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Overview of supernova modeling with PHOENIX

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Abstract. We discuss the information that can be obtained by comparing detailed NLTE PHOENIX models to observed supernova spectra. We show that the progenitor chemical composition, total reddening of the supernova, and accurate distances can be obtained with synthetic spectra that provide good fits to both the shape of the SED and the spectral line-shapes in the observed spectra.

Key words. Radiative Transfer — Cosmology: distance scale — Stars: atmospheres — Supernovae: SN 1999em

1. Introduction

Peter Hauschildt (see his contribution this volume) has already described the methods used in the PHOENIX code. Here I want to discuss what can be learned via the detailed modeling of supernova spectra. I will focus in this talk on Type IIP supernovae, but much can be learned about other types of supernovae as well from detailed models of time-series of their spectra.

PHOENIX (see Hauschildt & Baron 1999, 2004,and references therein) is a generalized, stellar model atmosphere code for treating both static and moving atmospheres. The goal of PHOENIX is to be both as general as possible so that essentially all astrophysical objects can be modeled with a single code, and to make as few approximations as possible. Approximations are inevitable (particularly in atomic data where laboratory values for most quantities are unknown); however, the agreement of synthetic spectra with observations across a broad class of astrophysical objects is a very good consistency check. We have modeled Planets/BDs (Barman et al. 2002; Allard et al. 2001; Schweitzer et al. 2001, 2002), Cool Stars (Hauschildt et al. 1999; Hauschildt et al. 1999), Hot Stars (βCMa, ϵCMa, Deneb Aufdenberg et al. 1998, 1999, 2002), α-Lyrae, Novae (Hauschildt et al. 1997; Schwarz et al. 1997), and all types of supernovae (SNe Ia, Ib/c, IIP, IIb Baron et al. 1995b; Lentz et al. 2001; Baron et al. 1999; Mitchell et al. 2002).

PHOENIX solves the radiative transfer problem by using the short-characteristic method (Olson et al. 1987; Olson & Kunasz 1987) to obtain the formal solution of the special relativistic, spherically symmetric radiative transfer equation (SSRTE) along its characteristic rays. The scattering problem is solved via the use of a band-diagonal approximation to the discretized Λ-operator (Hauschildt 1992; Olson & Kunasz 1987; Hauschildt, Störzer, & Baron 1994) as our choice of the approximate

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Λ-operator. This method can be implemented very efficiently to obtain an accurate solution of the SSRTE for continuum and line transfer problems using only modest amounts of computer resources.

We emphasize that `PHOENIX` solves the radiative transfer problem including a full treatment of special relativistic radiative transfer in spherical geometry for all lines and continua. In addition we enforce the generalized condition of radiative equilibrium in the Lagrangian frame, including all velocity terms and deposition of energy from radiative decay or from external irradiation.

We also include a full non-LTE treatment of most ions, using model atoms constructed from the data of Kurucz (1993, 1994a,b) and/or from the CHIANTI and APED databases. The code uses Fortran-95 data structures to access the different databases and model atoms from either or both databases can be selected at execution time.

Absorption and emission is treated assuming complete redistribution and detailed depth-dependent profiles for the lines. Fluorescence effects are included in the NLTE treatment. The equation of state used includes up to 26 ionization stages of 40 elements as well as up to 600 molecules.

2. Introduction to Supernovae

On February 23, 1987 SN 1987A was discovered in the LMC, the first supernova discovered in the local group since the invention of the telescope. With this discovery the field of supernova research expanded rapidly. Prior to this time, supernova research had been a relatively small field, either as part of stellar evolution and nuclear astrophysics or in astronomy being pursued by a few individuals interested in using supernovae as cosmological probes. After SN 1987A and the launch and repair of the Hubble Space Telescope supernova research greatly expanded. SN 1987A has been called by Bob Kirshner the "second most well studied star". Of course with the discovery of the dark energy (Riess et al. 1998; Garnavich et al. 1998; Perlmutter et al. 1999) the interest in supernovae has truly exploded. Most of the work has focused on using Type Ia supernovae as standard candles, but interest in core collapse supernovae has also remained high.

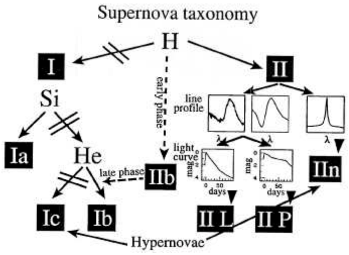

Fig. 1. Supernovae are classified by their spectra Type II show strong hydrogen Balmer lines and Type I do not. The further subclassifications are based both on spectra and light curves. Here we will focus on normal Type IIP supernovae. Diagram courtesy of Rollin Thomas

Supernovae are classified according to their spectra. Although as illustrated in Figure 1 (courtesy of Rollin Thomas) the taxonomic zoo of supernovae includes photometric selection criteria. In this talk, we will focus on modeling spectra of "normal" Type IIP supernovae, although `PHOENIX` can and has been used to model all types of supernovae. Type IIP supernovae are thought to be the result of the core-collapse of a massive star whose hydrogen envelope is intact, and that doesn't have a dense circumstellar medium that the ejecta will interact with. In contrast, Type Ia supernovae, which have been used as cosmological probes, are thought to be the result of the thermonuclear explosion of a Chandrasekhar mass white dwarf. All other supernova types are thought to be the result of core collapse of a massive star whose outer envelope has been strongly altered either via mass loss or through binary interaction.

3. Results Obtained from detailed models

The great strength of `PHOENIX` is that we can make very detailed models treating all important species in NLTE and including the effects of gamma-ray deposition, which pro-

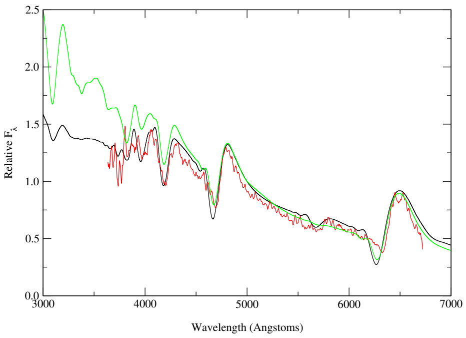

Fig. 2. A model with solar metalicity and one with $Z = Z_\odot/30$ are compared to the observed spectrum of SN 1993W on Aug 20, 1993, clearly the progenitor was a low metalicity star.

duces MeV electrons, which then change the matter ionization state via both primary and secondary ionization. Here, we focus on Type IIP models, some of the work presented below has been discussed in Baron et al. (2003) and Baron et al. (2004, 2000).

Since supernovae are basically spherical, as the ejecta expands geometrical dilution allows us to peer deeper and deeper into the ejecta. Thus early spectra probe the outer parts of the ejecta, and those at later times probe deeper layers, allowing us to "peel the onion" and learn both about the progenitor composition and the effects of stellar evolution and the explosion itself. This is illustrated in Figure 2 which shows a very early spectrum of SN 1993W and two model spectra, one with solar metalicity ($Z = Z_\odot$), the other with metalicity $Z = Z_\odot/30$. Clearly the lower metalicity fit is much better and thus we can determine via a detailed spectral model the metalicity of the progenitor. This is very useful, because other methods of metalicity determination of supernovae (such as H II regions or Lick indices) determine the metalicity of the environment where the supernova occurred, not that of where the star was born. Additionally, we can use these direct probes to calibrate the other more conventional methods.

3.1. Supernova Reddening

Another interesting result of detailed modeling, which has important cosmological implications is that models of the early spectra of SNe IIP can determine the reddening. This is important because the result of the detailed models is the total reddening to the object, both that caused by foreground dust in the Milky Way and that caused by dust in the parent galaxy of the supernova. Figure 3 illustrates this for SN 1999em an extremely well-observed SN IIP in NGC 1637. Here two models with different bolometric luminosities are presented (the total bolometric luminosity in the observer's frame is a required boundary condition for our set of equations). It is convenient to parameterize the total bolometric luminosity in terms of a "model temperature" $T_{\rm model}$

$$L = 4\pi\, R^2\, \sigma\, T^4_{\rm model}$$

where R is the radius of the photosphere (the point where $\tau_{\rm std} = 1$, where $\tau_{\rm std}$ is the total continuum optical depth at 5000 Å), and σ is the radiation constant. $R = v t$ where v is determined by finding the best fit to the observed spectral lineshapes (or is prescribed by a hydrodynamical calculation of the explosion), and t is the time since explosion. In Figure 3 we see that both models do a pretty good job of fitting the observed spectra, however, the cooler model $T_{\rm model} = 11,500$ K has a strong feature due to Ca H+K, that is not present in the observed spectrum, in the hotter model, $T_{\rm model} = 12,000$ K, the feature is absent. In order for the hotter model and cooler model to both fit the overall colors, the assumed reddening was changed from a color excess $E(B-V) = 0.05$ in the cooler model to $E(B-V) = 0.10$ in the hotter model. Using temperature indicators such as Ca H+K, thus allows us to determine the total reddening to SN 1999em to be very close to $E(B-V) = 0.10$.

4. Distances From Supernovae

While the discovery of the dark energy using SNe Ia has been truly one of the most impor-

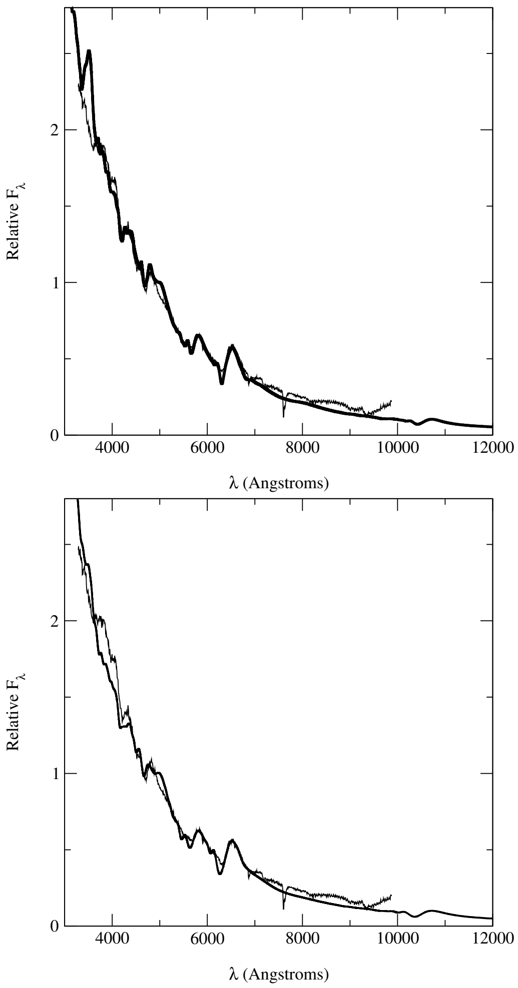

Fig. 3. A model of SN 1993W with $T_{\rm model}$ = 11,500 K and $E(B - V) = 0.05$ (top) is compared to the spectrum of SN 1999em on Oct 29, 1999, about 5 days after explosion. The fit is good, but Ca H+K is strong in the model, but absent in the observation. In the bottom panel, $T_{\rm model}$ = 12,000 K and $E(B - V) = 0.10$, the fit is still good and Ca H+K is no longer significant, thus the reddening in the parent galaxy for SN 1999em is likely to be close to $E(B - V) = 0.1$.

tant astronomical discoveries of our time, all of the work with SNe Ia is empirical, based on observed SNe Ia template light curves. Another method of determining distances using supernovae is the "expanding photosphere method" (EPM, Kirshner & Kwan 1974; Branch et al. 1981; Eastman & Kirshner 1989; Eastman et al. 1996) a variation of the Baade-Wesselink method (Baade 1926). The EPM method assumes that for SNe IIP, with intact hydrogen envelopes, the spectrum is not far from that of a blackbody and hence the luminosity is approximately given by

$$L = 4\pi \zeta^2 R^2 \sigma T^4$$

where R is the radius of the photosphere, T is the effective temperature, σ is the radiation constant, and ζ is the "dilution factor" which takes into account that in a scattering dominated atmosphere the blackbody is diluted (Hershkowitz, Linder, & Wagoner 1986a,b; Hershkowitz & Wagoner 1987). The temperature is found from observed colors, so in fact is a color temperature and not an effective temperature, the photospheric velocity can be estimated from observed spectra using the velocities of the weakest lines,

$$R = v\,t,$$

the dilution factor is estimated from synthetic spectral models, and t comes from the light curve and demanding self-consistency.

Both an advantage and disadvantage of EPM is that it primarily requires photometry. Spectra are only used to determine the photospheric velocity, colors yield the color temperature, which in turn is used to determine the appropriate dilution factor (from model results). This method suffers from uncertainties in determining the dilution factors, the difficulty of knowing which lines to use as velocity indicators, uncertainties between color temperatures and effective temperatures, and questions of how to match the photospheric radius used in the models to determine the dilution factor and the radius of the line forming region (Hamuy et al. 2001; Leonard et al. 2002). In spite of this the EPM method was successfully applied to SN 1987A in the LMC (Eastman & Kirshner 1989; Branch 1987) which led to hopes that the EPM method would lead to accurate distances, independent of other astronomical calibrators. Recently, the EPM method was applied to the very well observed SN IIP 1999em (Hamuy et al. 2001; Leonard et al. 2002; Elmhamdi et al. 2003). All three groups found a distance of 7.5–8.0 Mpc. Leonard et al. (2003) subsequently used *HST* to obtain a Cepheid distance to the parent galaxy of SN 1999em, NGC 1637, and found 11.7 ± 1.0 Mpc, a value 50% larger than that obtained with EPM.

With modern detailed NLTE radiative transfer codes, accurate synthetic spectra of all types of supernovae can be calculated. The **S**pectral-fitting **E**xpanding **A**tmosphere **M**ethod (SEAM, Baron et al. 1995a, 1996; Lentz et al. 2001; Mitchell et al. 2002) was developed using the generalized stellar atmosphere code `PHOENIX` (for a review of the code see Hauschildt & Baron 1999). While SEAM is similar to EPM in spirit, it avoids the use of dilution factors and color temperatures. Velocities are determined accurately by actually fitting synthetic and observed spectra. The radius is still determined by the relationship $R = vt$, (which is an excellent approximation because all supernovae quickly reach homologous expansion) and the explosion time is found by demanding self consistency. We note that when using an explosion model, SEAM requires no determination of velocities via spectral fitting, the radius of each matter element is simply determined by using homology. This is an important difference from EPM, where the velocity is determined using the absorption positions of lines and Dessart & Hillier (2005) have shown that the measured position of features will be both above and below the photosphere. SEAM does not require the existence of a photosphere, which is good since it doesn't exist. SEAM uses all the spectral information available in the observed spectra simultaneously which broadens the base of parameter determination. Since the spectral energy distribution is known completely from the calculated synthetic spectra, one may calculate the absolute magnitude, M_X, in any photometric band X,

$$M_X = -2.5 \log \int_0^\infty S_X(\lambda)\, L_\lambda\, d\lambda + C_X$$

where S_X is the response of filter X, L_λ is the luminosity per unit wavelength, and C_X is the zero point of filter X determined from standard stars. Then one immediately obtains a distance modulus μ_X, which is a measure of the distance

$$\mu_X \equiv m_X - M_X - A_X = 5 \log (d/10\text{pc}),$$

where m_X is the apparent magnitude in band X and A_X is the extinction due to dust along the line of sight both in the host galaxy and in our own galaxy. Baron et al. (2000) found that the early spectra were quite sensitive to the assumed reddening and hence determined a value of $E(B-V) = 0.1$ for SN 1999em. The SEAM method does not need to invoke a blackbody assumption or to calculate dilution factors.

We used the above method to calculate the distance to SN 1999em. The models were taken from Model S15 of Woosley & Weaver (1995). The model was expanded homologously and the gamma-ray deposition was parameterized to be consistent with the nickel mixing found in SN 1987A (Mitchell et al. 2001). The abundances were taken directly from the model, and the effects of radioactive decay were taken into account. We used observed photometry of Leonard et al. (2002) and Hamuy et al. (2001) in $UBVRIZ$. Our favored value is 12.5 Mpc for which we find a formal error of ±1.8 Mpc if we add in quadrature the error in determining the effective temperature (∼ 500 K), the error in determining the velocity (∼ 500 km s^{-1}), and the formal error in the mean (see Baron et al. 2004,for more details).

Figure 4 compares observed and model spectra, details of the modeling will be discussed elsewhere. Overall the fits are excellent, except on November 28 where the blue part of the spectrum is poorly fit, this is due to the fact that at this late time the spectrum forms over a much larger mass range of the ejecta and so we are sensitive to the detailed mixing of both nickel and helium which we have not attempted to adjust in the models. We find the explosion date to be 5.3 d prior to discovery on Oct 29, 1999. Errors in the explosion date primarily affect the absolute magnitudes of the early spectral models since they are more sensitive to errors in the explosion date than are later epochs. If the estimated time from explosion is too small, the models will have radii which are too small ($R = vt$). With smaller

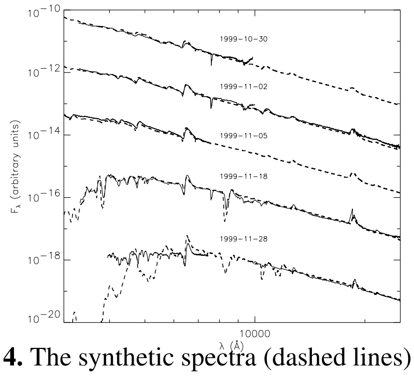

Fig. 4. The synthetic spectra (dashed lines) are compared to observed spectra (solid lines) at 5 different epochs. The observed spectra were obtained at CTIO for Oct 30, Nov 2, and Nov 18 (Hamuy et al. 2001), at *HST* and FLWO on Nov 5 (Baron et al. 2000) and the optical spectrum on Nov 28 was obtained at Lick (Leonard et al. 2002) while the IR was obtained at CTIO (Hamuy et al. 2001). The observed fluxes have been offset for clarity.

emitting area, they will be dimmer and hence appear to be closer. The ability to compare synthetic spectra with observational spectra is clearly an advantage of the SEAM method. The good agreement with the Cepheid result shows that quality fits to SNe IIP can give distances accurate to 20%, *without adjusting metalicities, helium mixing, or nickel mixing*. Once we have completed a large grid of models which vary these parameters we should be able to reduce the uncertainties even more, thus SNe IIP will become important cosmological probes.

5. Conclusions

Detailed NLTE models of supernovae can determine the composition structure of the progenitor (which can be used to probe the first stars with JWST) and the total reddening to the supernova. Detailed time series can provide clues to the stellar evolutionary history of the progenitor star as well as information about the mixing produced in the explosion. The SEAM method provides a distance consistent with that of Cepheids. The SEAM method applied to a set of cosmological SNe IIP (observable out to $z \lesssim 0.5$) supernovae can help to understand the systematics of the purely empirical SNe Ia results.

Detailed NLTE modeling of the spectral lineshapes of supernovae provides information on stellar evolution, the explosion mechanism, the chemical composition of the progenitor, and the environment of the supernova, as well as cosmologically useful distance determinations.

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