Supernovae with two maximums in the bolometric light curve

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Resumen / El crecimiento en las estrategias de observación de los relevantamientos ópticos está remodelando el panorama de la astronomía transitoria, lo que permite identificar y estudiar las supernovas (SNs) desde sus primeras etapas, en fases que proveen valiosa información sobre la estrella que explota. Por ello, son más frecuentes los casos en los que la emisión detectada desafía los modelos existentes, haciendo necesario explorar explicaciones alternativas. Con respecto a las SNs que presentan una curva de luz (CL) con dos máximos claramente definidos en la luminosidad bolométrica, se encuentra en la literatura que la morfología observada en ambos picos es diversa, así como la razones físicas que podrían causarla. Una posibilidad que se introdujo originalmente para explicar la forma de la CL de doble pico de SN2005bf, es que en el material eyectado se haya formado una distribución doble del níquel radioactivo, ^{56}Ni. En este estudio asumimos una forma paramétrica simple para la ubicación de dicho isótopo en dos capas separadas y analizamos el comportamiento de la CL ante la variación de este perfil aplicando un código radiativo-hidrodinámico 1D. Nos interesa la aplicabilidad de este modelo a SNs con brillo normal, en estrellas que ya han perdido la envoltura rica en hidrógeno. Presentamos el ajuste de CLs sintéticas a un conjunto de SNs para las cuales este modelo puede ser aplicado y discutimos en cuáles otros casos este escenario es menos favorable.

Abstract / The growth in the observational strategies of optical surveys is reshaping the panorama of transient astronomy, which allows supernovae (SNe) to be identified and studied since their earliest stages, in phases that provide valuable information about the exploding star. For this reason, there are more frequent cases in which the detected emission challenges the existing models, making necessary to explore alternative explanations. Regarding the SNe that present a light curve (LC) with two clearly defined maximums in the bolometric luminosity, it is found in the literature that the morphology observed in both peaks is quite diverse, as well as the physical reasons that could cause it. One possibility that was originally introduced to explain the LC shape of SN2005bf is that a double distribution of the radioactive nickel, ^{56}Ni, forms in the material to be ejected. In this study we assume a simple parametric form for the location of that isotope in two separate layers and we analyze the behavior of the LC due to the variation of this profile applying a 1D radiative-hydrodynamic code. We are interested in the applicability of this model to SNe with normal brightness, in stars that have already lost the hydrogen-rich envelope. We present the fit of synthetic LCs to a set of SNe for which this model can be applied and discuss in which other cases this scenario is less favourable.

Keywords / supernovae: general — supernovae: individual (SN2005bf-like)

1. The framework

The observed bolometric light curve (LC) of core collapse SNe is normally powered by the decay of radioactive material syntethized during the collapse and explosion. Altough there have been advances (e.g. Imasheva et al. 2022; Gabler et al. 2021) it is difficult to calculate the ^{56}Ni yield and its location from first principles. In 1D calculations it is widely used to prescribe *ad-hoc* the ^{56}Ni profile inside the progenitor star. In this way the nickel is mixed-up to a tunable mass fraction of the total mass M. Hydrodynamical instabilities and turbulence are usually invoked for the mixing. In our calculations we apply a versatile code that has the possibility of using an arbitrary distribution of any element (Bersten et al., 2011).

A double-peaked nickel distribution was assumed for the first time to explain the unusual LC morphology of SN 2005bf (Folatelli et al., 2006) and later explored for few similar cases. The scenario of a separate nickel-rich layer relays on the idea that jet-like outflows involved in the explosion may induce nucleosynthesis of radioactive elements somewhere at the outer layers of the ejecta before the SN shock front arrives. The case of a GRB missaligned from the line of sight or a jet choked inside of the star could perhaps explain the two layered ^{56}Ni profile. Soker (2022) presentes an updated revision on the role of jets in exploding SNe.

In Orellana & Bersten (2022) we considered this scenario in more detail, with consistent preliminary results before presented to the Argentine comunity in Orellana & Bersten (2021). We went also to revise the published morphology of observed double-peaked SNe and found

Oral contribution

that both peaks has diverse forms, in many cases, at a filter band but without a calculated bolometric LC.

Our approach was systemathic: we have fixed all but one of the parameters of a simple nickel profile, and move the free parameter by turn, to identify its individual effect on the LC. The constrains that we considered were that the external layer of nickel has a lower mass than the inner one, and that the total M(^{56}Ni) is within the range of previously published mass values in normal stripped-envelope SNe (Anderson, 2019).

2. Selected results from the study

In our numerical scheme the mass fraction of ^{56}Ni, named X is a function of the Lagrangian mass coordinate which is directly mapped to the mass fraction, f. The abundances of all the other elements in a given shell add $(1-X)$ for normalization. This modification to the composition of the progenitor provides of an extra power from the decay of the nickel that produces gamma-rays and positrons. A gray approximation is applied for the propagation of the γ-rays.

The simple profile proposed consists of two boxes for the nickel abundance, with constant $X_{\rm in}$ and $X_{\rm out}$ respectively, and $X = 0$ at other places. The inner component has the usual partial-mixing sense. It is adjacent to the compact remnant and extends from the inner border of the ejecta, f_0, up to a fraction, f_1. The outer component is placed from f_2, to f_3, so it can be truncated below the surface, or reach it if $f_3 = 1$.

All the details can be found in Orellana & Bersten (2022) where the effect of each parameter on the bolometric LCs are shown. We have focused on stripped-envelope progenitors, and we show here complementary results for the same `He11` progenitor evolved with the code MESA (Paxton et al., 2011), exploded with $E_{\rm exp} = 2\times10^{51}$ erg, and with a compact renmant of 2.15 $M_\odot$.

In Figure 1 and 2 the $X_{\rm in}$ is fixed to 0.047, $f_0 = 0.199$, $f_1 = 0.25$, $f_2 = 0.91$ and $f_3 = 0.991$. The parameters affect the total M(^{56}Ni), the values for each case were included in Orellana & Bersten (2022). The effect of the variation in the external abundance of nickel on the first peak of the LC is quite notorious for the values we have adopted. This is explained by the fact that the energy coming from the outer radioactive material is covered by an optically less thick layer, then its energy emerges sooner than the outcome from the inner nickel.

The evolution of the temperature and velocity at the thermalization depth, where the emitted Black Body (BB) is defined, are affected by the energy from the external nickel-rich layer. Through convolution of the BB flux $F(\lambda, t)$ as

$$\mathrm{Mag}(t) = -2.5\log\frac{\int d\lambda F(\lambda,t)S(\lambda)}{\int d\lambda S(\lambda)} \quad (1)$$

where $S(\lambda)$ is the filter transmission curve, we estimated the light curves in magnitudes, and color indexes. We expect the results of Figure 2 could be measurable in order to strength the case for this scenario, but for this we need rapid-cadence observations obtained in the first few hours-to-days after explosion. Hopefully the

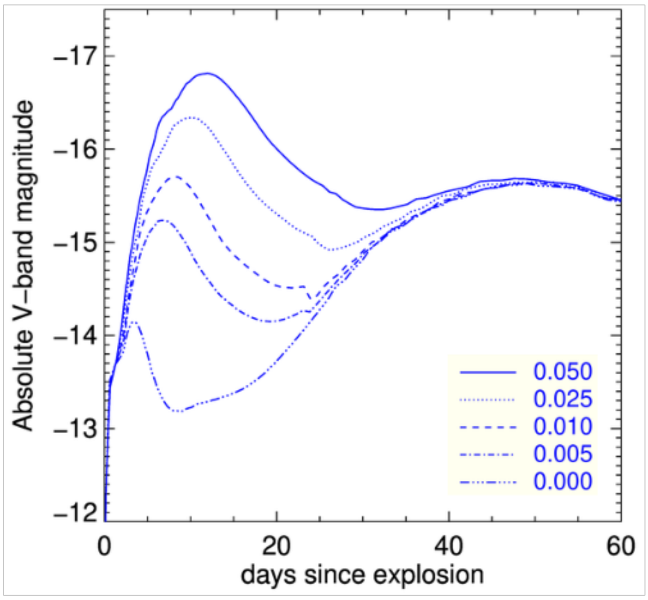

Figure 1: Effect of variation of $X_{\rm out}$, external abundance as mass fraction of ^{56}Ni, on the visual magnitude.

Precision Observations of Infant Supernova Explosions POISE, (Burns et al., 2021) can provide evidence if a SN with two maximums in the LCs is observed.

3. Comparison of ^{56}Ni profiles for fitted SNe

A family of observed SNe have been discused into the double-nickel context. We revisited the modelling for them: SN2005bf (Tominaga et al., 2005), PTF2011mnb (Taddia et al., 2018), SN2019cad (Gutiérrez et al., 2021), and SN2008D (Modjaz et al. 2009; Tanaka et al. 2009; Bersten et al. 2013). They share a LC evolution signed by an initial rise followed by the double peak in the observed bolometric data. That morphology is difficult to explain by other models.

At Figure 3 we compare the profiles of the optimal models of the bolometric LCs shown in Figure 4. They were not shown together in Orellana & Bersten (2022), however a visual comparison is worthy. SN2008D has a fast evolution in the LC with the second peak at a timescale of ~ 17 d. This is similar to the time when the other three SNe of the sample present the first and weakest peak. This early feature is then indicative that a rather different profile of the ^{56}Ni is required. To fit the first maximum, the double profile of nickel is pushed to the extreme case where it reaches the surface of the star with a very shallow location, and the abundance of radioactive material is particularly high there ($X_{\rm out} = 0.71$). The model shown here for this SN has 0.074 $M_\odot$ in the inner region and 0.018 $M_\odot$ at the outer layer.

For SN2005bf, SN2008D and SN 2019cad, the hypothesis of a constant standard gamma-ray opacity $\kappa_\gamma = 0.03$ cm^2/g does not accommodate the complete observed LC. A decrease in the gamma ray opacity, known as leakage, is required to fit the late time observations. This has been suggested to result from asymmetries in the ejecta (Branch & Wheeler, 2017).

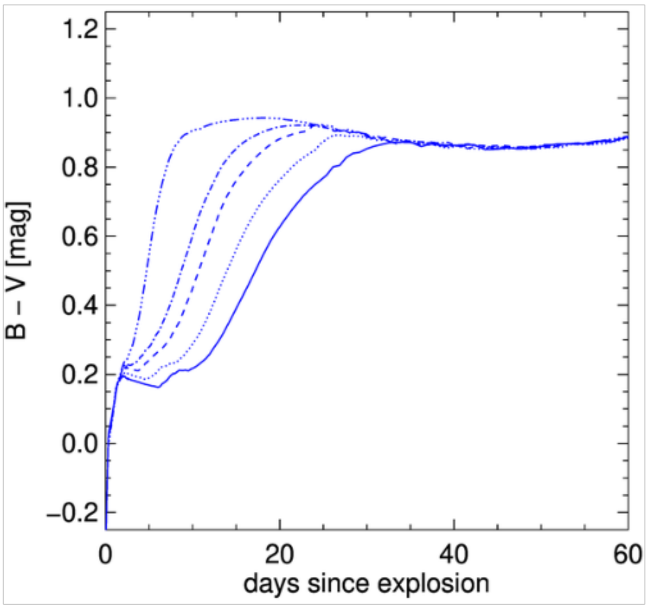

Figure 2: Effect of the external abundance of nickel on the color evolution. The broadband photometry reflects the effect on the temperature $T_{\rm th}$ and the evolution of the thermalization depth. The line types follow the same legend of Fig. 1.

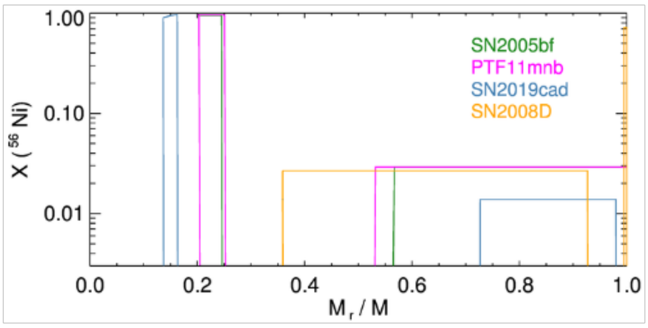

Figure 3: Initial abundance of ^{56}Ni as a function of the interior mass fraction in the preSN star for a sample of double peaked SNe. In yellow, SN2008D requires a strongly inverted profile in comparison with the other three cases.

4. Conclusions

The mechanisms that could be responsible for the doubled distribution of ^{56}Ni deserve further investigation in order to produce better nucleosynthetic yields into the stellar interior, and a self consistent case.

The calculated LCs occur with different timescales depending on several quantities beyond the radioactive content: the progenitor and the energetics of the explosion are also important. Our conclusion is that the SNe whose data resemble the SN2005bf morphology could be potentiated by the double ^{56}Ni profile. That is, a bolometric rise prior to the two peaks seems more favourable for the double-nickel case. From the literature, other scenarios fail to explain the data unless a combination of power sources is invoked.

The light curves reminiscent of type IIb SNe, with a steep initial decline in the observed bolometric LC

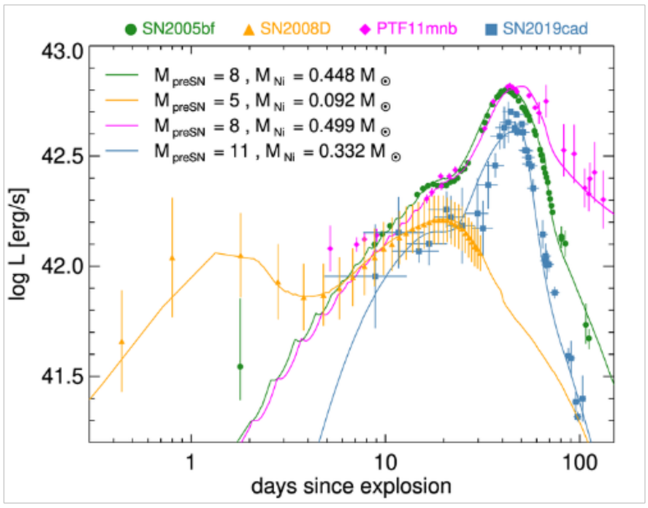

Figure 4: The four SNe selected to apply the proposed model. The presence of a raising phase before the first peak was a critical characteristic for our sample selection. Note the early data of SN2008D with the first peak at ∼ 1 day. At the legend we provide the progenitor mass and total ^{56}Ni mass.

within less than few days after the explosion becomes less feasible for this model, because it requires a large abundance of radioactive elements near the stellar surface, and is more difficult at the moment to justify such a strongly inverted distribution. Early detections and followup of SNe are encouraged to obtain a better picture of these unfrequent double-peaked SNe.

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