Abstract. We briefly describe the current version of the PHOENIX code. We then present some results on the modeling of Type II supernovae and show that fits to observations can be obtained, when account is taken for spherically symmetric, line-blanketed, expanding atmospheres. We describe the SEAM method of obtaining distances to supernovae and briefly discuss its future prospects.

1. The PHOENIX Code

PHOENIX (see Hauschildt & Baron 1999, 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, ǫCMa, 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 (SS-RTE) 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 Λ-operator. This method can be implemented very efficiently.

1Department of Physics and Astronomy, University of Oklahoma, 440 West Brooks, Rm. 131, Norman, OK 73019, USA
2Computational Research Division, Lawrence Berkeley National Laboratory, MS 50F-1650, 1 Cyclotron Rd, Berkeley, CA 94720-8139 USA
3Laboratoire de Physique Nucléaire et de Haute Energies, CNRS-IN2P3, University of Paris VII, Paris, France
4Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany
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. Early Supernova Spectra and Distances

Early spectra of supernovae are important to model with synthetic spectra. Due to the geometrical dilution, early spectra tell us about the composition and velocity structure of the outermost layers of the supernova ejecta. Therefore, they can provide clues to the progenitor structure of SNe Ia, the primordial composition of all types of supernovae and the nearby circumstellar medium. Baron et al. (2003) showed that detailed models of the early spectra of SN 1993J could reveal the primordial metallicity as well as the total reddening to the supernova.

With all large computer codes, code improvement is an ongoing process. We recently improved the NLTE equation of state and Figure 1 compares the results with and without the improvement. The change is not dramatic and in the right direction, the newer model fits Hα better.

We (Baron et al. 2000) were also able to determine the reddening to SN 1999em, by modeling the early spectra. We found that $E(B - V) = 0.1 \pm 0.05$ for the total (foreground plus parent) color excess.

In order to determine the values of the fundamental cosmological parameters, an accurate distance indicator visible to high redshift is required. Supernovae are extremely bright and hence can be detected at cosmological distances with modern large telescopes. The reliability of SNe Ia as distance indicators improved significantly with the realization that the luminosity at peak was correlated with the width of the light curve (Phillips 1993) and hence that SNe Ia were correctable candles in much the same way that Cepheids are (Phillips et al. 1999; Goldhaber et al. 2001; Riess et al. 1993). This work and the development of highly efficient search strategies (Perlmutter et al. 1997) sparked two groups to use SNe Ia to measure the deceleration parameter and to discover the dark energy (Riess et al. 1998; Perlmutter et al. 1999).

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. 1999).
Early Spectra

Figure 1. A comparison of synthetic spectra of SN 1993W on Aug 20, 1993 using old (incorrect) and new (correct) NLTE equation of state. The change is not dramatic, but H α is better fit with the new EOS.

Figure 2. The left panel displays a model with a lower temperature and extinction \( E(B-V) = 0.05 \), while the right panel shows a model with a higher temperature and extinction \( E(B-V) = 0.10 \). The Ca II H+K line is very temperature sensitive at this early phase and the higher extinction is clearly preferred.

[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, \( \sigma \) is the radiation constant, and \( \zeta \) 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 effective 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.

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 $11.7 \pm 1.0$ Mpc.

With PHOENIX, accurate synthetic spectra of all types of supernovae can be calculated. The Spectral-fitting Expanding Atmosphere Method (SEAM) [Baron et al. 1995a, 1996; Lentz et al. 2001; Mitchell et al. 2002] was developed using PHOENIX. 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. 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 particular 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 $X$, $L_\lambda$ 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 $\mu_X = m_X - M_X - A_X = 5 \log (d/10 \text{pc})$, where $m_X$ is the apparent magnitude in band $X$ and $A_X$ is the extinction due to dust along the line of sight either in the host galaxy or in our own galaxy. The SEAM method does not need to invoke a blackbody assumption or to calculate dilution factors.

3. Fits and Conclusions

Using the latest version of PHOENIX version 13.06, we have calculated synthetic spectra of SN 1999em using 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. No attempt was made to adjust the metallicity or helium mixing. The model had abundances: $X = 0.64$ $Y = 0.34$ $Z = 0.019$. Figure 3 shows the results are quite close to observed results except at the latest epoch where the blue is strongly dependent on the exact abun-
dances. With these models we are able to obtain a reasonably accurate distance to SN 1999em \cite{Baron2004}.

Figure 3. The synthetic spectra are compared to observed spectra at 5 different epochs. The observed spectra were obtained at CTIO for Oct 30, Nov 2, and Nov 18 \cite{Hamuy2001}, at HST and FLWO on Nov 5 \cite{Baron2000} and the optical spectrum on Nov 28 was obtained at Lick \cite{Leonard2002} while the IR was obtained at CTIO \cite{Hamuy2001}. The observed fluxes have been offset for clarity.

Results from both nearby and high-z searches require quantitative spectroscopy to interpret their results. Results from hydrodynamical calculations also require quantitative spectroscopy to validate/falsify their results. The SEAM method applied to both nearby and high-z samples will yield interesting cosmological results. SEAM provides a route to obtaining cosmological parameters completely independent from SNe Ia.

Acknowledgments. We thank Doug Leonard and Mario Hamuy for helpful discussions. This work was supported in part by NASA grant NAG5-3505, NSF grants AST-0204771 and AST-0307323, an IBM SUR grant to OU and NASA grants NAG 5-8425 and NAG 5-3619 to UGA. PHH was supported in part by the Pôle Scientifique de Modélisation Numérique at ENS-Lyon. This research used resources of: the San Diego Supercomputer Center (SDSC), supported by the NSF; the National Energy Research Scientific Computing Center (NERSC), which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098; and the Höchstleistungs Rechenzentrum Nord (HLRN). We thank all these institutions for a generous allocation of computer time.

References

Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357
Aufdenberg, J. P., Hauschildt, P. H., & Baron, E. 1999, MNRAS, 302, 599
Aufdenberg, J. P., Hauschildt, P. H., Baron, E., Nordgren, T. E., Burnley, A. W., Howarth, I. D., Gordon, K. D., & Stansberry, J. A. 2002, ApJ, 570, 344
Aufdenberg, J. P., Hauschildt, P. H., Shore, S. N., & Baron, E. 1998, ApJ, 498, 837
Baade, W. 1926, Astr. Nach., 228, 359
Barman, T. S., Hauschildt, P. H., Schweitzer, A., Stancil, P. C., Baron, E., & Allard, F. 2002, ApJ, 569, L51
Baron, E., Branch, D., Hauschildt, P. H., Filippenko, A. V., & Kirshner, R. P. 1999, ApJ, 527, 739
Baron, E., Hauschildt, P. H., Branch, D., Austin, S., Garnavich, P., Ann, H. B., Wagner, R. M., Filippenko, A. V., Matheson, T., & Liebert, J. 1995a, ApJ, 441, 170
Baron, E., Hauschildt, P. H., Branch, D., Kirshner, R. P., & Filippenko, A. V. 1996, MNRAS, 279, 799
Baron, E., Hauschildt, P. H., & Young, T. R. 1995b, Physics Reports, 256, 23
Baron, E., Nugent, P., Branch, D., & Hauschildt, P. 2004, ApJ, submitted
Baron, E., Nugent, P. E., Branch, D., Hauschildt, P. H., Turatto, M., & Cappellaro, E. 2003, ApJ, 586, 1199
Baron, E. et al. 2000, ApJ, 545, 444
Branch, D. 1987, ApJ, 320, L23
Branch, D., Falk, S. W., McCall, M. L., Rybski, P., Uomoto, A. K., & Wills, B. J. 1981, ApJ, 244, 780
Eastman, R. & Kirshner, R. P. 1989, ApJ, 347, 771
Eastman, R., Schmidt, B. P., & Kirshner, R. 1996, ApJ, 466, 911
Elmnhandi, A., Danziger, I. J., Chugai, N., Pastorello, A., Turatto, M., Cappellaro, E., Altavilla, G., Benetti, S., Patat, F., & Salvo, M. 2003, MNRAS, 338, 939
Goldhaber, G. et al. 2001, ApJ, 558, 359
Hamuy, M. et al. 2001, ApJ, 558
Hauschildt, P. H. 1992, JQSRT, 47, 433
Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ, 512, 377
Hauschildt, P. H., Allard, F., Ferguson, J., Baron, E., & Alexander, D. 1999, ApJ, 525, 871
Hauschildt, P. H. & Baron, E. 1999, J. Comp. Applied Math., 109, 41
Hauschildt, P. H., Schwarz, G., Baron, E., Starrfield, S., Shore, S., & Allard, F. 1997, ApJ, 490, 803
Hauschildt, P. H., Störzer, H., & Baron, E. 1994, JQSRT, 51, 875
Hershkowitz, S., Linder, E., & Wagoner, R. 1986a, ApJ, 301, 322
Hershkowitz, S. & Wagoner, R. 1987, ApJ, 322, 967
Kirshner, R. P. & Kwan, J. 1974, ApJ, 193, 27
Kurucz, R. 1993, CDROM No. 1: Atomic Data for Opacity Calculations, SAO Cambridge, MA
—. 1994a, CDROM No. 22: Atomic Data for Fe and Ni, SAO Cambridge, MA
—. 1994b, CDROM No. 23: Atomic Data for Mn and Co, SAO Cambridge, MA
Lentz, E., Baron, E., Branch, D., & Hauschildt, P. H. 2001, ApJ, 557, 266
Leonard, D. C. et al. 2002, PASP, 114, 35
—. 2003, ApJ, 594, 247
Mitchell, R., Baron, E., Branch, D., Hauschildt, P. H., Nugent, P., Lundqvist, P., Blinnikov, S., & Pun, C. S. J. 2002, ApJ, 574, 293
Mitchell, R., Baron, E., Branch, D., Lundqvist, P., Blinnikov, S., Hauschildt, P. H., & Pun, C. S. J. 2001, ApJ, 556, 979
Olson, G. L., Auer, L. H., & Buchler, J. R. 1987, JQSRT, 38, 431
Olson, G. L. & Kunasz, P. B. 1987, JQSRT, 38, 325
Perlmutter, S. et al. 1997, ApJ, 483, 565
—. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M., Lira, P., Suntzeff, N. B., Schommer, R. A., Hamuy, M., & Maza, J. 1999, AJ, 118, 1766
Riess, A. et al. 1998, AJ, 116, 1009
Riess, A. G., Press, W. H., & Kirshner, R. P. 1995, ApJ, 438, L17
Schwarz, G., Hauschildt, P. H., S. Starrfield, E. B., Allard, F., Shore, S., & Sonneborn, G. 1997, MNRAS, 284, 669
Schweitzer, A., Gizis, J. E., Hauschildt, P. H., Allard, F., Howard, E. M., & Kirkpatrick, J. D. 2002, ApJ, 566, 435
Schweitzer, A., Gizis, J. E., Hauschildt, P. H., Allard, F., & Reid, N. 2001, ApJ, 555, 368
Woosley, S. E. & Weaver, T. A. 1995, ApJS, 101, 181