Temporal and Spectral Modelling of Intermediate Luminosity type Ib Supernova SN 2015ap.

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Abstract

In this work, we present the observed photometric and spectroscopic properties of a type Ib supernova (SN) SN 2015ap. Our aim in this work is to model a reliable progenitor for SN2015ap, which can undergo core-collapse and explain the observed properties of this SN. Initially, this SN shows some broad-lined features like SN2008D, and later it shows features matching with normal type Ib supernovae (SNe). We tried to synthetically reproduce the explosion. For this purpose, we modeled a 12 M_{sun} zero-age main sequence (ZAMS) star and evolved it until the onset of core-collapse using the stellar evolution code MESA. Thereafter, synthetic explosions are produced using SNEC and STELLA, which provide properties such as bolometric luminosity, black body radius, temperature, and velocity evolution of the photo-sphere. We compare the observed parameters of SN 2015ap with those produced by synthetic explosion and find satisfactory agreement with each other supporting a 12 M_{sun} progenitor for SN 2015ap.

Introduction

Supernovae (SNe) are the final fates of stars. These are bright and extremely powerful explosions that mark the death of stars. Type Ib SNe lack prominent Hydrogen-features in their early spectra but display strong Helium features. Two progenitor scenarios have been proposed for these catastrophic events. The first case involves a relatively low mass progenitor (≥ 12 M_{sun}) in a binary system, where the primary star lost its H-envelope through the transfer of mass to the companion star. The second case considers massive Wolf-Rayet (WR) star (> 20 to 25 M_{sun}) that lost mass via stellar winds. For the case of SN 2015ap, based on literature and also from our analysis, we choose a 12M_{sun} ZAMS model as the possible progenitor. The outcomes of the synthetic explosion of such a progenitor model agree satisfactorily with the observed properties.

Photometric Properties

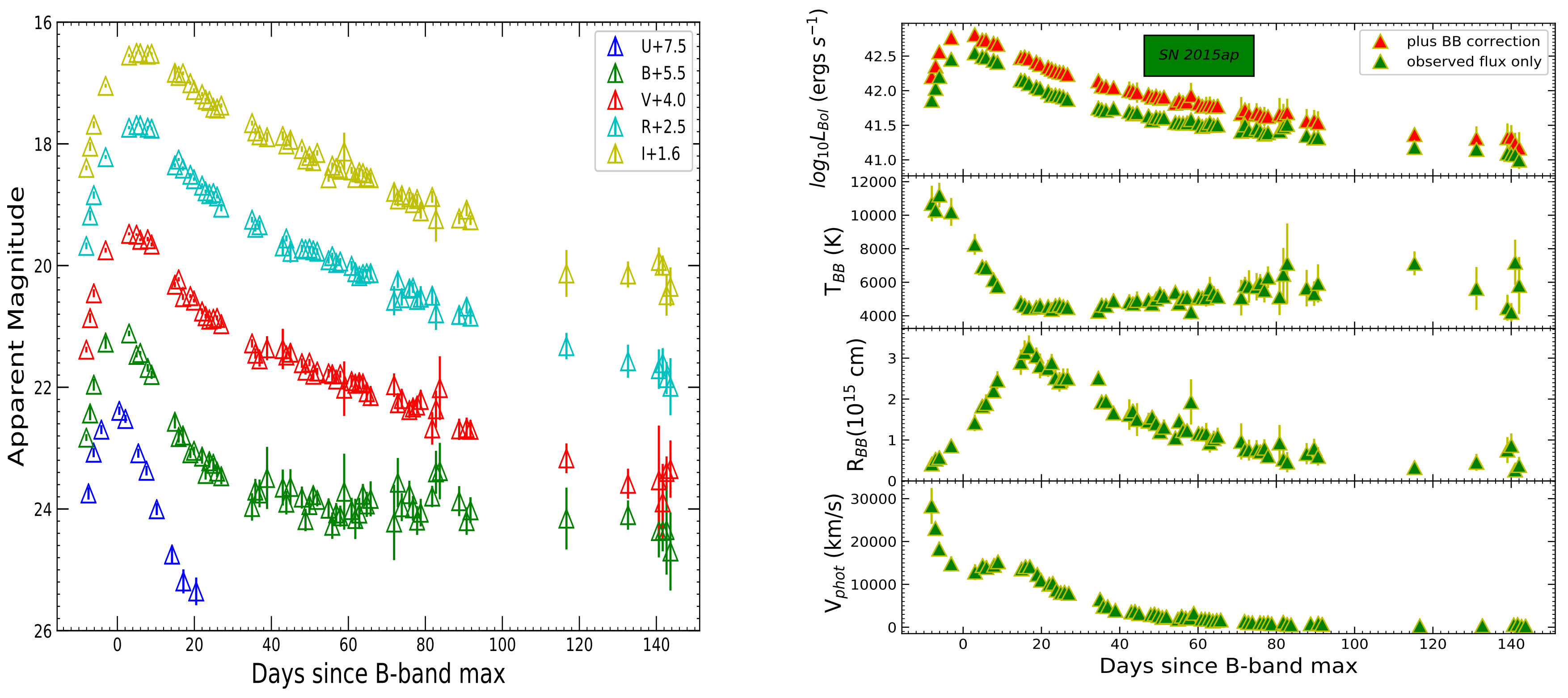


Fig 1 : The left panel shows the UBVRI bands light curves of SN 2015ap with BVRI data taken with the KAIT telescope and U band data take from Swift UVOT. The top plot of right panel shows the bolometric light curves and the remaining three plots show the photospheric temperature, radius and velocity evolutions respectively.

The left panel of fig.1 shows the UBVRI light curve with BVRI band data take from the KAIT telescope and U band data obtained from **Swift UVOT** available at SOUSA (Brown et al. 2014). The top plot of right panel shows the bolometric light curve and the remaining three plots shows the photospheric temperature, radius (both calculated from SUPERBOL (Nicholl et al. 2018)), and velocity evolution calculated from the prior knowledge of explosion epoch (t_{exp}) and photospheric radii at various epoch ($V_{ph}=R_{bb}/t_{exp}$).

Spectroscopic Properties

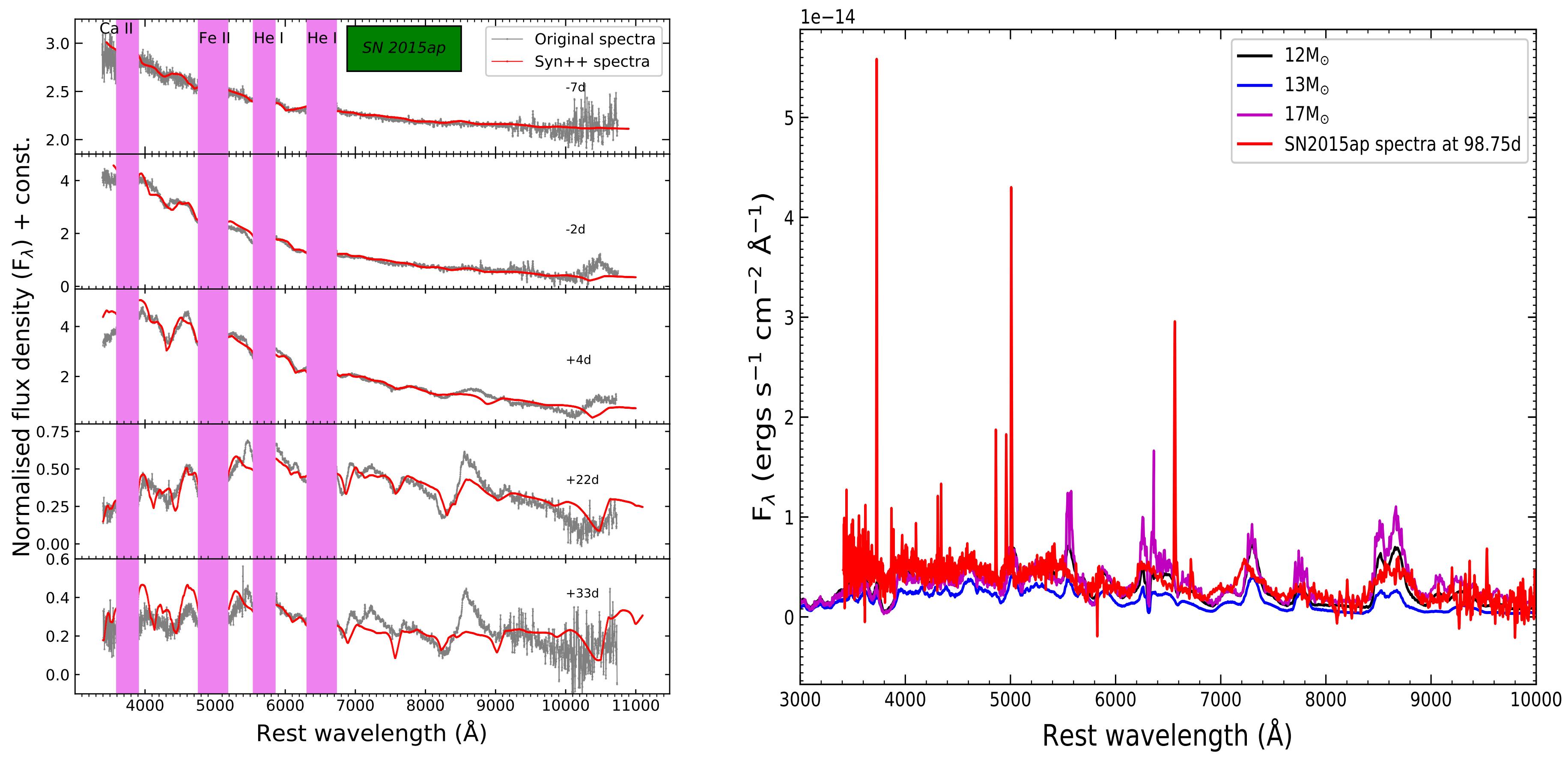
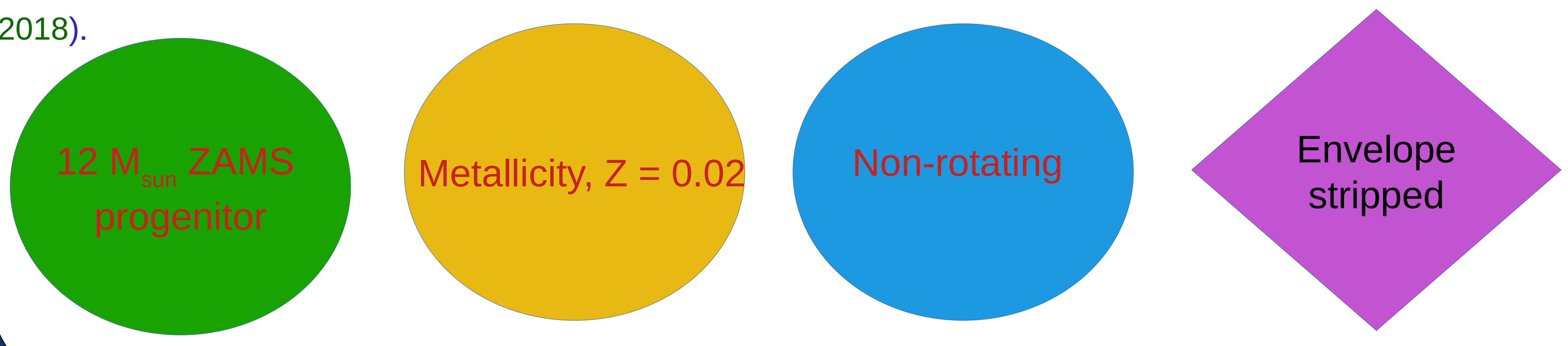


Fig 2 : The left panel shows the SYN++ (Thomas et al. 2011) modeling of the spectra of SN 2015ap at epochs -7d,-2d, +4d, +22d and +33d since B-band maximum. The prominent He I features are nicely produced. The right panel shows the 12, 13 and 17Msun models plotted over +98.75 days since explosion spectrum of SN 2015ap.

The left panel of fig. 2 shows SYN++ modeling of the spectra of SN 2015ap at various epochs easily producing the typical He I features of a type Ib SN. The 12, 13, and 17 M_{sun} model spectra from Jerkstrand (2015) are plotted over the SN 2015ap spectrum at +98.75 d since explosion. The 12 and 17 M_{sun} spectra match nicely the SN 2015ap spectrum (fig. 2; right panel), indicating a range of 12-17M_{sun} progenitor for SN 2015ap, agreeing with Gangopadhyay et al. 2020.

Progenitor model using MESA

Based on the photometric and spectroscopic properties, we consider a non-rotating, 12M sun ZAMS model as the possible progenitor for SN 2015ap. Following Gangopadhyay et al. 2020, the metallicity is taken to be Z = 0.02. Then the model is evolved until the onset of core-collapse using MESA (Paxton et al. 2011, 2013, 2015 & 2018).



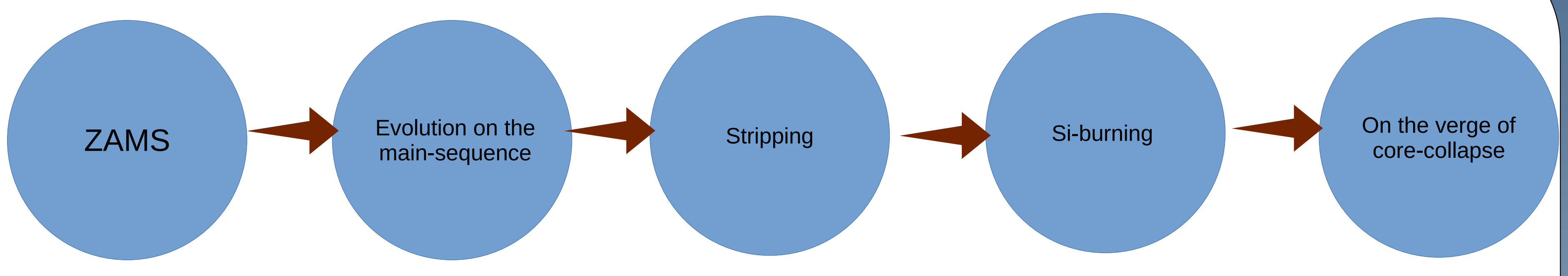
12 M_{sun} ZAMS progenitor

Metallicity, Z = 0.02

Non-rotating

Envelope stripped

Fig. 3 : Properties of our model



ZAMS

Evolution on the main-sequence

Stripping

Si-burning

On the verge of core-collapse

Fig. 4 : Evolution sequence of our model

The various assumptions of our models are shown in fig.3. We start with a non-rotating, solar metallicity (Z=0.02) 12 M_{sun} ZAMS star as the possible progenitor. The various stages of evolutions are shown in fig. 4. After landing on the ZAMS, the model evolves through main-sequence and reaches in the giant/supergiant phase. Thereafter, the envelope of the model is artificially stripped with a rate ≥ $10^{-4}M_{sun}$ yr^{-1} unless it has a Hydrogen mass 0.01M_{sun}. Then, the model heads towards Si-burning phase and finally reaches on the verge of core-collapse by developing an inert Fe-core. The snapshots of physical conditions and chemical compositions of our mode is shown in fig. 5 at the stage of giant/supergiant phase and on the verge of core-collapse.

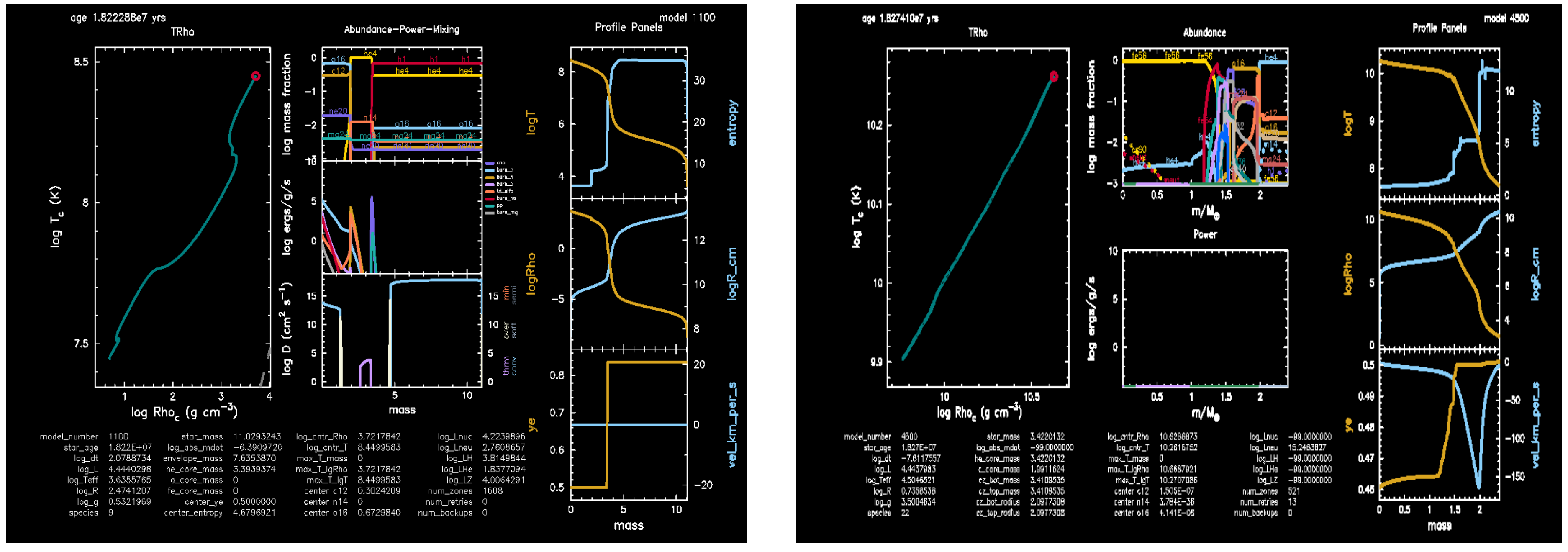


Fig 5 : The left panel shows the physical and chemical conditions of our model progenitor in the giant/supergiant stage marked by the enormous radius (rightmost mid plot). The right panel shows the physical and chemical condition of the model progenitor on the verge of core-collapse which is marked by a core density and core temperature of 10^{10} K and 10^{10} g cm^{-3} (leftmost plot). The onset of core-collapse here could also be inferred by the middle-plot showing the highest mass fraction of Fe near the core.

Synthetic explosions using SNEC & STELLA

When the model reaches on the verge of core-collapse, the outputs of MESA are fed as input to SNEC (Morozova et al. 2015; publicly available) and STELLA (available with MESA). Along with the MESA output files as input, there are certain control parameters that control the synthetic explosion in STELLA or SNEC which includes the mass of central core excised, ejecta mass, nickel mass, total explosion energy, and even the distribution of the Nickel, etc. Initially, considering the radioactive decay of Ni-Co as the prominent powering mechanism for type Ib SNe, we simulated the explosion. Later on, we also tried the Magnetar powering mechanism for SN 2015ap as it shows resemblance to SN 2008D, which has broader spectral features in its early spectra and also X-ray emission in later phases. The explosion parameters are shown in fig. 6.

	M_{Ni} $(M_\odot)$	M_{ej} $(M_\odot)$	E_{tot} 10^{51} ergs
SN 2015ap			
Arnett's model^a	0.14 ± 0.02	2.2 ± 0.6	*
SNEC (Ni distributed up to $M(r) = 3.3\,M_\odot$)	0.135	2.02	3.7
SNEC (Ni distributed up to $M(r) = 1.45\,M_\odot$)	0.1	2.02	6.5
SNEC Magnetar model	0.0	2.02	2.2
From STELLA	0.193	1.92	3.6

Fig 6 : The explosion parameters for synthetic explosions produced using STELLA and SNEC for Ni-Co decay and Magnetar models. * K. E. of ejecta ~ 1.05 x 10^{51} is calculated from Arnett's model.

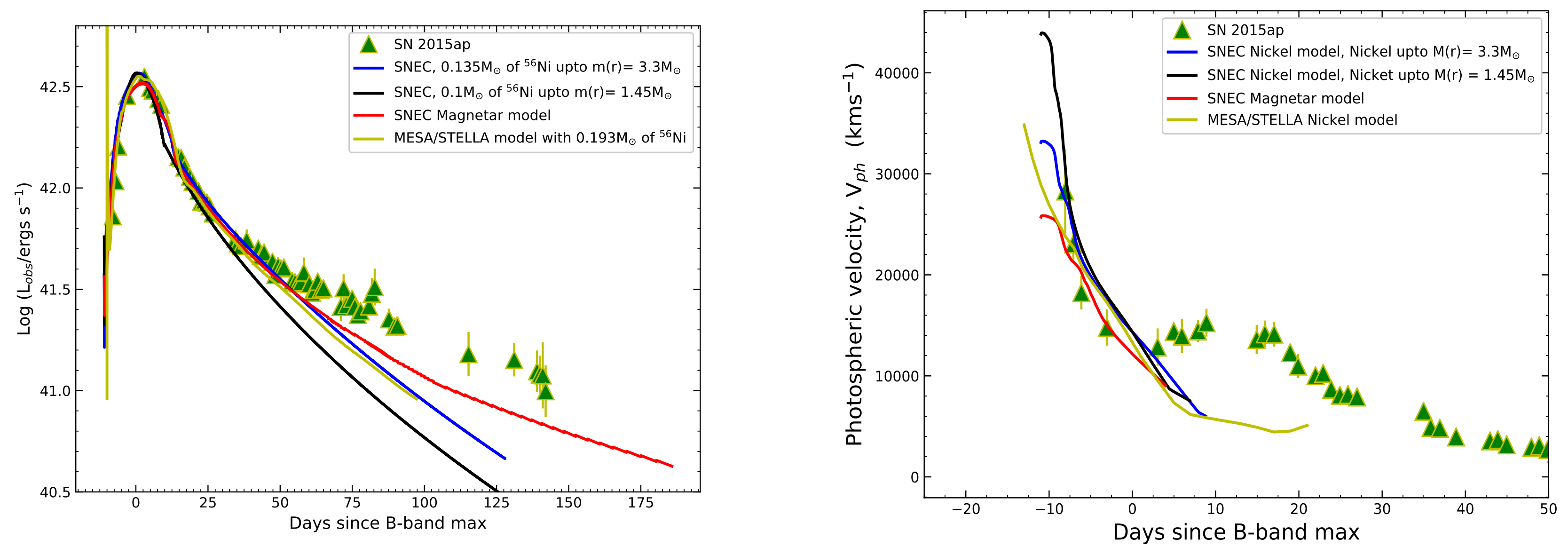


Fig 7 : The left panel shows the STELLA/SNEC produced luminosity light curve matched with the observed bolometric light curve. The right panel shows the STELLA/SNEC produced velocity evolutions matched with the observed velocity evolutions.

Results and Conclusions

1) The photometric and spectroscopic analysis of SN 2015ap have been performed.

2) Based on these studies, a 12 M_{sun} ZAMS model is evolved up to the onset of core-collapse and synthetic explosions are produced using SNEC and STELLA.

3) The SNEC/STELLA produced parameters satisfactorily agree with the observed ones (calculated using Arnett's model).

4) Although, magnetar model explains the observed properties much better then Ni-Co model (fig. 7), but the parameters of magnetar model are unphysical (e.g. slow rotation indicated by initial rotation perod of ~ 70 ms, low magnetar rotational energy ~ 10^{48} ergs and very high progenitor radis ~ 1200 Rsun).

References & Acknowledgments

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