May or June at $m \approx 12.5$.

The late-time luminosity of these events can not simply be the shock energy deposited by the explosion which would have long since dissipated in the adiabatic expansion. Maximum light could plausibly be explained by the ejection of $\sim 0.2\ M_\odot$ of ^{56}Ni (Wheeler and Levreault 1985), an amount consistent with the iron abundance determined by Graham *et al.* (1986). If so, decay of ^{56}Co should provide some late-time energy input. Neglecting the $8^d.8$ *e*-fold time associated with the decay of ^{56}Ni to ^{56}Co, the expression for the energy deposited by γ-rays and positrons (Wheeler, Branch, and Falk 1980) can be written as

$$L_\gamma = 1.42 \times 10^{43}\ \text{ergs s}^{-1}\ e^{-t/111^d} D_\gamma (M_{\text{Ni}}/M_\odot), \quad (1)$$

and

$$L_+ = 5.47 \times 10^{41}\ \text{ergs s}^{-1}\ e^{-t/111^d} D_+ (M_{\text{Ni}}/M_\odot), \quad (2)$$

respectively, where D_γ and D_+ are the deposition functions representing the efficiency of conversion of γ-rays and positrons to optical energy and M_{Ni} is the mass of ^{56}Ni originally ejected.

For SN 1983n the epoch of observation of the spectra in Figure 1 is well established as 226^d. An integral over the observed flux from ~ 3300 to ~ 7500 Å gives $f = 6.66 \times 10^{-12}$ ergs cm^{-2} s^{-1} and $f = 1.48 \times 10^{-11}$ ergs cm^{-2} s^{-1} if a correction is made for extinction with $A_v = 1.0$. Adopting a distance of 8.3 Mpc (long scale) gives $L \approx 1 \times 10^{41}$ ergs s^{-1}. From equations (1) and (2) this luminosity gives $D_\gamma M_{\text{Ni}} \approx 0.06\ M_\odot$ or $D_+ M_{\text{Ni}} \sim 1.6\ M_\odot$. These values are consistent with the ejection of $\sim 0.25\ M_\odot$ of ^{56}Ni and $D_\gamma \approx 0.25$ at the epoch of observation. Taken at face value this would imply that appreciable γ-ray deposition is still occurring, plausibly due to a rather large ejected mass, and that the positron deposition is still negligible. A value $D_\gamma \approx 0.25$ is perhaps consistent with the rather slow rate of decline of the light curves of SN Ib compared to SN Ia for which the ejecta are increasingly transparent to γ-rays at this epoch. If there is appreciable flux below 3300 Å the value of D_γ could be larger for the same Ni mass. If the distance to M83 is less than assumed above, then D_γ and/or M_{Ni} would be decreased accordingly, although it would still seem likely that γ-ray deposition dominates that of positrons.

For SN 1985f the epoch of observation is uncertain. We will assume 250^d to be specific. Begelman and Sarazin (1986) estimate $L = 3.4 \times 10^{41}$ ergs s^{-1} integrating over the spectrum of Filippenko and Sargent on February 28 and assuming a reddening of $A_v = 0.7$ and a distance of 10.6 Mpc on the long scale. This corresponds to a flux of $\sim 2.5 \times 10^{-11}$ ergs s^{-1} cm^{-2}. We estimate $f \sim 5 \times 10^{-12}$ ergs s^{-1} cm^{-2} for the Filippenko-Sargent spectrum and roughly twice that with an allowance for reddening. An integral over the spectrum of SN 1985f in Figure 1 gives $f = 1.27 \times 10^{-12}$ ergs s^{-1} cm^{-2} with no correction for reddening and $f = 2.98 \times 10^{-12}$ ergs s^{-1} cm^{-2} with a correction for reddening of $A_v = 1.0$. This spectrum extends only to 4300 Å. Extrapolation of the spectrum to ~ 3000 Å would approximately double the integrated flux, and we are somewhat uncertain of the absolute flux calibration. Assuming $f \approx 1 \times 10^{-11}$ ergs s^{-1} cm^{-2} and hence $L \approx 1.3 \times 10^{41}$ ergs s^{-1}, equations (1) and (2) give $D_\gamma M_{\text{Ni}} \approx 0.09\ M_\odot$ and $D_+ M_{\text{Ni}} \approx 2.3\ M_\odot$. This result, within the rather large uncertainties, is quite consistent with the conditions deduced for SN 1983n.

Alternatively, a circumstellar nebula formed by a wind of constant mass-loss rate could provide a nearly constant source of shock heating given by

$$L_{\text{sh}} = 3 \times 10^{40}\ \text{ergs s}^{-1}\ \dot{\mathscr{M}}_{-4}\ v_{\text{SN},9}^3 / v_{W,8}, \quad (3)$$

where $\dot{\mathscr{M}}_{-4}$ is the mass-loss rate in units of $10^{-4}\ M_\odot$ yr^{-2}, $v_{\text{SN},9}$ is the velocity of the supernova ejects in units of 10^9 cm s^{-1}, and $V_{W,8}$ in the velocity of the wind in units of 10^8 cm s^{-1}. This source of energy might contribute at the epochs under consideration.

The potential relation between SN Ib and the oxygen-rich remnant Cas A depends on the magnitude of SN Ib and the extinction and limits on apparent brightness for Cas A. At maximum SN Ib are of order $M_B \approx -17 + 5\log(H_0/100$ km^{-1} s^{-1} Mpc^{-1}). Troland, Crutcher, and Heiles (1985) have recently estimated that patchy extinction toward Cas A could be as large as ~ 9 mag. If $M \approx -17$ to -18.5 then the apparent magnitude of an SN Ib at the site of Cas A would have been $m \sim 2.7$–4.2. This is presumably much brighter than Cas A was at maximum light, particularly if it was Flamsteed's event estimated to be $m \approx 6$ mag (Ashworth 1980). Thus while the oxygen enrichment in the late-time SN Ib events is reminiscent of Cas A and related remnants (N132D in the LMC and the remnant in NGC 4449) there may be significant photometric differences that prevent an immediate identification between the two classes of objects. We note that if Cas A were really subluminous, it must have ejected $\ll 0.1\ M_\odot$ of ^{56}Ni and hence represents a completely different class of explosive event from SN Ia, b or SN II.

IV. CONCLUSIONS

The spectral similarity of the object in NGC 4618 with SN 1983n 8 months after maximum light leaves little room for doubt that they belong to the same class of supernovae, Type Ib. The evidence for oxygen in the late-time spectra of these events added to the hydrogen deficiency, the presence of circumstellar nebulae and the close association with H II regions suggests that the progenitors are Wolf-Rayet stars (Harkness *et al.* 1986). Work is underway to interpret the very different yet remarkably uniform spectra of the SN Ib SN 1983n and SN 1984l, up to 2 months past maximum to see if the deduced composition and structure are compatible with an origin in Wolf-Rayet stars. Parallel efforts are underway to see if exploding Wolf-Rayet stars can mimic the observed optical light curves of SN Ib. It would clearly be of great interest to obtain spectral observations of a SN Ib event in the interval 2–4 months past maximum when the transition is made from the "SN I-like" spectrum to that displayed in Figure 1.

A plausible case can be made that the light curves of SN Ib are powered by the decay of $\sim 0.2\ M_\odot$ of ^{56}Ni created in the explosion. If this is the case, calculations of the sort pioneered by Axelrod (1980*a*, *b*) for a rapidly expanding SN I iron-rich nebula excited by radioactive decay must be undertaken for an oxygen-rich nebula to ascertain if such a model can account for the observed spectra in addition to the approximate total luminosity. Graham (1985) points out that estimates of the iron abundance based on observations of the 1.644 μm [Fe II] line a year after maximum in SN 1983n, well into the epoch illustrated in Figure 1, were based on Axelrod's predicted emissivity for an iron nebula, and hence that these estimates must be altered if instead O I dominates the cooling.

Finally we note that SN Ib are not particularly rare (Branch 1986). This suggests that they cannot come from very massive stars. The mass-loss rate required to produce a hydrogen-deficient core may have to involve a binary companion. SN Ib may represent an important nucleosynthetic source of oxygen, and provide evidence that some stars with massive oxygen mantles succeed in converting core collapse to an explosion.

We thank Alexei Filippenko, Craig Sarazin, and Greg Shields for useful conversations and Gary Ferland for the use of his emission-line code. The research of R. P. H., E. C., and J. C. W. is supported in part by NSF grant AST 8413301, and that of H. D. and D. G. by NSF grant AST 8314962 and Welch Foundation Grant F-910. E. C. is in addition supported by a post-doctoral fellowship from the Italian Ministry of Education.

REFERENCES

Ashworth, W. B., Jr. 1980, *J. Hist. Astr.*, **11**, 1.
Axelrod, T. S. 1980*a*, Ph.D. thesis, University of California, Santa Cruz.
______. 1980*b*, in *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 80.
Begelman, M. C., and Sarazin, C. L. 1986, *Ap. J.* (*Letters*), **302**, L59.
Bertola, F. 1964, *Ann. d'Ap.*, **27**, 319.
Bertola, F., Mammano, A., and Perinotto, M. 1965, *Asiago Contr.*, No. 174.
Branch, D. 1986, *Ap. J.* (*Letters*), **300**, L51.
Cahen, S., Schaeffer, R., and Cassé, M. 1986 in *Nucleosynthesis and Its Implications on Nuclear and Particle Physics*, ed. J. Audouze and N. Mathieu (Dordrecht: Reidel), p. 243.
Chevalier, R. A. 1984, *Ap. J.* (*Letters*), **285**, L63.
Elias, J. H., Matthews, K., Neugebauer, G., and Persson, S. E. 1985, *Ap. J.*, **296**, 379.
Filippenko, A. V., and Sargent, W. L. W. 1985, *Nature*, **316**, 407.
______. 1986, *A.J.*, **91**, 691.
Graham, J. R. 1985, private communication.
Graham, J. R., Meikle, W. P. S., Allen, D. A., Longmore, A. J., and Williams, P. M. 1986, *M.N.R.A.S.*, **218**, 93.
Harkness, R. P., Wheeler, J. C., Margon, B., Downes, R., Kirshner, R. P., Uomoto, A., Dinerstein, H. L., and Garnett, D. R. 1986, in preparation.
Levreault, R. 1985, private communication.
Nomoto, K., Thielemann, F.-K., and Yokoi, K. 1984, *Ap. J.*, **286**, 644.
Panagia, N., *et al.* 1986, preprint.
Panagia, N., Sramek, R. A., and Weiler, K. W. 1986, *Ap. J.* (*Letters*), **300**, L55.
Richter, O.-G., and Rosa, M. 1984, *Astr. Ap.*, **140**, L1.
Sramek, R. A., Panagia, N., and Weiler, K. W. 1984, *Ap. J.* (*Letters*), **285**, L63.
Stone, R. P. S., and Baldwin, J. A. 1983, *M.N.R.A.S.*, **204**, 347.
Sutherland, P. G., and Wheeler, J. C. 1984, *Ap. J.*, **280**, 282.
Troland, T. H., Crutcher, R. M., and Heiles, C. 1985, *Ap. J.*, **298**, 808.
Uomoto, A., and Kirshner, R. P. 1985, *Astr. Ap.*, **149**, L7.
Wheeler, J. C., Branch, D., and Falk, S. W. J. 1980, in *Proc. of the Texas Workshop on Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 199.
Wheeler, J. C., and Harkness, R. P. 1986, in *Proc. of the Hawaii Workshop on the Distance Scale and Departures from the Hubble Flow*, ed. B. F. Madore and R. B. Tully, in press.
Wheeler, J. C., and Levreault, R. 1985, *Ap. J.* (*Letters*), **294**, L17.
Woosley, S. E., Axelrod, T. S., and Weaver, T. A. 1984, in *Stellar Nucleosynthesis*, ed. C. Chiosi and A. Renzini (Dordrecht: Reidel), p. 263.

E. CAPPELLARO: Osservatorio Astrofisico di Asiago, University of Padova, I-36016 Asiago, Italy

H. L. DINERSTEIN, D. R. GARNETT, R. P. HARKNESS, and J. C. WHEELER: Department of Astronomy, University of Texas, Austin, TX 78712

C. M. GASKELL: Astronomy Department, Ohio State University, 174 West 18th Avenue, Columbus, OH 43210