PRELIMINARY SPECTRAL ANALYSIS OF THE TYPE II SUPERNOVA 1999em

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ABSTRACT

We have calculated fast direct spectral model fits to two early-time spectra of the Type II plateau SN 1999em, using the SYNOW synthetic spectrum code. The first is an extremely early blue optical spectrum and the second a combined Hubble Space Telescope and optical spectrum obtained one week later. Spectroscopically this supernova appears to be a normal Type II, and these fits are in excellent agreement with the observed spectra. Our direct analysis suggests the presence of enhanced nitrogen. We have further studied these spectra with the full non-LTE general model atmosphere code PHOENIX. While we do not find confirmation for enhanced nitrogen (nor do we rule it out), we do require enhanced helium. An even more intriguing possible line identification is complicated Balmer and He I lines, which we show falls naturally out of the detailed calculations with a shallow density gradient. We also show that very early spectra such as those presented here combined with sophisticated spectral modeling allow an independent estimate of the total reddening to the supernova, since when the spectrum is very blue, dereddening leads to changes in the blue flux that cannot be reproduced by altering the “temperature” of the emitted radiation. These results are extremely encouraging since they imply that detailed modeling of early spectra can shed light on both the abundances and total extinction of SNe II, the latter improving their utility and reliability as distance indicators.

Subject headings: radiative transfer — stars: atmospheres — supernovae: individual (SN 1999em)

1. INTRODUCTION

SN 1999em was discovered by the Lick Observatory Supernova Search (IAU Circ. 729446) on October 29.44 UT and confirmed by the BAO supernova group on October 29.7 UT. It was followed spectroscopically and photometrically by ground-based observatories and was the subject of a Supernova Intensive Studies (SINS) Hubble Space Telescope (HST) observation on 1999 November 5. SN 1999em is in the SABc galaxy NGC 1637, with a heliocentric recession velocity of 717 km s⁻¹. The first spectrum taken on 1999 October 29 is extremely blue and displays strong Balmer features typical of Type II supernovae with a characteristic velocity of around 10,000 km s⁻¹.

SN 1999em appears to have been a normal Type IIP, likely the result of a core collapse in a star with a massive hydrogen envelope (Leonard et al. 2000). The early and weak radio emission (IAU Circs. 7318 and 733616) hints that the star did not experience significant mass loss shortly before the explosion, which is also thought to be the normal situation for SNe IIP (see Weiler et al. 2000 and references therein). The lack of circumstellar interaction makes SNe IIP “clean” cases to model, resulting in more reliable atmospheric modeling, which in turn makes SNe IIP ideal for cosmological use. Because SN 1999em was observed earlier and over a wider wavelength range than any other normal bright SN IIP, it is a perfect test bed for our understanding of SNe IIP. These supernovae are of particular interest as distance indicators.

2. OBSERVATIONS

The observed spectra we use in this paper were obtained on 1999 November 4 at the Fred L. Whipple Observatory (FLWO) and on 1999 October 29 at the Cerro Tololo Inter-American Observatory (CTIO). Leonard et al. (2000) find that on October 29 the V light curve is rising. The point at November 4–5 is on a broad maximum prior to the plateau. The light curve settles down to a plateau phase on about November 20.

3. SYNOW MODELS

We have used the fast, parameterized supernova synthetic spectra code SYNOW to make an initial investigation of line identifications and expansion velocities. The code is discussed in detail by Fisher (2000), and recent applications include Fisher et al. (1999), Millard et al. (1999), and Hatano et al. (1999a). SYNOW spectra consist of resonant-
scattering profiles superimposed on a blackbody continuum. For the two synthetic spectra presented here, the radial dependence of all line optical depths is a power law of index 8. The observed spectra have been corrected for a redshift of 717 km s\(^{-1}\) and for reddening of \(E(B-V) = 0.05\) mag (see below).

In Figure 1 the CTIO observed spectrum of October 29 is compared with a synthetic spectrum for which the continuum blackbody temperature \(T_{bb}\) and the excitation temperature \(T_{exc}\) are 13,000 K, the velocity at the photosphere \(V_{\text{phot}}\) is 11,000 km s\(^{-1}\), and only lines of hydrogen, He \(\text{I}\), and N \(\text{II}\) are considered. The relative strengths of the lines of an ion are fixed by local thermodynamic equilibrium (LTE) at the excitation temperature, but the absolute strengths of the lines of each ion are controlled by a free parameter. The strength of the hydrogen lines has been chosen to make \(H\beta\) and \(H\gamma\) about the same as in the observed spectrum; the relative optical depths of the hydrogen lines are of course fixed by atomic physics, so the poor fit to \(H\alpha\) is due to a deficiency of the resonant-scattering source function for this transition. The only noticeable line of He \(\text{I}\) in the synthetic spectrum is that of \(\lambda 5876\). Lines of N \(\text{II}\) have been introduced so that \(\lambda 4623\) and \(\lambda 5567\) can account for the absorptions near 4500 and 5500 Å, in which case N \(\text{II} \lambda 5029\) also affects the synthetic spectrum slightly near 5000 Å. (In SYNOW when a particular species is introduced, all the lines of that species are included with their relative strengths set by assuming LTE populations, but we focus here on the strong optical features that are relevant to the observed spectra.) The hydrogen and He \(\text{I}\) identifications are definite, and (in anything remotely like LTE) we can offer no alternative to the N \(\text{II}\) lines. However, see § 4.1.1 regarding the possibility that some of the “N \(\text{II}\)” lines may actually be due to hydrogen.

In Figure 2 the HST-observed spectrum of November 5 is compared with a synthetic spectrum that has \(T_{bb} = T_{exc} = 9500\) K, \(V_{\text{phot}} = 8000\) km s\(^{-1}\), and lines of hydrogen, Ca \(\text{II}\), Mg \(\text{II}\), Fe \(\text{II}\), and Ni \(\text{II}\). The resonance-scattering approximation gives good fits to the features produced by \(H\beta\), \(H\gamma\), and \(H\delta\). Ca \(\text{II}\) contributes only the blend due to \(\lambda 3945\) (the H and K lines), and Mg \(\text{II}\) contributes little other than the blend due to \(\lambda 2798\) (the h and k lines). All other features in the synthetic spectrum are produced by Fe \(\text{II}\) and, to a lesser extent, by Ni \(\text{II}\). The H, Ca \(\text{II}\), and Mg \(\text{II}\) identifications are definite. The ultraviolet spectrum evidently is mainly a blend of singly ionized iron-peak lines; Fe \(\text{II}\) definitely is present, and Ni \(\text{II}\) probably contributes significantly. Other iron-peak ions that have not been introduced here may also affect the observed spectrum.

4. PHOENIX MODELS

4.1. October 29

The Galactic extinction to NGC 1637 corresponds to a color excess of \(E(B-V) = 0.03\) mag, but the observed spectrum of SN 1999em shows a distinct Na D interstellar absorption line that may indicate additional reddening in the parent galaxy. We have calculated a grid of detailed fully line-blanketed PHOENIX models in order to determine the “temperature” of the observed spectrum. With most supernova spectra we can trade off higher temperatures for larger reddening within prescribed limits (such that the atmosphere does not become so hot or cool that strong unobserved lines would predominate). Here with this very early, very blue spectrum, we found that we were not able to freely exchange temperature for reddening, so that the reddening was well determined to be \(E(B-V) \approx 0.05\) and the “temperature” was about 11,000 K. Figure 3 displays a fit with \(T_{\text{model}} = 11,000\) K and solar compositions; the observed spectrum has been dereddened with \(E(B-V) = 0.05\) mag. The abundances were taken to be solar throughout the model atmosphere, and the density was assumed to follow a power law with \(\rho \propto r^{-n}\) and \(n = 7\), somewhat shallower than in the SYNOW fits, though we do not regard the difference as being too significant, since the true density structure is unlikely to follow an exact power law. We also present models with \(n = 9\) (see § 4.2).

The fit is rather good, and the \(T_{\text{model}}\) cannot be significantly reduced since the Ca \(\text{II}\) H + K line becomes very strong in the synthetic spectrum with \(T_{\text{model}} = 10,000\) K, but it is weak in the observed spectrum. Also, the observed feature due to He \(\text{I} \lambda 5876\) is not reproduced in the synthetic spectrum. Hotter models are not ruled out, but at \(T_{\text{model}} = \)
12,000 K the Ca II H + K feature becomes weaker and there is a clear flux deficiency in the red. Normally one expects that one can trade off reddening for temperature in the red part of the spectrum, and this is indeed the case within a certain range of reddening. We assume a standard (Cardelli, Clayton, & Mathis 1989) reddening law with $R = 3.1$. However, since the spectrum depends strongly on the strength of the Ca II H + K feature, we find that $T_{\text{model}} = 11,000 \pm 500$ K; the $T_{\text{model}} = 12,000$ K model requires an extinction $E(B-V) \approx 0.15$ to reproduce the red flux, but it then does a poor job in the blue. Thus, we find that $E(B-V) \approx 0.05$ and $E(B-V) < 0.15$. We show a model with $E(B-V) = 0.10$ below.

We also found that we could not reproduce the He I $\lambda 5876$ feature by enhancing the amount of gamma-ray deposition. Therefore, guided by the indications of enhanced N in the SYNOW fits, we calculated a series of spectra where we enhanced He by a factor of 2.5 (reducing H appropriately), and we enhanced N by a factor of 10 (reducing C + O). This fit is shown in Figure 4, where now the He I $\lambda 5876$ fits well, but $T_{\text{model}} = 11,500$ K in order to keep the Ca H + K feature from becoming too strong in the synthetic spectrum. Figure 5 with $T_{\text{model}} = 12,000$ K, the same compositions, and $E(B-V) = 0.10$ shows that the effects of the Ca H + K feature can be reduced by increasing the model temperature and increasing the reddening modestly. Therefore, we conclude that there is strong evidence for enhanced helium in SN 1999em (a similar result was found for SN 1987A; Arnett et al. 1989; Eastman & Kirshner 1989; Lundqvist & Fransson 1996; Blinnikov et al. 2000). We note at these early times that the material is hot enough for the optical helium lines to be excited even in LTE (see Hatano et al. 1999b), so while gamma-ray deposition was needed in, e.g., SN 1993J (see Baron et al. 1995a and references therein), it is not required at these early times.

### Complicated Balmer and He I Lines

We attempted to confirm the evidence in the SYNOW fits that nitrogen is also enhanced and that N II contributes to...
the observed features at 5679, 5029, and 4623 Å. To do this we reduced the abundance of nitrogen from its solar value by a factor of 10. This synthetic spectrum showed that the λ5679 and λ5029 features do decrease, but the feature that is attributed to λ4623 in the SYNOW fits is still present (this is not surprising since the feature also appears in Figure 3 with solar compositions). Guided by the LTE line spectra presented by Hatano et al. (1999b), we reduced carbon by a factor of 10 from its solar value, and the λ4600 feature remained. Finally, reducing both carbon and oxygen by a factor of 10 from their solar values (leaving N fixed) still produces a feature with, if anything, a better shape than in previous calculations. Thus, with the “usual suspects” the source of the λ4600 feature remains unidentified, and the evidence for enhanced nitrogen is weakened, but it does a good job on the λ5679 and λ5029 features.

The lack of a strong candidate for the λ4600 feature leads us to consider more exotic line identifications. Careful examination of Figure 3 reveals that even with solar compositions features appear in the synthetic spectrum at the approximately correct wavelength positions. This led us to test the hypothesis that the features are actually produced by “complicated P Cygni” profiles, that is, the usual wide P Cygni profile with the peak centered near zero velocity and a second P Cygni profile with a second absorption minimum around 20,000 km s⁻¹. Figure 6 displays the synthetic calculation with the metallicity reduced to Z = Z₀/100. One can be confident that all the lines in this synthetic spectrum are produced solely by hydrogen and helium, and it is clear that each line is associated with high-velocity absorption, which matches the observed lines very well. (It may be a true P Cygni feature, with both a peak and a dip, but it is probably premature to decide that at this point.) This is due to the shallow density gradient and high model temperature that keeps the actual electron temperature above 8000 K all the way to the highest velocity in the model, 37,500 km s⁻¹. Complicated non-LTE effects vary the Balmer level populations in the mid-velocity range, producing the double P Cygni lines, i.e., there exist two line-forming regions for hydrogen and helium. This is the first time that we have encountered this result, and it shows that, particularly in differentially expanding flows, one cannot be certain of line identifications until careful synthetic spectral models have been calculated. Therefore, we believe that the features that we have heretofore attributed to N II (and which would require enhanced N) are in actuality due to H I and He I, which form secondary features at high velocity. Since this appears in our modeling without any special parameters (i.e., Fig. 3), we believe this is a true non-LTE effect produced simply by the shallow density gradient.

4.2. November 4–5

Guided by our results in § 4.1, we have computed full non-LTE models for the epoch observed with HST using...
both solar and enhanced He+N compositions (since we have not ruled out enhanced N, we will continue to use it for expediency). Figure 7 shows our best fit for solar compositions and \( n = 7 \) with \( T_{\text{model}} = 8100 \) K. Figure 8 displays our best fit for the enhanced He+N compositions, where we have also found that the fit is improved by setting \( T_{\text{model}} = 9000 \) and \( n = 9 \). Also displayed is a ground-based optical spectrum obtained on 1999 November 4 at the FLWO, which lends support for enhanced He. All the models show unobserved strong features in the range 2000–3500 Å, which could be due to iron-peak elements. Thus, it is possible that the metallicity of SN 1999em was somewhat less than solar, but we will study this question in future work.

5. CONCLUSIONS

Moreover, we have shown that both direct synthetic spectral fits and detailed non-LTE models do a good job of reproducing the observed optical+UV spectra of SN 1999em. We have shown that detailed non-LTE spectral modeling of very early spectra of Type II supernovae can provide an independent estimate to the total reddening as well as abundance information. Specifically, we find that \( E(B-V) \approx 0.05–0.10 \) and \( E(B-V) \approx 0.15 \) mag, and we find strong evidence for helium enhanced by at least a factor of 2 over the solar value. We obtain the striking result that observed features are likely due to “complicated P Cygni” lines of hydrogen and helium, and thus one needs to be especially careful with line identifications in hot differentially expanding flows. That the observed complicated profiles fall right out of the PHOENIX calculations is remarkable and lends strong support to the reliability of the modeling.

The fact that planned supernova search programs will preferentially find supernovae very early, combined with our results that the extinction can be determined by modeling the very early spectra, lends promise to the use of Type II supernovae as distance indicators, through the use of phenomenological applications like the “expanding photosphere method” (Baade 1926; Kirshner & Kwan 1974; Branch et al. 1981; Schmidt, Kirshner, & Eastman 1992; Eastman, Schmidt, & Kirshner 1996) or through sophisticated modeling of the “spectral-fitting expanding atmosphere method” (Baron et al. 1993, 1995a, 1996; Baron, Hauschildt, & Branch 1994; Baron, Hauschildt, & Young 1995b).

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