Optical follow-up observations of PTF10qts, a luminous broad-lined Type Ic supernova found by the Palomar Transient Factory

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ABSTRACT
We present optical photometry and spectroscopy of the broad-lined Type Ic supernova (SN Ic-BL) PTF10qts, which was discovered as part of the Palomar Transient Factory. The SN was located in a dwarf galaxy of magnitude $r = 21.1$ at a redshift $z = 0.0907$. We find that the $R$-band light curve is a poor proxy for bolometric data and use photometric and spectroscopic data to construct and constrain the bolometric light curve. The derived bolometric magnitude at maximum light is $M_{\text{bol}} = -18.51 \pm 0.2$ mag, comparable to that of SN 1998bw ($M_{\text{bol}} = -18.7$ mag) which was associated with a gamma-ray burst (GRB). PTF10qts is one of the most luminous SNe Ic-BL observed without an accompanying GRB. We estimate the physical parameters of the explosion using data from our programme of follow-up observations, finding that it produced a larger mass of radioactive nickel compared to other SNe Ic-BL with similar inferred ejecta masses and kinetic energies. The progenitor of the event was likely an $\sim 20 M_\odot$ star.

Key words: supernovae: general – supernovae: individual: PTF10qts.

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1 INTRODUCTION

Type Ic supernovae (SNe Ic) are classified from their optical spectra as having no hydrogen or helium present (for a review of SN classification, see Filippenko 1997). They constitute ~10 per cent of the total number of SNe in the local Universe (Li et al. 2011). SNe Ic are believed to be core-collapse events from either a massive Wolf–Rayet star that has lost its outer layers via a wind-loss mechanism (Gaskell et al. 1986) or a less massive star where the envelope has been stripped by a binary companion (Podsiadlowski, Joss & Hsu 1992; Nomoto, Iwamoto & Suzuki 1995). For a recent review of the progenitors of all core-collapse SNe, see Smartt (2009).

One subgroup of SNe Ic, referred to as broad-lined Type Ic supernovae (SNe Ic-BL) or sometimes ‘hypernovae’, exhibits very high line velocities in the spectra, indicating an explosion with high kinetic energy per unit mass. These objects have been linked to gamma-ray bursts (GRBs), initially with the observation that the broad-lined, energetic SN 1998bw was coincident with the long-duration GRB 980425 (Galama et al. 1998). Subsequently, five other spectroscopically confirmed SNe have been identified with GRBs or X-ray flashes (XRFs) between redshifts z of 0.03 and 0.2: GRN 030329/SN 2003dh (Hjorth et al. 2003; Matheson et al. 2003; Stanek et al. 2003), GRB 031203/SN 2003lw (Cobb et al. 2004; Gal-Yam et al. 2004; Malesani et al. 2004; Thomsen et al. 2004), XRF 060218/SN 2006aj (Cobb et al. 2006; Ferrero et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Pian et al. 2006; Sollerman et al. 2006), XRF 100316D/SN 2010bb (Chornock et al. 2010; Cano et al. 2011b; Starling et al. 2011; Bufano et al. 2012), and GRB 130702A/SN 2013dx (Cenko et al. 2013; D’Elia et al. 2013; Schulze et al. 2013; Singer et al. 2013). There are also a large and growing number of cases where the optical afterglow of GRBs or XRFs exhibits features typical of (or consistent with) those of SNe Ic-BL (for example, Soderberg et al. 2005; Bersier et al. 2006; Berger et al. 2011; Cano et al. 2011a; Sparre et al. 2011; Melandri et al. 2012; Jin et al. 2013; Levai et al. 2013; Xu et al. 2013).

However, there are also many examples of high-energy SNe Ic for which no associated GRB has been found, including SN 1997ef (Mazzali, Iwamoto & Nomoto 2000) and SN 2002ap (Gal-Yam, Ofek & Shemmer 2002; Mazzali et al. 2002; Foley et al. 2003). It has been suggested that all high-energy SNe Ic form GRBs and that we do not observe the gamma-ray jet because of our viewing angle (Podsiadlowski et al. 2004). This hypothesis is supported by the rates and measurements of the energetics (Smartt et al. 2009), but not by radio observations (Soderberg et al. 2006).

The Palomar Transient Factory (PTF; Law et al. 2009; Rau et al. 2009) was an optical survey of the variable sky using a 7.3 square degree camera installed on the 48 inch Samuel Oschin telescope at Palomar Observatory. PTF conducted real-time analysis and had a number of follow-up programmes designed to obtain colours and light curves of detected transients from a variety of facilities (Gal-Yam et al. 2011). A major science goal of PTF was to conduct an SN survey free from host-galaxy bias and sensitive to events in low-luminosity hosts. Such a survey was particularly suitable to search for SNe Ic-BL, which appear to be more abundant in low-luminosity dwarf galaxies (Arcavi et al. 2010).

In this paper, we present optical photometry and spectra of PTF10qts, an SN Ic-BL. Section 2 describes the observations, which are analysed in Section 3. We summarize our results in Section 4. Throughout the paper, we assume $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$.

![Figure 1. Light curve of PTF10qts from photometry taken on the P48 and P60 telescopes. The data points are given in Table 1 and converted to absolute magnitudes. The solid line represents the R-band light curve of SN 1998bw (Galama et al. 1999), the first GRB-SN, and the dot–dashed line shows the R-band light curve of SN 2006aj (Ferrero et al. 2006), which was accompanied by an XRF. The dashed line shows SN 2003jd (Valenti et al. 2007). No K-corrections have been applied to the individual PTF10qts data, except the long-dashed red line which shows the PTF10qts R$_{PTF}$ points K-corrected using spectra where possible.](https://academic.oup.com/mnras/article-abstract/442/3/2768/1038922)
the non-detection on 2010 August 2 (MJD = 55410.244), we can determine the date of explosion to within 3 d; thus, we constrain the rise time in the $R$ band to $12.7 \pm 1.5$ d in the observed frame or $11.6 \pm 1.4$ d in the rest frame.

The data points in Fig. 1 have been corrected for Milky Way extinction, $E(B - V) = 0.029$ mag, using the dust maps of Schlegel, Finkbeiner & Davis (1998) and the extinction curve of Cardelli, Clayton & Mathis (1989). The equivalent width of the Na i D line at zero redshift measured in the spectrum of PTF10qts taken at $+7$ d is $0.15 \pm 0.12$ Å, which can be converted to a measurement of extinction via the relation of Turatto, Benetti & Cappellaro (2003).

The measured value of $E(B - V) = 0.024 \pm 0.019$ mag is consistent with that determined from the dust maps (but see Poznanski et al. 2011). This is also consistent with the value derived from Poznanski, Prochaska & Bloom (2012) of $E(B - V) = 0.021^{+0.009}_{-0.014}$ mag. We observe no Na i D at the redshift of the SN, so no correction has been applied for host-galaxy extinction. The correction for Milky Way extinction has been applied to the individual points shown in Fig. 1, with no $K$-corrections (see below).

The data points in Fig. 1 also shows the $R$-band light curves of three other SNe Ic for comparison. SN 1998bw is a broad-lined SN Ic and the first GRB-SN; the values of $M_R$ are similar for both objects. We also include SN 2006aj, which was accompanied by an XRF, and SN 2003jd, which appears to be spectroscopically similar to PTF10qts (see Section 2.2). From the raw $R$-band light curve, it appears that the SN reaches a more luminous absolute magnitude than SN 1998bw, but with a light-curve width more similar to those of SN 2003jd and SN 2006aj. The long-dashed line shows the $R$-band light curve of PTF10qts with $K$-corrections based on the photospheric spectra. This confirms that the $R$-band light curve is slightly more luminous than that of SN 1998bw, but the decline rate is faster. $K$-corrections are discussed in more detail in Section 3.2.

### 2.2 Optical spectroscopy

Follow-up spectroscopy of PTF10qts was carried out at a number of international observatories and is summarized in Table 2. The SN was classified as an SN Ic-BL based on its broad features and lack of obvious hydrogen and helium, and weak silicon in the spectra. The photospheric spectra are plotted in Fig. 2, where all phases are given relative to $R$-band maximum for each object. Standard IRAF routines as well as custom IDL procedures were used to remove bias and flat-field correct the spectra, as well as to create wavelength and flux solutions for the data. These were then applied to the frames and calibrated spectra were extracted from the data. All spectra of PTF10qts are publicly available via WISEREP\(^2\) (Yaron & Gal-Yam 2012).

We compare the spectra of PTF10qts to those of other known SNe Ic and SNe Ic-BL in Figs 3–6. Again, all phases are given relative to the $R$-band maximum for that particular object. We divide our spectra into four periods of observation – pre-maximum, $+7$ d after $R$-band maximum, $+14$ d, and $+21$ d – consider each of these separately.

2 http://www.weizmann.ac.il/astrophysics/wiserep/
Table 2. A summary of spectroscopic observations of PTF10qts. The phase is relative to $R$-band maximum (2010 August 16.6) and then converted to the rest frame. Note that for the Lick/Kast spectrum, the blue side resolution is 4.1 Å (full width at half-maximum, FWHM) and the red side resolution is 9.1 Å (FWHM). The velocities, as plotted in Fig. 7, are determined from the Si $\text{II}$ 6355 Å line.

| Date (UT)   | Phase (d) | Telescope         | Range (Å) | Resolution (Å pixel$^{-1}$) | Velocity (1000 km s$^{-1}$) |
|-------------|-----------|-------------------|-----------|-----------------------------|-----------------------------|
| 2010-08-13  | −3.6      | P200/DBSP         | 3505–10 100 | 5                           | −                           |
| 2010-08-15  | −1.8      | Lick/Kast         | 3480–10 000 | 4.1/9.1                     | 19.1 ± 0.75                |
| 2010-08-25  | +7.4      | TNG/DOLORES       | 3360–8050  | 2.25                        | 14.4 ± 0.5                 |
| 2010-09-02  | +14.8     | P200/DBSP         | 3440–9850  | 2                           | 12.0 ± 0.5                 |
| 2010-09-05  | +17.4     | P200/DBSP         | 3440–9850  | 2                           | 8.5 ± 0.75                 |
| 2010-09-09  | +21.2     | KPNO/RC Spec      | 3620–8140  | 2                           | −                           |
| 2011-04-27  | +231.7    | Keck/LRIS         | 3100–10 200 | 2                           | −                           |

Figure 2. Photospheric spectra of PTF10qts. The phases are given in the rest frame relative to $R$-band maximum. The spectra are labelled showing important species discussed in the text. The number in parentheses shows the offset applied to each spectrum.

Figure 3. A comparison of spectra before maximum light. Telluric features are marked. The spectra are labelled showing important species discussed in the text. The number in parentheses shows the offset applied to each spectrum.

Our next phase of spectroscopy is around two weeks past maximum light. As seen in Fig. 5, the SN ejecta have expanded sufficiently that we can now see individual features, such as the Si $\text{II}$ lines around 6200 Å and strong Ca $\text{II}$ absorption at 8100 Å. The velocity of the Ca $\text{II}$ near-infrared (NIR) triplet is $\sim 18 000$ km s$^{-1}$ (measured from the blueshift of the feature’s minimum), which is higher than that for both SN 2003jd and SN 2004aw as shown in the figure. In the blue we also see absorption caused by Mg $\text{II}$, Ca $\text{II}$, and Fe $\text{II}$. Visually the spectra retain their similarity to those of SN 2003jd, SN 2004aw, and to a lesser degree SN 1998bw without O $\text{I}$ which is still absent. This may be indicative of a smaller ejecta mass.
The final spectrum of PTF10qts taken during the photospheric phase is shown in Fig. 6. It is quite noisy, but visually the spectral evolution continues to be similar to those of SN 2003jd and SN 2004aw. There may be slight absorption from $O\ I$ visible in these later spectra. This raises the possibility of a sequence of oxygen masses in SNe Ic-BL ranging from strong in SNe such as SN2004aw, through objects like SN2003jd and finally objects like PTF10qts which show no oxygen.

From this spectral comparison, we conclude that PTF10qts is not a good match to any single well-observed SN Ic-BL over its entire evolution, although at some phases there appear to be reasonable matches to other known SNe Ic-BL. PTF10qts lacks the very high velocities (i.e. energy per unit mass) of SN 1998bw, and the spectral features (related to element abundances) do not match those seen in the lower velocity examples of SN 2003jd, SN 2004aw, and SN 2006aj.

3 DISCUSSION

3.1 Velocity determination

Before determining the physical parameters of this SN, it is necessary to constrain the SN photospheric velocity at maximum light, which is typically characterized by the minimum of the blueshifted absorption of the $Si\ II$ feature around $\sim6150$ Å. However, as seen below, we use two different methods which involve two different dates for maximum light and we do not have the spectral coverage around these times to measure values directly from spectra, along with the additional problem of the SN features being blended together so the $Si\ II$ line which is thought to give a clear determination of the photospheric velocity is not always visible as a separate feature.

In Fig. 7, we show the velocities of PTF10qts (bowtie) compared to a number of other types of SNe, including the two we will use for analogues – SN1998bw and SN2006aj. We can define the velocity to use in later analysis in different ways such as the velocity at maximum light in the $R$ band or the velocity at the maximum of the bolometric light curve. The time between explosion and maximum varies between SNe, but if we wanted a uniform time, we could also take a fixed date after explosion.

Applying these three methods to PTF10qts reveals that both the $R$-band and bolometric maxima fall between the first two velocity measurements from the spectra. We interpolate linearly between the velocities measured at $-1.8$ d and $+7.4$ d as given in Table 2 and assign PTF10qts a photospheric velocity of $17\ 000\ \pm\ 1500\ km\ s^{-1}$. Due to the small difference in rise times for the bolometric and $R$-band light curves for SN1998bw and SN2006aj, we use two different velocities for these objects in the following sections and assign an error of $\pm\ 1000\ km\ s^{-1}$ to each one. We have been conservative with the velocity errors, but they are only a small contribution to the final error on the physical parameters we derive below.

3.2 $R$ band as a proxy for bolometric

We first attempt to use the $R$-band light curve, which has the best phase coverage, to estimate some of the physical parameters of the SN explosion. It has also been suggested that the $R$ band can be used
A comparison of spectra around +19.30 mag for PTF10qts), and also SN 2006aj, $R_{2011}$ − $R_{Kv}$ 442, (2) 0.86 mag). Note that the $R$ band of the local comparison of SNe we $R_{R} − R_{\pm} = −\alpha_{K}$, the photospheric velocity. We have chosen to use $R_{R} 2008 0.06$ and $17 000 \text{ km s}^{-1}$ and (1) differ from the light curve for PTF10qts shown in Fig. $K − R_{\pm}$ for SN 2006aj.

A plot of the photospheric velocities of SNe at different times after $R_{\tau}$ 2008 0.06 and $17 000 \text{ km s}^{-1}$ and (1) differ from the light curve for PTF10qts shown in Fig. $K − R_{\pm}$ for SN 2006aj.

Unfortunately, as discussed above, there is no single good analogue of PTF10qts. Instead, we take two examples for which bolometric light curves and other physical parameters are well modelled, and we use their properties to estimate the ejecta mass $M_{ej}$, kinetic energy $E_{k}$, and nickel mass $M^{56Ni}$ of PTF10qts. We adopt SN 1998bw, as this is the most similar in absolute $R$ magnitude to PTF10qts at maximum light ($R = −19.16$ mag for SN 1998bw compared to $R_{PTF} = −19.30$ mag for PTF10qts), and also SN 2006aj, which is similar spectroscopically. Radiative transfer models of their light curves have been developed to derive the physical parameters of these explosions (Nakamura et al. 2001; Mazzali et al. 2006a).

In order to compare properly PTF10qts with existing samples in the literature, we use photometry and spectra to measure $R − I$ colours and obtain the transformation from magnitudes in $R_{PTF}$ to $R$ as in Ofek et al. (2012) and Jordi, Grebel & Ammon (2006). We find that given the sparse light-curve coverage, it is not possible to infer a relationship between $R − I$ and phase. We therefore assume a constant value of $R − I = 0.24 ± 0.12$ mag, which is the mean of all the measured values. This corresponds to $R = R_{PTF} − 0.14 ± 0.01$ mag, where the quoted uncertainty comes only from the colour term.

Given the redshift of PTF10qts, the observed $R$ band is very different from the observed $R$ band of the local comparison of SNe we have used. To compensate for this, we calculate $K$-corrections using the spectra of PTF10qts following Humason, Mayall & Sandage (1956). The spectra acquired on August 25 (TNG) and September 9 (KPNO) fall short of covering the full $R$ band by a few hundred angstroms when shifted to the rest frame. Therefore, at wavelengths longer than their red end, we assumed that their behaviour is similar to the spectra taken on August 15 (Lick) and September 2 (P200), respectively, based on the similarity of the spectra at bluer wavelengths. We then interpolated the measurements to obtain $K$-corrections at 0 and $+15$ d relative to $R$-band maximum. The calculated values are $−0.174$ and $−0.027$, respectively.

We interpolated the $R$-band light curve of PTF10qts to obtain final values of $R(0) = −19.27 ± 0.06$ and $R(15) = −18.69 ± 0.06$ mag. The uncertainties include measurement errors, uncertainties in the $K$-correction, and conversion from $R_{PTF}$ to $R$. We therefore find $\Delta m_{15}(R) = 0.58 ± 0.08$ mag for PTF10qts. This is similar to that of SN 1998bw ($\Delta m_{15}(R) = 0.56$ mag), but much smaller than that of SN 2006aj ($\Delta m_{15}(R) = 0.86$ mag). Note that the $K$-corrected values in $R$ differ from the light curve for PTF10qts shown in Fig. 1, as that is for $R_{PTF}$.

Using Arnett (1982), we know the following relations for an SN at maximum light:

$$M_{ej} \propto \tau^{2} v_{\text{phot}}$$

as a proxy for bolometric when calculating the physical parameters of the explosion (Droit et al. 2011). We employ a well-studied example as an analogue and scale the physical parameters based on the modelling of that object. Ideally, the analogue would match the light curve and the spectrum. This is particularly important for SNe Ic-BL, as the kinetic energy is dominated by the broadest parts of the lines. These features are usually blended; thus, as well as matching the velocities, it is important to match the spectra to reduce the error when scaling the parameters.

Figure 6. A comparison of spectra around +21 d after maximum light. The spectra are labelled showing important species discussed in the text. The number in parentheses shows the offset applied to each spectrum.

Figure 7. A plot of the photospheric velocities of SNe at different times after explosion. Different symbol shapes correspond to different types of SNe: diamond – Ib; square – Ic/Ic-BL; circle – GRB/SNe; triangle – XRF/SN Ic; cross – XRF/SN Ib; and bowtie – PTF10qts. This figure is augmented from the one produced in Mazzali et al. (2008).
Table 3. A summary of the physical parameters assumed for SN 1998bw and SN 2006aj, and those derived for PTF10qts first in the $R$ band and then using the bolometric light curve. $E_K$ is the kinetic energy and $L_i$ is the peak luminosity in either $R$ or bolometric. The parameters for SN 1998bw and SN 2006aj are either measured from their published light curves or, in the case of $E_K$, $v$, $M_{ej}$, and $M(Ni)$, taken from the modelling in Nakamura et al. (2001) and Mazzali et al. (2006a), respectively.

| Parameter                | SN 1998bw | SN 2006aj | PTF10qts | PTF10qts |
|--------------------------|-----------|-----------|----------|----------|
| $\Delta m_{15}(R)$ (mag) | 0.56      | 0.86      | 0.58     | 0.58     |
| $v$ (km s$^{-1}$)         | 19 000 ± 1000 | 15 000 ± 1000 | 17 000 ± 1500 | 17 000 ± 1500 |
| $L_R$ (erg s$^{-1}$)      | $1.87 \times 10^{52}$ | $1.08 \times 10^{52}$ | $(2.10 \pm 0.05) \times 10^{52}$ | $(2.10 \pm 0.05) \times 10^{52}$ |
| $\tau$ (d)               | 17        | 10.5      | 11.6     | 11.6     |
| $M_{ej}$ (M$_\odot$)     | 10 ± 1    | 1.8 ± 0.8 | 8.3 ± 2.6 | 4.3 ± 1.3 |
| $E_K$ (erg)               | $(50 \pm 10) \times 10^{51}$ | $(2 \pm 1) \times 10^{51}$ | $(33.4 \pm 4.4) \times 10^{51}$ | $(6.1 \pm 3.9) \times 10^{51}$ |
| $M(Ni)$ (M$_\odot$)       | 0.43 ± 0.05 | 0.2 ± 0.04 | 0.34 ± 0.09 | 0.42 ± 0.08 |

| R band                    |          |           |          |          |
|---------------------------|----------|-----------|----------|----------|
| $\Delta m_{15}(R)$ (mag) | 0.56      | 0.86      | 0.58     | 0.58     |
| $v$ (km s$^{-1}$)         | 19 000 ± 1000 | 15 000 ± 1000 | 17 000 ± 1500 | 17 000 ± 1500 |
| $L_R$ (erg s$^{-1}$)      | $1.87 \times 10^{52}$ | $1.08 \times 10^{52}$ | $(2.10 \pm 0.05) \times 10^{52}$ | $(2.10 \pm 0.05) \times 10^{52}$ |
| $\tau$ (d)               | 17        | 10.5      | 11.6     | 11.6     |
| $M_{ej}$ (M$_\odot$)     | 10 ± 1    | 1.8 ± 0.8 | 8.3 ± 2.6 | 4.3 ± 1.3 |
| $E_K$ (erg)               | $(50 \pm 10) \times 10^{51}$ | $(2 \pm 1) \times 10^{51}$ | $(33.4 \pm 4.4) \times 10^{51}$ | $(6.1 \pm 3.9) \times 10^{51}$ |
| $M(Ni)$ (M$_\odot$)       | 0.43 ± 0.05 | 0.2 ± 0.04 | 0.34 ± 0.09 | 0.42 ± 0.08 |

| Bolometric               |          |           |          |          |
|--------------------------|----------|-----------|----------|----------|
| $\tau$ (d)               | 21.7 ± 0.5 | 16.6 ± 0.5 | 16.8 ± 1 | 16.8 ± 1 |
| $v$ (km s$^{-1}$)         | 20 000 ± 1000 | 16 000 ± 1000 | 17 000 ± 1500 | 17 000 ± 1500 |
| $L_{bol}$ (erg s$^{-1}$)  | $8.32 \times 10^{52}$ | $5.85 \times 10^{52}$ | $(7.7 \pm 1.4) \times 10^{52}$ | $(7.7 \pm 1.4) \times 10^{52}$ |
| $\eta_{bol}$ (d)         | 15        | 9.6       | 13.4     | 13.4     |
| $M_{ej}$ (M$_\odot$)     | 10 ± 1    | 1.8 ± 0.8 | 5.1 ± 0.9 | 2.0 ± 0.3 |
| $E_K$ (erg)               | $(50 \pm 10) \times 10^{51}$ | $(2 \pm 1) \times 10^{51}$ | $(18.5 \pm 6.6) \times 10^{51}$ | $(25.1 \pm 1.4) \times 10^{51}$ |
| $M(Ni)$ (M$_\odot$)       | 0.43 ± 0.05 | 0.2 ± 0.04 | 0.36 ± 0.1 | 0.36 ± 0.08 |

Note that for SN 2006aj, the light-curve data for the $R$ band end at +12 d relative to $R$-band maximum, but the bolometric light curve extends to +14 d owing to the availability of data in other filters. We evaluated bolometric magnitudes from these by assuming a constant bolometric correction with respect to the $V$ band. We obtain the same result if we extrapolate just the $R$-band light curve over the longer interval.

This estimate is significantly different from the value obtained using the relationship in Drout et al. (2011, ~0.2 M$_\odot$), despite the fact that PTF10qts is not unusual in either its $\Delta m_{15}(R)$ or $M_R$ values (see their fig. 22). This is because their relation relies purely on the absolute magnitude of the SN at maximum and does not take into account differences in rise times. In this study, we see that PTF10qts has a similar peak magnitude in the $R$ band to SN1998bw, but the rise time is ≈5.5 d shorter. This would imply a much reduced nickel production in PTF10qts which is not reflected in the Drout et al. (2011) estimation.

The fact that we obtain an even lower value with the Drout et al. (2011) formula is curious; however, it also predicts a lower nickel mass for SN1998bw at 0.34 M$_\odot$. The value for SN2006aj is in good agreement with that obtained from the modelling – 0.19 M$_\odot$. We attribute this to the fact that SN1998bw has a much longer rise time than all of the SNe used in Drout et al. (2011), whereas SN2006aj has a more typical rise time.

The simplification of assuming $L \propto M(Ni)/\tau$ is not appropriate for comparing SNe with significantly different rise times or where the SNe deviate from parabolic light curves where $\tau \propto 1/\Delta m_{15}(R)$. We can see that this is not the case for both $R$-band and bolometric light curves in Figs 1 and 8.

These results clearly show that it is not possible to use just the $R$ band to determine the physical parameters of this SN and so we would caution the extension of the Drout et al. (2011) relations to other SNe, in particular where the rise time is poorly constrained or differing from ≈10–12 d. Instead we now focus on the generation of a bolometric light curve.

3.3 Bolometric light curve

We combine photometric and spectroscopic data to construct a pseudo-bolometric light curve, as this will remove the assumption

4 We use the term pseudo-bolometric as the light curve we generate is from the UV to NIR only and cannot be described as truly bolometric as it excludes contributions at wavelengths outside this region, particularly gamma-rays.
Optical observations of SN Ic-BL PTF10qts

...that the bolometric corrections from the $R$ band for PTF10qts and either analogue are the same at all phases.

Bolometric fluxes were computed from the six spectra by integrating their dereddened signal in the interval 4000–8500 Å. As when calculating the $K$-corrections, we extend the August 25 (TNG) and September 9 (KPNO) spectra in the red to cover this range of wavelengths. We have also computed bolometric fluxes from the photometry at all epochs in which at least three bands were covered. After correcting for Milky Way reddening, we converted them to fluxes according to Fukugita et al. (1996), and then splined and integrated them in the observed 4000–8500 Å range. In the rest frame, the red boundary of this integration interval corresponds to $\sim 7800$ Å; thus, we have increased all bolometric fluxes by 15 per cent to account for the ultraviolet (UV) and NIR contributions (based on comparisons to other SNe that have been observed accurately both in the optical and NIR). Considering the uncertainty related to this assumption and the lack of UV information, we associate an uncertainty of 20 per cent with each bolometric flux.

When combining the data points generated by these two different routes, we noted that the spectroscopically derived points were systematically offset by a small amount to brighter magnitudes than the photometrically derived points. We attribute this offset to inconsistencies in the two methods used to derive the individual points. To align the spectroscopically generated points, we used the bolometric light curve of SN 1998bw (itself generated via the photometric route) and fitted it to just the photometrically derived data points of PTF10qts, allowing a temporal ‘stretch’ and constant-magnitude shift-up and shift-down. Treating this warped light curve as a template, we then used $\chi^2$ minimization to apply a constant shift to the spectroscopically derived data to bring them in line with the photometrically derived points. The final bolometric light curve is reported in Fig. 8, where phases are plotted relative to the date of bolometric maximum, which occurs 1.84 rest-frame days after $R$-band maximum.

Comparing the shapes of bolometric light curves is another approximate way to examine the physical similarity of PTF10qts to other SNe Ic-BL: supernovae with similar physical properties will have similarly shaped light curves. In Fig. 8, we show PTF10qts with the bolometric light curves of other SNe Ic-BL so that the dates of maximum align. We see that the bolometric light curve of PTF10qts is most similar to that of SN 1998bw, although the later points of PTF10qts may decline slightly faster, implying a lower nickel mass in PTF10qts. SN 2006aj is also a good match around maximum if it is made brighter by 0.5 mag, although the light curve is narrower, so we would expect a higher kinetic energy and nickel mass in PTF10qts than SN 2006aj. We can use these observations as a sanity check when deriving physical properties from the bolometric light curve. We also show that SN 2003jd, which is a good match at some spectroscopic phases, is a poor match to the bolometric light curve before maximum brightness, again showing that spectroscopic similarity does not always mean the physics of the SN explosion are the same.

We estimate the physical parameters using the relationships discussed in Section 3.2, but now using the bolometric quantities. With bolometric data significantly before maximum brightness, we can switch to using $\tau$, the light-curve width, instead of just the post-maximum $\Delta m_{15} \propto 1/\tau$, which we have shown to be only an approximation. We define $\tau$ to be the width at peak magnitude minus 0.5 mag. This should better reflect the differences between the SN light curves because, as Fig. 8 shows, after maximum the slopes of SN 1998bw, SN 2006aj, and PTF10qts are very similar, but before maximum, they differ significantly. For PTF10qts, SN 1998bw, and SN 2006aj, we measure $\tau = (16.8 \pm 1, 21.7 \pm 0.5, 16.6 \pm 0.5)$ d, where now PTF10qts is much less similar to SN 1998bw and more like SN 2006aj.

We measure the quantities when using both the SN 1998bw and SN 2006aj bolometric light curves, and these results are given in Table 3. We again see how important it is to choose an analogue which matches both the spectroscopy and the light curve, as the estimates of the physical parameters based on SN 1998bw and SN 2006aj do not agree. This is due to the different values of $E_{\lambda}/M_{ej}$ and mass of $^{56}$Ni for the two analogues. We take the weighted mean of the two analogues as the best estimate of the physics of PTF10qts: $M_{ej} = 2.3 \pm 0.3$ $M_\odot$ and $E_{\lambda} = (3.2 \pm 1.4) \times 10^{51}$ erg. We also derive a nickel mass of $M(^{56}$Ni) = 0.36 ± 0.07 $M_\odot$. The measurements of the ejecta mass and the kinetic energy are lower than those found using just the $R$ band, and the nickel mass is slightly higher. We note that these estimates are similar to those for SN 2010ah (Mazzali et al. 2013), but the spectra are very different.

To estimate the zero-age main sequence (ZAMS) mass of the progenitor, we use the models of Sugimoto & Nomoto (1980) and assume a remnant mass of 2 $M_\odot$ as in their models. PTF10qts corresponds to a progenitor star with a ZAMS mass of $\sim 20$ $M_\odot$.

3.4 Nebular spectrum

We can also estimate the nickel mass from the nebular spectrum, which was obtained with LRIS at the Keck-I telescope 230 rest-frame days after $R$-band maximum. This is shown in Fig. 9 with a continuum subtracted from it. Also shown is a synthetic spectrum. The observed spectrum has a low signal-to-noise ratio, so the resultant model fit parameters should not be used to draw any firm conclusions. We used a code for the synthesis of nebular spectra as described by Mazzali et al. (2001). The synthetic spectrum was obtained using $M(^{56}$Ni) = 0.35 ± 0.1 $M_\odot$, which is in good agreement with the estimate from the bolometric light curve. The red part of the spectrum also appears to indicate a low oxygen mass ($\sim 0.7$ $M_\odot$) in the SN, which would support the lack of detection in the post-maximum spectra (Fig. 5); however, the blueshifted profile of the [O i] emission suggests that the line may not yet be optically thin. The oxygen mass may therefore be underestimated, although we tried to take this into account in the model by requiring a stronger line than the observed one.
A spectrum of PTF10qts obtained at the Keck 10 m telescope ±0.0907 by the PTF. We find that the Fermi contains a compilation of all SNe Ic-BL published in the literature, which is a smaller mass than some other SN Ic-BL Fermi sr. This implies that there is a very low probability of finding an event.

\[ \frac{1}{\text{sky area}} \times \text{SN Ic-BL} \times \text{probability of GRB} \]

To explore this more fully, in Fig. 10 we compare PTF10qts to SN 1998bw, it is still photometrically similar and the event was nickel-rich SN Ic-BL. We thus call PTF10qts a "nickel-rich SN Ic-BL".

Although PTF10qts is not spectroscopically similar to SN 1998bw, it is still photometrically similar and the event was clearly energetic. We used Interplanetary Network (IPN) data to search for a possible GRB companion to PTF10qts in case gamma-rays had been detected by any of the orbiting satellites. The IPN includes Mars Odyssey, Konus-Wind, RHESSI, INTEGRAL, Swift-Burst Alert Telescope (BAT), Suzaku, AGILE, MESSENGER, and Fermi (Gamma-ray Burst Monitor (GBM)).

The date of the PTF10qts explosion is uncertain; we know only the first detection of the SN, 2010 August 5. The observed rise time of PTF10qts is estimated to be 12.7 ± 1.5 d. We searched for a GRB around 16 days before PTF10qts maximum light (allowing for any delay between a GRB and the emergence of the SN). This corresponds to a date range of 2010 August 1–5.

During this period, six bursts were detected by the nine spacecraft of the IPN. During the same period, there were also 14 unconfirmed bursts which have been excluded from further analysis. The sample also excludes bursts from known sources such as anomalous X-ray pulsars and soft gamma repeaters.

Of these six bursts, three were observed with the coded fields of view of the Swift-BAT or INTEGRAL IBIS instruments, which have a positional accuracy of several arcminutes. These bursts were inconsistent with the position of PTF10qts. Two were observed either by the Fermi GBM alone or by the Fermi GBM and one or more near-Earth spacecraft. The GBM error contours are not circles, although they are characterized as such, and they have at least several degrees of systematic uncertainties associated with them. Since no other confidence contours are specified, it is difficult to judge accurately the probability that any particular GBM burst is associated with the SN. In this analysis, we have simply multiplied the 1σ statistical-only error radius by 3 to obtain a rough idea of the 3σ error contours. One further event was observed by Konus and MESSENGER, and in this case the probability that this burst was due to PTF10qts is 0.04, excluding this as burst as coincident with the SN.

The total area of the localizations of the six bursts was ∼0.04 × 4π sr. This implies that there is a very low probability of finding an unassociated gamma-ray source coincident with our SN during the time window we are investigating.

There is another approach to the probability calculation. Since only 0 or 1 GRB in our sample can be physically associated with the SN, we can calculate two other probabilities. The first is the probability that, in our ensemble of six bursts, none is associated by chance with the SN. Let \( P \) be the fraction of the sky which is occupied by the localization of the i-th burst. Then the probability that no GRB is associated with the SN is

\[ P(\text{No GRB}) = \prod_i (1 - P_i). \]

For our sample, this probability is 0.96.

The second probability is that any one burst is associated by chance with the SN, and that all the others are not:

\[ P(\text{One GRB by chance}) = \sum_i P_i \prod_{j \neq i} (1 - P_j). \]

For our sample, this probability is 0.004.

This analysis covers a very narrow range of dates for any potential GRB burst. If we extend the search period to the 30 d preceding the first optical detection of PTF10qts, there is still no statistically significant detection of any gamma-rays associated with the SN event. In light of this, we assume that we have not detected any gamma-rays associated with PTF10qts.

4 CONCLUSIONS

We have presented optical follow-up data for the SN Ic-BL PTF10qts, discovered at \( z = 0.0907 \) by the PTF. We find that the \( R \)-band light curve of PTF10qts is not a good representation of the bolometric light curve; hence, we used photometric and spectroscopic data to produce a pseudo-bolometric light curve from which to estimate the physical parameters of the SN explosion.

PTF10qts appears to be an SN Ic-BL from a progenitor of \( \lesssim 20 M_\odot \), which is a smaller mass than some other SN Ic-BL events, such as SN 1998bw, SN 2003dh, and SN 2003lw for which the progenitors are all believed to be \( \geq 35 M_\odot \). However, PTF10qts produces a similar amount of \( 56Ni \) to these events, which are all associated with GRBs. A search of IPN data found no evidence for gamma-rays associated with the SN event though. PTF10qts falls on the general trends of SNe Ic in terms of the relation between
### Table 4. Summary of the explosion properties of well-studied SNe Ic-BL.

| Object | Host          | Distance (Mpc) | Distance method | $M^{46}\text{Ni}$ (M⊙) | $E_K$ (10^{42} erg) | $M_{\text{ej}}$ (M⊙) | Velocity (km s⁻¹) | $M_{\text{rem}}$ (M⊙) | ZAMS Method | References |
|--------|---------------|----------------|----------------|-------------------------|---------------------|---------------------|-------------------|---------------------|--------------|------------|
| SN 1997ef | UGC 04107    | 48.95          | z              | 0.15                    | 8                   | 10                  | 9500              | 2.4                 | 30–35        | M          | 1          |
| SN 1998bw* | ESO 184082   | 35.1           |                | 0.4                     | 50                  | 10                  | 10 500            | >3.0                | 40           | M          | 2          |
| SN 2002ap | NGC 0628     | 8              | TF             | 0.07                    | 4–10                | 2.5–5               | 5000              | 2.5                 | 20–25        | M          | 3          |
| SN 2003dh* | anonymous    | 810.3          | z              | 0.38                    | 37.5                | 7.5                 | 18 000            | 2.4                 | 25–40        | M, 4, 5     |
| SN 2003jd | MCG 0159021  | 76.7           | z              | 0.36 ± 0.04             | 7.5 ± 2             | 3.0 ± 0.5           | 13 500            | >3.0                | 22–28        | M          | 6          |
| SN 2003lw* | anonymous    | 487.4          | z              | 0.55 ± 0.1              | 60 ± 10             | 13 ± 2              | 18 000            | >3.0                | 40–50        | M          | 7          |
| SN 2004ap | NGC 3997     | 72.5           | z              | 0.3 ± 0.05              | 3.5 ± 0.9           | 5 ± 0.5             | 13 500            | 2.4 ± 0.5           | 20–40        | I (94I)     |
| SN 2005Kz | MCG 0834032  | 114            | z              | 0.47 ± 0.38             | 2.2 ± 0.8           |                     |                   |                     | F            | 9          |
| SN 2006aj* | anonymous    | 146.7          | z              | 0.21                    | 2                   | 1.8                 | 15 000            | 1.4                 | 20           | M          | 10, 11     |
| SN 2007bg | anonymous    | 152.1          | z              | 0.12 ± 0.02             | 4 ± 1               | 1.5 ± 0.5           | 9000              |                     | F            | 9          |
| SN 2007D | UGC 02653    | 97             | z              | 1.5 ± 0.5               | 1.5 ± 0.5           |                     |                   |                     | F            | 9          |
| SN 2007ru | UGC 12381    | 62             | z              | 0.4                     | $5\pm_{3.3}$        | 1.3 ± 0.1           | 20 000            |                     | I (94I/98bw)  | 13         |
| SN 2009bb | NGC 3278     | 46.7           | z              | 0.22 ± 0.06             | 18 ± 7              | 4.1 ± 1.9           | 15 000            |                     | F/I (02ap)   | 14         |
| SN 2009mz* | anonymous    | 2765.1         | z              | 0.35                    | 2.3                 | 1.4                 | 17 000            |                     | D            | 15         |
| SN 2010ah | SDSS J114402.98+554122.5 | 221.4 | z | 0.25 ± 0.05         | 12 ± 4              | 3.3 ± 1             | 18 000            | 1.5–3               | 24–28        | I (98bw/02ap) | 16, 17      |
| SN 2011uy | SDSS J123527.19+270402.7 | 301.5 | z | 0.09 ± 0.2         | 11                   | 4.7                 | 19 200            |                     | D            | 18         |
| SN 2010bh | anonymous    | 264.9          | z              | 0.12 ± 0.02             | 9.7 ± 5.5           | 3.2 ± 1.6           | 1.74 × 2006aj     | I (06aj)           | 19         |
| PTF10qts | SDSS J164137.53+285820.3 | 414.9 | z | 0.36 ± 0.07         | 2.7 ± 0.9           | 2.1 ± 0.2           | 15 000            | 2                   | 20 ± 2       | I (98bw/06aj) | 22         |
| SN 2012au | NGC 4790     | 23.5           | TF             | 0.3                     | 10                  | 3–5                 | 15 000            |                     | F            | 23         |

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*): accompanied by a GRB or XRF.

****: Tully–Fisher relation; z: luminosity distance converted from redshift using the same cosmology as this paper.

^: Photospheric velocity derived from spectra.

^: Refers to the method(s) used for calculating the physics of the explosion. M: radiative transfer modeling, F: fitting of an analytical model as in Ref. 6, I: interpolation using other SNe, D: relations from Ref. 9.

^: Derived quantity equal to $M_{\text{ej}}/E_K^{1/4}$.

References — 1: Iwamoto et al. (2000), 2: Nakamura et al. (2001), 3: Mazzali et al. (2002), 4: Mazzali et al. (2003), 5: Deng et al. (2005), 6: Valenti et al. (2007), 7: Mazzali et al. (2006b), 8: Taubenberger et al. (2006), 9: Drout et al. (2011), 10: Mazzali et al. (2006), 11: Pian et al. (2006), 12: Young et al. (2010), 13: Sahu et al. (2009), 14: Pignata et al. (2011), 15: Berger et al. (2011), 16: Corsi et al. (2011), 17: Mazzali et al. (2013), 18: Sanders et al. (2012), 19: Bufano et al. (2012), 20: Cano et al. (2011b), 21: Olivares et al. (2012), 22: this work, 23: Milisavljevic et al. (2013).
progenitor mass and kinetic energy, but for its ZAMS mass of \( \sim 20 \, M_\odot \), it produced more \( ^{56}\text{Ni} \) than would be expected. This is evidenced by its luminous light curve, but its narrower light-curve width when compared to SN 1998bw (\( \tau = 21.7 \, \text{d} \) compared to \( \tau = 16.8 \, \text{d} \)). We note that the \( ^{56}\text{Ni} \) masses we obtained by analogy with SN 1998bw and SN 2006aj using the \( R \)-band light curve (line 7 of Table 3) are different from those calculated via the bolometric light curve (line 14 of Table 3). This indicates that the \( R \)-band light curve is not a completely reliable proxy for the bolometric light curve, and the latter is preferable when evaluating physical parameters.

We would caution the use of physical relationships based on monochromatic light curves for use as anything other than a first approximation. This is because assumptions such as constant opacity, constant bolometric correction, and \( L \propto 1/\tau \) are oversimplifications. In this study, we have compared two methods using \( R \)-band and bolometric data. We find that the bolometric method is more suitable, but is still only an approximation. A constraint on the time of explosion is required for this to provide anything other than a lower limit on the nickel mass. The physical parameters of an SN explosion of this type can only be determined with full modelling of the light curve and spectra.

We encourage future observations of similar objects discovered early and with light curves and spectral coverage across the entire UV–optical–infrared range in order to better understand their nature.

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