Updates in CASTOR v 2.0

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Contents

1 General approach

We were inspired by the workflow and the user-friendly interface of `superbol` (Nicholl et al. 2018) to update `CASTOR`. This new version sees many updates in many different aspects, from the training set, to the usage of parallelization and to the estimation of some parameters. The first main difference with respect to `CASTOR v1.0` Simongini et al. 2024a is the usage: now, one can easily use `CASTOR` from its terminal, with the simple command:

```
python3 castor2.0.py
```

We summarize some general differences:

- The user can now decide to give as input time of explosion, redshift, distance, extinction, or let the code find them automatically.
- The user can now decide to use the available spectra of the source or to use the spectra of the reference supernova instead.
- Every Gaussian Process is now handled with the `scikit` library.
- Every Gaussian Process is now performed in parallel. We set a `n_cores` variable equal to 5, which defines how many cores can be employed for the parallel process.

2 Training set

The first big change with respect to the previous version is the training set. Now each supernova is provided with the information of its time of explosion, in order to control the direct comparison without providing any possible bias to it. The information of the time of explosion is found in the same references as listed in Simongini et al. 2024. New supernovae are included in the new training set, including most recent events and superluminous supernovae (Table 1). The total number of supernovae is now 150. Fig. 1 shows some important properties of the new training set: redshift, class, filters and number of spectra.

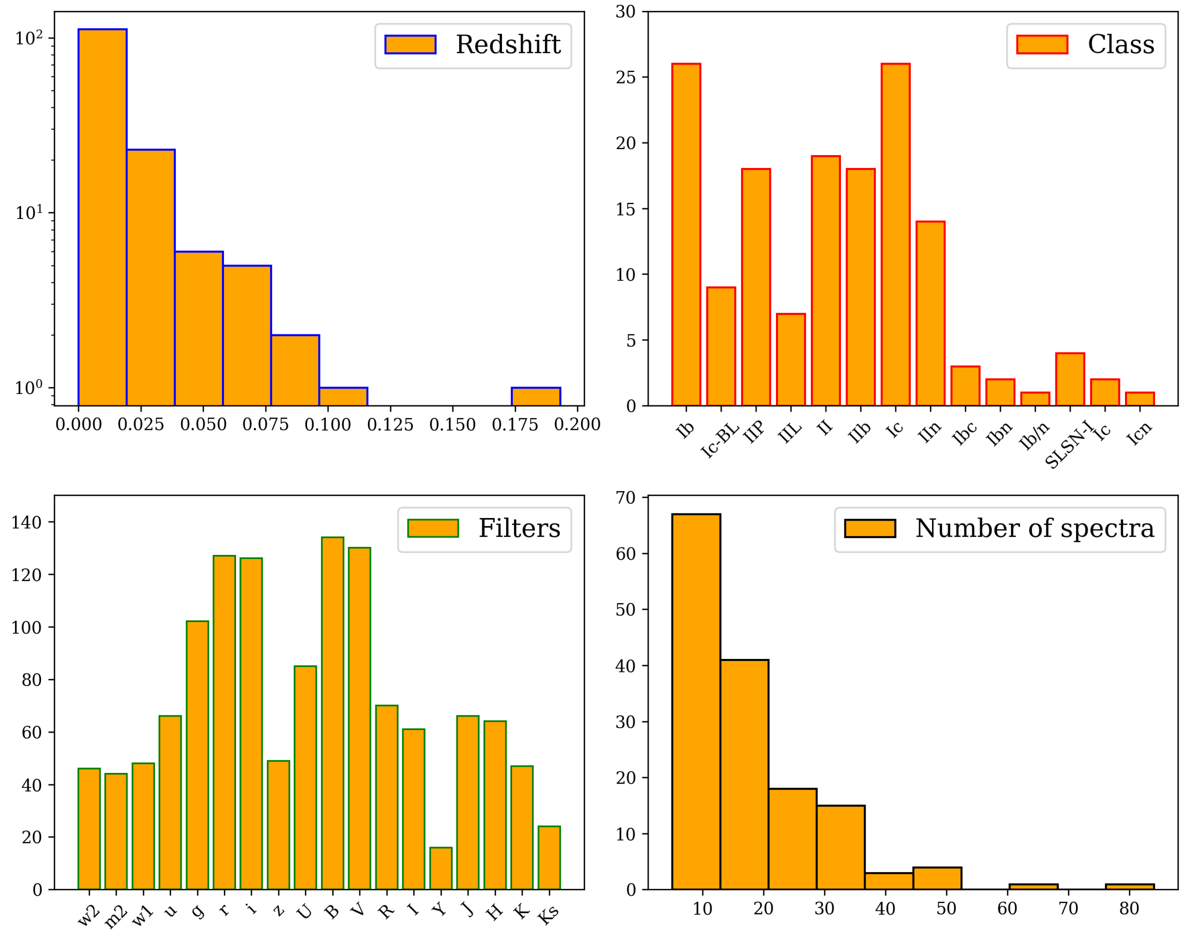

Figure 1: Properties of the new training set: (top left) redshift distribution; (top right) available classes; (bottom left) available filters; (bottom right) number of spectra.

Table 1: New addition to the training set

name	class	redshift	t_0	Filters	Spectra	Reference
SN1996W	II	0.0058	50179.5	U, B, V, R, I	9	Inserra+2013
SN1998S	IIn	0.002795	50874.7	B, V, R, I, J, H, K	23	Fassia+2000
SN2004aw	Ic	0.0163	53083	U, B, V, R, I	26	Taubenberger+2006
SN2004ex	IIb	0.017549	53291.56	u, g, r, i, B, V	7	Stritzinger+2018
SN2004ff	IIb	0.022649	53308.14	u, g, r, i, B, V, Y, J, H	6	Stritzinger+2018
SN2004gk	Ic	0.000407	53336.31	B, V, r, i, J, H, Ks	35	Bianco+2014
SN2005aw	Ic	0.0095	53451.01	u, g, r, i, B, V	5	Stritzinger+2018
SN2005az	Ic	0.008456	53457	B, V, r, i, J, H, Ks	22	Bianco+2014
SN2005kl	Ic	0.003486	53686.14	B, V, r, i, J, H, Ks	8	Bianco+2014
SN2005mf	Ic	0.026762	53723.33	U, B, V, r, i, J, H, Ks	6	Bianco+2014
SN2006ba	II	0.019	53813	g, r, i, B, V	5	Stritzinger+2018
SN2006bf	IIb	0.024	53818.93	B, g, V, g, r, i, Y, J, H	6	Stritzinger+2018
SN2006fo	Ib	0.0207	53988.56	B, g, V, r, i	11	Stritzinger+2018
SN2006lc	Ic	0.0162	54023.91	u, B, g, V, r, i	9	Stritzinger+2018
SN2006jc	Ibn	0.005574	54018.38	U, B, V, r, i, J, H, Ks	84	Bianco+2014
SN2007ag	Ib	0.020711	54149.95	B, g, V, r, i	7	Stritzinger+2018
SN2007C	Ib	0.005611	54109.85	u, B, g, V, r, i	26	Stritzinger+2018
SN2007ce	Ic	0.046	54221.28	B, V, r, i, J, H, Ks	10	Bianco+2014
SN2007I	Ic	0.021638	54110.64	B, V, r, i, J, H, Ks	7	Bianco+2014
SN2007kj	Ib	0.017899	54371.54	u, B, g, V, r, i	10	Stritzinger+2018
SN2008bn	II	0.0242	54558.22	U, B, V, r, i	11	Hicken+2017
SN2008gc	Ib	0.0492	54744.44	B, g, V, r, i	6	Stritzinger+2018
SN2009er	Ib-pec	0.035	54977.93	B, V, r, i, J, H, Ks	10	Bianco+2014
SN2009K	IIb	0.0117	54844.89	u, B, g, V, r, i	9	Stritzinger+2018
SN2009of	Ib	0.016	55053.3	U, g, r, R, i, z	5	Karamehmetoglu+2023
SN2009Z	IIb	0.0248	54865.17	u, B, g, V, r, i	11	Stritzinger+2018
SN2010mj	Ib	0.0655	55339.4	U, g, r, R, i	5	Karamehmetoglu+2023
SN2011hw	Ibn	0.023	55869.5	w2, m2, w1, U, B, V, R, I	23	Pastorello+2015
SN2011kg	SLSN-I	0.193	55916	u, B, g, r, i, z, J	12	Inserra+2013b
SN2015ap	Ib	0.01	57272.24	u, B, g, V, r, R, i, I	19	Aryan+2021
SN2015bn	SLSN-I	0.1136	57044.33	w2, m2, w1, u, B, g, V, r, R, i, I, z, J, H, K	28	Nicholl+2016
SN2015da	IIn	0.006669	57030.44	u, U, B, g, V, r, R, i, I, z, J, H, K	19	Tartaglia+2020
SN2017egm	SLSN-I	0.0307	57896	w2, m2, w1, u, U, B, g, V, r, i, z, J, H, K	51	Zhu+2023
SN2017gmr	II	0.005	57999.09	u, U, B, g, V, r, R, i, I, z	7	Andrews+2019
SN2018is	II-P	0.005811	58133.1	U, B, g, V, r, i, z	22	Dastidar+2025
SN2018ivc	II	0.0038	58444	m2, w1, U, B, g, V, r, R, I	66	Bostroem+2020
SN2021csp	Icn	0.083	59256.47	w2, m2, w1, u, g, r, i, z	5	Perley2022
SN2021irp	II	0.02	59310.3	B, V, r, i, J, H, K	10	Reynolds2025
SN2023ixf	II-L	0.0008	60082.75	w2, m2, w1, u, U, B, g, V, r, i, z, J, H, Ks	20	Zimmerman+2023
SN2024bch	II-L	0.003839	60337.39	w2, m2, w1, U, B, g, V, r, i	16	Andrews+2025

2.1 Calibration

As new supernovae have been added to the training set, a new calibration is necessary. As described in Simongini et al. 2024, the calibration is a process in which photometric magnitudes and spectroscopic magnitudes at the same epoch and in the same bandwidth are compared to determine a global calibration of the dataset, which is expressed as two values: a and b. The new calibration is showed in Fig. 2. From the weighted linear fit on the magnitude points we obtain $a = 0.9063 \pm 0.0026$ and $b = 1.4732 \pm 0.0384$.

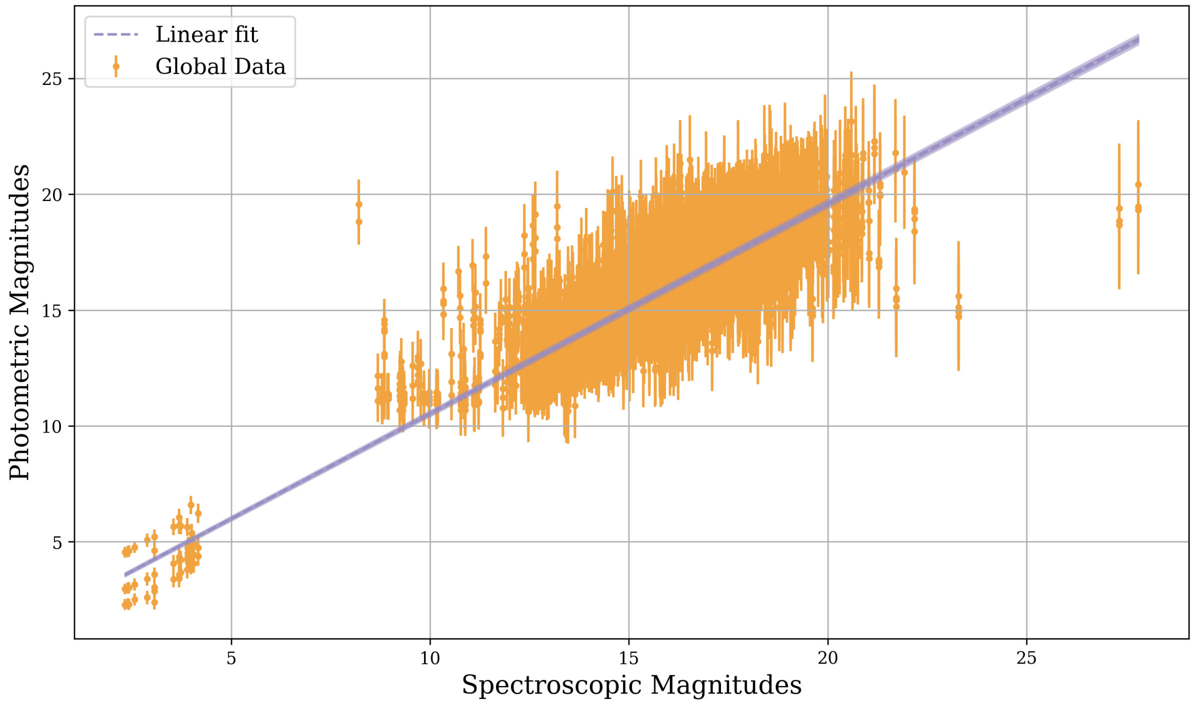

Figure 2: The calibration process is carried out by fitting a linear function (purple line) on magnitudes from light curves (y-axis) and magnitudes from spectra (x-axis), taken at every available epoch and every available filter from the each supernova in the training set.

3 Synthetic spectra

There are only minor changes in the reconstruction of the synthetic spectra but are worth a mention:

- Safer selection of real spectral points from the reference supernova (we limit the number of total spectral points at 5000 and give priority to fluxes derived from light curves).
- Accurate scaling of real spectral points for templates reconstruction: now the spectra of the reference supernova undergo a scaling defined by the order of magnitude of the fluxes from light curves to ensure compatibility.
- Reconstruction of synthetic spectra is now controlled by a limiting cores function to ensure it does not go over 5 cores in total.
- Now the user can choose to use only the available spectra of the supernova-of-study

4 Parameters

There are big differences in the estimation of the parameters. New parameters have been added to the map, and some of the old parameters have been refined.

Extinction

The estimation method of the extinction doesn't differ with respect to the first version of the software. However, two major updates have being made:

- The user can now import manually a value of extinction.
- The absorption is evaluated following the prescription by McCall2004 for each individual filter, instead of assuming a plain $R_V = 3.1$ for each filter.

Bolometric luminosity

In Simongini et al. 2024, the bolometric luminosity is effectively taken as the interpolation of a SED but this estimate is highly dependent on the spectral coverage of the available light curves, thus it is more correct to define that estimate as "pseudo-bolometric" luminosity. The bolometric luminosity is now estimated from the absolute magnitudes. First, we convert every apparent magnitude into absolute magnitude following the standard relation for every filter x:

$$M_x = m_x - 5\log_{10}(d) + 5 - A_x \tag{1}$$

where M_x is the absolute magnitude, m_x is the apparent magnitude and A_x is the relative absorption. Subsequently, we convert every absolute magnitude light curve into monochromatic luminosity using the following relation:

$$M(\lambda) - M_\odot(\lambda) = -2.5\log\left(\frac{L(\lambda)}{L_\odot}\right) \tag{2}$$

where $L_\odot = 3.828 \times 10^{33}$ is the Solar luminosity, $M_\odot(\lambda)$ is the monochromatic Solar absolute magnitude and $M(\lambda)$ and $L(\lambda)$ are the monochromatic absolute magnitude and luminosity of a given filter. The Solar magnitudes relative to every filter are taken from Willmer 2018[1]. The bolometric luminosity is then calculated as the sum of the monochromatic luminosities at all wavelengths.

Velocity of the ejecta

In this new version of the software, to allow unsupervised analysis of big datasets, we let the velocity of the ejecta be estimated automatically, without the direct input of the user. In order to do that, we translated in code every step that, in the previous version, was done by the user itself. First, we identify spectral peaks, finding the closest peak to known reference lines and select significant peaks by filtering based on their distance from a median value. We use the `find_peaks` tool from the `scipy.signal` library (citazione). Then, we fit a polynomial curve to the spectral data around the peaks and select only the fits with a R^2 value greater than 0.9. The region around the peak, which was initially set manually by the user, is now found iteratively, to achieve the best R^2. This procedure is similar to what now is made for redshift estimates. In that case, however, more stringent cuts are applied and the user can choose between 3 different results. **NB: the automatic redshift procedure is still in phase of test, thus we suggest the user to insert manually the redshift value i.e. from the TNS report.**

Photospheric parameters

We estimate photospheric parameters by fitting blackbody models to spectral energy distributions (SEDs) derived from light curves. We explore a range of temperatures (10,000–50,000 K) and radii (5,000–30,000 solar radii) with defined step sizes. For each combination of temperature and radius, we integrate the flux within each filter's bandpass to construct an SED. Using a curve-fitting method, we model the observed SED with a blackbody function, incorporating distance (dist) constraints. We iteratively refine the temperature and radius estimates by averaging results over multiple parameter sets, ultimately deriving the most representative photospheric temperature and radius for each epoch

[1] Data are publicly available at https://mips.as.arizona.edu/~cnaw/sun.html

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