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EARLY-TIME SPECTRA OF TYPE Ic SUPERNOVAE: FURTHER EVIDENCE FOR THE PRESENCE OF HYDROGEN

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ABSTRACT

Comparison of the early-time optical spectra of the Type II SN 1985L and the Type Ic SN 1987M confirms the previously suspected presence of Hα in SN 1987M. The Hα line has a P Cygni profile in both objects, but it is not as prominent as in the Type II SN 1987K, whose spectrum at late times became indistinguishable from that of SNs Ic. A spectrum of the Type Ic SN 1991A reveals a weak but nearly unmistakable Hα emission line; faint Hα emission may also be present in the Type Ic SN 1990aa. These observations support the hypothesis that SNs Ic and SNs II are physically related, with the main variable being the amount of hydrogen in the outer envelope. The fact that O I λ7774 absorption is strong in the early-time spectra of SNs Ic, but absent in the corresponding spectra of SNs II, may be consistent with this hypothesis. However, the data do not yet conclusively eliminate white dwarf models for SNs Ic.

Subject headings: supernovae: individual (SN 1985L, SN 1987M) — white dwarfs

1. INTRODUCTION

Type I supernovae (SNs I), defined by the absence of hydrogen lines in their optical spectra, can be divided into several observationally distinct categories (e.g., Harkness & Wheeler 1990; Branch, Nomoto, & Filippenko 1991). During the first 5–6 weeks following the explosion, classical SNs Ia exhibit a deep absorption trough near 6150 Å, now thought to be produced by Si II λ6355 (Pskovskii 1969; Branch et al. 1982).[2] The early-time spectra of SNs Ib, by contrast, show absorption lines of He I (especially He I λ5876) that grow progressively stronger during the first 2 months; the Si II trough is weak or absent. Neither the Si II nor the He I lines are conspicuous in SNs Ic, although at late times SNs Ic are (thus far) indistinguishable from SNs Ib.

It is generally agreed that SNs Ia are white dwarfs undergoing deflagrations or detonations; see the excellent reviews by Woosley & Weaver (1986) or Wheeler & Harkness (1990). The nature of the progenitors and explosion mechanisms of SNs Ib and Ic, on the other hand, are subjects of considerable debate. A few scenarios involving white dwarfs have been advanced (e.g., Woosley 1986, 1990; Branch & Nomoto 1986; Khokhlov & Ergma 1986; Iben et al. 1987), and additional ones are currently being considered. A majority of studies, however, have focused on core collapse in reasonably massive stars that previously lost their outer layer of hydrogen (e.g., Wheeler & Levreault 1985; Begelman & Sarazin 1986; Filippenko & Sargent 1986; Uomoto 1986; Gaskell et al. 1986; Schaeffer, Cassé, & Cahen 1987; Harkness et al. 1987; Ensman & Woosley 1988; Fransson & Chevalier 1989; Shigeyama et al. 1990; Nomoto, Filippenko, & Shigeyama 1990). Strong observational evidence in favor of this hypothesis comes from the discovery (Filippenko 1988) that the early-time spectrum of at least one SN Ib/Ic, SN 1987K, showed a prominent P Cygni profile of Hα; indeed, near maximum brightness SN 1987K was classified as a SN II. Detailed modeling will be necessary, however, to determine whether an exploding white dwarf having a thin hydrogen envelope can also produce a spectrum of similar appearance.

The presence and profile of hydrogen in the early-time spectra of other SNs Ib or Ic could provide important clues to the nature of their progenitors. Filippenko (1988) listed several SNs Ib/Ic that may exhibit weak Hα emission, and Filippenko, Porter, & Sargent (1990) suggested that SN Ic 1987M also shows Hα absorption. The spectral synthesis conducted by Jeffery et al. (1991, hereafter JBFN) is consistent with this conclusion. However, as noted by JBFN, the identification is not definite. In this *Letter* a comparison with the Type II SN 1985L provides additional evidence for the presence of Hα emission and absorption in SN 1987M. Moreover, Hα emission is almost certainly visible in the recent Type Ic SN 1991A, and a weaker Hα line may be present in SN Ic 1990aa. Important differences between the spectra of these objects and SN 1987K, discussed here, could be related to the thickness of the hydrogen envelope.

2. P CYGNI Hα PROFILE IN SN 1987M

An early-time optical spectrum of SN 1987M is illustrated in Figure 1, together with a spectrum of the Type II SN 1985L (Filippenko & Sargent 1986) obtained at a roughly comparable phase. Line identifications for SN 1987M, determined by the spectral synthesis of JBFN, are shown below the spectrum. (Fe II may contribute to the dip at 6170 Å, although this was not explicitly indicated by JBFN.) For each absorption line in SN 1987M, there is a corresponding feature in the spectrum of SN 1985L, as shown by the dashed lines, but the derived expansion velocities are systematically larger in SN 1987M.

The local maximum near 6500 Å in SN 1987M is clearly identified with Hα emission; as in SN 1985L, the line centroid is blueshifted, probably because we are seeing primarily the near side of an optically thick, expanding shell. The absorption component of the P Cygni Hα profile is stronger in SN 1987M than in SN 1985L, but SNs II are known to exhibit a very wide

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[2] This feature was absent, or barely visible, prior to maximum brightness in the spectroscopically peculiar and highly luminous SN 1991T (Filippenko et al. 1992). It was clearly present, but less prominent than usual, by ~1 week past maximum. Over the next 2 months the spectrum gradually metamorphosed to that of typical SNs Ia, which are dominated by iron.

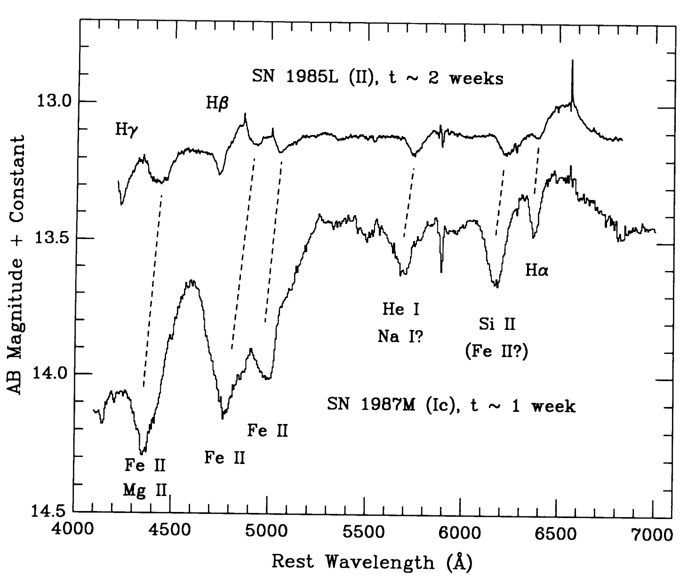

FIG. 1.—Comparison of the early-time optical spectra of SN 1985L (Type II) and SN 1987M (Type Ic). Absorption lines common to both spectra are marked. Note the presence of Hα, having a P Cygni profile, in SN 1987M. AB magnitude = $-2.5 \log f_\nu - 48.6$, where the units of f_ν are ergs s^{-1} cm^{-2} Hz^{-1} (Oke & Gunn 1983).

range of Hα profiles; in some cases (e.g., Filippenko 1989) the absorption component is extremely weak or absent. The Hβ and Hγ P Cygni profiles in SN 1985L do not have obvious counterparts in SN 1987M, perhaps because of contamination by the relatively strong Fe II lines in the latter object. (The weak absorption line near the blue end of the SN 1987M spectrum is unlikely to be Hγ, and it has not yet been identified; see JBFN.)

Filippenko & Sargent (1986) stated that, aside from the possible presence of Si II absorption, SN 1985L is a fairly typical SN II. Actually, however, we now know that the hydrogen Balmer lines are unusually weak relative to the metal lines; compare, for example, with spectra of SN 1987A shown by Phillips et al. (1988) and others. This peculiarity, and the overall spectral similarity of SN 1985L and SN 1987M, suggest that SN 1985L may have had an origin similar to that of SNs Ic. Therefore, one might expect that SN 1985L evolved into a SN Ib/Ic in the nebular phase, as did SN 1987K (Filippenko 1988). This did not, in fact, occur; a spectrum of SN 1985L obtained 9–10 months past maximum exhibits strong, broad Hα emission (Schlegel 1990b). Significant differences in the residual amounts of hydrogen in the outer envelopes of the progenitors (helium stars, for instance) may account for the seemingly related characteristics of SN 1985L, SN 1987K, and SN 1987M.

3. Hα EMISSION IN OTHER TYPE Ic SUPERNOVAE

To assess how frequently weak Hα is present in the early-time spectra of SNs Ic, a large sample of high-quality spectra is required, together with spectral synthesis calculations (e.g., JBFN) that build confidence in the line identifications. Since bright SNs Ic are relatively rare, at least a few more years will be needed before a definitive conclusion can be reached. The recent discovery of several SNs Ic, however, allows some useful preliminary comparisons to be made.

SN 1990aa and SN 1991A were discovered by the Berkeley Automated Supernova Search Team (Perlmutter et al. 1990; Pennypacker et al. 1991). Considerable efforts were made to obtain spectra of both objects over a long time interval, using CCD spectrographs at the Cassegrain focus of the 3 m Shane reflector at Lick Observatory (Miller & Stone 1987). The details of the observations, reductions, and interpretations will be presented elsewhere; in this paper only the earliest Lick spectra are examined. These were procured on 1990 September 27 UT (SN 1990aa) and 1991 January 6 (SN 1991A), about 2–3 weeks past maximum brightness, at an air mass of 1.0–1.1. The spectra span the range 3900–9900 Å, with a wavelength-dependent resolution of 10–16 Å. Clouds of variable thickness were present during both sets of observations, especially that of SN 1991A. This affected the absolute photometry and the photon count rate, but not the relative spectrophotometry. It is estimated that the continuum at 4000 Å does not systematically deviate by more than ~0.2 mag from its true level relative to 9000 Å. The signal-to-noise ratio varies over the approximate range 20–50, generally being worst near the ends of the spectra.

Figure 2 shows the calibrated spectra of SN 1990aa and SN1991A and compares them with early-time ($t \approx 1$ week past maximum) spectra of SN 1987K (Filippenko 1988) and SN 1987M (Filippenko et al. 1990). As discussed in preceding sections, SN 1987K was a SN II that metamorphosed into a SN Ib/Ic, and the spectrum of SN Ic 1987M exhibits weak Ha (with a P Cygni profile). The overall similarity of the spectrum of SN 1987M to the spectra of SN 1990aa and SN 1991A leads to an unambiguous classification of Type Ic for the latter two objects (Filippenko & Shields 1990; Filippenko 1991a); there is no deep trough near 6150 Å, and the He I lines are not strong. The initial classification of Type Ia for SN 1990aa, by Della Valle (1990) and Benetti, Cappellaro, & Turatto (1990), was based on these authors' identification of Si II $\lambda 6355$ in their

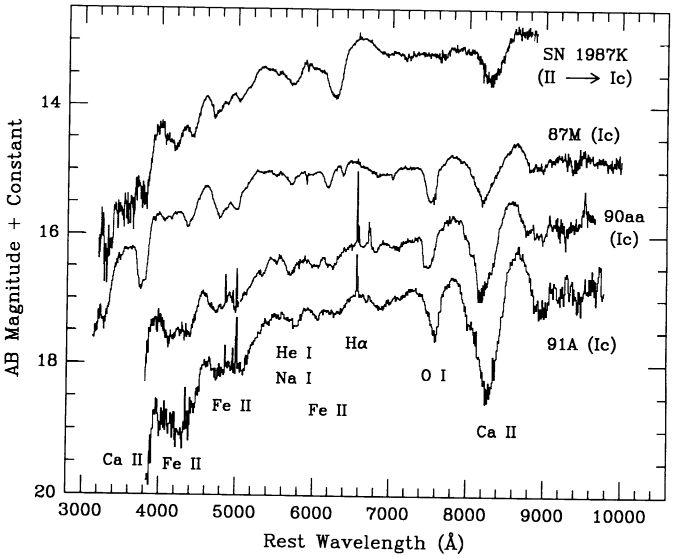

FIG. 2.—Early-time spectra of several SNs Ic, compared with the spectrum of SN 1987K, which was initially Type II but later changed to Type Ic. The narrow emission lines in the spectra of SN 1990aa and SN 1991A are due to superposed H II regions. O I $\lambda 7774$ absorption is prominent in the spectra of the SNs Ic, but not in SN 1987K. The Ca II line shows a wide range of strengths. Hα is obvious in SN 1987K; it is also present in SN 1991A, SN 1987M, and probably SN 1990aa.

spectra. However, as noted by JBFN, the possible Si II line in SNs Ic is much weaker relative to other features than in typical SNs Ia. In general, classification ambiguities can be minimized with flux-calibrated spectra covering a wide wavelength range, and especially with multiple spectra obtained during the first few months after an explosion.

Careful inspection of Figure 2 reveals the presence of broad Hα in the spectrum of SN 1991A, as in SN 1987K and SN 1987M, but here the profile consists of nearly pure emission. The broad bump occurs in a spectral region that is otherwise quite featureless, and it is centered on the narrow Hα emission line produced by the surrounding H II region. Pure emission profiles of Hα are known to occur in some SNs II (e.g., Filippenko 1989; Schlegel 1990a). Broad Hβ and Hγ emission are not visible in the spectrum of SN 1991A, but contamination of Fe II and other lines is substantial. Based on its early-time spectrum, SN 1991A could be classified as a SN II, but its late-time spectrum (to be discussed elsewhere) was dominated by strong [O I] λλ6300, 6364 emission, and it did not exhibit broad Hα. Also, few if any SNs II show O I λ7774 in their early-time spectra (see § 4). Thus, SN 1991A was undoubtedly a SN Ic, not a SN II.

SN 1990aa may also have a broad Hα emission line, although it is less prominent than in SN 1991A. Once again, the absorption component is weak or absent, unlike the case in SN 1987M. Both SN 1990aa and SN 1991A were superposed on bright H II regions, while SN 1987M was not. It is possible that there are minor differences in the progenitors of these objects, and this may account for the slight dissimilarities in the Hα profile. Moreover, the weak absorption line near 6200 Å may be predominantly Fe II in SN 1990aa (Benetti & Branch 1991) rather than Si II as in SN 1987M. Nevertheless, the overall resemblance of the three spectra is striking. The most important conclusion to draw from this is that weak Hα is probably not rare in the early-time spectra of SNs Ic.

4. DISCUSSION

Filippenko (1988) and Filippenko et al. (1990) have argued that the presence of Hα in SN 1987K, together with the object's spectral evolution, suggest a close physical connection between SNs Ib/Ic and SNs II (e.g., Nomoto et al. 1990). This idea is strengthened by the data presented here, at least for SNs Ic; Hα is weak, but almost certainly visible, in SN Ic 1987M and SN Ic 1991A, and it may be present in SN Ic 1990aa, although in each case the strength and profile of Hα differ from those in SN 1987K.

There is, however, a very significant difference between the spectra of these SNs Ic and SN 1987K. All three SNs Ic have a very deep O I λ7774 absorption line, whereas SN 1987K does not. Filippenko et al. (1990) mentioned this fact when comparing SN 1987K and SN 1987M. They suggested that a thin, essentially unenriched envelope of hydrogen effectively hides the oxygen-rich layer in SN 1987K. In this case, the P Cygni profile attributed to the Ca II near-infrared triplet in SN 1987K would have to be produced by the calcium normally present (with roughly solar abundances) in a hydrogen envelope, as in typical SNs II. A similar conclusion would hold for most of the other features (largely due to iron) in the spectrum of SN 1987K. Indirect observational support for the hypothesis of a cloaked oxygen layer comes from observations of SN II 1990H and SN II 1987A: at early times, when the photosphere coincided with the outermost layer of hydrogen, O I λ7774 absorption was absent, but after about 100 days this line began to appear (Filippenko 1991b).

If SNs Ic contain only a small amount of hydrogen in their envelopes, the O I line might be expected to have the observed strength. On the other hand, given the detection of hydrogen, a substantial quantity of helium is probably also present, and it is not immediately clear why the helium does not hide the deeper oxygen layer. Perhaps mixing plays an important role (e.g., Shigeyama et al. 1990). These various possibilities will have to be explored through spectral synthesis calculations.

A substantial fraction of the Ca II near-infrared triplet in SNs Ic may be a consequence of the overabundance of intermediate-mass elements, and its strength should be inversely correlated with the amount of hydrogen in the envelope. The spectra of SNs Ic in Figure 2 demonstrate that the Ca II line is strongest in SN 1991A, whose Hα line does not have a P Cygni absorption component, and weakest in SN 1987M, whose Hα line does show absorption. Detailed modeling is required to determine whether the shape of the Hα line is indeed an indicator of the amount of hydrogen in the envelope.

Despite being quite suggestive, these observations do not yet rule out white dwarf models for SNs Ic. For example, we could be seeing an outer layer of hydrogen accreted by the white dwarf immediately prior to the explosion. In this case, it is possible that a slow deflagration, such as that discussed by Woosley (1990), could produce the weak hydrogen in the early-time spectrum, in addition to all the features normally associated with SNs Ic.

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