Using LSST late-time photometry to constrain Type Ibc supernovae and their progenitors

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ABSTRACT

Over its lifespan, the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) will monitor millions of supernovae (SNe) from explosion to oblivion, yielding an unprecedented $ugrizy$ photometric dataset on their late-time evolution. Here, we show that the photometric evolution of Type Ibc SNe can be used to constrain numerous properties of their ejecta, without the need for expensive spectroscopic observations. Using radiative-transfer simulations for explosions of He-star progenitors of different initial masses, we show that the $g$-band filter follows primarily the strength of the $\text{Fe} \text{II}$ emission, the $r$-band [$\text{O} \text{I}$,$\lambda\lambda 6300, 6364 and $\text{[N II]}\lambda\lambda 6548, 6583$, the $i$-band [$\text{Ca} \text{II}\lambda\lambda 7291, 7323$, and the $z$-band the $\text{Ca} \text{II}$8498 – 8662 triplet, and hence provides information on nucleosynthetic yields. Information on weaker lines, which may be used, for example, to constrain clumping, is absent. However, this deficiency may eventually be cured by improving the physical realism of radiative-transfer simulations through a closer connection to physically consistent 3D explosion models, and by the judicial selection of a much smaller set of observational samples. Degeneracies inherent to the SN radiation will affect the interpretation of photometric measures, but line fluxes from nebular-phase spectra are similarly compromised. Importantly, our “family” of Type Ibc SN models follows a distinct trajectory in color-color magnitude diagrams as the ejecta evolve from 100 to 450 d, allowing one to disentangle different progenitors or explosions. This photometric procedure provides a promising approach to study statistical samples of SNe Ibc and to confront them to ever improving progenitor and explosion models, to capture the onset of late-time interaction with circumstellar material, or to identify events currently unknown.

Key words. line: formation – radiative transfer – supernovae: general

1. Introduction

The supernova (SN) community is approaching an important turning point. In the last few decades, the discovery of massive star explosions has grown from a few per year to many each night (see, e.g., Sullivan 2013), thanks to numerous all-sky surveys such as PTF (Law et al. 2009), Pan-STARRS (Kaiser et al. 2010), ASAS-SN (Shappee et al. 2014), or ATLAS (Tonry et al. 2018). In parallel, the modeling of SN radiation has expanded considerably, with the development of numerous tools to model light curves and/or spectra. However, much of this modeling has focused on only a few well-observed nearby events. Because of obvious observational challenges, these studies are also biased in favor of the high brightness, photospheric phase rather than the low-brightness, ever dimming, nebular phase.

With the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST; LSST Science Collaboration et al. 2009), the SN discovery rate will be further enhanced. To maximize the use of this treasure-trove of data there is an urgent need to develop photometric techniques that can constrain SN properties, and be used to provide constraints on stellar and galactic evolution, as currently attempted with spectroscopy. Photometry is less time consuming than spectroscopy, can be obtained for fainter objects, and is gathered in a systematic manner with modern, untargeted sky surveys. Further, the very faint magnitude detection limit allows a monitoring of SNe out to very late times. A continuous photometric light curve of SNe can thus be built from maximum light until late times, yielding information competitive with that obtained using spectra that are much harder to obtain, and which have a much poorer temporal coverage.

The LSST will yield an unprecedented number of SNe suitable for statistical analyses, with estimates of ~ 3.3 million Type II SNe and 580 thousand Type Ibc SNe for a ten year survey. Within a redshift of 0.07, the total would be about 25 thousand Type II SNe and about eight thousand Type Ibc SNe. About 4400/4300/3000 of such SNe Ibc will have LSST photometric detections in $g$/$gri$ at 100 days after maximum light. At 200 d, these numbers change to 2300/2000/1700 and at 300 d, they are 400/380/380. These estimates come from the Photometric LSST Astronomical Time Series Classification Challenge (PLAsTiCC; Kessler et al. 2019; Hložek et al. 2020) and are based at nebular times on the theoretical light curves of Dessart et al. (in preparation)1. In the absence of dust (and molecule emission) the coverage from ~ 3600 ($u$ band) to ~ 9700 Å ($y$ band) captures typically 70% of the SN light at nebular times, and thus permits the determinations of the SN’s properties.

1 ZTF obtains $g$ and $r$ band photometry down to $20-20.5$ mag and therefore captures a subset of what LSST will provide in terms of depth and spectral coverage. Similarly, Pan-STARRS obtains $grizy$ photometry down to $21$ mag, and thus does not go as deep as the LSST.
minification of the bolometric luminosity, although reddening and distance (redshift) may not be trivial to estimate accurately. Correction for host contamination is also easier and more robustly done with difference imaging and photometry, as compared to typical slit spectroscopy.

During the photospheric phase, the bolometric luminosity, the brightness in various photometric filters, and the colors, provide constraints on the progenitor radius and the global properties of the ejecta such as its mass and kinetic energy. However, they provide only limited information on the composition with the exception of $^{56}$Ni (i.e., in ejecta where its decay provides the main energy source for the SN luminosity). In contrast, at nebular times, the ejecta is relatively optically thin, and the SN radiation is primarily seen as line emission. This is particularly evident in Type Ib (and IIb) and Ic SNe at about a year post explosion when most of the optical flux is contained in [O I], [Ne I], 6364 and [Ca II], 7291, 7323.

Omitting the line profile morphology, the photometry yields very similar information to spectroscopy at late times—the relative strength of important emission lines may be inferred from a well chosen optical color. For example, the $r-i$ color contains essentially the same information as the flux ratio of the [O I] 6300, 6364 and [Ca II] 7291, 7323 lines (modulo the contribution of the [N II] 6548, 6583 line in the lower mass models; Fig. A.1). With radiative transfer modeling one can potentially constrain the mass of the elements associated with this line emission (Frasn'c & Chevalier 1989). Although this has been done so far exclusively using the detailed information in spectra, the LSST motivates the use of photometric measures alone to deliver similar constraints on the ejecta nucleosynthesis.

With the large number of SNe that will be monitored for years by the LSST, such a photometric approach may be applied to a statistical sample of SNe, constraining some properties of the ejecta and progenitor, as well as connecting these to the host populations that will also be resolved in finer detail than ever before (by the LSST itself, as well as with the next generation large telescopes; see, e.g., Galbany et al. 2018, Kuncarayakti et al. 2018).

In the next section, we illustrate how photometry, and in particular colors, can be used to assess the relative strength of line emission in SNe Ib/c at nebular times, allowing one to identify different types of ejecta composition based on photometry alone. In Section 3, we discuss the limitation of this method and possible workarounds for these. In Section 4, we present our conclusions.

Table 1. Ejecta properties of our set of Type Ibc models from D21.

| Model | $M_{\text{ZAMS}}$ [M$_\odot$] | $M_{\text{preSN}}$ [M$_\odot$] | $M_{\text{ej}}$ [M$_\odot$] | $E_{\text{kin}}$ [10$^{51}$ erg] | $^{56}$Ni [M$_\odot$] |
|-------|------------------|------------------|------------------|------------------|------------------|
| he2p6 | 13.85 | 2.15 | 0.79 | 0.13 | 0.71 | 2.28(-2) | 1.22(-2) |
| he2p9 | 14.82 | 2.37 | 0.93 | 0.37 | 0.77 | 5.03(-2) | 2.32(-2) |
| he3p3 | 16.07 | 2.67 | 1.20 | 0.55 | 0.84 | 1.51(-1) | 0.40(-2) |
| he3p5 | 16.67 | 2.81 | 1.27 | 0.41 | 0.87 | 1.72(-1) | 2.92(-2) |
| he4p0 | 18.11 | 3.16 | 1.62 | 0.63 | 0.92 | 3.10(-1) | 4.45(-2) |
| he4p5 | 19.50 | 3.49 | 1.89 | 1.17 | 0.95 | 4.19(-1) | 8.59(-2) |
| he5p0 | 20.82 | 3.81 | 2.21 | 1.51 | 0.97 | 5.92(-1) | 9.77(-2) |
| he6p0 | 23.33 | 4.44 | 2.82 | 1.10 | 1.00 | 9.74(-1) | 7.04(-2) |
| he7p0 | 25.68 | 5.04 | 3.33 | 1.38 | 0.90 | 1.29(0) | 1.02(-1) |
| he8p0 | 27.91 | 5.63 | 3.95 | 0.71 | 0.84 | 1.71(-1) | 3.03(0) |
| he12p0 | 35.74 | 7.24 | 5.32 | 0.81 | 0.23 | 3.03(0) | 7.90(-2) |

Notes: The table columns correspond to the ZAMS mass, the preSN mass, the ejecta mass, the ejecta kinetic energy (1 foe = 10$^{51}$ erg), and the cumulative yields of $^4$He, $^{16}$O, and $^{56}$Ni prior to decay (see discussion in D21). Numbers in parentheses represent powers of ten.

2. Colors as a proxy for line-flux ratios

Figure 1 shows the $ugriz$ LSST filters together with a nebular spectrum for a SN ejecta arising from the explosion of a star that started on the He zero age main sequence with a mass of 6 M$_\odot$ (Dessart et al. 2021a; hereafter D21; this model would most likely have been classified as a SN Ib; Dessart et al. 2020). This spectrum is dominated by lines of moderate to large strength such as Mg i 4471, Na i 5896, 5890, [O I] 6300, 6364, [N II] 6548, 6583, [Ca II] 7291, 7323, O I 7771 − 7775, and Ca II 8498 − 8662, together with many weak Fe II lines contributing a moderate but extended background emission between 4000 and 5500 Å. In some models characterized by low ionization, Fe recombines, and the Fe II emission in the blue disappears in favor of Fe I emission further to the red (D21).

The emission from low-redshift Type Ib/c SNe ($z \lesssim 0.07$) is captured in a “convenient way” by the LSST photometric filters since the landmarks of their nebular spectra fall in distinct filters. The strong Fe II emission, which arises from the He-rich shell at all times or from the O-rich shell at early times, falls in the g band. [O I] 6300, 6364 falls in the r band, together with weaker contributions from Fe II lines early on and by [N II] 6548, 6583 later on in progenitors that retained their He/N shell all the way to core collapse. [Ca II] 7291, 7323 falls in the i band and dominates over other contributions from Fe II or Ni II, while Ca II 8498 − 8662 falls in the z band. Finally, we mention the u band which will provide insights into the possible interaction of the ejecta with circumstellar material.

In Type II SNe, Hα is always strong and falls in the same filter as [O I] 6300, 6364 so the [O I] line flux contribution to the r-band magnitude cannot easily be made in H-rich ejecta with such photometric filters. Type II SNe are thus not included in the following discussion.

Of interest here is whether one may constrain the progenitors and yields of Type Ib/c SNe based on photometry alone. In other words, can photometry alone distinguish robustly progenitors that died with different abundances of O, He, or N. Practically, this requires that differences in line fluxes seen in explosion models of different age, composition, energetics, correspond to clear differences in photometric properties. Degeneracies that lead to similar line fluxes or line flux ratios from distinct models will impact both photometric and spectroscopic measures — this issue concerns the physics of SN ejecta and
the degeneracy of the SN radiation itself. Extensive time coverage that is available with photometry may help to break some of these degeneracies.

To test the usefulness of photometry, Dessart et al. (in preparation) employed the He-star explosion simulations of D21 and evolved these from an earlier time of 100 d (rather than 200 d) to about 450 d after explosion with the nonlocal thermodynamic equilibrium time-dependent radiative transfer code CHiFGEN (Hillier & Dessart 2012). The sample of models includes CMFGEN 200 d) to about 450 d after explosion with the nonlocal thermodynamic equilibrium time-dependent radiative transfer code CHiFGEN (Hillier & Dessart 2012). The sample of models includes CMFGEN evolved these from an earlier time of 100 d (rather than preparation) employed the He-star explosion simulations of D21.

The g-band brightness reflects primarily the strength of Fe ii emission, with a growing contribution from Mg ii at late times. D21 found that this Fe ii emission is relatively strong in the lower mass He-star models, since Fe ii is the primary coolant for the He-rich shell (which represents 90% of the ejecta mass in model he2p6) or for the O-rich shell when O is partially ionized (model he5p0 here). The r band contains [O ii] 7323, which forms in the O-rich shell and is strong at earlier times when the ejecta is not too optically thin. In contrast, [N ii] 6548, 6583 ( [O i] 6564, 6662) forms in the Fe ii shell and is a more direct way to distinguish the models.

The slowly growing r–i color indicates a progressive though modest strengthening of [Ca ii] 6548, 6583 with Hα, as observed in SN 1993J (Matheson et al. 2000). Finally, the z band is a good tracer of Ca ii emission. The latter is strong around 100 d and weakens in time. In contrast, [N ii] 6548, 6583 ([O i] 6564, 6662) strengthens continuously from 100 to 450 d in models with a massive He-rich (O-rich) shell. Models of greater mass, or of lower expansion rate, tend to be more recombed and thus lie at higher g − r values (redder color).

Some photometric properties of our models are shown in Fig. 2. Because the kinetic energy tends to increase with ejecta mass, the fading rate is similar between models. The decay power varies by about a factor of ten (the initial 56Ni mass covers the range 0.01 up to 0.1 M⊙), while in all models the fraction of γ rays that escape increases by a factor of about five between 100 and 450 d. Hence, the bolometric light curves appear ordered in mass and do not cross as time passes. When considering photometry, and especially observations, the magnitude in a given band will depend on, for example, the 56Ni mass, and the distance, reddening, and redshift of the SN. In contrast, working with colors directly takes out the issue with distance, and takes out some of the influence of variations in 56Ni mass. So, color is a more direct way to distinguish the models.

The bottom three panels of Fig. 2 illustrate the color evolution in g − r, r − i, and r − z. The g−r color reflects primarily the strength of Fe ii emission, with a growing contribution from Mg ii at late times. D21 found that this Fe ii emission is relatively strong in the lower mass He-star models, since Fe ii is the primary coolant for the He-rich shell (which represents 90% of the ejecta mass in model he2p6) or for the O-rich shell when O is partially ionized (model he5p0 here). The r band contains [O ii] 7323, which forms in the O-rich shell and is strong at earlier times when the ejecta is not too optically thin. In contrast, [N ii] 6548, 6583 ([O i] 6564, 6662) strengthens continuously from 100 to 450 d in models with a massive He-rich (O-rich) shell. Models of greater mass, or of lower expansion rate, tend to be more recombed and thus lie at higher g − r values (redder color).

The i band is mostly sensitive to [Ca ii] 7291, 7323, which forms in the Fe/He and Si/S shells of the ejecta (Jerkstrand et al. 2015; D21). The slowly growing r − i color indicates a progressive though modest strengthening of [Ca ii] 7291, 7323 relative to [O i] 7323. In models with a He-rich shell, [Ni ii] 7323, which forms in the O-rich shell and is strong at earlier times when the ejecta is not too optically thin. Therefore, the i band is a good tracer of Ca ii emission. The latter is strong around 100 d and weakens in time. In contrast, [N ii] 6548, 6583 ([O i] 6564, 6662) strengthens continuously from 100 to 450 d in models with a massive He-rich (O-rich) shell. Models of greater mass, or of lower expansion rate, tend to be more recombed and thus lie at higher g − r values (redder color).

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In all cases, the $\text{[Ca} \text{ii]} \lambda \lambda 7291, 7323$ is stronger at late times (for additional discussion and details, see D21 and Dessart et al., in preparation).

A more direct way to distinguish the models shown in Fig. 2 is to consider the color-color magnitude diagram $r-i$ versus $g-r$ (Fig. 3). Not only do the models lie in different parts of the diagram, but the trajectories they follow as they evolve are distinct. Lower mass models lie at small (negative) $g-r$ values, only moving to the right at late times, preferentially at small (negative) $r-i$ values because of the strong flux in the $r$ band due to $\text{[O} \text{ii]} \lambda \lambda 6300, 6364$ and $\text{[Ni} \text{ii]} \lambda \lambda 6548, 6583$. Higher mass models, with a greater $O$ yield, are systematically redder and lie at higher $g-r$ values, with a small $r-i$ value that reflects the dominance of $\text{[O} \text{ii]} \lambda \lambda 6300, 6364$ over the optical spectrum. These photometric properties are based on a subset of the He-star explosion models of D21, which have their own idiosyncrasies. The present set of trajectories is primarily illustrative but it shows that this color-color magnitude diagram captures the basic spectral families drawn out by these models – the photometry conveys rich information similar to that contained in spectra.

Even today one struggles to obtain a well sampled spectral evolution at nebular times. Often, the spectra are truncated in the blue or in the red, so that $\text{[Ca} \text{ii]} \lambda \lambda 7291, 7323$ (and especially $\text{Ca} \text{ii]} \lambda \lambda 8498 \rightarrow 8662$) may not be observed. Many observations are stopped at around 300 d and the coverage up to that phase is often sparse. Spectra are often noisy in distant objects, especially at later times. Figure 4 shows the $r-i$ color evolution for a few SNe Ib and Ic, together with the small model set used here. Here, the photometry is computed from the spectra by convolution with the LSST filters, which was a challenge for the reasons given above. Nonetheless, Fig. 4 confirms that the relative strength of $\text{[O} \text{ii]} \lambda \lambda 6300, 6364$ and $\text{[Ca} \text{ii]} \lambda \lambda 7291, 7323$ is captured with photometry alone.\footnote{An offset between models and observations does not imply that the method is invalid, but instead that the models are in tension with observations. The present models arise from a limited grid of theoretical models without any tuning. The numerous potential deficiencies of the models are discussed in D21, and include the adoption of He-star models initially, the assumption of spherical symmetry in both the explosion models and in the radiative transfer, the neglect of clumping and molecule formation, the large abundance of stable Nickel explosively produced etc. Figures 23–27 in D21 show that these He-star explosion models (and their variants at higher/lower explosion energies – see D21 for details) reproduce satisfactorily the representative spectra of SNe Ib, Ic and Ic so they evidently also reproduce the corresponding photometry.}

In Fig. 3 is modified after successive redshift increments of 0.02, so the method would not then work. But for higher redshifts around 0.2, the strong lines fall again within a filter, with $\text{[O} \text{ii]} \lambda \lambda 6300, 6364$ now in $i$ and $\text{[Ca} \text{ii]} \lambda \lambda 7291, 7323$ in $r$. Figure A.3 illustrates how the color-color magnitude diagram shown in Fig. 3 is modified after successive redshift increments of 0.02. At nebular times, the photometric evolution will also help in identifying some events or phenomena. Interaction with H-rich circumstellar material will lead to a strong H$_\alpha$ emission that will dominate the SN radiation, which will fall primarily in the $r$ band (for zero redshift). A fast evolving light curve with a persistent and dominant brightness in $u$ and $g$ would be indicative of a Type Ibn (Pastorello et al. 2008; Hosseinzadeh et al. 2017).

Photometric analyses, and associated statistical analyses, will play an important role in analyzing and interpreting LSST SN data. However, it will still be important to obtain spectra for

![Fig. 4. LSST $r-i$ color evolution for the Type Ibc simulations of D21 and Dessart et al. (in preparation) together with the counterpart for Type Ib SN 2004ao, and Type Ic SNe 2004gk and 2013ge (Modjaz et al. 2014; Shivvers et al. 2019; Drout et al. 2016). The photometry is inferred from the spectra, by convolution with the LSST filter transmission curves, uncorrected for reddening or redshift – both are small. The data were retrieved from WISEREP (Yaron & Gal-Yam 2012).](image)
selected objects. For example, multiepoch spectra could greatly assist in improving photometric modeling and interpretation, and in removing biases in photometric analyses. Further, modeling of SN spectra is still under development, and thus high quality spectra (over a large passband) throughout a SN evolution, combined with high quality photometric data, will be needed to test the radiative-transfer models.

By focusing on the color evolution, one takes a more global look at the evolution and properties of SN Ibc ejecta, as opposed to a line-by-line analysis with spectra. This different, and in cases complementary approach to spectroscopy, has nonetheless numerous merits and strengths. In some sense, the debate is not whether one is superior to the other. The LSST will soon be in operation and one ought to extract the information encoded in that photometric data. As illustrated here, this photometric information is very rich.

4. Conclusion

We have presented the nebular-phase radiative properties of a wide range of He-star explosions that cover both standard and other, more stripped-envelope scenarios (Dessart et al. 2012). Further work is needed to address this issue in stripped-envelope SNe. Crucially, LSST photometry, and color–color diagrams formed from that photometry, will provide strong statistical constraints on SN properties and the progenitors that give rise to these SNe, and hence can directly address the issue.

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Appendix A: Additional figures

Figure A.1 illustrates the close correspondence between the ratio of the combined \([\text{O}\,\text{i}]\,\lambda\lambda\,6300,\,6364\) and \([\text{N}\,\text{ii}]\,\lambda\lambda\,6548,\,6583\) fluxes with that of \([\text{Ca}\,\text{ii}]\,\lambda\lambda\,7291,\,7323\) for models he2p6, he4p0, he5p0, he6p0, he8p0, and he12p0. These curves are analogous to the \(r - i\) color curves shown in Fig. 2 and Fig. 4.

Figure A.2 shows the spectral evolution for the low-mass model he2p6 and the high-mass model he8p0 from 100 to about 450 d after explosion. A detailed description of the spectral properties is given in D21 and in Dessart et al. (in preparation).

Figure A.3 shows how the model trajectories in the color-color magnitude diagram of Fig. 3 are modified after successive redshift increments of 0.02. For redshifts below about 0.06, the strongest spectral lines remain within the same LSST filter as for a redshift of zero. Increasing the redshift to 0.1 leads to significant changes because the strong emission lines in \(r\) and \(i\) approach and cross the edge of these filters. Nonetheless, the respective models are still distinguishable.
Fig. A.2. Evolution of the optical spectrum of model he2p6 (left) and he8p0 (right) from 100 to about 450 d. Overplotted is the contribution from bound-bound transitions associated with various ions. The spectrum that includes all Fe I, Fe II, and Fe III bound-bound transitions is labeled by the key “Iron”.
Fig. A.3. Same as Fig.3 but for redshift increments of 0.02 from 0 at top left to 0.1 (bottom right).