BAAA, Vol. 61A, 2019
R. Gamen, N. Padilla, C. Parisi, F.A. Iglesias & M.A. Sgró, eds.

Asociación Argentina de Astronomía
Boletín de artículos científicos

A Bolometric study of the Stripped–Envelope SN 2010jr

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Resumen / Las supernovas (SN) de envoltura removida provienen del colapso gravitatorio de estrellas masivas que han perdido su envoltura de hidrógeno y/o helio. Con el estudio de sus curvas de luz podemos restringir los parámetros físicos de la explosión y las propiedades de la estrella progenitora. Esta investigación utiliza la fotometría de la SN 2010jr en el ultravioleta, óptico, e infrarrojo para construir y ajustar las curvas de luz de cada filtro a través del método de procesos gaussianos. Luego, para cada época calculamos la distribución de energía espectral, la cual ajustamos e integramos en frecuencia para obtener finalmente la curva pseudo-bolométrica en el rango de longitudes de onda observado. La curva pseudo-bolométrica nos permitirá calcular el tiempo de explosión y estimar parámetros fundamentales de la SN tales como la masa de níquel sintetizado en la explosión, la energía cinética y la masa total eyectada.

Abstract / Stripped-Envelope supernovae come from the core collapse of massive stars that have lost their Hydrogen and/or Helium envelopes. Studying their light curves (LCs) we can constrain the physical parameters of the explosion and their progenitor properties. This research used the photometry of SN 2010jr in the ultraviolet (UV), optical and near-infrared (NIR) to construct and fit the LCs of each filter through the Gaussian Process (GP) method. Then, for each epoch we calculate the Spectral Energy Distribution, which we fit and integrate in frequency to finally obtain the pseudo-bolometric LC in the observed wavelength range. The pseudo-bolometric LC will enable us to calculate the explosion time of the SN and constrain fundamental parameters like nickel mass synthesized in the explosion, the kinetic energy and the total ejected mass.

Keywords / Supernovae: individual: SN 2010jr — methods: data analysis

1. Introduction

The process related with the end of the life in massive stars ($> 8M_{\odot}$) is called a core-collapse supernova explosion. In these events the SN brightness increases suddenly and can sometimes even outshine its own host galaxy. We classify a SN as a type II when Hydrogen lines are present in the spectra (Filippenko, 1997). If there are no Hydrogen lines, the SN is a type I. In addition, type I are divided into the presence (IA) or lack (IB and IC) of the Si II line. We can also differentiate between IB and IC using the He I line.

The Stripped-Envelope supernovae (SESNe) comprise the types IB, IC and IIB. These SNe are characterized by a three-phase pattern in the shape of their LCs. These trace the different processes in the SN evolution: the shock breakout (SBO), the cooling phase and thermalization. The SBO is rarely detected because it occurs immediately after core-collapse and last only a few hours (e.g. Bersten et al. 2018). The next phase is sometimes observed at a couple of days after explosion (Bufano et al., 2014). It is characterized by an early LC decline produced by the adiabatic cooling following the SBO passage through the envelope. Finally, we have the third peak that is due to thermalization of γ rays from the decay of the ^{56}Ni synthesized in the explosion (Gangopadhyay et al. 2018). By constructing a bolometric LC we can determine the physical parameters of the explosion such as total ejected mass, nickel mass and kinetic energy. We can also infer further properties of the SN progenitor such as the pre-explosion radius by modelling the cooling phase.

2. Observations and data

Our study object is the type IIb SESN 2010jr discovered in Nov 12.09 UT, 2010, at 16.2 mag. The data set consists of (1) photometry in the *g',r',i',z',J,H,K* filters from GROND (Gamma-ray Burst Optical/Near-infrared Detector) mounted at the 2.2-m MPG telescope at La Silla Observatory (Greiner et al., 2008) and (2) photometry in the *V,B,U,UVm1,UVw1,UVw2* filters from the UV/Optical telescope (UVOT) at the Neil Gehrels *Swift* Observatory (Gehrels et al., 2004).

A representative LC sample is presented in Fig. 1. The LCs show two stages: the early optical and UV emission by the cooling phase, which is dominated by the energy deposited by the shock wave and the brightening to a broad maximum due to the decay of radioactive material synthesized during the explosion.

3. Analysis

3.1. UV, optical and NIR LCs through GP

One of our work aims is implement the GP prediction to accurately describe the LC behavior in between the observed data points. In Fig. 2, we use the GP framework

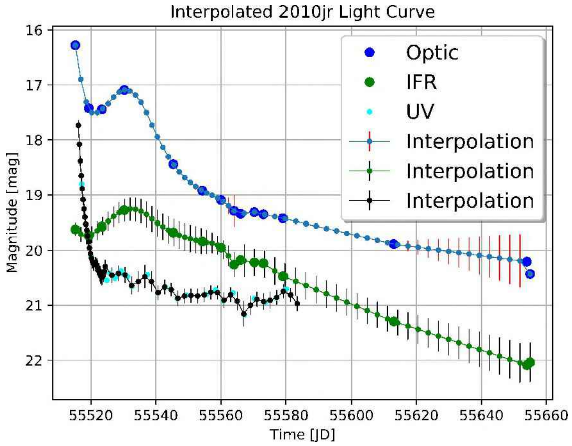

Figure 1: The LCs of SN 2010jr (magnitude against MJD) in g,H, $UVw2$, representative of each wavelength range (optical, NIR and UV). We arbitrarily offset the LC in magnitude for aesthetic purposes. The interpolation corresponds to a combined quadratic fit for the early phase around maximum and a linear fit for the late phase of the radioactive tail.

GPy[*] and the python library GEORGE (Ambikasaran et al. 2015) to interpolate the data. The GP is a regression method that generate predictions alongside with error bars and it is based on the Gaussian distribution for which we used the Rational Quadratic Kernel prediction from the result of testing many kernels:

$$K(x_i, x_j) = K\left(1 + \frac{(x_i - x_j)^2}{2al^2}\right)^{-a}, \tag{1}$$

where l is the length-scale and determines the wiggles in the function, K is the output variance related with the mean average distance from the function and a is the scale parameter related with the function smoothness.

We compared the GP results (Fig. 2) with those from Fig. 1. The prediction in between points is better using GP than the polynomial interpolation, because in the latter we are forcing linear and quadratic behavior. We also evidenced that large errors are due to lack of data in a given range (e.g. at late times in the UV filters; bottom panel, Fig. 2). For this reason we need data in several filters. On the other hand, for both methods we can see the LC starting with a bright magnitude, reaching the main peak, and then decreasing over the time, which is consistent with the post SN explosion process.

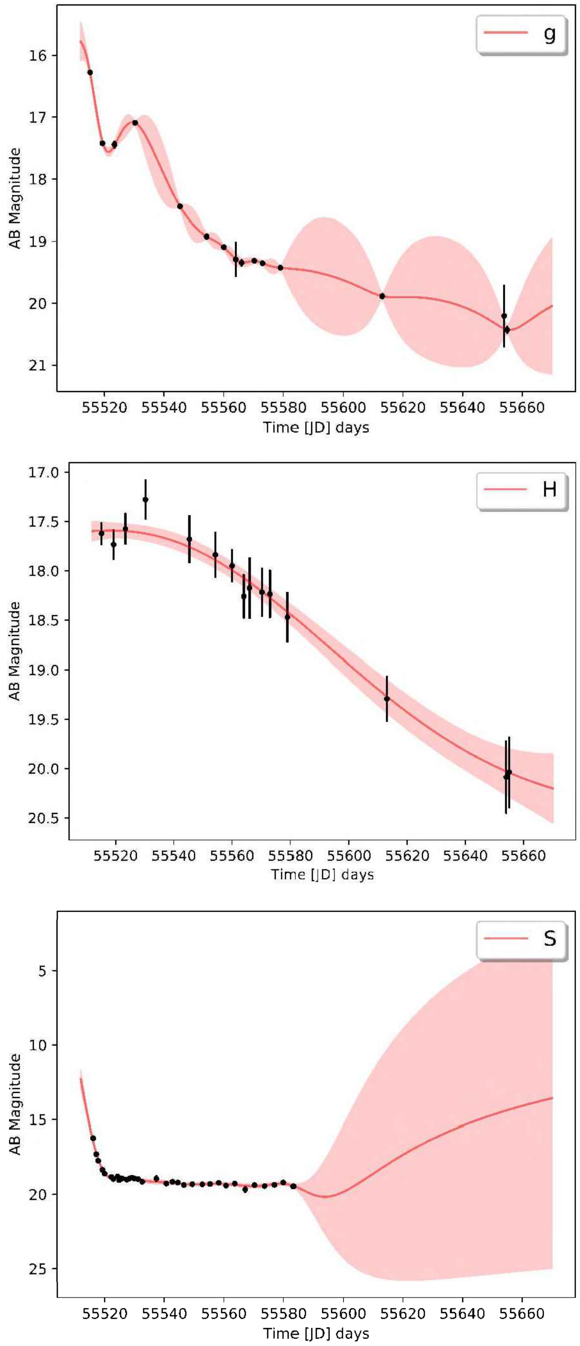

Figure 2: AB magnitude against MJD time: LCs, using GP to interpolate. Representative LCs for optical g band (top), NIR H band (middle) and UV $UVw2$ band (bottom) are shown. While the red line is the best fit, the pink areas depict the uncertainty of the modelling.

3.2. SEDs and pseudo-bolometric LCs

After GP modelling all the LCs in the UV, optical and NIR bands, we built the pseudo-bolometric LC. First, we proceed to integrate the SEDs frequency range. For this purpose, we converted magnitudes into flux at the central wavelength filter and obtained the SEDs shown in Fig. 3. To obtain the SED, it is necessary to (1) correct the magnitudes for Galactic foreground extinction, (2) use the heliocentric redshift to correct the central wavelengths of the filters, and (3) correct the magnitudes for host-galaxy extinction (taken from Bufano et al. 2014). Finally, The total flux is converted into luminosity using the distance[**].

The Fig. 3 shows the expected behavior of the SN

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[*] GPy: A Gaussian process framework in python. `http://github.com/SheffieldML/GPy`

[**] `http://ned.ipac.caltech.edu`

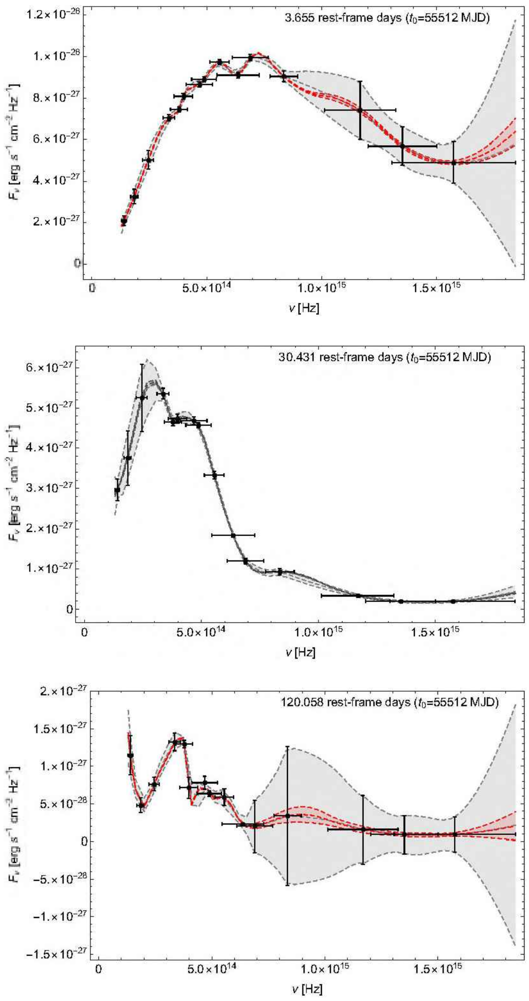

Figure 3: Representative SEDs of SN 2010jr at three different rest-frame times: before maximum (top), after maximum (middle) and at the radioactive tail (bottom). Each SED covers the UV, optical and NIR. The red line is the data interpolation and the gray region is the corresponding error.

SED. At the early times we observe a peak at higher frequencies (top panel), which is then cooling towards lower frequencies as the SN expands (middle). The late-time SED (bottom) is probing the nebular regime during the radioactive tail, thus no clear black-body maximum is observed. The interpolation was obtained with a polynomial fitting (quadratic and linear) and using a Simpson's rule to integrate between the data points. Currently we are improving our kernel for the SED interpolation implementing the GP method.

Finally, from the bolometric LC in Fig. 4 we can determine the main parameters of the SN explosion such as total ejected mass, kinetic energy and synthesized ^{56}Ni mass, using the Morozova et al. 2015 models in the pseudo-bolometric LCs. Moreover, the early behavior of the bolometric LC shows the cooling phase. From this interesting feature of SN 2010jr we can derive the radius of the progenitor prior to explosion.

4. Summary and discussion

Multi-wavelength photometry of SN 2010jr has been interpolated through GP of each LC that together cover the range $0.170 - 2.1\mu m$, including *Swift*/UVOT and GROND data. We concluded that the best covariance matrix for the LCs interpolation is the Rational-Quadratic-Kernel, because it give us an accurate fitting for the intervals in which we have no data.

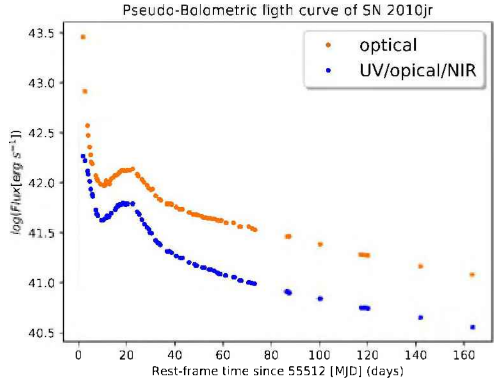

Figure 4: Pseudo-bolometric LCs of SN 2010jr in two wavelength ranges: optical (orange) and UV/optical/NIR (blue).

SEDs composed by 14 photometric data points have been interpolated and integrated over wavelength. We will implement the GP method for the SED interpolation by replacing the use of the Simpson's rule for integration over wavelength.

We constructed optical and UV/optical/NIR pseudo-bolometric LCs with the purpose of studying the physical parameters of the explosion and the progenitor-star properties prior to explosion. The ^{56}Ni is related with the peak brightness and the shape of the LC is determined by both the explosion kinetic energy and the total ejected mass. We are currently working on a model to determine accurately rise times for a sample of SESNe to constrain the physical parameters using the pseudo-bolometric LC and different properties of the SN such as the progenitor types which still remains an open question in the field.

Acknowledgements: J.P. thanks support from the Chilean Astronomical Society (SOCHIAS), the Argentine Association of Astronomy (AAA) and Departamento de Astronomía, Universidad de Chile. Support for F.O.E. is provided by the Ministry of Economy, Development and Tourism's Millennium Science Initiative through grant IC120009, awarded to the Millennium Institute of Astrophysics (MAS), and by the FONDECYT grant nr. 11170953.

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