

LET THERE BE LIGHT:
EARLY OBSERVATIONS OF THE NORMAL TYPE IA SUPERNOVA iPTF 16abc
SHOW NO EVIDENCE FOR A DARK PERIOD

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ABSTRACT

Early observations of type Ia supernovae (SNe) provide a unique probe of their progenitor systems and explosion physics. Here, we report the intermediate Palomar Transient Factory (iPTF) discovery of an extraordinarily young Type Ia supernova, iPTF 16abc. The initial detection of the SN was made only 0.18 d after the time of first light. In the ~ 24 hr after discovery, iPTF 16abc rose by ~ 2 mag in the g_{PTF} band, which is very rare for young type Ia SNe. Furthermore, by measuring the evolution of the photospheric velocity we determine that the time of explosion for iPTF 16abc is approximately equal to the time of first light. Spectra obtained in the week after explosion reveal the presence of strong C II absorption, which steadily fades over that time period. We show that the unusually fast, near-linear rise in flux for iPTF 16abc cannot be explained by either SN shock breakout and the associated subsequent cooling or the collision of the SN ejecta with a stellar companion. Instead, we show each of the unusual characteristics of iPTF 16abc: (i) the rapid, near-linear rise, (ii) the lack of a dark period between explosion and first light, and (iii) the strong lines from ionized carbon in the earliest spectra, can all be explained if radioactive ^{56}Ni is strongly mixed throughout the SN ejecta. In the next few years, dozens of very young *normal* SNe Ia will be discovered, and observations similar to those presented here will constrain the white dwarf explosion mechanism.

Keywords: methods: observational — supernovae: individual (iPTF 16abc)

1. INTRODUCTION

Although Type Ia supernovae (SNe Ia) have been extensively used as standardizable candles, their progenitor systems and explosion physics are still debated (see a recent review by Maoz et al. 2014). Extremely detailed observations in the hours to days after explosion are one of the most promising avenues to further constrain this problem.

While the shock breakout of a SN Ia occurs on a sub-second timescale, the subsequent quasi-adiabatic expansion and cooling of the unbound ejecta produces thermal emission that can be used to infer the radius of the exploding star (Piro et al. 2010; Rabinak & Waxman 2011). Comparing models of this cooling emission to the earliest-phase data of SN 2011fe, Bloom et al. (2012) concluded that the explosion came from a star with $R_* \lesssim 0.02R_\odot$, where R_\odot is the solar radius. Combining the radius constraint with the measured ejecta mass Bloom et al. derive the mean density of the progenitor star, confirming that at least some type Ia SNe come from compact and degenerate stars.

Early phase observations of SNe Ia from a white dwarf (WD)+non-degenerate binary may detect excess emission, relative to most type Ia SNe, due to the collision of the SN ejecta with the non-degenerate companion (Wheeler & Iben 1973; Kasen 2010). This excess emission was first detected in iPTF 14atg (Cao et al. 2015), a low-velocity SN Ia with a significant and declining ultraviolet (UV) pulse detected within a few days of the SN explosion. This UV pulse is best interpreted as a SN ejecta-companion collision. While such emission requires a favorable geometric alignment and is only expected in $\lesssim 10\%$ of SNe Ia (Kasen 2010), many studies have searched for signatures of an ejecta-companion interaction, typically resulting in non-detections (e.g., Hayden et al. 2010a; Bianco et al. 2011; Foley et al. 2012; Bloom et al. 2012; Olling et al. 2015; Zheng et al. 2013; Goobar et al. 2015; Shappee et al. 2016b; Im et al. 2015). A possible exception is SN 2012cg, which exhibited excess blue emission in its early-phase light curve Marion et al. (2016) (though see Shappee et al. 2016a for an interpretation that does not invoke ejecta-companion interaction).

The vast majority of SNe Ia are observed to be powered purely by the radioactive decay of ^{56}Ni . While the detection of SN shock cooling or ejecta-companion interaction is rare, the level of ^{56}Ni mixing in the SN ejecta can fundamentally alter the appearance of the SN shortly after explosion. SNe Ia experience a dark period after the SN shock breakout but before radioactive energy diffuses into the photosphere (Piro & Nakar 2014). The duration of this dark period is set by how

the newly synthesized ^{56}Ni is mixed and deposited into different layers of the ejecta. In the case of strong mixing, the dark period is short, or non-existent, as photons from ^{56}Ni decay can reach the photosphere rapidly. This also leads to blue optical colors and a rapid initial rise in the observed light curve. If the mixing is weak and the ^{56}Ni is confined to the innermost layers of the ejecta, the dark period can last for several days as the radioactive energy diffuses to the photosphere. The early evolution of such SNe results in redder colors and a more moderate rise in luminosity (Piro & Morozova 2016). Thus, the early light curves of even non-exotic type Ia SNe convey information about their progenitor systems by constraining the distribution of synthesized ^{56}Ni , which in turn constrains the explosion mechanism.

In this paper, we report observations of an extraordinarily young SN Ia, iPTF 16abc, which was discovered by the intermediate Palomar Transient Factory (iPTF) on 2016 April 3.36¹ at R.A. = 13^h34^m45.49^s, Dec. = +13^d51^m14.3^s (J2000) with a g_{PTF} -band magnitude of 21.31 ± 0.27 (Miller et al. 2016). The transient is spatially coincident with a tidal tail of the galaxy NGC 5221, which lies at a distance of ~ 100 Mpc. iPTF 16abc is not detected to a limit of $g = 22.1$ mag on April 2.42, less than 1 d prior to discovery, and rose by ~ 2 mag in the 24 hr following its initial detection. Our spectroscopic follow-up campaign classified iPTF 16abc as a normal SN Ia (Cenko et al. 2016). Our observations and analysis provide multiple lines of evidence that the ^{56}Ni produced by iPTF 16abc was strongly mixed throughout the ejecta.

2. OBSERVATIONS

During the spring of 2016, the iPTF survey observed the field of iPTF 16abc every night in either the g_{PTF} - or R_{PTF} -band.² Survey observations were conducted with the CFH12K camera (Starr et al. 2000) on the Palomar Observatory 48-inch telescope (P48). Images were processed by the IPAC image subtraction and discovery pipeline which subtracts off the background galaxy light with stacked pre-SN images and performs forced

¹ All times in this paper are in UTC.

² P48 observations of iPTF 16abc is reported in the g_{PTF} and R_{PTF} filters throughout, which are similar to the SDSS g' and r' filters, respectively (see Ofek et al. 2012 for details on PTF calibration). The correction from the g_{PTF} and R_{PTF} filters to SDSS g' and r' requires knowledge of the intrinsic source color (see Eqns. 1 and 2 in Ofek et al. 2012). The spectral diversity of SNe Ia in the days after explosion is poorly constrained, and as a result the color terms for iPTF 16abc at these epochs are unknown. We proceed by assuming g_{PTF} and R_{PTF} calibration is on the AB system, which strictly speaking is incorrect, but this does not fundamentally alter any of our conclusions.

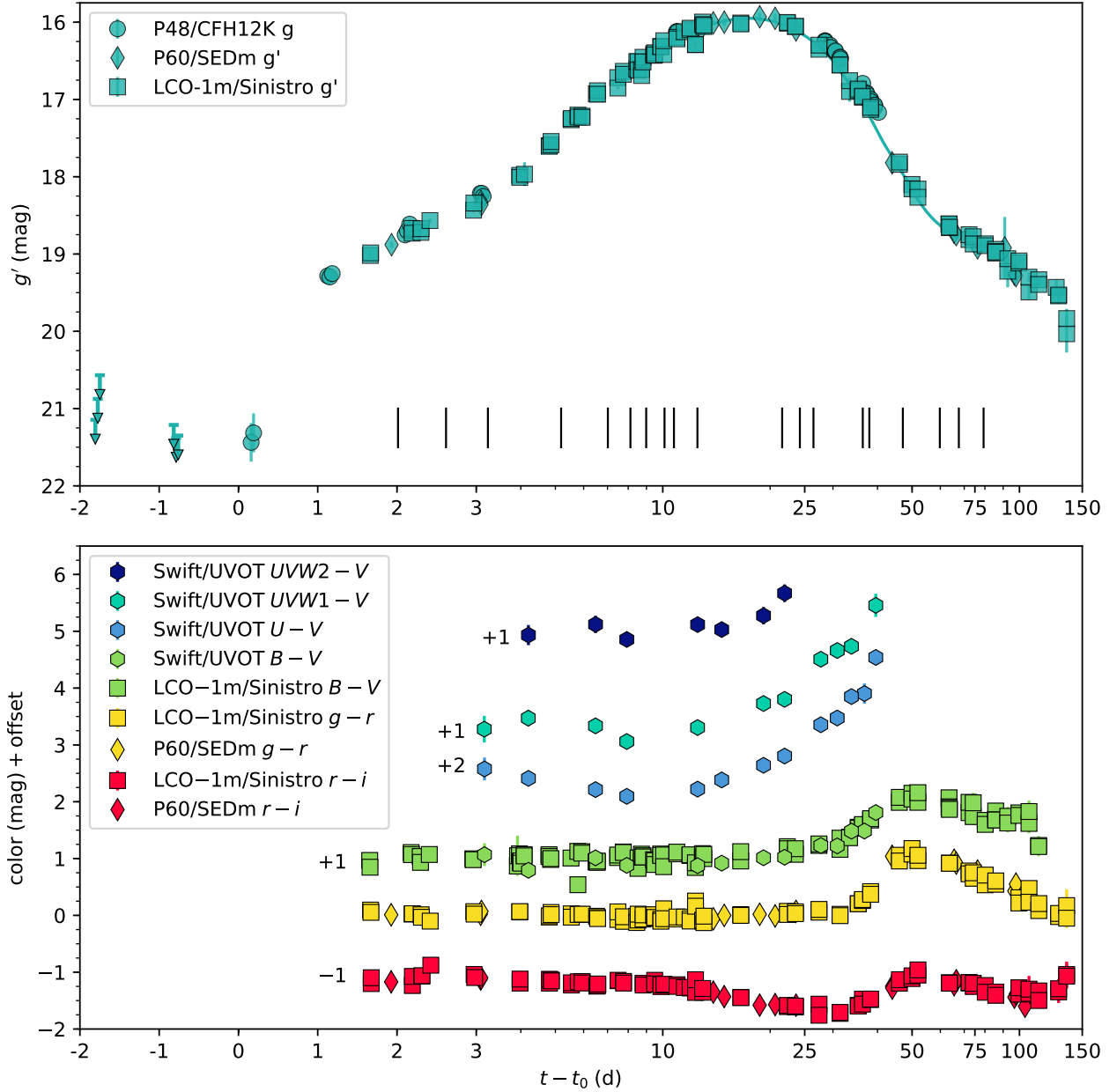


Figure 1. Photometric evolution of iPTF 16abc. *Top:* The g -band light curve of iPTF 16abc. Observations from different telescopes are shown with different symbols. Time is measured in rest-frame d relative to the time of first light, t_0 (see §4.1). Note that the horizontal axis is shown with a linear scale for $-2 \text{ d} \leq t - t_0 \leq 3 \text{ d}$ and a log scale for $t - t_0 > 3 \text{ d}$. The solid curve represents the best-fit model from SALT2 (§3.2). The black ticks near the bottom of the panel show epochs of spectroscopic observations. *Bottom:* Color curves of iPTF 16abc. Each color curve is represented with a different color, with each symbol corresponding to a different instrument, as detailed in the legend. Magnitude offsets applied to each color curve are also shown.

point-spread-function (PSF) photometry at the location of the SN (Masci et al. 2017). The photometry is then calibrated to the PTF photometric catalog (Ofek et al. 2012).

After discovery, photometric observations in the g' , r' and i' filters were obtained with the SED Machine (SEDm; Blagorodnova et al. 2017, in prep.) mounted on the Palomar Observatory 60-inch telescope (P60). We utilized the Fremling Automated Pipeline (Fremling et al. 2016) to subtract galaxy light from the SEDm images using archival Sloan Digital Sky Survey (SDSS) images as a reference. This pipeline then performed forced-PSF photometry at the location of iPTF 16abc, which is calibrated to the SDSS catalog (Ahn et al. 2014).

Photometric observations in the $BVg'r'i'$ filters were conducted by the Las Cumbres Observatory (LCO) 1-m telescope network. PSF photometry was measured on these images using the `lco_gtsnpipeline` pipeline (Valenti et al. 2016). The BV magnitudes are calibrated to the Fourth USNO CCD Astrograph Catalog (Zacharias et al. 2013), and the $g'r'i'$ magnitudes are calibrated to SDSS Data Release 6 (Adelman-McCarthy et al. 2008).

The *Swift* satellite observed iPTF 16abc on 14 epochs, beginning ~ 15 d pre-maximum light through ~ 22 d post maximum. The SN flux is measured via aperture photometry on Ultraviolet-Optical Telescope (UVOT) images via the usual procedures in `HEASoft`, including corrections for the coincident loss and aperture loss. The image counts are converted to physical fluxes using the latest calibration (Breeveld et al. 2011). There are no pre-SN UVOT images at the SN location in the *Swift* archive. Visual inspection of the UVOT images suggests negligible host-galaxy contamination in our UVOT flux measurements. No X-ray emission is detected from iPTF 16abc by the *Swift* X-ray Telescope (XRT).

The g -band discovery data and color curves of iPTF 16abc are illustrated in Figure 1. For convenience, magnitudes in *all* filters are in the AB system with a zero point of 3631 Jy. As previously noted the color terms necessary to convert the g_{PTF} and R_{PTF} to the AB system are unknown and assumed to be zero.

Spectroscopic observations of iPTF 16abc were taken with a variety of telescopes and instruments over multiple epochs spanning from a couple of days after explosion to two months after B -band maximum. An observing log is listed in Table 1. The spectra were reduced using standard routines in `IDL/Python`. The optical spectral evolution of iPTF 16abc is illustrated in Figure 2, which excludes high-resolution Very Large Telescope (VLT) spectra for clarity.

3. REDDENING, CLASSIFICATION AND HOST GALAXY

3.1. Reddening

A detailed study of the reddening towards iPTF 16abc is presented in a companion paper (Ferretti et al. 2017, submitted). Briefly, the foreground Galactic extinction toward iPTF 16abc is $E(B - V) = 0.0279$ mag (Schlafly & Finkbeiner 2011). The high-resolution spectra presented in Ferretti et al. (2017) show multiple absorption components for both the Ca II H+K and Na I D doublets. While the equivalent width (EW) of these lines is quite large, implying a large amount of extinction (e.g., Poznanski et al. 2012), Ferretti et al. compare the evolution of iPTF 16abc to the well-observed normal type Ia SN 2011fe and find evidence for only a small amount of extinction. The empirical relation between the EW of Na I D and extinction is known to have a large scatter, and thus, we instead adopt $E(B - V) = 0.05$ mag as the local extinction for iPTF 16abc (Ferretti et al. 2017). For the remainder of our analysis we therefore adopt a total, Galactic + host galaxy, line-of-sight extinction of $E(B - V) = 0.0779$ mag.

3.2. Classification

Using the Supernova Identification (SNID; Blondin & Tonry 2007) package, we find the low-resolution spectrum of iPTF 16abc at +18.8 d is best matched by normal SNe Ia. Several characteristic features of a SN Ia, such as Si II, S II, can be easily identified in the spectra of iPTF 16abc (Figure 2).

To determine the brightness and time of B -band maximum for iPTF 16abc, we fit the P60 light curves with the `sncosmo` software package.³ This fit includes a SALT2 template (Guy et al. 2007) modified by the line-of-sight extinction curve (Fitzpatrick 1999) with $E(B - V)$ values from §3.1 and $R_V = 3.1$.

We determine the time of rest-frame B -band maximum to be $\text{MJD}_{\text{max}} = 57499.54 \pm 0.23$, the coefficient of the zeroth principle component $x_0 = 0.0086 \pm 0.0003$, the coefficient of the first principle component $x_1 = 0.96 \pm 0.15$, and the color term $c = 0.033 \pm 0.029$. The best-fit model also gives an unreddened apparent peak magnitude of $m_B^* = 15.80 \pm 0.04$ mag in the SN rest frame.

For convenience, in the following sections, we define the best-fit value $\text{MJD}_{\text{max}} = 57499.54$ as the time of B -band maximum, $T_{B_{\text{max}}}$, which we also adopt as phase $t = 0$.

³ The `sncosmo` Python module is available at <https://sncosmo.readthedocs.io/en/v1.5.x/>.

Table 1. Spectroscopic observations of iPTF 16abc

Observation MJD	SN phase	Telescope	Instrument	Wavelength Coverage (Å)
57483.26	−16.4	DCT	DeVeny ¹	3301–7499
57483.88	−15.8	Gemini-North	GMOS ²	3800–9200
57484.51	−15.1	Keck-II	DEIMOS ³	5500–8099
57486.51	−13.1	Keck-II	DEIMOS ³	5500–8099
57488.38	−11.3	Keck-I	LRIS ⁴	3055–10411
57489.51	−10.1	LCOGT-2m	FLOYDS ⁵	3301–8999
57490.40	−9.3	LCOGT-2m	FLOYDS ⁵	3301–9999
57491.55	−8.1	LCOGT-2m	FLOYDS ⁵	3300–9998
57492.20	−7.5	VLT	X-shooter ⁶	3300–24550
57494.00	−5.7	VLT	UVES ⁷	
57503.32	+3.7	LCOGT-2m	FLOYDS ⁵	3300–9999
57506.00	+6.3	NOT	ALFOSC ⁸	3602–8098
57508.27	+8.6	LCOGT-2m	FLOYDS ⁵	3301–9999
57518.42	+18.8	Keck-I	LRIS ⁴	3071–10208
57520.03	+20.4	VLT	X-shooter ⁶	3300–24789
57529.40	+29.8	LCOGT-2m	FLOYDS ⁵	4000–8998
57542.41	+42.8	LCOGT-2m	FLOYDS ⁵	4000–8998
57550.40	+50.8	LCOGT-2m	FLOYDS ⁵	4001–8999
57562.38	+62.7	LCOGT-2m	FLOYDS ⁵	4800–9300

¹The Deveny Spectrograph (Bida et al. 2014)

²The Gemini Multi-Object Spectrograph (Hook et al. 2004)

³DEep Imaging Multi-Object Spectrograph (Faber et al. 2003)

⁴Low-Resolution Imaging Spectrometer (Oke et al. 1995)

⁵FLOYDS <https://lco.global/observatory/instruments/floyds>

⁶X-shooter (Vernet et al. 2011)

⁷Ultraviolet and Visual Echelle Spectrograph (Dekker et al. 2000)

⁸The Andalucia Faint Object Spectrograph and Camera <http://www.not.iac.es/instruments/alfosc>

3.3. Host Galaxy

After establishing iPTF 16abc as a normal SN Ia, we use the latest calibration (Betoule et al. 2014) of the Phillips relation (Phillips 1993) using m_B^* , x_1 and c to derive a distance modulus $\mu = 34.88 \pm 0.10$ mag to the SN, provided that the host galaxy of iPTF 16abc has a stellar mass less than $10^{10} M_\odot$. We note that a more massive host galaxy would result in a larger inferred distance modulus that is nevertheless consistent within the uncertainties.

The location of iPTF 16abc is spatially coincident with a tidal tail of galaxy NGC 5221. Theureau et al. (2007) derived a distance modulus of 35.0 ± 0.4 mag to NGC 5221 from the Tully-Fisher relation, which is consistent with that of iPTF 16abc.

Separately, Courtois & Tully (2015) observe the 21-cm line in NGC 5221 and measure a redshift of 0.0234, which we adopt for the remaining analysis in this paper.

4. FIRST LIGHT AND EXPLOSION TIME

4.1. Light Curve Fit

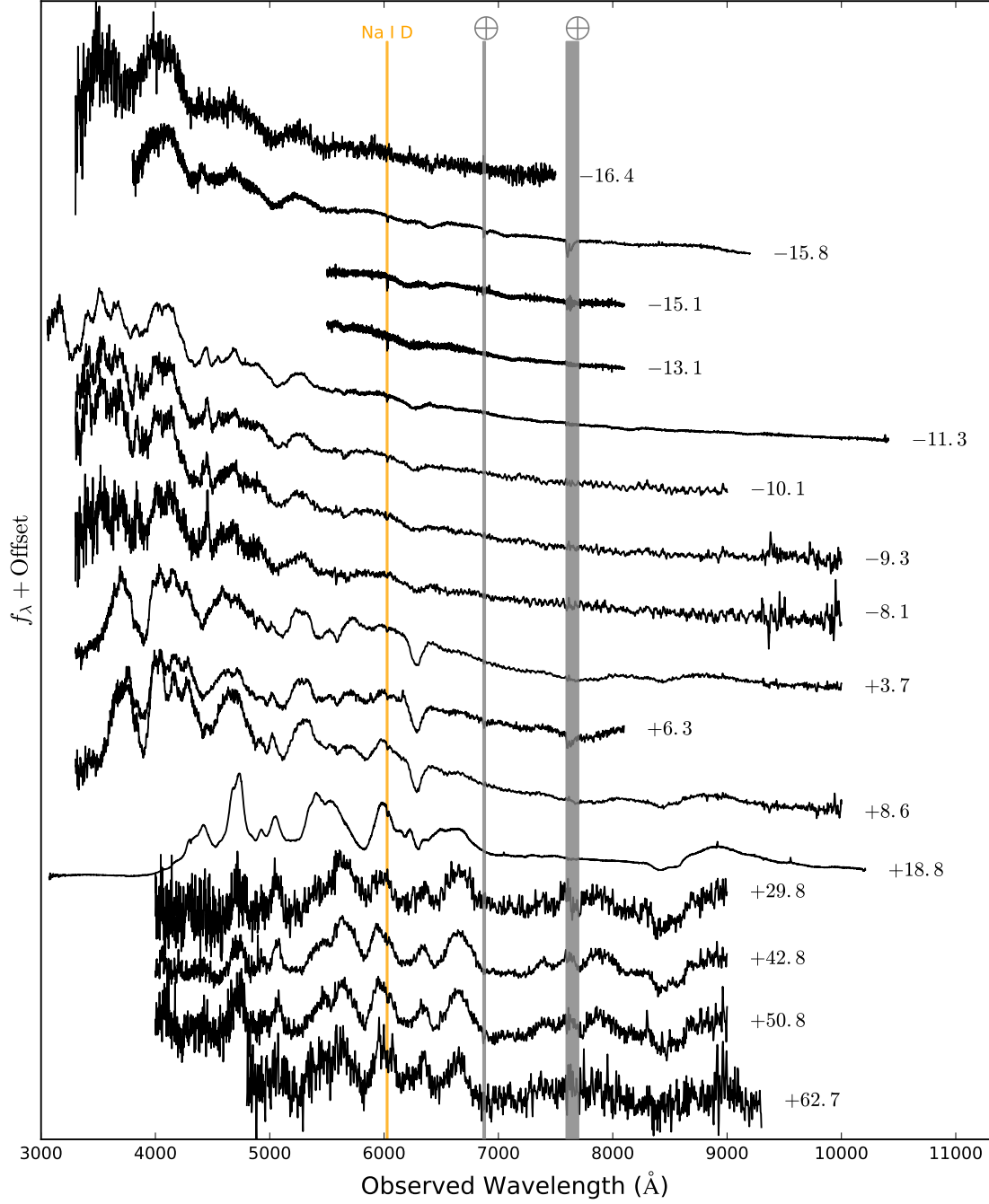


Figure 2. Observed spectral sequence of iPTF 16abc. For clarity, offsets have been applied to each spectrum which are normalized by their median flux between 6,000 and 7,000 \AA . The phase of each spectrum relative to $T_{B,\text{max}}$ is shown. Telluric absorption bands are grayed out. The narrow Na I D absorption is also highlighted in orange.

The time of first light for SNe is usually estimated by extrapolating early-phase light curves to determine when the SN is equal to 0. Assuming an ideal expanding fireball with constant temperature, Arnett (1982) derives that $f \propto t^2$, where f is the SN flux and t is the time since explosion. Despite the basic assumption of a constant temperature at early times, multiple studies have found that the early emission from type Ia SNe can be described as a power law in time, with power-law index consistent with 2, i.e. $f \propto t^2$ (e.g., (Conley et al. 2006; Hayden et al. 2010b; Ganeshalingam et al. 2011)).

As our observations include especially early observations of iPTF 16abc, there are upper limits ~ 1 d prior to the discovery epoch, we model the early flux from iPTF 16abc as a power law, but allow the power-law index to vary, as opposed to fixing it at 2, to account for potential variations in the photospheric temperature during expansion:

$$f(t) \begin{cases} = 0, & \text{when } t < t_0 \\ \propto (t - t_0)^\alpha, & \text{when } t > t_0 \end{cases}, \quad (1)$$

where t_0 is the time of first light, α is the power-law index, and t is measured in the rest-frame of the SN. To determine t_0 and α we fit the earliest observations of iPTF 16abc. Due to slight variations in the passbands, we fit the model to the relative flux measured in the g_{PTF} -band, which is the only filter with observations prior to first light, a necessity for constraining t_0 .

To determine the best fit parameters, we search a large grid over t_0 , α and the proportionality constant, and minimize χ^2 . The modeling results show that the SN flux rises approximately linearly between $t = -18$ d and $t = -14$ d. Figure 3 shows the best-fit result and the joint marginal distribution of t_0 and α . From the best-fit model we obtain $\alpha = 0.98 \pm_{0.14}^{0.16}$ and $t_0 = -17.91 \pm_{0.15}^{0.07}$ d, where the uncertainties represent the marginalized 95% confidence intervals. Our first detection of iPTF 16abc occurred ~ 0.15 d after the SN first light. Figure 3 additionally shows g' -bands observations from P60 and LCO, where we have normalized the flux assuming that the g magnitudes from each instrument have the same zero-point. This assumption is incorrect (see §2), and, as expected, the residuals show a systematic offset between the g_{PTF} -band and the g' -band. Nevertheless, if we ignore this systematic and fit all of the g -band observations simultaneous we obtain marginalized best-fit parameters that are consistent within the uncertainties with the g_{PTF} -only values above. In the analysis that follows, the precise values of the best-fit parameters is not important. The critical finding here is that $\alpha \approx 1$ and $t_0 \approx -18$ d.

As previously noted, the early emission from most SNe Ia can be explained via a $f \propto t^2$ model, including SNe with extremely early observations like iPTF 16abc, such as SN 2011fe (Nugent et al. 2011). Thus, the near-linear rise in flux over the first few days after first light for iPTF 16abc is unusual. To our knowledge this behavior has only been observed in 2 other SNe (2013dy, 2014J; Zheng et al. 2013, 2014). Any model to explain the observations of iPTF 16abc must be able to account for this unusual behavior in the days after first light.

4.2. Expansion Velocity Fit

As previously noted, t_0 does not correspond to the time of explosion, t_{exp} , for type Ia SNe as the SN may experience a dark phase following shock breakout before radioactive energy can diffuse to the photosphere. Piro & Nakar (2014) instead suggest that measurements of the photospheric velocity be used to determine t_{exp} given that the ejecta begin expanding from the moment of explosion. Assuming a constant opacity in the ejecta, Piro & Nakar find that the photospheric velocity evolves as $v_{ph} \propto (t - t_{\text{exp}})^{-0.22}$. While the photospheric velocity is not easy to measure, line velocities of Si II or Ca II can be used as a proxy (Piro & Nakar 2014; Shappee et al. 2016b).

In the case of iPTF 16abc, the Ca II IR triplet is very weak, likely due to high temperatures in the ejecta. Thus, we determine the photospheric velocity from the Si II $\lambda 6355$ line. Visual inspection shows no sign of multi-velocity components of Si II, and that C II $\lambda 6580$ line overlaps the red wing of the Si II line (see Figures 2 and 5). Consequently, we model the observed spectra between 5,900 and 6,500 Å (rest-frame) as the combination of two gaussian kernels plus a linear baseline, which accounts for Si II, C II and the continuum, respectively. The expansion velocity of Si II is measured by the central wavelength of the Si II Gaussian kernel.

We fit the measured velocities of Si II $\lambda 6355$ to the $v \propto (t - t_{\text{exp}})^{-0.22}$ model by minimizing the χ^2 value and find the best-fit explosion time relative to $T_{B,\text{max}}$ in the SN rest frame to be $t_{\text{exp}} = -17.45 \pm_{0.16}^{0.14}$ d, where the uncertainties represent the 95% confidence interval (Figure 4). Following the analysis in Piro & Nakar (2014), we additionally alter the power-law index to -0.20 and -0.24 to examine the sensitivity of the result on the assumed power-law index. We find that this variation in the power-law index result in inferred explosion times that vary by ≈ 1 d (Figure 4). Given the theoretical expectation that $v \propto t^{-0.22}$, we adopt $t_{\text{exp}} = -17.45 \pm 0.5$ d, where the uncertainty reflects possible variations in the power-law index (see Piro & Nakar 2014).

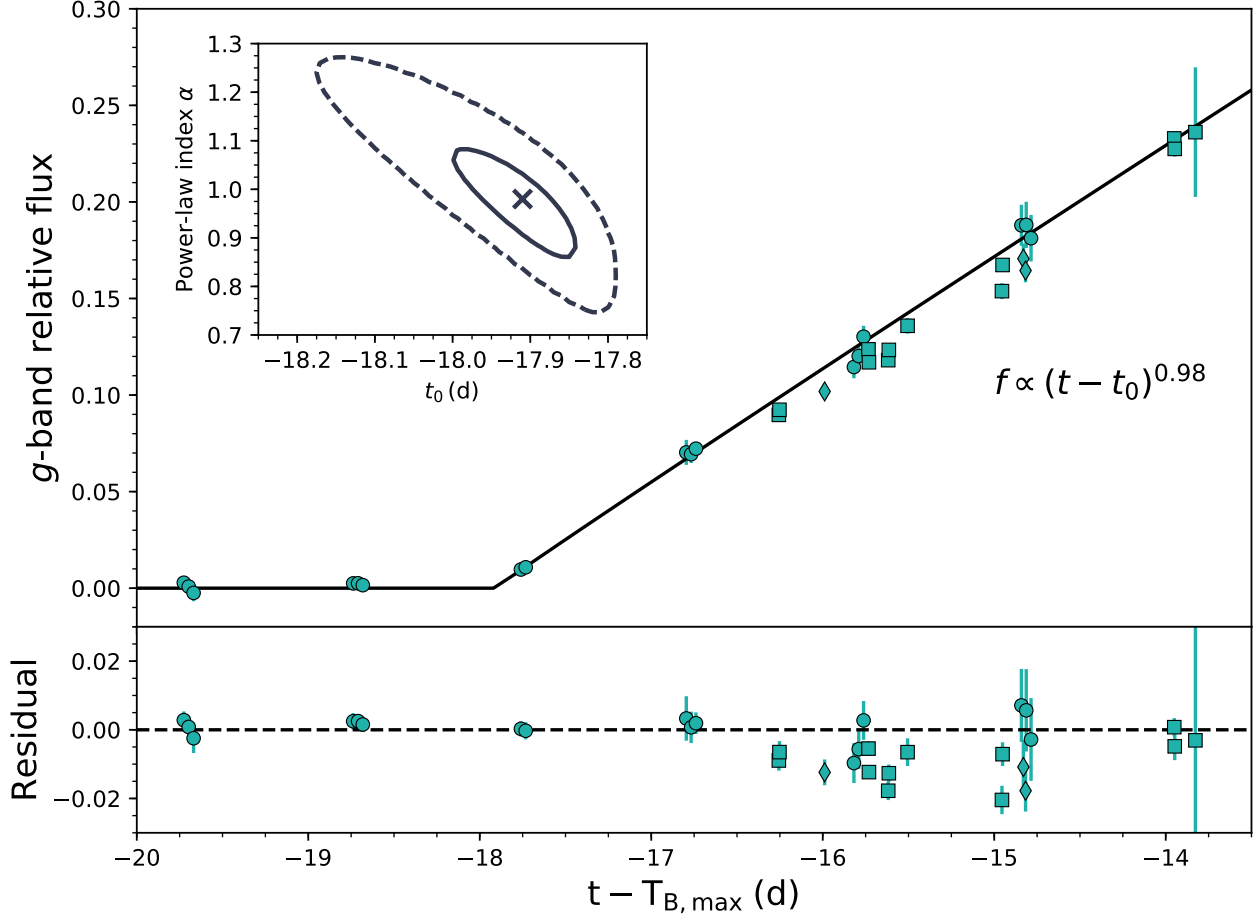


Figure 3. Best-fit power-law model to describe the early flux from iPTF 16abc in the g_{PTF} -band. The model flux, adopting best-fit parameters $\alpha = 0.98$ and $t_0 = -17.94$ d, is shown as a solid black line in the top panel. The lower panel shows the model residuals, and the symbols are the same as in Figure 1. The model is fit to just the g_{PTF} -band observations to avoid systematic difference between the filters (see the text for further details). The joint distribution of t_0 and α is illustrated in the inset of the upper panel. The solid and dashed contours represent the 68% and 99.7% confidence levels.

Comparing our estimates for t_{exp} and t_0 (left panel of Figure 4), we find that $t_0 \lesssim t_{\text{exp}}$. Since physical causality requires $t_{\text{exp}} < t_0$, we draw the qualitative conclusion that $t_0 \simeq t_{\text{exp}}$, which is consistent to within the uncertainties.

4.3. Strong and Short-Lived Carbon Features

The early spectra of iPTF 16abc exhibit unusually strong absorption due to C II $\lambda\lambda 6580, 7234$. We highlight the evolution of these spectral features in Figure 5. From these spectra we see that C II $\lambda 6580$ is as strong as Si II $\lambda 6355$ at $t \approx -16$ d. The strength of the C II lines declines with time to the point where they are no longer detectable more than 1 wk after explosion.

Similar to our analysis of the Si II $\lambda 6355$ line, we can measure velocities and pseudo-equivalent widths (pEWs) of C II $\lambda\lambda 6580, 7234$. We compare the velocity evolution of the C II lines to Si II in the right panel

of Figure 4 and the pEW evolution is shown in Figure 6. These measurements confirm the qualitative analysis from Figure 5: namely, the pEW of C II $\lambda 6580$ is comparable to that of Si II $\lambda 6355$ at $t \approx -16$ d and the pEW of C II decreases until the feature is no longer detectable around $t = -10$ days.

The detection of C II in SNe Ia spectra is relatively rare as it requires both unburned carbon, which is likely only present in the outermost layers of the ejecta, and non-local thermal equilibrium effects in order to excite the ionized carbon (e.g., Thomas et al. 2007). Spectra obtained around or after $T_{B,\text{max}}$ rarely show C II as the photosphere has receded from the outermost ejecta, while pre-max spectra show evidence for C II in $\sim 1/4$ of all normal SNe Ia (e.g., Parrent et al. 2011; Silverman & Filippenko 2012; Thomas et al. 2011), but the signatures are typically weak. While we caution that the sample of normal SNe Ia with spectra taken within a few days

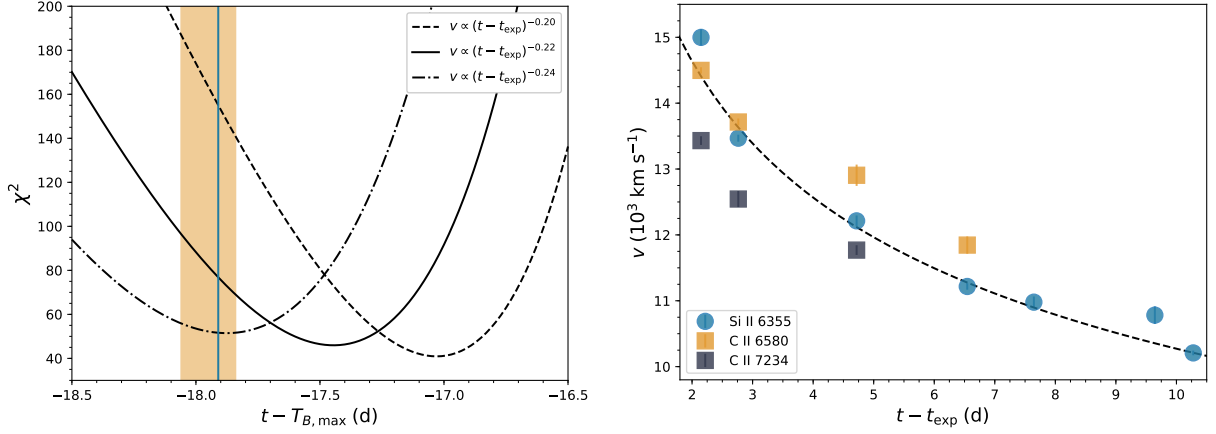


Figure 4. Constraints on t_{\exp} from fitting the velocity evolution of Si II. *Left panel:* the dashed, solid and dash-dotted curves show χ^2 for fitting power laws with indices -0.20 , -0.22 and -0.24 , respectively. The blue vertical line and the orange shaded region indicate t_0 and its 95% confidence interval from Section 4.1, respectively. *Right panel:* Observed Si II $\lambda 6355$ velocities (blue circles) and the best-fit power-law model with an index of -0.22 (dashed line). Additionally the measured velocities of C II $\lambda\lambda 6580, 7234$ are shown.

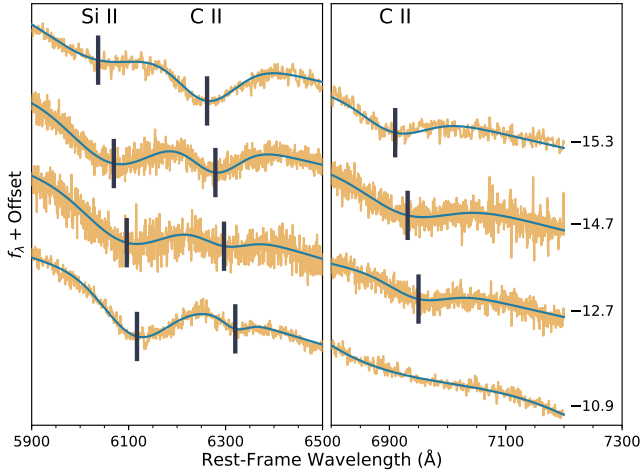


Figure 5. Evolution of the C II features observed in the early spectra of iPTF 16abc. The raw spectra are shown in orange, while the solid blue lines show the best-fit models including gaussian components for each line and a linear component for the continuum (see text for further details). The dark grey vertical lines show the measured line centers, indicating the decline in the photosphere velocity in the \sim wk after explosion (note that C II $\lambda 7234$ is not detected in the -10.9 d spectrum). The phase of each spectrum relative to $T_{B,\max}$ is shown to the right of each spectrum.

of explosion is small, SN 2013dy is the only other object known to have strong C II features like iPTF 16abc (Zheng et al. (2013)). As a counterexample, SN 2011fe only exhibited weak C II features in its first spectra (Parrent et al. 2012). Thus, models of iPTF 16abc must explain the anomalously strong C II absorption observed shortly after explosion.

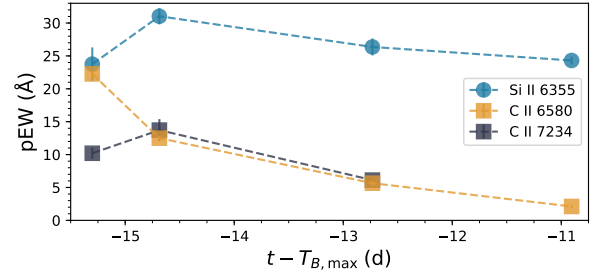


Figure 6. Evolution of the pseudo-equivalent width of Si II $\lambda 6355$, and C II $\lambda\lambda 6580, 7234$ in the week following explosion.

5. DISCUSSION

We have identified several unusual properties in the early observations of iPTF 16abc, including: (i) a near-linear photometric rise in the days after explosion, (ii) the lack of a dark phase typical of most SNe Ia, and (iii) the presence of strong C II absorption. While most SNe Ia are powered purely by radioactive decay, the observed radiation shortly after explosion can also include contributions from SN shock cooling or the collision of the SN ejecta with a non-degenerate companion. Here we consider those scenarios as a possible explanation for the early behavior of iPTF 16abc.

5.1. SN Shock Cooling

The shock breakout of a SN Ia lasts for a fraction of a second due to compact size of the exploding star. Emission from the subsequent cooling phase may last for several days, however (e.g., Piro et al. 2010). Following the analysis of Bloom et al. (2012) for SN 2011fe, we com-

pare the early-phase g_{PTF} light curve of iPTF 16abc with two shock cooling models (Rabinak & Waxman 2011; Piro et al. 2010). From this analysis, we constrain the iPTF 16abc progenitor radius to be $< 1R_{\odot}$. Our observations of iPTF 16abc cannot place tight constraints on the size of SNe Ia progenitors. Indeed, for a typical WD radius, such as that inferred for SN 2011fe ($\lesssim 0.02\text{--}0.04 R_{\odot}$; Bloom et al. 2012; Piro & Nakar 2014), the expected emission from shock cooling is ~ 2 mag fainter than the P48 g_{PTF} detection limit. Thus, we conclude that shock cooling does not contribute to the early emission from iPTF 16abc.

5.2. SN-Companion collision

The detection of excess emission due to the collision of the SN ejecta with a non-degenerate companion requires a favorable orbital alignment relative to the line of sight. Thus, from geometric considerations alone the probability of detecting ejecta-companion interaction is low, $\sim 10\%$. Kasen (2010) calculates that the collision of SN ejecta with a companion generates thermal emission with a spectrum that peaks in the UV. The resulting g -band emission is expected to be weak.

To examine the possibility of a SN-companion signature in the early light curve of iPTF 16abc, we employ the Kasen (2010) model and assume canonical values for the ejecta mass, $1.4 M_{\odot}$, expansion velocity, 10^4 km s^{-1} , and a constant opacity, $0.2 \text{ cm}^2 \text{ g}^{-1}$. We calculate the expected g_{PTF} brightness of an ejecta-companion collision at the distance of iPTF 16abc behind a total reddening of $E(B-V) = 0.0779 \text{ mag}$ using the parameterized equations in Brown et al. (2012). If we assume the binary is aligned with the optimal orientation relative to the line of sight, a binary separation of $a \approx 2 \times 10^{13} \text{ cm}$ is needed to explain the initial detection of iPTF 16abc, as shown in Figure 7. This model does not, however, match the g_{PTF} evolution for $t > t_0 + 1 \text{ d}$ (though it is possible that the SN photosphere dominates the companion-interaction signature at this phase). Furthermore, this model significantly overpredicts the observed flux in the *Swift*/UVW1 filter $\sim 3.1 \text{ d}$ after t_0 . As such, we do not favor such a model as the explanation for the early emission from iPTF 16abc.

Figure 7 additionally shows that a companion at $a = 10^{14} \text{ cm}$ provides a good match to the observations $\sim 1\text{--}3 \text{ d}$ after t_0 if $t_{\text{exp}} \approx t_0 + 0.3 \text{ d}$. Like the $a = 2 \times 10^{13} \text{ cm}$ model, this model significantly overpredicts the observed UV flux from iPTF 16abc. Additionally, this model cannot account for the brightness of iPTF 16abc at the epoch of discovery. The challenges associated with each of the previous two models lead us to conclude that the early evolution of iPTF 16abc cannot be explained via

the interaction of the SN ejecta with a red-giant companion.⁴ We cannot, however, exclude the presence of a red-giant companion as our calculations have assumed that the binary is aligned with the optimal geometry relative to the line of sight. If the geometry is not favorable, then it is possible that signatures from interaction with a companion are not visible.

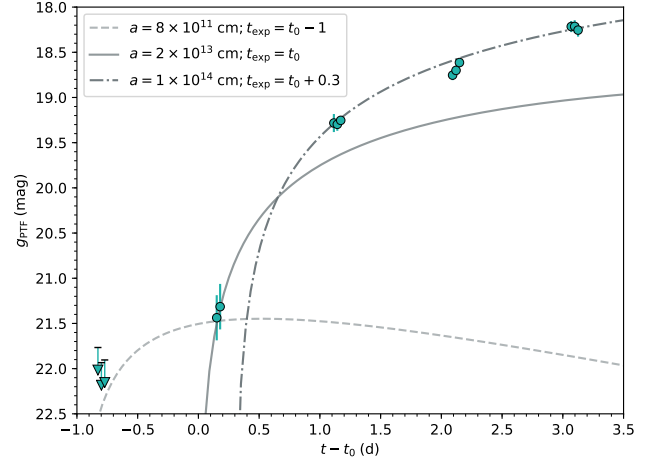


Figure 7. Comparison of SN ejecta-companion interaction models with the early g_{PTF} light curve of iPTF 16abc. Detections are shown as circles, while 3σ upper limits are shown as downward facing arrows. expected g_{PTF} light curve for the smallest orbital separation capable of explaining the initial detection of iPTF 16abc. This model also requires $t_{\text{exp}} \approx t_0 - 1 \text{ d}$. Assuming $t_{\text{exp}} = t_0$, interaction with a companion at $a = 2 \times 10^{13} \text{ cm}$ matches the initial detection of iPTF 16abc (solid line). This model significantly overestimates the UV flux detected from iPTF 16abc $\sim 3 \text{ d}$ after explosion (see text). The g_{PTF} observations $\sim 1\text{--}3 \text{ d}$ after t_0 are well matched to companion-interaction models for $a = 10^{14} \text{ cm}$ if $t_{\text{exp}} \approx t_0 + 0.3 \text{ d}$ (dash-dot line). This model significantly underestimates the flux at the epoch of discovery, while also overestimating the UV flux. Thus, none of these possibilities uniquely explain the early flux from iPTF 16abc. *amiller: Add Swift light curve and photometry to make it clear that two large companions don't explain the observations? Also – make labels for this fig bigger*

Finally, we examine the minimum binary separation capable of explaining the observed brightness at the epoch of discovery. Figure 7 shows that models with $a \approx 8 \times 10^{11} \text{ cm}$ peak at $\sim 21.5 \text{ mag}$ in the g_{PTF} -band, provided that $t_{\text{exp}} \approx t_0 - 1 \text{ d}$. To explain just the epoch of discovery, models with larger a would require even earlier explosion times, which is not compatible with our non-detections the night before discovery, while models

⁴ The Kasen (2010) model assumes Roche-lobe overflow, meaning that $a > 10^{13} \text{ cm}$ implies a companion with $R_* \gtrsim 100 R_{\odot}$.

with smaller a are not bright enough. While it is otherwise compatible with the observations, we do not favor the $a \approx 8 \times 10^{11}$ cm model as the explanation for the early flux from iPTF 16abc because it does not explain the 2 mag rise in the ~ 24 hr after discovery.

Recently, Hosseinzadeh et al. (2017) showed that the early light curve of SN 2017cbv has a clearly resolved bump in the U , B , and g' bands in the ~ 5 d after explosion. Hosseinzadeh et al. find that the bump can be explained via the combination of ejecta-companion interaction and the normal evolution of a type Ia SN. A challenge for this model is that it significantly overpredicts the UV brightness of the SN compared to what is observed. It is argued in Hosseinzadeh et al. (2017) that the shock resulting from the companion collision may not be a blackbody, which could reconcile the model with the observed UV photometry. Qualitatively, iPTF 16abc and SN 2017cbv exhibit similar characteristics: both feature strong C II absorption in their early spectra and a bump in their early light curves. Below, we argue for circumstellar interaction and strong ^{56}Ni mixing as a possible explanation for iPTF 16abc, and indeed Hosseinzadeh et al. (2017) consider these possibilities for SN 2017cbv as well. While there are arguments in favor of and against each of these possibilities, we believe that the early behavior of SN 2017cbv and iPTF 16abc reflect a common physical origin. *amiller: should this paragraph be in the conclusions?*

5.3. Interaction with Diffuse Material

Here we consider a model that has not, as of yet, been discussed in the context of iPTF 16abc. In the context of SN 2011fe, Dessart et al. (2014) recently examined pulsational delayed-detonation (PDD) models as an explanation for some SNe Ia. Briefly, PDD models differ from “standard” delayed detonation (DD) models in that the initial deflagration causes the WD to expand resulting in the release of some unbound material. As the bound material contracts, eventually a subsequent detonation occurs.⁵ An important consequence of this sequence for PDD models is that they naturally produce material that avoids burning, unlike DD models that typically leave no unburnt material. This enables the presence of significantly more carbon in the outer layers of the SN ejecta (Dessart et al. 2014).

While examining observations of SN 2011fe in the context of DD models, Dessart et al. (2014) find that the models are universally too faint and red at early times, ~ 24 –48 hr after explosion. These discrepancies can be

somewhat improved if the newly synthesized ^{56}Ni is artificially mixed throughout the SN ejecta (see §5.4 for further details on the importance of mixing). Instead, Dessart et al. (2014) find that PDD models provide a better match to observations. Briefly, the diffuse material surrounding the WD heats the outer layers of the SN ejecta leading to a steeper more luminous rise, with bluer colors in the few days after explosion. Importantly, the PDD models are nearly indistinguishable from DD models around and post peak.

Qualitatively, the PDD models provide a better match to the observations of iPTF 16abc than DD models. In particular, PDD models provide higher luminosities and faster rise times in the days after explosion, a more rapid evolution towards blue optical colors, and the formation of strong C II lines that gradually disappear in the \sim week after explosion. Quantitatively, there are still some shortcomings of the models presented in Dessart et al. (2014). In particular, the power-law index for the g -band rise is $\alpha \approx 3$ for each of the PDD models, which is significantly more steep than $\alpha = 0.98$, which we measure for iPTF 16abc. The optical colors for iPTF 16abc are blue from our first epoch ~ 1.7 d after explosion and remain approximately constant in the 10 d after explosion, whereas the PDD models in Dessart et al. (2014) either exhibit distinct color evolution (i.e. are not constant) or are too red in the first few days after explosion. Nevertheless, the PDD models presented in Dessart et al. (2014) provide several attractive explanations for the unusual features in the early behavior of iPTF 16abc, and it may be possible that small adjustments to the model, e.g., additional mixing of the radioactive products from the explosion, can better match iPTF 16abc.

5.4. Strong ^{56}Ni Mixing as an Explanation for iPTF 16abc

Having ruled out other possibilities we now consider whether the unusual properties of iPTF 16abc can be explained simply by invoking strong mixing in the SN ejecta. As previously mentioned, strong mixing can lead to a short dark phase and C II absorption. Here we additionally examine if strong mixing can explain the rapid, near-linear rise in the light curve.

In Figure 8 we compare model calculations from Piro & Morozova (2016) to the observed photometry of iPTF 16abc. The Piro & Morozova models employ a piston driven explosion to explode a single WD progenitor model. As the piston explosion does not result in any nucleosynthesis, the distribution of ^{56}Ni in the ejecta must be prescribed by hand, which enables their study of the effects of mixing on the resulting SN emis-

⁵ Dessart et al. (2014) note that the deflagration and detonation in their PDD models are artificially triggered.

sion. Each model employs a fixed $0.5 M_{\odot}$ of ^{56}Ni that has been distributed throughout the ejecta via boxcar averaging (see their Figure 1). The resulting light curves are synthesized using the SuperNova Explosion Code (SNEC; Morozova et al. 2015), as shown in Figure 8. Broadly speaking, the results can be summarized as follows: SN with strong mixing exhibit a rapid almost linear rise and quickly develop blue colors, whereas models where the ^{56}Ni is confined to the innermost layers of the ejecta remain very faint for days after explosion while exhibiting relatively red optical colors during this period. The fast rise and blue color of iPTF 16abc are consistent with the strong mixing models from Piro & Morozova (2016), as shown in Figure 8. We conclude that the early observations of iPTF 16abc can be explained if the ^{56}Ni synthesized in the explosion is mixed into the outermost layers of the SN ejecta.

6. CONCLUSION

We have presented observations of the extraordinarily early discovery of the normal Type Ia supernova iPTF 16abc. Our fast-response follow-up campaign allowed us to draw the following conclusions:

- Extrapolation of the early light curve shows that the initial detection of iPTF 16abc occurred only ~ 0.2 d after the time of first light.
- The early emission from iPTF 16abc is powered solely by radioactive ^{56}Ni decay. We find no evidence for detectable signatures of SN shock cooling or the collision of the SN ejecta with a non-degenerate binary companion.
- The velocity evolution of the SN ejecta shows that the time of explosion is approximately equal to the time of first light. This constitutes the first major piece of evidence that ^{56}Ni is strongly mixed into the outer layers of the supernova ejecta.
- The strong and short-lived carbon features seen in the earliest spectra of iPTF 16abc can only be explained if there is incomplete burning during the explosion and there is a non-thermal radiation source in the outermost layers of the ejecta to excite the ionized carbon. ^{56}Ni decay is the likely source of the non-thermal emission, providing another piece of evidence for strong mixing in the ejecta of iPTF 16abc.

Does anyone know of any theoretical studies that specifically predict incomplete burning and strong Ni mixing?

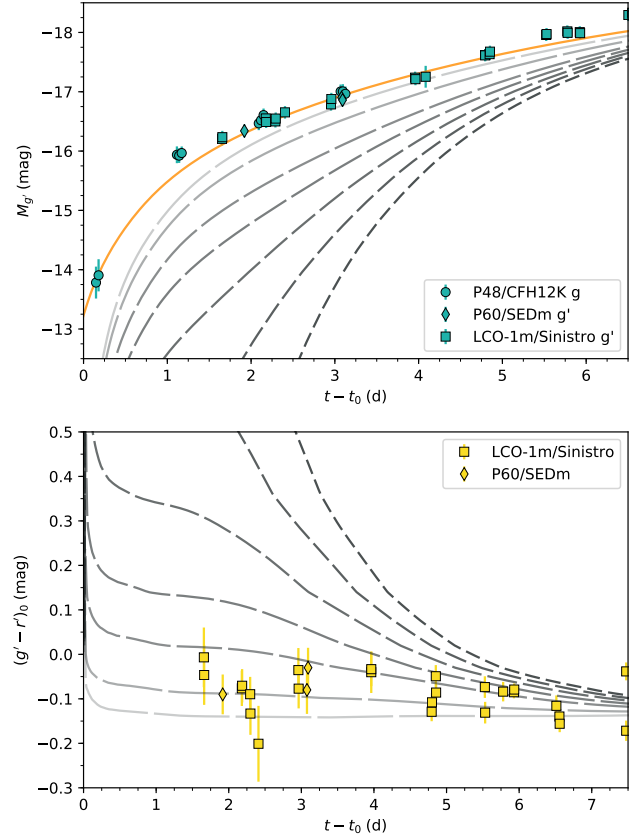


Figure 8. Photometric comparison of iPTF 16abc and the theoretical models of Piro & Morozova (2016). The amount of ^{56}Ni mixing in the SN ejecta increases from the short-dash, dark lines to the long-dash, light lines. *Top:* M_g vs. time, where the observed g -band magnitudes have been corrected to M_g using the distance modulus to iPTF 16abc (§3.3) and the total line-of-site reddening ($E(B - V) = 0.078$ mag; Ferretti et al. 2017, submitted). *Bottom:* $(g' - r')_0$ vs. time. The observed colors have been corrected for reddening.

- Finally, we show that the early light curve evolution and colors of iPTF 16abc are well matched by the theoretical models of Piro & Morozova (2016) that include significant mixing of ^{56}Ni into the outer layers of the SN ejecta.

Taken together, these observations all indicate that the nucleosynthetic products from the explosion are well mixed throughout the SN ejecta. There are elements of the PDD models from Dessart et al. (2014) that are attractive for explaining iPTF 16abc, in particular, the strong C II absorption seen at early times. In the future, it would be useful to investigate PDD models that incorporate strong ^{56}Ni mixing to see if they better replicate the observations of iPTF 16abc.

Extremely early observations of young SNe provide a “smoking gun” to probe the mixing level in the ejecta,

which, in turn, is a result of the explosion mechanism. Wide-field, high-cadence surveys, such as the Zwicky Transient Facility (Bellm 2016) and ATLAS (Tonry 2011, 2013), will discover a large number of very young supernovae over the next few years. These surveys will generate large observational samples that probe SNe in the hours after explosion. While the sample of extremely young SNe Ia will grow by more than an order of magnitude, the detection of shock breakout cooling and ejecta-companion interaction will prove challenging. Given the diminutive size of WDs, the thermal emission following shock breakout can only be detected to ~ 10 Mpc on 1-m class telescopes. Furthermore, only $\sim 10\%$ of single-degenerate progenitors are expected to give rise to detectable emission following the collision of the SN ejecta with the binary companion (Kasen 2010). Despite these limitations, this study of iPTF 16abc shows that the early detection of SNe Ia can constrain the explosion physics by probing the amount of mixing in the SN ejecta. Moving forward, a large sample of such objects will enable strict constraints on the proposed explosion mechanisms for type Ia SNe.

Finally, we close by emphasizing the importance of fast-response photometric and spectroscopic follow-up campaigns. Without the early recognition of the youth of this SN and the associated follow-up, much of the analysis presented herein would not have been possible. The ability to trigger such observations is essential to improve our understanding of the physics of SNe Ia.

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