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SPECTRUM SYNTHESIS OF THE TYPE Ia SUPERNOVAE SN 1992A AND SN 1981B

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ABSTRACT

We present non-LTE synthetic spectra for the Type Ia supernovae SN 1992A and SN 1981B, near maximum light. At this epoch both supernovae were observed from the UV through the optical. This wide spectral coverage is essential for determining the density structure of a SN Ia. Our fits are in good agreement with observation and provide some insight as to the differences between these supernovae. We also discuss the application of the expanding photosphere method to SNe Ia which gives a distance that is independent of those based on the decay of ^{56}Ni and Cepheid variable stars.

Subject headings: distance scale — supernovae: individual (SN 1992A, SN 1981B)

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are valuable distance indicators for cosmology and the elements they eject are important for nucleosynthesis. They appear to be thermonuclear disruptions of carbon-oxygen white dwarfs that accrete from companion stars until they approach the Chandrasekhar mass, and there is a suspicion that the propagation of the nuclear burning front involves a transition from a deflagration to a detonation. (For a review of these issues, see Branch & Khokhlov 1995). Detailed modeling of the atmospheres and spectra of SNe Ia is needed to advance our understanding of SNe Ia. Comparison of synthetic and observed spectra provides information on the temperature, density, velocity, and composition of the ejected matter and thus constrain hydrodynamical models. In addition, the expanding photosphere method yields distances to individual events that are independent of distances based on the decay of ^{56}Ni in SNe Ia and of Cepheid variable stars in the parent galaxies.

2. DESCRIPTION OF THE MODELS

We use the computer code PHOENIX 4.8 to compute our model atmospheres and synthetic spectra for SNe 1992A and 1981B (Hauschildt 1992a, b, 1993). This code uses an accelerated Λ-iteration (ALI or operator splitting) method to solve the time independent, spherically symmetric, fully relativistic radiative transfer equation for lines and continua to all orders in v/c including the effects of relativistic Doppler shift, advection, and aberration. The multilevel non-LTE rate equations are solved self-consistently for Ca II, Mg II, and Na I using an ALI method. Simultaneously we solve for the special relativistic condition of radiative equilibrium in the Lagrangian frame using a modified Unsöld-Lucy temperature correction scheme. Line transfer, including line blocking, is treated accurately.

The generalized non-LTE equation of state (EOS) is solved for 40 elements and up to six ionization stages per element. The numerical solution of the EOS is based on Brent's method for the solution of nonlinear equations which is very robust and fast (Brent 1973). In addition to the non-LTE lines, the models include, self-consistently, line blanketing of the metal lines selected from the latest atomic and ionic line list of Kurucz (1993). The continuous absorption and scattering coefficients are calculated using the cross sections as described by Hauschildt et al. (1992).

The source function for the metal lines can be written as follows:

$$S_l = (1 - \alpha) \int \Phi_\nu J_\nu d\nu + \alpha B_\nu(T) \,.$$

Since the calculation of α would require a full non-LTE treatment of all lines and continua, which is beyond our present ability to acquire atomic data, we adopt an average value for α for all the metal lines in LTE. Due to the velocity gradient in SN Ia the shape of the lines does not depend heavily on α; however, α does have an effect on the overall color of the spectrum. Therefore, it is necessary to treat α as a parameter to fit in concert with the temperature. Eventually the majority of elements in the atmosphere will be treated in non-LTE and α will no longer be needed as a fitting parameter.

The effects of nonthermal collisional ionization by primary and secondary electrons produced by collisions with gamma rays due to the decay of ^{56}Ni and ^{56}Co are modeled using the continuous slowing down approximation (Swartz 1991; Garvey & Green 1976).

3. COMPARISON TO OTHER WORK

Past and present methods for computing synthetic spectra of SNe Ia near maximum light can be categorized by the physics used to treat the following: (1) atomic level populations, (2) continuum transfer, and (3) radioactive decay of ^{56}Ni.

The simple models of Branch et al. (1985) and Jeffery (Kirshner et al. 1993) incorporate neither continuum transfer nor gamma-ray deposition. The level populations for their models are parameterized and the ratio of the upper to lower level is governed by the assumption of resonance scattering. The advantage of these codes is that they require small amounts of CPU time while still producing very useful line identifications as well as providing information about ejection velocities and the composition of the supernova.

The Monte Carlo method of Mazzali & Lucy (1993) for the synthesis of early time SNe Ia spectra is based on a Schuster-Schwarzschild approximation. Their model has a sharp photosphere above which continuum transfer is neglected. The temperature structure is determined by assuming radiative equilibrium and the level occupation numbers are obtained

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through a modified version of the nebular approximation, neglecting the effects of the fast electrons produced by the decay of ^{56}Ni. Their code produces reasonable fits in the optical in a small amount of time while taking rough account of departures from LTE.

Branch et al. (1991) presented a full non-LTE calculation of an SN Ia atmosphere. The synthetic spectrum produced in this paper was crude (none of the parameters were fine tuned for fitting purposes), but the overall agreement is not bad. More recent work by Miller et al. (1995) has shown major improvements in the fits. The strength of these calculations is that they are based on a vast amount of atomic data and all species are treated in non-LTE, however, they are nonphysical in several ways. The radiative transfer is not calculated self-consistently and the continuum transfer assumes a static atmosphere in order to solve the rate equations. Line blocking is treated with a heuristic approximation and line transfer is accomplished assuming the Sobolev approximation. Energy conservation is not enforced and the change in the electron density due to the decay of ^{56}Ni is neglected. Finally, these calculations require a prohibitive amount of computer time.

Another recent non-LTE calculation has been carried out by Höflich (1995). His focus is on the comparison of light curves and spectra of detailed hydrodynamic explosion models with observation. The synthetic spectra produced by his code are not adjusted by changing parameters such as the velocity at the photosphere or the temperature and density gradients, but rather are the results of a hydrodynamic calculation. The advantage of this type of calculation is the one can directly compare, through spectra and light curves, one hydrodynamic model to another. The disadvantage are that the fits rarely reproduce the correct strength or velocity placement of the observed lines, although good fits have been produced for SNe II (Hauschildt & Ensman 1994). In contrast to our models much of the line transfer is performed assuming the Sobolev approximation and line blocking is approximated by a "quasi-continuum" opacity. The relativistic terms in the radiative transfer equation are treated approximately and the thermalization parameter, α for each line considered in LTE is calibrated by a global fit to that produced by the ions treated in non-LTE.

The calculations of Harkness (Wheeler et al. 1993) are the most similar to ours in terms of the physics incorporated in the model atmosphere. Their calculations include both continuum transfer and the effects of ^{56}Ni decay. The major difference is that all of their atoms are treated in LTE whereas we include a number of important atoms in non-LTE.

4. MODEL PARAMETERS

The model atmospheres are characterized by the following parameters Hauschildt et al. 1994; Baron et al. 1995; Allard et al. 1994): (1) the reference radius R_0, which is the radius where the continuum optical depth in extinction at 5000 Å is unity, (2) the effective temperature $T_{\rm eff}$, which is defined by means of the co-moving luminosity, L, and R_0 ($T_{\rm eff}^4 = L/4\pi R_0^2 \sigma$), (3) the expansion velocity, v_0, at the reference radius, (4) the density, $\rho_{\rm out}$, at the outer edge of the envelope, (5) the e-folding velocity, v_e, which defines the density by $\rho(r) = \rho_0 e^{-v/v_e}$, or the power-law index, N, which defines the density by $\rho(r) = \rho_0 r^{-N}$, (6) the continuum thermalization parameter α, (7) a nonthermal ionization deposition function, and (8) the element abundances. In all of our models of SNe Ia atmospheres, the abundances were taken from the carbon deflagration model W7 (Nomoto, Thielemann, & Yokoi, 1984). To obtain our model abundances we homogenized the zones in W7 with velocities greater than 8000 km s^{-1}. The value of α was assumed to be 0.1, the rise time, t_r, was taken to be 17 days (i.e., the reference radius at maximum light is $R_0^{\rm ML} = v_0 t_r$), and the deposition function was local. We ensured that our choice of outer density had no effect on the models, decreasing its value by an order of magnitude had no effect on the resultant spectrum.

5. RESULTS

Figure 1 shows a comparison of SN 1992A, at 5 days after maximum light, with our best-fit synthetic spectrum. The fit is a very reasonable one. It nicely follows the strong Fe peak line blanketing in the UV, the red edge of the Ca II H + K lines near 4000 Å, the Mg II and Fe II troughs at 4500 and 5000 Å and the S II "W" between 5200 and 5400 Å. The noticeable discrepancies occur with the two Si II features at 3900 Å and 5900 Å and the O I feature at 7500 Å. We believe that these features are due to non-LTE effects and that the fit will improve once these species are calculated in non-LTE. Included in this figure is a LTE synthetic spectrum to illustrate the importance of non-LTE for our models.

Figure 2 shows our fit to SN 1981B at maximum light. Once again the overall fit is good, although there are still the discrepancies with the O I and Si II features. The advantage of fitting this observed spectrum is that it goes far enough into the red to show the Ca II infrared triplet near 8400 Å. This feature really helps in the determination of the structure of the supernova. Unlike some of the other LTE features, the Ca II infrared triplet, which is treated in non-LTE, is sensitive in different ways to changes in the velocity, temperature and density gradients. This makes it an invaluable part of the spectrum to have in order to obtain a good and meaningful fit. This is in contradistinction to atmospheres of SNe II, which are dominated by hydrogen, where the infrared triplet is rather insensitive to such changes.

Since SN 1992A was observed by both the *HST*, in the UV, and by CTIO, in the optical, with good signal to noise, we were

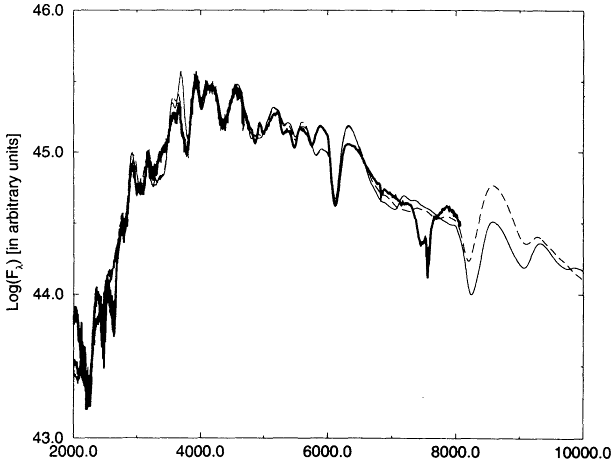

FIG. 1.—Non-LTE synthetic spectrum, *thin line*, LTE synthetic spectrum, *dashed line*, vs. the spectrum of SN 1992A, *thick line*, at 5 days after maximum blue light (Kirshner et al 1993). While the LTE spectrum fits the Ca H + K feature well the IR triplet absorption is weak and the emission is strong, in contrast to SN 1981B at a similar time. The non-LTE H + K absorption feature sppears too narrow, however, we believe that the observed width is produced by non-LTE Si II.

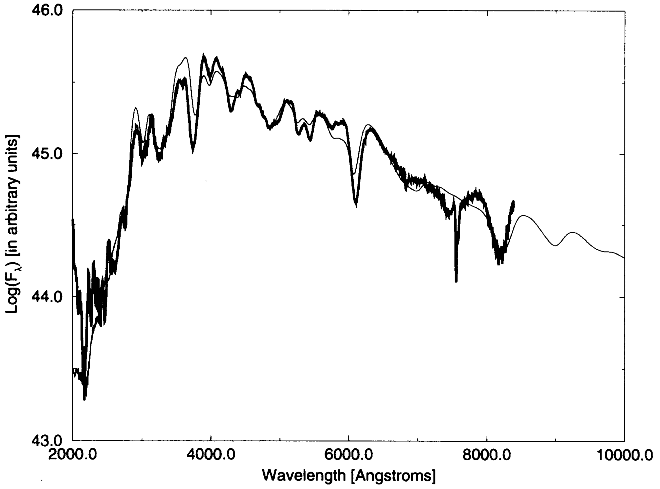

FIG. 2.—Synthetic spectrum, *thin line*, vs. the spectrum of SN 1981B, *thick line*, at maximum blue light (Branch et al. 1983).

able to constrain our models using this "full" spectral coverage. (The data obtained by the *IUE* for SN 1981B is rather noisy.) The UV provides crucial information for the understanding of the model atmosphere's density and temperature gradients. Figure 3 shows the problems inherent in fitting an observed spectrum solely in the optical by comparing our best fit to SN 1992A incorporating exponential and power-law density gradients. In the optical it is a toss up as to which one fits the observed spectrum better; however, one can easily see that blueward of 3750 Å the power law atmosphere has an extreme excess of flux. This difference in flux is due to the different temperature gradients created by each density profile. One should therefore treat models which fit only a part of the "full" spectrum with some suspicion (Pistinner et al. 1995).

6. DISCUSSION

The input parameters as well as the results of our fits to these SNe Ia are listed in Table 1. Making the well-founded assumption of homologous expansion, the reference radius is determined by $R_0 = v_0 t$ and hence our models predict the total emitted flux. Thus, we can convolve our flux with standard filters to predict absolute magnitudes. The absolute magnitudes were obtained using filter functions of Hamuy et al. (1992) as described in Baron et al. (1995).

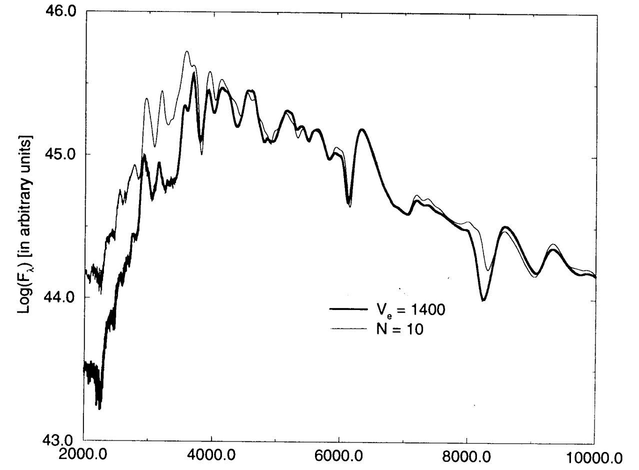

FIG. 3.—Two synthetic spectra. An $N = 10$ power-law density gradient, *thin line*, vs. a $v_e = 1400$ exponential density gradient, *thick line*.

TABLE 1

THE PARAMETERS USED TO FIT SN 1992A AND 1981B WITH THE RESULTING ABSOLUTE MAGNITUDES AND COLORS

Model	v_0 (km s^{-1})	t (days)	$T_{\rm eff}$ (K)	v_e (km s^{-1})	$M_{\rm bol}$	M_B	$B-V$
1981B...	11400	17	9200	1500	−19.31	−19.80	0.08
1992A...	8000	22	8900	1400	−18.99	−19.57	0.16

NOTE.—Since SNe Ia have a large UV deficit, the bolometric correction is positive.

To estimate our errors we conservatively assume errors of $0^{\rm m}.2$ in the velocity, $0^{\rm m}.2$ for discrepancies in the composition and $0^{\rm m}.25$ for the thermalization parameter α which compensates the lack of species considered in non-LTE. We are presently implementing an Fe II model atom with 472 levels and 4505 non-LTE transitions (Hauschildt et al. 1995) which will lower the error due to α. Adding these in quadrature we arrive at error bars of $\pm 0^{\rm m}.38$ for the absolute magnitudes.

With reasonable fits to two SNe Ia we can address the differences between them (Phillips 1993, Branch et al. 1993, 1994). A comparison of these SNe Ia would only be straightforward if performed at a similar time in their evolution (i.e. at maximum light). The spectra of SN 1992A was taken at 5 days after maximum light when it had already decreased $0^{\rm m}.3$ in the blue from its peak (Suntzeff 1992). This would then make it almost the same magnitude as SN 1981B when it was at maximum light ($M_B = -19^{\rm m}.9$). Yet this assumes that both these SNe Ia had a rise time of 17 days and there is some evidence that this is not the case.

If the light curves of these SNe Ia are compared to the light curve of SN 1990N (which has a well observed premaximum light curve) one notices that SN 1981B has a similar shape to SN 1990N while the light curve of SN 1992A rises and falls faster than both of them. This implies that SN 1992A had a shorter rise time. How much shorter should be resolved when a full EPM analysis of these SNe Ia are performed over a wide range in time around maximum light. For now we can estimate the rise time for these supernovae by making the simple assumption that the width of a light curve directly corresponds to its rise time. We use SN 1990N as a baseline light curve and fix its rise time at 20 days. The 20 days is arrived at by adding the 2.5 days it took the PDD3 model of SN 1990N (Khokholov et al. 1992) to reach the first observed data point to the 17.5 days it then took for the supernova to reach maximum light. To obtain the rise time of SN 1981B and SN 1992A we linearly interpolate the width of the light curve $0^{\rm m}.7$ below maximum from SN 1990N. The width of SN 1981B was 90% that of SN 1990N and SN 1992A was only 70% of SN 1990N giving rise times of 18 and 14 days, respectively. Given our peak blue magnitudes of $M_{B_{92A}} = -19^{\rm m}.9$ and $M_{B_{81B}} = -19^{\rm m}.8$, and using our derived rise times we may write the absolute magnitudes as

$$M_{B_{92A}} = -19.4 - 5\log(t_r/14) \pm 0^{\rm m}.4$$

$$M_{B_{81B}} = -19.9 - 5\log(t_r/18) \pm 0^{\rm m}.4\ .$$

Note that the difference between the absolute magnitudes of these two SNe Ia is the same as implied by the Tully-Fisher (Pierce 1994) and surface-brightness-fluctuations (Tonry 1994, private communication) distances to their parent galaxies (see Phillips 1993; Vaughan et al. 1995), but arrived at in a very different manner. The two absolute magnitudes given above, together with the observational Hubble diagram for SNe Ia (Vaughan et al. 1995), give $H_0 \simeq 45 \pm 12$ km s^{-1} Mpc^{-1}. With apparent magnitudes $B = 12.0 \pm 0.1$ for SN 1981B (Leibundgut et al. 1991) and 12.6 ± 0.1 for SN 1992A (Suntzeff 1992) the distance moduli are

$$\mu_{92A} = 32.1 + 5 \log (t_r/14) \pm 0\overset{\text{m}}{.}4$$

$$\mu_{81B} = 31.9 + 5 \log (t_r/18) \pm 0\overset{\text{m}}{.}4\ .$$

7. CONCLUSIONS

We have presented spectral fits to SN 1981B and 1992A near maximum light which match the observed spectra well. It is apparent that we need to add Si II and O I to our list of non-LTE species. Our models have shown the necessity of having both optical and UV coverage of an SNe Ia to constrain the density and temperature structures. Finally, we have demonstrated the ability to carry out an EPM analysis that provides a distance to SNe Ia independent of those based on the radioactive decay of ^{56}Ni and Cepheid variable stars.

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