RevMexAA (Serie de Conferencias), **10**, 157–162 (2001)

EXTREME TYPE IIP SUPERNOVAE AS YARDSTICKS FOR COSMOLOGY

P. Höflich,[1] O. Straniero,[2] M. Limongi,[3] I. Dominguez [4] and A. Chieffi [3]

RESUMEN

Hemos estudiado los efectos evolutivos como función del corrimiento al rojo en las supernovas producidas por colapso gravitacional y su aplicación en cosmología, basándonos en una extensa red de modelos con masas comprendidas entre 13 y 25 $M_\odot$ y sus curvas de luz.

Al disminuir la metalicidad, Z, e incrementar la masa, las explosiones tienden a producirse cuando el progenitor es una supergigante azul (SGA) y consecuentemente se obtienen supernovas subluminosas, $\approx 1.5^m$ más débiles que una supernova *normal* producida en la explosión de una supergigante roja (SGR). Los progenitores de baja masa tienden a explotar como supergigantes rojas incluso cuando Z es pequeña. Analizamos las consecuencias que de ello se derivan en la evolución química.

Identificamos que las SNs IIP *extremas* constituyen una clase muy homogénea, por lo que podrían emplearse para la determinación de distancia con una exactitud dentro del 30%. Debido a que presentan curvas de luz características, pueden identificarse sin recurrir al espectro, y su seguimiento observacional se limitaría a un intervalo reducido de brillo. Esto hace posible el empleo de las 'SNs IIP extremas' como indicadores de distancia hasta un corrimiento al rojo ≈ 3 usando telescopios de 8 metros de tamaño. SIRTIF podría aumentar el límite observacional en una magnitud.

ABSTRACT

Evolutionary effects with redshift of core collapse supernovae and their application to cosmology have been studied based on an extensive grid of stellar models between 13 and 25 $M_\odot$, and their light curves after the explosion.

With decreasing metallicity Z, and increasing mass, progenitors tend to explode as compact Blue Supergiants (BSG) and produce subluminous supernovae which are about 1.5^m dimmer compared to 'normal' SNeII with Red Supergiant (RSG) progenitors. Progenitors with small masses tend to explode as RSGs even with low Z. The consequences are obvious for probing the chemical evolution.

We identify *extreme* SNe IIp supernovae as a rather homogeneous class which may allow their use as standard candles for distance determination accurate within 30%. Due to their unique light curves, no spectra need to be taken for their identification, and follow–up observations can be limited to a very small dynamical range in brightness. This means that distance determination by 'extreme SNe IIp' are possible up to redshifts of ≈ 3 using 8–meter class telescopes. SIRTIF may push the limit by another magnitude.

Key Words: **COSMOLOGY — SUPERNOVAE: GENERAL**

[1] Dept. of Astronomy, University of Texas, Austin, TX 78681, USA.
[2] Osservatorio Astronomico di Collurania, 64100 Teramo, Italy/
[3] Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio, Italy.
[4] Departmento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain.

1. INTRODUCTION

Supernovae are among the brightest single objects which may reach the same brightness as the entire host galaxy. This allows one to measure distances on cosmological scales if the intrinsic brightness of the object is known. During the last few years, the main attention has been drawn by Type Ia Supernovae because the homogenity in their properties allows accurate distance determinations based on either statistical correlations in combination with exact calibrations by $\delta - Ceph.$ stars (Phillips et al. 1987; Saha et al. 1997), or detailed models. Both the empirical and the theoretical approach provided consistent values for H_o (e.g. Müller & Höflich 1994; Riess et al. 1995; Hamuy et al. 1996; Höflich & Khokhlov 1996; Nugent et al. 1996). The routine detections of SNe Ia at redshifts of 0.5 to 1.2 provided strong evidence for a positive cosmological constant (e.g. Perlmutter et al. 1999, Riess et al. 1999). For the latter results, an absolute accuracy of about 10% is required. This leaves potential systematic effects of SNe Ia properties with redshift as a major concern (Höflich, Wheeler & Thielemann 1998), and it explains the goal to extend the current efforts to large redshifts. In the current scenario, SNe Ia are thermonuclear explosions of white dwarfs which have grown to the Chandrasekhar mass M_{Ch} by accretion of H or He rich material from a companion, and by burning of the accreted material to C/O. The strength of He shell flashes and the wind around accreting WD is very metal dependent. For Z $\lesssim 0.1\times$solar, the WD may not reach M_{Ch} (Nomoto et al. 2000, fully consistent with our findings). SNe Ia may not (or rarely) occur at large redshifts. From the observational point of view, another restriction for the use of SNe Ia is that both spectra and light curves have to be taken to identify the objects.

The other class of SN, core collapse supernovae, are thought to be the final results of massive stellar evolution for stars with main sequence masses $\gtrsim 10M_\odot$. The light curves and spectra depend sensitively on the initial stellar mass, metallicity, mass loss and explosion energy. Therefore, these objects show a wide variety of brightness and properties of the light curves which prevents their use as quasi–standard candles. On the other hand, these objects will occur soon after the initial star formation period and, therefore, can be used to probe the structure of the universe at high z.

In this work, we present a study focussed on core collapse supernovae to answer the following questions: How do the light curves of core collapse supernovae depend on the metallicity which must be expected to decrease with redshift? Can we identify a subclass among the core collapse supernovae which can be used as quasi–standard candles, and what accuracy do we expect? Can this subclass be identified purely by their light curves, without a follow–up which requires to "go" much fainter than maximum light?

2. MODEL CALCULATIONS

The stellar evolution has been calculated from the pre–main sequence to the onset of the core collapse using the evolutionary code FRANEC (Chieffi & Straniero 1989; Straniero et al. 1997; Chieffi, Limongi & Straniero 1998). Stellar evolution models have been constructed for masses of 13, 15, 20 and 25 $M_\odot$ and for metallicities Z of 0.02, 0.006, 0.001, and 0. *Extreme* SNe IIp with plateau phases longer than 50 to 60 days are produced if most of the hydrogen rich envelope is retained (Fig. 1). Rather moderate mass loss does not alter significantly the structure of both the core and the envelope of such stars and, consequently, the brightness of the LCs during the plateau phase (Chieffi et al. 2000, in preparation, and below). For some of the model, mixing of radioactive ^{56}Ni has been imposed. The model parameters have been selected to demonstrate certain effects and to cover the extremes rather than to provide a 'best' model optimized to reproduce a given observation. For low metallicities Z, models explode as compact BSG ($R_\star \leq 100R_\odot$) rather than as extended RSG ($500R_\odot \leq R_\star \leq 1500R_\odot$). We find that all the zero metallicity models end up as a BSG while all the solar metallicity ones end up as a RSG. At intermediate Z, there is the general trend that the more massive stars end up as BSG while the less massive ones end up as RSG. The limiting mass depends on Z (Fig. 1). Whether a star ends as a RSG or a BSG depends sensitively on the H–shell burning or, more precisely, on the inner boundary of the H–rich layers which, in turn, depends on the chemical mixing of H/He assumed in the calculations which may change for a variety of reasons such as common envelope evolutions, stellar rotation, turbulent mixing, etc.

Based on the final stellar structures, the hydrodynamical explosion and light curves have been constructed using our one–dimensional radiation–hydro code (e.g. Höflich & Khokhlov 1996, and references therein). After the core collapse and the formation of the neutron star, the explosion is triggered by depositing the explosion

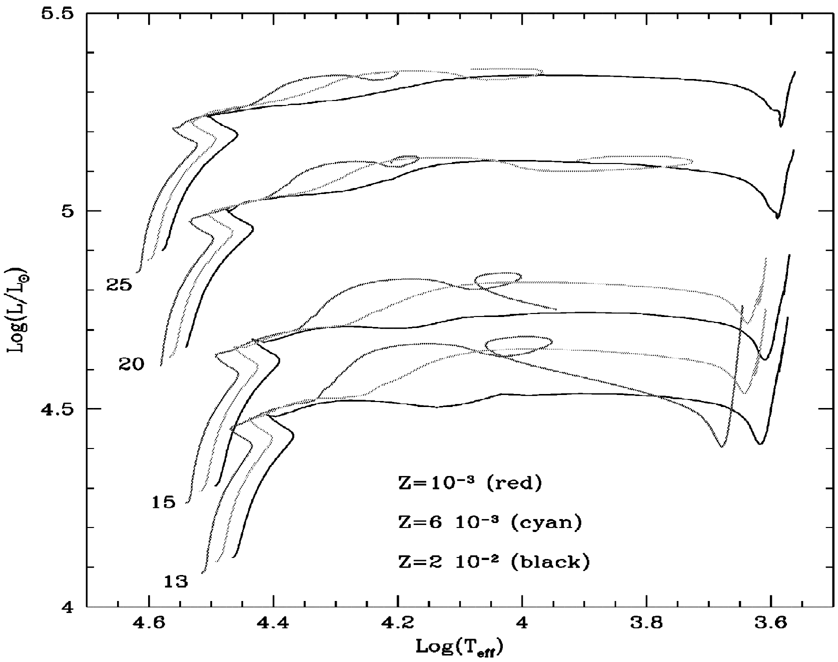

Fig. 1. Stellar evolution from the main sequence to the onset of the core collapse for masses between 13 and 25 $M_{\odot}$ with metallicities Z=0.02 (black), 0.066 (light grey) and 0.001(grey).

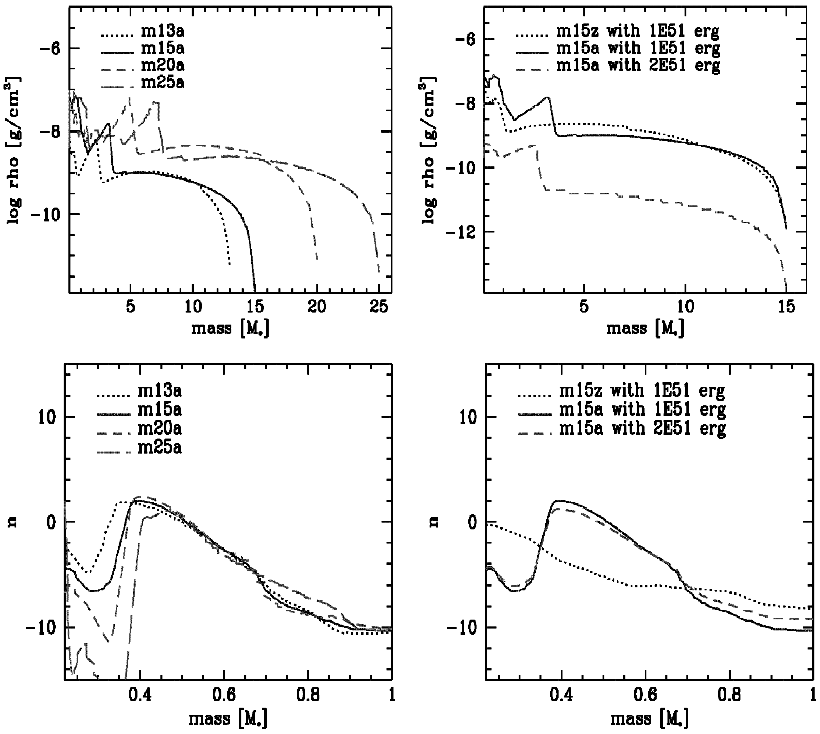

Fig. 2. Density profiles and density gradients n ($\rho \propto r^{-n}$) at day 5 for various masses, metallicities and explosion energies. The models are identified by their names mXXY where XX gives the mass in solar units and Y=a,z stands for solar and zero metallicity, respectively. Note the similarity of the density structures for all RSGs independent from mass and final kinetic energy of the expanding envelope E_{kin}.

The Seventh Texas-México Conference on Astrophysics: Flows, Blows and Glows (Austin, Texas, 6-8 April 2000)
Editors: William H. Lee and Silvia Torres-Peimbert

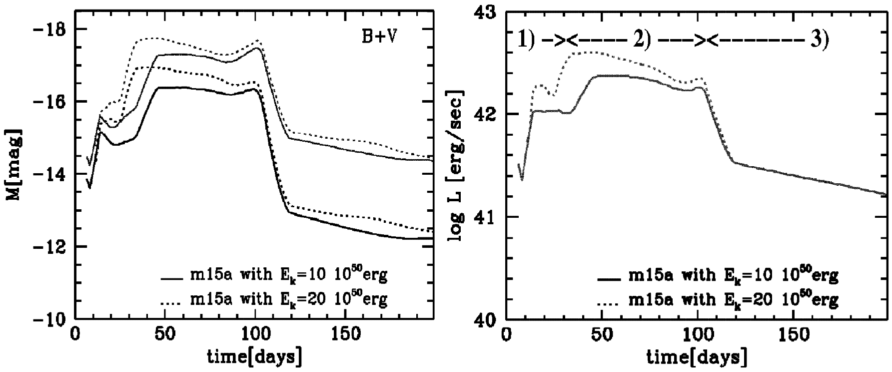

Fig. 3. Influence of the explosion energy on the bolometric, B and V light curves for a RSG of 15 solar masses without mixing of ^{56}Ni.

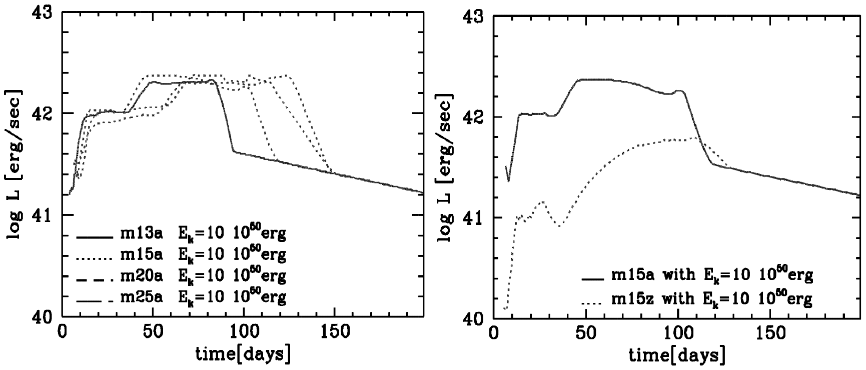

Fig. 4. Bolometric light curves for various masses and solar metallicity (left) and a 15 $M_{\odot}$ star with zero and solar metallicity (right) with $E_{kin} = 1 \times 10^{51}$ erg.

energy above the neutron star. The explosion energy is adjusted to provide a final kinetic energy E_{kin} of 1 or 2×10^{51} erg. Due to the similarity in the final stellar structures, the density slopes of the hydrogen rich envelopes are very similar for RSG progenitors during the phase of homologous expansion (Fig. 2). Three phases can be distinguished for the light curves (Figs. 3 and 4): 1) Most of the envelope is ionized. This phase depends sensitively on the explosion energy, mixing of radioactive Ni, and the mass of the progenitor, e.g. either strong mixing or $E_{kin} \leq 1 foe$ will cause a steep and steady increase in B and V; 2) The emitted energy is determined by the receding (in mass) of the H recombination front which is responsible for both the release of stored, thermal and the recombination energy. At the recombination front, the opacity drops by about three orders of magnitude providing a self–regulating mechanism. If too little energy is released, the opacity drops fast causing an increase in the speed at which the the photosphere is receding. In turn, this causes a larger energy release. In case too much energy is released, the opacity stays high and, consequently, the release of stored energy is reduced. Hydrogen recombines at a specific temperature at or just below the photosphere. Consequently, the effective temperature and the color indices remain largely unchanged during the recombination phase. Due to the flat density profiles of the expanding envelopes in the RSG case, the photospheric radius and, thus, the luminosity L stays almost constant. In contrast, for exploding BSG, the resulting steep density gradients result in a steadily increasing radius and, since the recombination temperature hardly changes, in a steadily increasing brightness (Fig. 4). After the recombination front has passed through the H-rich envelope, the brightness drops fast. During phase 3), L is given by the instant energy release by radioactive decay of ^{56}Co. In all models, the escape probability for γ–rays remains very small up to 300 or 400 days after the explosion. The size of the drop in L depends mainly on the amount of ejected ^{56}Ni.

3. FINAL DISCUSSION AND CONCLUSIONS

Light curves for plateau supernovae have been studied. A set of detailed calculations for stellar evolution and light curves have been computed for a variety of initial masses, explosion energies, mixing during the stellar evolution or during the explosion, and metal abundances.

Based on our models, we suggest the use of a subclass of Type II Supernovae, the *extreme* SNeIIp, as quasi standard candles. These objects are characterized by a plateau phase in excess of 50 to 60 days (e.g. SN1999em). They can be understood as explosions of Red Supergiants which have undergone rather moderate mass loss during the stellar evolution. The V brightness during the plateau phase changes/declines by about 0.2 to 0.7 ^{m}. The mean absolute brightness in $V(\approx 17.4 - 17.8^m)$ during the plateau phase is rather insensitive to the mass of the progenitor and the explosion energy (within $\approx 0.6^m$). Note that line blocking in B and, in particular, in the UV depends on the metallicity causing a somewhat larger spread. The overall similarity of the LCs is caused by the similarity of the density structures of red giants, the resulting *flat* density slopes, the expanding H–rich envelope and the 'self–regulating' propagation of the recombination front which determines the brightness during the plateau phase.

In contrast, if the progenitor explodes as a blue supergiant, the resulting steep density profile results in a long lasting phase of increasing photospheric radius and brightness. The maximum brightness is lower by about 1.5^m compared to the explosion of a RSG because of the increased expansion work for BSGs.

It is well known from SN1987A that low metallicity stars may explode as blue supergiants. Qualitatively, this tendency is reproduced by our models. Note, however, that we showed above that, at the lower end of the mass scale, the star may explode as a RSG even for Z as low as a 10^{-3}. The mass dependence of the final outcome has two main consequences. Firstly, the discovery probability for SNe II at high z will decrease with the progenitor mass. The supernovae statistics will be systematically biased, starting at $z \approx 1$. The consequences for the study of the chemical evolution and the element production at high red-shifts (e.g. by NGST) shall be noted. Secondly, even at high redshifts, some *extreme* SNe IIp should be visible. Taking their unique properties, they may prove to be the key for the use of SN for cosmology at high z before SNe Ia occur.

Although the use of *extreme* SNe IIp will not achieve the same accuracy as Type Ia Supernovae, there are some distinct advantages: 1) due to their unique light curves and colors, no spectrum is required for identification. 2) The requirements on the time coverage of the light curves are very moderate: Three or four deep images with a sample rate of 50 to 60 days in the rest frame will allow their discovery, identification and their use for cosmology. At some time, two color images should be taken to deselect flare star and to get a handle on the reddening. 3) Finally, there is no need to follow the light curves after the plateau towards dimmer magnitudes. For the use of SNe Ia, the requirement to obtain a spectrum limits the current use of SNIa of $\approx 24^m$ if 8m–class telescopes are employed. For the *extreme* SN IIp, 1) to 3) imply that the largest ground based telescopes with IR detectors can be used as search instruments which pushes the limit to about 27 to 28^m. Therefore, *extreme* SNe IIp may be used up to $z \approx 3$ using 8–meter class telescopes. SIRTIF may push the limit by another magnitude by long time exposures.

One potential pitfall is the anisotropic luminosity caused by aspherical explosions of core collapse SN. In general, the light of core collapse supernovae is polarized by $\approx 0.5...1\%$ (e.g. Wang et al. 2000). Polarization of this size corresponds to asymmetries in the envelope which produce directional dependence in the observed L of $\approx 0.3 ... 0.6^m$ (Höflich 1991). However, extended H rich envelopes tend to spherize the H–rich layers of the envelopes even if the explosions are assumed to be jet–like (Khokhlov, Höflich & Wang 2000 in preparation). This tendency is consistent with recent observations for SN1999em (Wang 2000, private communication).

The statistical data base for *extreme* SNe IIp is very incomplete. For the years 1998 and 1999, about 5 to 10 % of all nearby SN II fall into this category making the rate for this type about a factor of 3 to 5 less abundant than SNe Ia. However, the star formation rate at redshifts between 2 and 3 was higher by a factor of $\approx 3...5$ (Kravtsov & Yepes 2000) compared to the current rate, making the expected rates comparable to those of SNe Ia. For more details, see Chieffi et al. 2000 (in preparation).

PAH would like to thank the people at the Observatories in Teramo and Monteporzio for the hospitality during his stay when most of the work has been done. This research was supported in part by NASA Grant LSTA-98-022. The calculations for the explosion and light curves were done on a cluster of workstations financed by the John W. Cox-Fund of the Department of Astronomy at the University of Texas, and processors donated by AMD.

REFERENCES

Chieffi, A., Straniero, O. 1989, ApJS, 71, 48
Chieffi, A., Limongi, M., Straniero, O. 1998, ApJ, 502, 737
Hamuy, M. et al. 1996, AJ, 112, 2408
Höflich, P., Wheeler, J. C., Thielemann, F.K. 1998, ApJ, 495, 617
Höflich, P., Khokhlov, A. 1996, ApJ, 457, 500
Höflich, P. 1991, A&A, 257, 641
Kravtsov, A. V., Yepes, G. 2000, MNRAS, 318, 227
Müller, E., Höflich, P. 1994, A&A 281, 51
Nomoto, K., Umeda, H., Hachisu, I., Kato, M., Kobayashi, C., Tsujimoto, T. 2000, in "SNeIa: Theory and Cosmology", eds. J. Truran & J. Niemeyer, Cambridge University Press
Nugent, P. et al. 1996, Phys.Rev.Lett, 75, 394, & 1974E1, 51
Perlmutter, S. et al. 1999, ApJ, 117, 707
Phillips M.M. et al. 1987, PASP, 99, 592
Riess, A. G. et al. 1999, ApJ, 116, 1009
Riess, A. G., Press, W. H., Kirshner, R. P. 1995, ApJ, 438, L17
Saha, A. et al. 1997, ApJ, 486, 1
Straniero, O., Chieffi, A., Limongi, M. 1997, ApJ 490, 425
Wang, L., Howell, A., Höflich, P. & Wheeler, C. J. 2001, ApJ, in press

A. Chieffi, M. Limongi: Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio, Italy.
I. Dominguez: Departmento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain.
P. Höflich: Dept. of Astronomy, University of Texas, Austin, TX 78712, USA(pah@hej1.as.utexas.edu).
O. Straniero: Osservatorio Astronomico di Collurania, 64100 Teramo, Italy.