﻿\documentclass[twocolumn]{aastex63}

\usepackage{amsmath}

\usepackage{empheq}

\usepackage{mathrsfs}

\usepackage{textcomp}

\usepackage{enumitem}

\usepackage{gensymb}

\usepackage{hyperref}

\usepackage{graphicx}

\usepackage[caption=false]{subfig}

\usepackage{multirow}

\usepackage{longtable}

\usepackage{booktabs} % To thicken table lines

\usepackage{CJK}

\bibliographystyle{aasjournal}

\hypersetup{colorlinks, linkcolor={blue}, citecolor={blue}, urlcolor={blue}}

%\usepackage{lineno}

% \linenumbers

\newcommand{\vdag}{(v)^\dagger}

\newcommand\aastex{AAS\TeX}

\newcommand\latex{La\TeX}

\newcommand{\name}{SN2019dge}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%

%% The following section defines new commands for comments from co-authors

%%

\definecolor{DarkOrange}{RGB}{204, 85, 0}

\definecolor{LincolnGreen}{RGB}{17, 102, 0}

\def\ion#1#2{#1$\;${\footnotesize\rm{#2}}\relax}

\newcommand{\yy}[1]{{\color{red} yy: {#1}}}

\newcommand{\kde}[1]{{\color{DarkOrange} kde: {#1}}}

\newcommand{\todo}[1]{{\color{magenta} to-do: {#1}}}

\newcommand{\rztf}{$r\_\mathrm{ZTF}$}

\newcommand{\gztf}{$g\_\mathrm{ZTF}$}

\newcommand{\tfl}{$t\_\mathrm{fl}$}

\newcommand{\trise}{$t\_\mathrm{rise}$}

\newcommand{\tbmax}{$t\_{B,\mathrm{max}}$}

\newcommand{\package}[1]{\textsc{#1}}

%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Reintroduced the \received and \accepted commands from AASTeX v5.2

%\received{\today}

% \revised{January 10, 2019}

% \accepted{\today}

%% Command to document which AAS Journal the manuscript was submitted to.

%% Adds "Submitted to " the argument.

%\submitjournal{ApJ}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%

%% The following section outlines numerous optional output that

%% can be displayed in the front matter or as running meta-data.

%%

%% If you wish, you may supply running head information, although

%% this information may be modified by the editorial offices.

\shorttitle{\name,: an Ultra-Stripped Envelope SN}

\shortauthors{Yao et al.}

%%

%% You can add a light gray and diagonal water-mark to the first page

%% with this command:

\watermark{DRAFT}

%% where "text", e.g. DRAFT, is the text to appear. If the text is

%% long you can control the water-mark size with:

%% \setwatermarkfontsize{dimension}

%% where dimension is any recognized LaTeX dimension, e.g. pt, in, etc.

%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% This is the end of the preamble. Indicate the beginning of the

%% manuscript itself with \begin{document}.

\begin{document}

\pagenumbering{arabic}

\begin{CJK\*}{UTF8}{gbsn}

\title{\name: a Fast-rising Helium-rich Ultra-Stripped Envelope Supernova}

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\begin{abstract}

We present observations of \name\ (ZTF18abfcmjw), a helium-rich supernova with a fast-evolving light curve indicating an extremely low ejecta mass ($\approx 0.25\,M\_\odot$) and low kinetic energy ($\approx 5\times 10^{49}\,{\rm erg}$). Early photometry and spectroscopy reveal evidence of shock cooling from an extended helium-rich envelope of $\sim0.1\,M\_\odot$ located at $\sim 3\times 10^{12}\,{\rm cm}$ from the progenitor. Early-time \ion{He}{II} emission line suggests that the envelope might has a lower-density optically thin extension to $5\times 10^{13}\,{\rm cm}$. Subsequent spectra show signatures of interaction with helium-rich circumstellar material, which extends to $\sim 2\times

10^{16}\,{\rm cm}$. We interpret \name\ as the first helium-rich supernova from an ultra-stripped progenitor, which originates from a close binary system consisting of a mass-lossing helium star and a compact object (i.e., a white dwarf, a neutron star, or a black hole). The remnants of \name-like ultra-stripped SNe are probably compact neutron star binaries, some of which can merge within the age of the Universe. We infer that the ratio of the rate of \name-like ultra-stripped SNe to

core-collapse SNe is 1.7--24.3\%, corresponding to a local rate-density of $R\_{\rm dge}$ in the range of 1170--17030$\,{\rm Gpc^{-3}\, yr^{-1}}$. Ultra-stripped SNe and dynamical capture in globular clusters are two channels to form double neutron star systems. We should be able to address which one is the dominant channel by comparing ultra-stripped SNe rate estimated by future high-cadence optical surveys with the coalescence rate of local double neutron stars constrained by future LIGO/VIRGO gravitational wave experiments.

\end{abstract}

%% Keywords should appear after the \end{abstract} command.

%% See the online documentation for the full list of available subject

%% keywords and the rules for their use.

\keywords{supernovae: general -- supernovae: individual (SN2019dge/iPTF14gqr) -- stars: neutron}

%% From the front matter, we move on to the body of the paper.

%% Sections are demarcated by \section and \subsection, respectively.

%% Observe the use of the LaTeX \label

%% command after the \subsection to give a symbolic KEY to the

%% subsection for cross-referencing in a \ref command.

%% You can use LaTeX's \ref and \label commands to keep track of

%% cross-references to sections, equations, tables, and figures.

%% That way, if you change the order of any elements, LaTeX will

%% automatically renumber them.

%%

%% We recommend that authors also use the natbib \citep

%% and \citet commands to identify citations. The citations are

%% tied to the reference list via symbolic KEYs. The KEY corresponds

%% to the KEY in the \bibitem in the reference list below.

\vspace{1em}

\section{Introduction}

Type Ibc supernovae (SNe Ibc) are believed to be explosions of massive stars that have lost their hydrogen envelopes \citep{Filippenko1997, GalYam2017}. Their typical rise time ($t\_{\rm rise}$ in the range of 10--25\,d) and peak luminosity ($M\_{R\rm , peak}$ between $-17$ and $-19$\,mag) suggest ejecta mass ($M\_{\rm ej}$) of 1--5\,$M\_\odot$ and $^{56}$Ni mass ($M\_{\rm Ni}$) of 0.1--0.4\,$M\_\odot$ \citep{Drout2011, Taddia2018, Prentice2019}. The relatively low $M\_{\rm ej}$ and high rates of SNe Ibc are not compatible with prediction from the evolution of single massive stars, whose mass-loss rates are not high enough to strip most of the outer layers \citep{Smith2011, Lyman2016}. In contrast, Wolf-Rayet (WR) or helium star descendants of massive stars in close binary systems are thought to be the dominant progenitor for the Ibc population \citep{Dessart2012,

Eldridge2013}. The pre-SN star sheds its envelope by mass transfer to the companion, leaving a final

envelope mass of 1$M\_\odot$ or more

prior to explosion \citep{Yoon2010}.

SNe Ibc with the lowest $M\_{\rm ej}$ arise from core-collapse of a stellar core that stripped its

envelope to a greater extent. This can occur in tight binaries where a helium star transfers

mass to a companion that is small in size. Such a scenario was invoked by \citet{Nomoto1994} as one

way to explain the fast evolution of the Type Ic SN1994I with a carbon-oxygen progenitor star of $\sim

2\,M\_\odot$ and $M\_{\rm ej }\sim 0.9\, M\_\odot$. Should the degree of stripping be more extreme, we

may expect the so-called \textit{ultra-stripped} envelope SNe where $M\_{\rm ej}$ and $M\_{\rm Ni} $ are

on the order of $0.1 \, M\_\odot$ and $0.01 \, M\_\odot$, respectively \citep{Tauris2013,Tauris2015,

Suwa2015}. These weak explosions are the one of the two channels to form double neutron

star (DNS) binaries that are compact enough to merge within a Hubble

time due to gravitational wave (GW) radiation \citep{Tauris2017}. The other channel to

form compact DNSs is dynamical capture in a dense stellar environment

such as a globular cluster \citep{East2012, Andrews2019}. Ultra-stripped SNe are therefore

a promising progenitor channel of multi-messenger sources that can be jointly studied

by the LIGO/VIRGO network and electromagnetic efforts \citep{GW170817, MMA, Goldstein2017,

Coulter17, Hallinan17, Kasliwal2017}.

Compared with canonical SNe Ibc, we expect light curves of ultra-stripped SNe to be rapidly-evolving and subluminous due to the small amount of $M\_{\rm ej}$ and $M\_{\rm Ni}$ produced. Among the group of faint and fast objects, SN2005ek \citep{Drout2013}, SN2010X \citep{Kasliwal2010}, as well as

some of the calcium-rich gap transients such as iPTF10iuv \citep{Kasliwal2012} and iPTF16hgs

\citep{DeKC2018} have been suggested to be good candidates for ultra-stripped SNe

\citep{Moriya2017}. However, properties of these objects are also consistent with alternative

interpretations, including core-collapse of stars with extended hydrogen-free envelopes

\citep{Kleiser2014, KleiserFuller2018, KleiserKasen2018}, and explosive detonation of a helium shell on

the surface of white dwarfs \citep{Shen2010, Sim2012, Polin2019, De2020b}.

%and mergers of white dwarfs with neutron stars \citep{Margalit2016}.

The most convincing ultra-stripped event to date is the Type Ic SN iPTF14gqr \citep{De2018}. Its

radioactivity-powered emission reveals $M\_{\rm ej}\sim 0.2\, M\_\odot$ and $M\_{\rm Ni}\sim

0.05\,M\_\odot$, whereas the detection of early-time shock cooling signatures shows that the

progenitor is an extended massive star instead of a white dwarf, and therefore pins down its

core-collapse origin. Discovered within one day of explosion, iPTF14gqr also demonstrates the

importance of early-time observations in securely identifying ultra-stripped SNe.

Here we report discovery observations and modelling of the rapidly rising ($t\_{\rm rise}\lesssim 3$\,d)

subluminous ($M\_{r\rm ,\, peak} \sim -16.3$\,mag) helium-rich event SN2019dge (ZTF18abfcmjw)

discovered by the Zwicky Transient Facility (ZTF; \citealt{Bellm2019b}; \citealt{Graham2019}). \name\

provides the second consistent observation of an ultra-stripped SN, and the first helium-rich event in

this class. Section \ref{sec:obs} describes the discovery and follow up observations. Section

\ref{sec:properties} outlines the basic properties of the explosion and its host galaxy. Section

\ref{sec:modelling} shows modelling of the light curve and early-time spectra of this transient. Section

\ref{sec:interpretation} provides a discussion on the progenitor system, and Section \ref{sec:rates}

presents the estimated volumetric rates of \name-like ultra-stripped SNe. Section \ref{sec:conclusion}

gives a conclusion of this paper. Calculations in this paper assume a $\Lambda$CDM

cosmology with $H\_0= 70 \, \rm km \, s^{-1}\,

Mpc^{-1}$, $\Omega\_m = 0.27$ and $\Omega\_{\Lambda} = 0.73$ \citep{Komatsu2011}. UT times are

used throughout the paper.

%Alongside this paper, we have released our open-source analysis and all of

% the data utilized in this study at \url{https://github.com/yaoyuhan/\name,}.

All spectra and photometry are made available by the WISeREP repository \citep{Yaron2012}.

\section{Observations} \label{sec:obs}

\subsection{Discovery}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/detection.pdf}

\caption{ZTF $g$ band images centered on \name\ on Apr 10. From left to right are the new

image, the reference image, and the subtraction image. \ \label{fig:detection}}

\end{figure}

% In this section, I report values on Marshal

\name\ was discovered by ZTF, which runs on the Palomar Oschin Schmidt 48 inch (P48)

telescope. The first real-time alert \citep{Patterson2019} was generated on 2019 April 7 10:18:46 (JD

$=2458580.9297$) for a $g$-band detection at $20.66\pm0.34$ mag and J2000 coordinates $\alpha

= 17^{\mathrm{h}}36^{\mathrm{m}}46.75^{\mathrm{s}}$, $\delta =

+50^{\mathrm{d}}32^{\mathrm{m}}52.2^{\mathrm{s}}$.

%$\alpha = 17^{\mathrm{h}}36^{\mathrm{m}}46.76^{\mathrm{s}}$, $\delta =

%+50^{\mathrm{d}}32^{\mathrm{m}}52.5^{\mathrm{s}}$ (J2000)

On April 8, a new alert was flagged by a science program filter on the

GROWTH Marshal \citep{Kasliwal2019} that is designed to look for fast evolving transients.

Figure~\ref{fig:detection} shows the ZTF detection image on April 10. \name\ resides in a compact

galaxy SDSS J173646.73+503252.3. Our follow up spectra suggest a host redshift of

$z=0.0213$, corresponding to a luminosity distance of $D\_L = 93$\,Mpc.

\subsection{Follow up}

\subsubsection{HST Observation}

\begin{figure}

\centering

\includegraphics[width=0.6\columnwidth]{figures/offset.pdf}

\caption{\textit{HST} image of the field on Apr 22 in the F350LP filter. The position of \name\ is

marked by the red crosshairs.

%Images are combined using the prescription in \citet{Lupton2004}.

\label{fig:offset}}

\end{figure}

\textit{HST} observations were obtained as part of our \textit{Hubble Space Telescope} ($HST$)

``Rolling Snapshots'' pilot experiment (GO-15675, \citealt{Fruchter2018}). This new observational

approach requires the PI to update a list of objects of interest each week before the schedule is built,

giving the

scheduler flexibility to choose a possible source of snapshots. Under this program, we obtained a NUV

spectrum using the WFC3 G280 grism, a short (60\,s) direct image of this field in the F300X filter to

set the wavelength scale of the spectrum, as well as a longer exposure (200\,s) in the F350LP filter.

The image in the F350LP filter is shown in Figure~\ref{fig:offset}. It has very similar throughput to the

zeroth order of the G280 grism. We convolved this image to match the slight blurring of the zeroth

order G280 grism and then scaled and subtracted it, dramatically reducing host contamination from

the zeroth order host image.

As can be seen in Figure~\ref{fig:offset}, there is a surface brightness peak in the southwest of

\name\ ($\sim0.2$\,kpc away), which might be the galaxy center. Since the explosion site is offset

from the nucleus of the host, \name\ is not associated with a nuclear activity of any kind (AGN,

TDE, etc).

\begin{figure\*}[htbp!]

\centering

\includegraphics[width=\textwidth]{figures/lightcurve.pdf}

\caption{Galactic extinction corrected optical light curve of \name. The inset shows

the light curve in $g$ and $r$ bands zoomed around the region of maximum light. Epochs of

spectroscopy are marked with the letter `S' along the upper axis.\label{fig:lightcurve}}

\end{figure\*}

\subsubsection{Optical Photometry}

We perform forced PSF photometry on ZTF difference images following the steps illustrated in

\citet{Yao2019}. The sky region of \name\ is covered by two ZTF fields with fieldid (i.e., ZTF field

identifier) 763 and 1799. We exclude all data in field 1799 since the reference image was constructed

using images

obtained between May 25 2018 and July 12 2019 (see \citealt{Masci2019} for details of reference image

generation), which is after the explosion of the transient. Although the ZTF name of this object

(ZTF18abfcmjw) may indicate that the transient was discovered in 2018, this is due to an alert

generated on July 7 2018 from a candidate detection in negative subtraction (reference minus science)

in field 763. We note that the seeing at that night was 4.2 arcsec, larger than 99\% of Palomar nights.

The irregularly-shaped PSF might cause over-subtraction around the galaxy nucleus in the difference

imaging process.

Since field 763 was included in both the northern sky survey with two epochs (one

$g\, +$ one $r$) per three nights and the extragalactic high-cadence survey with six epochs (three

$g\,+$ three $r$) per night (see \citealt{Bellm2019a} for the ZTF experiments design), \name\ was

visited multiple times every night. Therefore, single-night flux measurements in the same

filter are binned (by taking the inverse variance-weighted average). This gives a pre-explosion

$r$-band limit of 18.95 mag (5$\sigma$ limit computed at the expected position of the transient) on

April 4 10:36:34. Five-$\sigma$ detections are converted to magnitude for further analysis.

Following the discovery of \name, we obtained follow-up photometry in $griz$ with the optical

imager (IO:O) on the Liverpool Telescope (LT; \citealt{Steele2004}). Digital image subtraction and

photometry for LT imaging was performed using the Fremling Automated Pipeline ({FPipe};

\citealt{Fremling2016}). \texttt{Fpipe} performs calibration and host subtraction against Sloan Digital

Sky Survey reference images and catalogs (SDSS, \citealt{Alam2015}).

LT and P48 photometry are shown in Figure~\ref{fig:lightcurve}. Absolute magnitude is determined by

correcting for the distance modulus

and Galactic extinction $E(B-V)=0.022$ estimated by \citet{Schlafly2011}, which builds upon

\citet{Schlegel1998}. We assume $R\_V=3.1$, and adopt reddening law from \citet{Cardelli1989}. We do

not correct for host-galaxy contamination given the absence of \ion{Na}{I} D absorption in all spectra

at the host redshift.

We obtained one epoch of late-time imaging with the Wafer Scale Imager for Prime (WASP) mounted

on the Palomar 200-inch telescope at $\approx 85$\,days from $r$-band peak. The data were obtained

in $r$-band with a total exposure time of 900\,s divided into dithered exposures of 300\,s each. The

data were reduced using standard techniques as described in \citet{De2020a}. Image subtraction was

performed using archival reference images from the Dark Energy Legacy Survey \citep{Dey2019}, using

the method described in \citet{De2020b}. The median 5$\sigma$ limiting magnitude of the image is $r

\approx 25$\,mag. However, the depth at the transient location is limited by the noise from the bright

host galaxy, and the transient was not detected to a 5$\sigma$ limiting magnitude of $r = 22.1$\,mag.

We also performed forced photometry on archival PTF/iPTF difference images spanning May 07 2009 to

June 13 2016 \citep{Law2009, Rau2009}.

%\footnote{We followed the procedure described in

% \url{http://web.ipac.caltech.edu/staff/fmasci/home/miscscience/forcedphot.pdf}}

No historical detection was found.

\input{tables/tab\_spec.tex}

\subsubsection{Swift Photometry}\label{subsubsec:swift}

Space-based observations with the \textit{Neil Gehrels Swift Observatory} (\textit{Swift};

\citealt{Gehrels2004}) was triggered on April 9 and April 10. Ultraviolet/Optical Telescope (UVOT;

\citealt{Roming2005}) data were obtained in the $UVW1$, $UVM2$, $UVW2$, $U$, $B$, and $V$

filters.

UVOT data are reduced using \texttt{HEAsoft} \citep{Heasarc} version 6.17 with a $3^{\prime\prime}$

circular aperture. To remove host-galaxy contribution at the location of the SN, we obtained a final

epoch in all broad-band filters

on June 23 2019 and measured the photometry with the same aperture used for the transient. We

present a table of our optical and UV photometry in \ref{sec:appphot\_data}.

% /Users/yuhanyao/Documents/GitHub/AT2019dge/meet/SwiftBC.pdf

In parallel with the UVOT observations, \textit{Swift} observed \name\ with its onboard X-ray telescope

(XRT; \citealt{Burrows2005}) between 0.3 and 10\,keV in the photon counting mode. We note that no

point sources were detected in the XRT event files with $\rm{SNR}>3$.

The 3$\sigma$ limits in count\,s$^{-1}$ in the April 9, April 10, and June 23 observations are $7.8\times

10^{-3}$, $5.8\times 10^{-3}$, and $6.1\times 10^{-3}$, respectively.

\subsubsection{Radio Follow-up}

Shortly after the discovery of \name, we initiated radio follow-up in order to constrain the

presence of a radio counterpart, as potentially expected in some rapid-rising transients with

circumstellar interaction \citep{Weiler2007, Horesh2013, HoPhinney2019}. We observed at high

frequency radio bands using the

Submillimeter Array (SMA, \citealt{Ho2004}) on UT 2019 Apr 09 between 15:49:17 and 19:51:26 UTC

under its target-of-opportunity program. The

project ID is 2018B-S047 (PI: Anna Ho). We did not detect \name\ in the resulting image, and the

3$\sigma$ upper limits are 2.25\,mJy at 230\,GHz and 8.4\,mJy at

345\,GHz.

%The actual rms are 0.75 mJy for the 230 GHz image and 2.8 mJy for the 345 GHz image.

\subsubsection{Spectroscopy}

We obtained eight optical spectroscopic follow-up of \name\ from $-1.1$\,d to $+314.4$\,d relative

to $g$-band peak using the Rapid Acquisition of Transients (SPRAT; \citealt{Piascik2014}) on the

Liverpool Telescope (LT), the Double Spectrograph (DBSP) on the 200-inch Hale telescope

\citep{Oke1982}, and the Low Resolution Imaging Spectrograph (LRIS) on the Keck-I telescope

\citep{Oke1995}. To extract the LT spectra, we use the automated SPRAT reduction pipeline, which is a

modification of the pipeline for FrodoSpec \citep{Barnsley2012}. The DBSP spectrum was reduced using

a \texttt{PyRAF}-based reduction pipeline \citep{Bellm2016}. LRIS

spectra were reduced and extracted using \texttt{Lpipe} \citep{Perley2019lpipe}.

A log of our spectroscopic observations is given in Table \ref{tab:spec}. We

present our sequence of spectra in Figure~\ref{fig:spectra\_early}, Figure~\ref{fig:spectra} and

Figure~\ref{fig:spectra\_late}.

\section{Properties of the Explosion and Its Host Galaxy} \label{sec:properties}

\subsection{Light Curve Properties}\label{subsec:lc\_properties}

\subsubsection{Peak Luminosity, Rise and Decline Timescale}\label{subsubsec:compare\_mag}

To estimate the epoch of maximum light, we interpolated the $g$- and $r$-band photometry with

three-order polynomial functions, as is shown in the inset of Figure~\ref{fig:lightcurve}. The time

window used in the fit is from ${\rm MJD}=58581.2$ to $58585.2$. \name\ was found to peak

at $M\_{g\rm , peak}=-16.45\pm0.03$\,mag on ${\rm MJD}=58583.19$, and $M\_{r \rm ,peak }

=-16.27\pm0.02$\,mag on ${\rm MJD}=58583.39$. Hereafter we use phase ($\Delta t$) to denote time

with respect to the $g$-band maximum light epoch, ${\rm MJD}=58583.2$.

\begin{figure}[htbp!]

\centering

\includegraphics[width=0.9\columnwidth]{figures/compare\_mag.pdf}

\caption{Comparison of the photometric evolution timescales ($t\_{\rm rise}$ and $t\_{\rm

decay}$) and peak absolute magnitude of \name\ (red asterisks) to other fast-evolving

transients (black dots). See the text for details.

\label{fig:compare\_mag}}

\end{figure}

The $g$- and $r$-band peak luminosity of \name\ ($\approx -16.3$\,mag) is around the lower limit

of stripped envelope SNe \citep{Drout2011, Taddia2018, Prentice2019}, and akin to those of the Ca-rich

gap transients, which occupy the luminosity `gap' between novae and SNe (peak absolute magnitude

$M\_R \approx -15.5$ to $-16.5$\,mag, \citealt{Kasliwal2012}).

To characterize the rise and decline timescales of \name, we calculate rise time ($t\_{\rm rise}$)

defined by how long it takes the $r$-band light curve to rise from 0.75\,mag below peak to peak,

and decline time ($t\_{\rm decay}$) determined by how long it takes to decline from peak by 0.75\,mag

(corresponding to half of maximum flux). Since \name\ shows no evidence of hydrogen

(Section \ref{subsec:spec\_properties}) and exhibits a fast rise (Figure~\ref{fig:lightcurve}), we compare

the $t\_{\rm rise}$, $t\_{\rm decay}$, and peak absolute magnitude between

\name\ and two other groups of transients:

\begin{itemize}

\item Fast-evolving hydrogen-deficient transients that are fainter than normal SNe Ia (i.e.

$<-19$\,mag), including

SN2002bj \citep{Poznanski2010},

SN2005ek \citep{Drout2013},

PTF09dav \citep{Sullivan2011},

SN2010X \citep{Kasliwal2010},

PTF10iuv \citep{Kasliwal2012},

iPTF14gqr \citep{De2018},

iPTF16hgs \citep{DeKC2018},

SN2018kzr \citep{McBrien2019},

and SN2019bkc \citep{Chen2020}.

\item ``Fast evolving luminous transients'' (FELT, \citealt{Rest2018}) or ``fast blue optical

transients'' (FBOT, \citealt{Margutti2019}).

We select well-studied representative objects of this population, including

KSN2015K \citep{Rest2018},

iPTF16asu \citep{Whitesides2017},

AT2018cow \citep{Prentice2018, Perley2019},

SN2018gep \citep{Ho2019},

and ZTF18abvkwla (also known as the Koala, \citealt{Ho2020}).

\end{itemize}

In Figure \ref{fig:compare\_mag}, peak magnitudes are given in (observer-frame) $r$-band, except for

KSN2015K where we only have observations in the \textit{Kepler} white filter, and iPTF16asu where the

rise was only caught in $g$-band. We only correct for Galactic extinction to compute $M\_{r\rm ,

peak}$ (assuming no host extinction). Note that iPTF14gqr and iPTF16hgs are two SNe exhibiting

double peaked light curves. Since rising of their first peaks were not captured, an upper limit of $t\_{\rm

rise}$ is calculated by taking the time difference between the first $r$-band detection and the latest

pre-discovery non-detection\footnote{For the second peak, $t\_{\rm rise}\sim5$\,d for iPTF14gqr and

$8<t\_{\rm rise}<20$\,d for iPTF16hgs.}, and absolute magnitude of the first $r$-band detection is

considered to be a fainter limit of $M\_{r\rm , peak}$ (plotted in the upper panel). In the lower panel,

since observation of iPTF14gqr does not extend to 0.75\,mag below its second peak, we present a

lower limit of its $t\_{\rm decay}$.

It is clear from the upper panel of Figure \ref{fig:compare\_mag} that \name\ rose faster than normal

Ca-rich events such as PTF09dav and PTF10iuv. The $t\_{\rm rise}$ of $\approx 2.0$\,d is similar to

the population of FELTs/FBOTs, but \name\ is substantially fainter. In the subluminous regime,

iPTF14gqr has $t\_{\rm rise}$ comparable to \name, and its first peak has been postulated to be caused

by the diffusion of shock-deposited energy out of an envelope around the progenitor star

\citep{De2018}.

The bottom panel of Figure \ref{fig:compare\_mag} shows that $t\_{\rm decay}$ of \name\ is

longer than the most rapid-fading SNe Ibc, such as SN2005ek, SN2018kzr,

and SN2019bkc. Its decay timescale is more similar to SN2002bj, SN2010X, the population of Ca-rich

transients (PTF09dav, PTF10iuv, iPTF16hgs), and likely iPTF14gqr. It has been suggested that the latter

group of events have radioactivity powered main peak with low mass of nickel ($M\_{\rm Ni} \lesssim 0.1

M\_\odot$).

\subsubsection{Bolometric Evolution}

\begin{figure}[!htbp]

\centering

\includegraphics[width=\columnwidth]{figures/Tbb\_Rbb\_log.pdf}

\caption{Evolution of blackbody properties (luminosity, temperature, radius) over time of

\name\ compared to iPTF14gqr and iPTF16hgs. We use the same method as applied in \name\ to

derive $L\_{\rm bb}$, $T\_{\rm bb}$, and $R\_{\rm bb}$ of iPTF14gqr and iPTF16hgs. }

\label{fig:Tbb\_Rbb\_Lbb}

\end{figure}

\begin{figure\*}[htbp!]

\centering

\includegraphics[width=\textwidth]{figures/compare\_color.pdf}

\caption{Comparison of the color evolution of \name\ with a subset of fast SNe shown in

Figure~\ref{fig:compare\_mag}. All colors have been corrected for Galactic extinction. Due to

absence of photometry in identical filters, we compare colors in corresponding filter pairs of

$B$/$g$, $R$/$r$ and $I$/$i$. Since all SNe shown here are at relatively low redshifts ($z\leq

0.063$), the observed colors probe similar rest-frame bands. \label{fig:compare\_color}}

\end{figure\*}

We constructed the bolometric light curve evolution by fitting a blackbody function to the spectral

energy distribution (SED) at epochs where at least detections in two filters are available (see details of

model fitting in Appendix \ref{subsec:bbfit}). We plot the physical evolution of \name\ with a

comparison to iPTF14gqr and iPTF16hgs in Figure~\ref{fig:Tbb\_Rbb\_Lbb}, where we have adopted the

explosion epoch of iPTF14gqr, iPTF16hgs, and \name\ estimated by \citet{De2018}, \citet{DeKC2018},

and Section \ref{subsec:fastrise} of this paper, respectively. The bolometric luminosity of \name\

reaches $\sim 5\times 10^{42}\,{\rm erg\, s^{-1}}$

at $\sim 1.5$\,d after the assumed explosion epoch. The subsequent decline displays an initial

fast drop of $0.36\,{\rm mag\,d^{-1}}$ at age 2--9\,d, and transitions to a slower drop of $0.11\,{\rm

mag\,d^{-1}}$ at age 10--30\,d.

The bolometric temperature of \name\ reaches as high as $\sim 2.3\times 10^4$\,K at age $1.5$\,d

and rapidly falls afterwards. The maximum $T\_{\rm bb}$ is much hotter than that observed in normal

SNe Ibc (6000--10000\,K, \citealt{Taddia2018}). Its early evolution is slower than iPTF14gqr, but

similar to iPTF16hgs and several other stripped envelope SNe displaying double-peaked light curve

(e.g., see Figure~2 of \citealt{Fremling2019}). Their first peaks have been modelled by cooling emission

from an extended envelope around the progenitor after the core-collapse SN (CCSN) shock breaks out

\citep{Modjaz2019}. After $\sim 8$\,d past explosion, $T\_{\rm bb}$ flattens to $6000\pm1000$\,K,

similar to the behavior of normal SNe Ibc at a much later phase ($\sim30$\,d after explosion,

\citealt{Taddia2018}).

Assuming that the photospheric radius can be approximated by $R\_{\rm bb}$ and linearly expands at

early phase, we fit a linear function to the first few $R\_{\rm bb}$ vs.~time measurements of \name\,

which gives $\approx 8224\, {\rm km\,s^{-1}}$. The radius remains flat at $\sim 6.7\times 10^3\,R\_\odot$

during age 8--30\,day, and even appears to slowly recede.

%The total integrated blackbody energy output during $t = 0.5$--30\,d is $\sim 2\times 10^{43}\,{\rm

%erg\,s^{-1}}$.

\subsubsection{Color Evolution}

We compare the color curves of other fast transients to that of \name\ in

Figure~\ref{fig:compare\_color}, in corresponding pairs of $B$/$g-R$/$r$ and $R$/$r-I$/$i$ colors. For

double-peaked events iPTF14gqr and iPTF16hgs, ``maximum'' time corresponds to epoch of maximum

light in the second peak.

The early-time blue color of \name\ arises from the high-temperature peak. Among other events,

SN2002bj, iPTF14gqr and iPTF16hgs exhibit earliest colors as blue as \name. Subsequently,

\name\ displays a color starting out blue and turning redder with time, consistent with a cooling

process.

One uniqueness of \name\ is that at $\sim6$--9\,d after maximum light, the $g-r$ color becomes bluer

by $\approx 0.2$\,mag, while after that the color continues to redden. We notice that iPTF14gqr

exhibits a similar trend --- around 4\,d before the second peak, its $g-r$ color stays flat before getting

redder afterwards, while around 2\,d before the second peak, its $r-i$ color also turns bluer by

$\approx 0.2$\,mag.

\begin{figure\*}[htbp!]

\centering

\includegraphics[width=\textwidth]{figures/spectra\_early.pdf}

\caption{Early-time spectra of \name. In panel (a), the original spectra are

shown in translucent colors, with the overlying black lines showing the same spectra convolved

with an ${\rm FWHM} = 800\, {\rm km\, s^{-1}}$ (for LT) or ${\rm FWHM} = 200\, {\rm km\,

s^{-1}}$ (for LRIS) Gaussian kernel. Prominent galaxy lines are marked by the

dash-dotted lines. In panel (b) (c) and (d), we show the observed spectra (not convolved with any

kernels) in velocity space around the \ion{He}{II} $\lambda 4686$, \ion{He}{I} $\lambda 5876$ and

H$\alpha$ emission lines.

\label{fig:spectra\_early}}

\end{figure\*}

\subsection{Spectroscopic Properties}\label{subsec:spec\_properties}

The phases of the spectra indicated in this section are relative to $g$-band peak.

\input{tables/tab\_eml\_fwhm.tex}

\subsubsection{Early Spectral Evolution} \label{subsubsec:spec\_early}

The very early spectra at $-1.1$, $-0.1$, and $+0.4$\,d show a blue continuum and strong galaxy

emission lines from the underlying \ion{H}{II} region (see Figure~\ref{fig:spectra\_early}). In

addition, these spectra also show prominent \ion{He}{I} $\lambda5876$ and high-ionization \ion{He}{II}

$\lambda4686$ narrow emission lines. We computed the equivalent width (EW) of \ion{He}{II} emission

using the spectral line and continuum wavelength ranges given by \citet{Khazov2016}. The EW is found

to be $-7.56\pm 1.07$ $-2.66\pm 1.30$, and $-3.77\pm 0.16$ in the $-1.1$\,d, $-0.1$\,d, and $+0.4$\,d

spectra.

In Table~\ref{tab:eml\_fwhm}, we show the measured Full width at

half-maximum intensity (FWHM) velocities of some emission lines by fitting a

Gaussian to the line profile. Since the \ion{S}{II} $\lambda\lambda 6716$, 6731 doublet is definitely from the host galaxy, their line widths serve as a practical measurement of instrumental line-broadening. As shown in column 2, FWHM velocities of the \ion{He}{II} and \ion{He}{I} emission lines are $\sim

550\,{\rm km\,s^{-1}}$ and $\sim 580\,{\rm km\,s^{-1}}$, much broader than the resolution of $\approx

270\,{\rm km\,s^{-1}}$, whereas H$\alpha$ is not well resolved. Thus, we infer that the hydrogen

emission is from the host galaxy, while the helium lines are from photoionized material in a region of

immediate environment exterior to the SN.

\begin{figure\*}[htbp!]

\centering

\includegraphics[width=\textwidth]{figures/spectra\_phot.pdf}

\caption{Photosperic phase spectra of \name. In panel (a), the original DBSP

spectrum is shown in translucent colors, with the overlying black lines showing the same

spectrum

convolved with an ${\rm FWHM} = 200\, {\rm km\, s^{-1}}$ Gaussian kernel. We mask prominent

galaxy lines in the DBSP spectrum in light red. In panel (b), we show the observed spectra (not

convolved with any kernels) in velocity space around \ion{He}{I} $\lambda 5876$ .

\label{fig:spectra}}

\end{figure\*}

\subsubsection{Photosperic Phase Spectral Evolution} \label{subsubsec:spec\_middle}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/hst\_opt.pdf}

\caption{Photosperic phase spectra of \name\ compared with

other SNe, including SN2000er \citep{Pastorello2008}, SN2002bj \citep{Poznanski2010}, iPTF14aki

\citep{Hosseinzadeh2017}, PTF12os and iPTF13bvn \citep{Fremling2016}. \ion{He}{I} transitions at

rest wavelength are marked by the vertical cyan lines (though note that not all of these lines are

visible in all spectra shown here).

\label{fig:hst\_opt}}

\end{figure}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/hst\_all.pdf}

\caption{\textit{HST} spectrum of \name\ compared with other SNe, including SN2006jc

\citep{Bufano2009}, SN1993J \citep{Jeffery1994}, SN2011fe \citep{Mazzali2014}, and Gaia16apd

\citep{Yan2017}.

\label{fig:hst}}

\end{figure}

Broad transient features show up in the $+12.0$ and $+14.3$\,d spectra (Figure~\ref{fig:spectra}).

These spectra are taken at the photospheric phase where emission comes from a photosphere

receding

(in mass coordinates) back through freely expanding SN ejecta.

The \textit{HST} spectrum contains little host-galaxy contamination

due to its high angular resolution. Prominent galaxy emission lines in the DBSP

spectrum are identified and plotted in light red to emphasize transient features. The existence of P-Cygni \ion{He}{I} $\lambda5876$ profile and non-existence of hydrogen nominally classify \name\ as

a Type Ib SN. We measure the velocity of the \ion{He}{I} $\lambda5876$ line by fitting a parabola to the

absorption minimum. The resulting fits give velocities of $\approx 6000\, {\rm km\,s^{-1}}$ and $ 5900\,

{\rm km\,s^{-1}}$ for the $+12.0$\,d and $+14.3$\,d spectra, respectively. This is lower than velocities

of normal SNe Ib measured from the \ion{He}{I} $\lambda5876$ absorption minimum ($\sim 10^4\, \rm

km\, s^{-1}$, \citealt{Liu2016}), but higher than that in Type Ibn SNe ($\sim 3000\, \rm km\, s^{-1}$,

\citealt{Hosseinzadeh2017}).

\begin{figure\*}[htbp!]

%

\centering

\includegraphics[width=\textwidth]{figures/spectra\_late.pdf}

\caption{Late-time spectra of \name. In panel (a), the original spectra are

shown in translucent colors, with the overlying black

lines showing the same spectra convolved with ${\rm FWHM} = 200\, {\rm km\,

s^{-1}}$ Gaussian kernels. We mask prominent galaxy lines in light red. Possible SN features are

marked by the dashed lines. In panel (b) (c) and (d),

the spectra at phase $+85.3$\,d, $+143.1$\,d, $+171.1$\,d, and $+314.4$\,d, are

binned by 1, 2, 3, and 1 pixel(s), respectively (1.16\,\AA\ per pixel). The binning

factors are chosen based on the

different signal-to-noise ratio (SNR) in these spectra (see exposure times in

Table~\ref{tab:spec}). Note that in panel (b), we plot evolution of \ion{He}{I} $\lambda 5876$,

$\lambda 6678$, and $\lambda 7065$ emissions in green, blue, and crimson, respectively.

\label{fig:spectra\_late}}

\end{figure\*}

In Figure~\ref{fig:hst\_opt}, we compare the photospheric phase optical spectra of

\name\ with other helium-rich events. Note that the DBSP spectrum has host emission lines

masked. \name\ is different from normal helium-rich stripped envelope SNe Ib/IIb or SNe Ibn in the

sense that its P-Cygni absorption minimum in the \ion{He}{I} $\lambda5876$ line is weaker. The

feature at $\sim5000{\rm \AA}$ is often attributed to \ion{He}{I} $\lambda 5016$ and \ion{Fe}{II} triplet

$\lambda\lambda\lambda4924$, 5018, and 5169 \citep{Liu2016}. The shape of this feature in

\name\ is similar to normal SNe Ib/IIb at much later phase ($\sim 20$\,d post maximum), indicating

that the spectral evolution of \name\ is faster. The complex absorption

profile at $\sim4500{\rm \AA}$ has been identified as a blend of \ion{Fe}{II}, \ion{Mg}{II} $\lambda 4481$

and \ion{He}{I} $\lambda 4472$ \citep{Hamuy2002}. In the DBSP spectrum, we detected \ion{O}{I}

$\lambda 7774$ and broad \ion{Ca}{II} at $\sim8500{\rm \AA}$ (due to the triplet at 8498, 8542, and

8662\AA) with clear P-Cgyni profiles; Both are major features of stripped envelope SNe

\citep{GalYam2017}.

In Figure~\ref{fig:hst}, we compare the \textit{HST} NUV spectrum with other types of SNe.

The UV part of \name\ is much weaker than a blackbody extrapolation of the optical spectra would

predict. This has also been seen in normal thermonuclear and CCSNe, and interpreted as strong

metal-line blanketing caused by iron-peak elements, particularly \ion{Fe}{II} and \ion{Co}{II}

\citep{Gal-Yam2008}. \name\ bears a close resemblance to SN1993J between 2000 and 4000\AA.

In Figure~\ref{fig:hst}, we also marked rest wavelength of \ion{Mg}{I} $\lambda2852$ and \ion{Mg}{II}

$\lambda \lambda 2796$, 2803. The emission features at $\sim2760{\rm \AA}$ in \name\ and

Gaia16apd are similar to the bump at $\sim2730{\rm \AA}$ in SN1993J, which was found to be a NLTE

\ion{Mg}{II} emission line \citep{Jeffery1994}. This resonance line is blueshifted from its rest wavelength,

%since the emitting material is very optically thick,

and is suggested to come from a circumstellar region that is distinctly separated from the SN

photosphere in velocity and excitation conditions \citep{Panagia1980,

Fransson1984}.

\subsubsection{Late-time Spectral Evolution}

Figure~\ref{fig:spectra\_late} shows late time spectra of \name\ obtained at $+85.3$,

$+143.1$, $+171.1$, and $+314.4$\,d. The general shape of the spectra is determined by the host

galaxy, while possible SN features are marked by the dashed lines. The right panels (b), (c), and (d)

highlight emission lines at wavelengths of \ion{He}{I}, [\ion{O}{I}], and [\ion{Ca}{II}]. In panel (c) of

Figure~\ref{fig:spectra\_late}, the [\ion{O}{I}] $\lambda \lambda 6300, 6363$ feature

consists of two narrow emission peaks. This doublet transitions share the same upper level ($\rm

^{3}P\_{1,2}$--$\rm ^{1}D\_2$). The observed intensity ratio $R \equiv F(6300/6364) \sim 3.1$ agrees

with the nebular condition, as one would expect in the optically thin regime \citep{Leibundgut1991,

Li1992}. In panel (d), we mark position of the [\ion{Ca}{II}] doublet in dashed lines, but only the

$\lambda 7324$ line is clearly detected. It presents a double-peaked profile with a peak separation of

$\sim 400\,{\rm km\,s^{-1}}$.

From panel (a) of Figure~\ref{fig:spectra\_late}, it is also clear that in the $+85.3$\,d spectrum, the

\ion{He}{I} and [\ion{Ca}{II}] lines have broader emission components with Lorentzian profile at the base

of the narrow emission lines. These Lorentz-shape components are not visible in the $+314.4$\,d

spectrum. Therefore, to further investigate the broader features, we subtract the $+314.4$\,d

spectrum from the $+85.3$\,d spectrum. The resulting subtraction

(Figure~\ref{fig:spec\_subtract}) reveals intermediate-width (FWHM $\sim

2000\,{\rm km\,s^{-1}}$) components of \ion{He}{I}, [\ion{Ca}{II}], and \ion{Ca}{II} IR triplet. It shares a

close resemblance to some

Type Ibn SNe, such as SN2011hw \citep{Pastorello2015} and SN2015G \citep{Shivvers2017}. These

intermediate-width features are too narrow to be explained by emission from

radioactivity-heated optically thin SN ejecta. Instead, they are probably emitted by a cold dense CSM

shell formed by radiative cooling from the post-shock material, as was proposed to be the case in interacting Type IIn/Ibn SNe \citep{Chugai1994, Smith2017}.

\begin{figure\*}

\centering

\includegraphics[width=\textwidth]{figures/spec\_host\_subtracted.pdf}

\caption{Subtracted late-time spectrum of \name\ compared with Type Ibn SNe SN2006jc

\citep{Shivvers2019},

SN2011hw \citep{Pastorello2015}, and SN2015G \citep{Shivvers2017}.

\label{fig:spec\_subtract}}

\end{figure\*}

Table~\ref{tab:eml\_fwhm} (column 3 and 4) gives the measured FWHM velocities of narrow emissions

shown in panel (b), (c), and (d) of Figure~\ref{fig:spectra\_late}. It can

be seen that the measured FWHM of other emission lines are similar to the \ion{S}{II} line-width. Therefore, we conclude that the observed narrow emissions are not well resolved.

Due to the low resolution of our LRIS spectra, we cannot directly rule out the possibility that the

narrow lines are emanating from the host galaxy. However, there are evidence indicating that they are

not merely a background contamination of an underlying \ion{H}{II} region:

\begin{enumerate}[label=(\roman\*)]

\item In the $+85.3$\,d spectrum, the \ion{He}{I} and [\ion{Ca}{II}] narrow emissions are on top of

intermediate-width Lorentzian components characteristic of electron scattering \citep{Huang2018},

which fades away in the $+314.4$\,d spectrum. However, the hydrogen Balmer lines do not have a

broader base in any of our spectra.

\item The flux intensities of \ion{He}{I}, [\ion{O}{I}], and [\ion{Ca}{II}] lines decrease by a

factor of approximately two from $+85.3$\,d to $+314.4$\,d, consistent with the temporal

evolution from an emission mechanism connected to the aging supernova. As a comparison, line

strengths of the strongest emissions in normal ionized nebulae (H$\alpha$, [\ion{O}{III}],

[\ion{O}{II}], [\ion{S}{II}], etc) do not follow this behavior.

\item Although the \ion{He}{I} and [\ion{O}{I}] lines labelled in panel (a) of Figure~\ref{fig:spectra\_late}

have been observed in \ion{H}{II} regions \citep{Peimbert2000, Peimbert2017}, the doublet [\ion{Ca}{II}]

$\lambda \lambda 7291$, 7324 has not been detected in gaseous nebulae \citep{Kingdon1995}.

\end{enumerate}

Taken together, we suggest that the narrow components ($\lesssim 270\,{\rm km\,s^{-1}}$) of

\ion{He}{I}, [\ion{Ca}{II}], [\ion{O}{I}] and \ion{Ca}{II} are also associated with the explosion. Their widths

might be consistent with the typical velocities of pre-shock CSM. The detection of these lines at

$>300$\,days after the SN explosion suggests that the circumstellar shell extends to $\gtrsim 2\times

10^{16}\,{\rm cm}$ ($\sim 1000$\,AU) from the progenitor.

\subsection{Host Galaxy Properties} \label{subsec:host}

We measure properties of the host galaxy using the spectrum obtained at phase $+314.4$\,d,

assuming that the most prominent nebular line emissions of H$\alpha$ and [\ion{N}{II}]

are from the host. The Galactic extinction corrected emission line fluxes of H$\alpha$ and [\ion{N}{II}]

$\lambda6584$ are $(24.15 \pm 0.54) \times 10^{-16}~{\rm erg\,cm}^{-2}\,{\rm s}^{-1}$ and $(1.92 \pm

0.10 ) \times 10^{-16}~{\rm erg\,cm}^{-2}\,{\rm s}^{-1}$, respectively. The fluxes were

measured by fitting a Gaussian profile to the emission line profiles,

measuring the integrated flux under the profile.

Using the \citet{Kennicutt1998} relation converted to a Chabrier initial mass function

\citep{Chabrier2003, Madau2014}, we infer a star-formation rate of $\approx 0.012 M\_\odot\, {\rm yr^{-1}}$ from the H$\alpha$ emission line. Note that this is a lower limit since the slit diameter in the

LRIS spectrum is 1.0 arcsec ($\sim 0.44$\,kpc at the distance of the host) and the extraction aperture

is 0.76 arcsec, whereas the host diameter is about 5 arcsec.

We also compute the oxygen abundance using the

strong-line metallicity indicator N2 \citep{Pettini2004} with the updated calibration reported in

\citet{Marino2013}. The oxygen abundance in the N2 scale is 8.23 $\pm$ 0.01 (stat) $\pm$ 0.05 (sys).

We choose not to use the O3N2 index since it requires line flux measurement of H$\beta$. As can be

seen in panel (a) Figure~\ref{fig:spectra\_late}, there is substantial stellar absorption around H$\beta$

(4861\AA). Compared to $12+{\rm log(O/H)\_{\rm solar}} \approx 8.69$

\citep{Asplund2009}, the derived N2 index suggests a significantly subsolar metallicity of $\approx

0.35 Z\_\odot$ ($Z\approx 0.005$). This estimate places \name's host galaxy in the lowest

10\% of the distribution of SNe Ibc host galaxy metallicities, while it is on the lowest 30\% in the range

of Type Ic-BL SNe host galaxy metallicities \citep{Sanders2012}.

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/SDSSJ17+50\_best\_model.png}

\caption{Spectral energy distribution of the host galaxy of \name. The observed photometric

data (with 1$\sigma$ error bars shown in blue lines) are shown in blue open squares, and the

model is shown in black curve ($\chi^2 = 0.38$). The relative residual flux is shown in the bottom

panel.

\label{fig:SEDfit}}

\end{figure}

We further determine the stellar mass ($M\_{\star}$) of the host galaxy by SED modeling using

\texttt{CIGALE} \citep{CIGALE19}. We adopt the stellar population synthesis models from \citet{BC03}

with the Chabrier IMF \citep{Chabrier2003}, and assume a double declining exponential star formation

history (SFH). In addition, a dust component is added using the \citet{DL07} model to account for dust

emission. Finally, the total SED model is attenuated by a modified Calzetti extinction law

\citep{Calzetti2000}. It assumes that the young stellar population is extincted by the normal Calzetti

law, and the old stellar population is extincted less heavily than that by a certain factor ($<$ 1).

We retrieved science-ready images from the Sloan Digital Sky Survey data release (DR9) (SDSS;

\citealt{Ahn2012a}), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, PS1)

DR1 \citep{Flewelling2016a}, the Two Micron All Sky Survey \citep[2MASS;][]{Skrutskie2006a}, and the

unWISE images \citep{Lang2014a} from the NEOWISE Reactivation Year-3 \citep{Meisner2017a}. We

augmented this data set with \textit{Swift}/UVOT observations that extend our wavelength coverage to

the

UV. The photometry was done with the software package \package{LAMBDAR} \citep[Lambda Adaptive

Multi-Band Deblending Algorithm in R;][]{Wright2016a}, to perform consistent photometry on images

that are neither pixel nor seeing matched, and tools presented in Schulze et al. (in prep). The UVOT

data were reduced in \texttt{HEAsoft} as described in Section \ref{subsubsec:swift}. The

measured host photometry is given in \ref{sec:appphot\_data}. The fitted SED is shown in Figure

\ref{fig:SEDfit}. The derived stellar mass is ${\rm log}(M\_{\star}/M\_{\odot}) = 8.4 \pm 0.1$, and the

inferred SFR is $0.015 \pm0.003\, M\_\odot\, {\rm yr^{-1}}$, comparable to the measurement inferred

from H$\alpha$. The host extinction, $E(B - V)$, is $0.02 \pm

0.02$\,mag and $0.01 \pm 0.01$\,mag for the young and old stellar population, respectively,

both of which are insignificant. The stellar mass and SFR of this galaxy are commo among the

hosts of stripped-envelope SNe in the PTF sample (Schulze et al. in prep).

% The inferred specific SFR (sSFR) is calculated to be $6\times 10^{-11}\,{\rm yr^{-1}}$.

\section{Modelling} \label{sec:modelling}

\subsection{Shock Cooling Powered Fast Rise} \label{subsec:fastrise}

SNe light curves are mainly powered by shock energy or radiative diffusion from a heating

source. We first examine if the peak of \name\ is likely to be powered by the radioactive decay of

$^{56}\rm Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$. With a peak luminosity of $L\_{\rm

peak}\approx 5\times 10^{42}\,{\rm erg \, s^{-1}}$ and a rise time of $t\_{\rm peak}\approx 2$--$4\,{\rm

d}$, \name\ falls into the unshaded region of \citet[][Fig.~1]{Kasen2017}, where an unphysical

condition of $M\_{\rm Ni} > M\_{\rm ej}$ is required. Therefore, we rule out radioactivity as the

power source for the fast rise of the light curve.

There have been clues for the early emission mechanism of \name,:

\begin{enumerate}[label=(\roman\*)]

\item The fast $t\_{\rm rise}$ of \name\ (Figure~\ref{fig:compare\_mag}) is reminiscent of shock

cooling emission.

\item The initial high temperature (middle panel of Figure~\ref{fig:Tbb\_Rbb\_Lbb}), blue color

(Figure~\ref{fig:compare\_color}), and relatively fast color evolution of \name\ are similar to

iPTF14gqr and iPTF16hgs, which have been modelled as shock cooling emission \citep{De2018,

DeKC2018}.

\item The color jump in $g-r$ is observed 6--9 days after maximum (left panel of

Figure~\ref{fig:compare\_color}). It is at roughly this phase that the change in bolometric luminosity

decline rate transitions from 0.36\,$\rm mag\, d^{-1}$ to 0.11 $\rm mag\, d^{-1}$

(upper panel of Figure~\ref{fig:Tbb\_Rbb\_Lbb}). This supports the idea that the dominant power

mechanisms before and after this transition are different.

\end{enumerate}

Therefore, we model the early light curve as cooling emission from shock-heated extended material,

which locates at the outer layers of the progenitor or outside of the progenitor. We use models

presented by \citet[][hereafter P15]{Piro2015} to constrain the mass and radius of the extended

material ($M\_{\rm ext}$ and $R\_{\rm ext}$, respectively), where $M\_{\rm ext}$ includes only mass

concentrated around $R\_{\rm ext}$. This model is built on analytical results of \citet{Nakar2014}.

Details of the model fitting to multi-band observations are illustrated in Appendix \ref{subsec:p15fit}.

\begin{figure}

\centering

\includegraphics[width=\columnwidth]{figures/Lbb.pdf}

\caption{Bolometric light curve for \name. Late-time quasi-bolometric light curve

estimated by computing $\nu L\_\nu$ in $r$-band is shown as empty grey circles. The dashed green

and dotted blue lines show the best fits of shock cooling and nickel decay models. The solid red line

shows the combination of the two components.}

\label{fig:Lbb}

\end{figure}

In Figure~\ref{fig:Lbb}, bolometric light curve measured in Section \ref{subsec:lc\_properties} are shown

in black. We also show late-time $r$-band $\nu L\_{\nu}$ measurements in grey empty circles as a

proxy of bolometric light curve evolution. The dashed green line shows the best-fit model of

$M\_{\rm ext} = 9.34 \pm 0.36 \times 10^{-2} M\_\odot$,

$R\_{\rm ext} =2.71\_{-0.17}^{+0.19}\times10^{12}$\,cm (i.e., $39.0\_{-2.5}^{+2.7} R\_\odot$),

and explosion epoch at phase $t\_{\rm exp}= -3.21 \pm 0.04$\,d (i.e., the explosion occurred 0.45\,d

before the first detection in $g$-band). The amount of energy passed into the extended material is

well constrained to be $E\_{\rm ext} = (1.15\pm 0.07) \times 10^{50}\,{\rm erg\, s^{-1}}$.

Given the simple assumptions of the model, we expect the constraints on $M\_{\rm ext}$ and $R\_{\rm

ext}$ to be only approximately accurate. We thus conclude that the early shock cooling emission was

produced by an extended envelope with a mass of $\sim 0.1 M\_\odot$ locating at a radius of $\sim

3\times 10^{12}\,{\rm cm}$ ($40\,R\_\odot$). There are now numerous cases of early cooling envelope

emission observed in CCSNe, where the extended material is estimated to have lower mass ($\sim

0.001$--$0.01 M\_\odot$) and larger radius ($\sim 10^{13}\, {\rm cm}$) compared to \name\

\citep{Modjaz2019}.

\subsection{Mass Loss Estimate from \ion{He}{II}} \label{subsec:flash}

Early-time low-velocity \ion{He}{II} $\lambda4686$ emission (Section \ref{subsubsec:spec\_early}) has

been detected in nearly twenty hydrogen-rich CCSNe and one hydrogen-poor SN iPTF14gqr. This

feature often fades away within a few hours to a few days after the explosion \citep{Yaron2017}. The

high ionization potential of this line requires high temperature or an ionizing flux, which might come

from either shock breakout or CSM interaction \citep{GalYam2014, Smith2015}. Due to the rapid

decrease in $T\_{\rm bb}$ at the three epochs of our early-time spectra and the similarity between

\name\ and iPTF14gqr, we favor shock cooling emission as the origin of recombination helium

lines. Therefore, we can use luminosity of the \ion{He}{II} $\lambda4686$ line to make an

order-of-magnitude estimate on properties of the emission material, following the procedure given by

\citet{Ofek2013} and \citet{De2018}.

Assuming that the immediate CSM around the progenitor has a spherical wind-density profile of the

form $\rho = K r^{-2}$, where $r$ is distance from the progenitor, $K\equiv \dot M / (4\pi v\_{\rm w})$ is

the wind density parameter, $v\_{\rm w}$ is the wind velocity, and $\dot M$ is the mass loss rate. The

integrated mass of the emitting material from $r$ to $r\_1$ is

\begin{align}

M\_{\rm He} = \int\_{r}^{r\_1}4\pi r^2 \rho(r) {\rm d}r=4\pi K \beta r

\end{align}

where $\beta \equiv (r\_1 - r) /r $ is assumed to be of order unity.

We can relate the mass of the \ion{He}{II} region to the \ion{He}{II}

$\lambda4686$ line luminosity using

\begin{align}

L\_{\lambda 4686} \approx \frac{A n\_e M\_{\rm He}}{m\_{\rm He}} \label{eq:L4686}.

\end{align}

Here

\begin{align}

A = \frac{4\pi j\_{\lambda 4686}}{n\_e n\_{\rm He^{++}}},

\end{align}

$ j\_{\lambda4868}$ (in ${\rm erg \, cm^{-3}\, s^{-1}\, sr^{-1}}$) is the emission coefficient for the

$\lambda4686$ transition. $m\_{\rm He}$ is mass of a helium nucleus, $n\_{\rm He^{++}}$ is the number

density of doubly ionized helium and $n\_e$ is the number density of electrons.

Assuming a temperature of $10^4$\,K, electron density of $10^{10}\,{\rm cm^{-3}}$, and Case B

recombination, we get $A=1.32\times 10^{-24}\,{\rm erg\, cm^{3}\, s^{-1}}$ \citep{Storey1995}.

Using $n\_e = 2 n\_{\rm He^{++}}$ and the density profile, Eq.~(\ref{eq:L4686}) can be written as

\begin{align}

L\_{\lambda 4686} \approx \frac{8\pi A \beta}{m\_{\rm He}^2} \frac{K^2}{r}.

\end{align}

The location of the emitting region can be constrained by requiring that the Thompson optical depth

($\tau$) in the region must be small for the lines to escape. We require

\begin{align}

\tau = n\_e \sigma\_{\rm T} \int\_{r}^{r\_1} {\rm d}r = \frac{2\sigma\_{\rm T}K\beta}{m\_{\rm He}r} \lesssim 1

\end{align}

Thus

\begin{align}

r^2 &\gtrsim \left (\frac{2\sigma\_{\rm T}\beta}{m\_{\rm He}} \right)^2 \frac{L\_{\lambda 4686} m\_{\rm

He}^2 r }{8\pi A \beta } \notag \\

r & \gtrsim L\_{\lambda 4686} \frac{\sigma\_{\rm T}^2 \beta }{2\pi A }

\end{align}

The $+0.4$\,d emission line flux is measured to be $F = (8.99\pm 0.71)\times10^{-16}\,{\rm erg\,

cm^{-2}\,s^{-1}}$, corresponding to $L\_{\lambda 4686} = 9.0\times 10^{38}\,{\rm erg\, s^{-1}}$.

Hence,

we get $r \gtrsim 4.8 \times 10^{13} \beta \,{\rm cm}$, $K \gtrsim 1.2\times 10^{14} \, {\rm

g\,cm^{-1}}$, and $M\_{\rm He} \gtrsim 3.7\times 10^{-5} \beta^2\, M\_{\odot}$. Adopting a wind

velocity of $v\_{\rm w} \approx 550 \, {\rm km\, s^{-1}}$ as measured from the \ion{He}{II} FWHM,

the mass loss rate can be constrained to be $\dot M \gtrsim 1.1\times 10^{-4}\,{M\_\odot\, \rm

yr^{-1}}$. The mass-loss timescale is therefore a few months before explosion. Note that these

estimates can be affected if the CSM cannot be well characterized by a spherically

symmetric $\rho(r) \propto r^{-2}$ density profile, or if the emitting region was confined to a thin

shell ($\beta \ll 1$).

\subsection{Constraints on Radio Emission}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/radio\_230GHz\_s2.pdf}

\includegraphics[width=\columnwidth]{figures/radio\_230GHz\_s0.pdf}

\caption{Maps of expected radio luminosity at 230\,GHz. The $x$-axis is the shock velocity $v\_s$.

The $y$-axis is wind mass-loss parameter $K$ in the case of $\rho \propto r^{-2}$

CSM environment in the upper panel, while in the bottom panel it is the number density $n\_0$ in the

constant-density case. The black contour in each panel shows the location of 3$\sigma$ upper limit

at 230\,GHz on \name. The phase space with a luminosity higher the black line in each panel is ruled

out by the

observation.

\label{fig:radio}}

\end{figure}

Radio emission in SNe is produced by shock accelerated electrons in the circumstellar material as they

gyrate in the post-shock magnetic field when the shock freely expands. Should the circumstellar

medium be formed by a pre-SN stellar wind, the radio synchrotron radiation can be used to probe the

pre-explosion mass-loss \citep{Chevalier1982}. High frequency ($\nu>90$\,GHz) bright

($\nu L\_\nu \gtrsim 10^{40} \, \rm erg\,

s^{-1}$) radio sources are often found to be associated with gamma-ray bursts (GRBs), TDEs, and

relativistic transients (see Figure~6 of \citealt{HoPhinney2019}). Among normal SNe Ibc, moderate

submillimeter luminosity at $\sim 5\times 10^{37}\, \rm erg\, s^{-1}$ has been observed in SN1993J

\citep{Weiler2007} and SN2011dh \citep{Horesh2013}.

Our SMA observations constrain the submillimeter luminosity of \name\ to $\nu L\_{\nu \rm ,

230GHz} < 5.3\times 10^{39}\, \rm erg\, s^{-1}$ and $\nu L\_{\nu \rm , 345GHz} < 3.0\times 10^{40}\, \rm

erg\, s^{-1}$. We place these upper limits in physical context using the synchrotron self-absorption

model given by \citet{Chevalier1998}. The expected radio luminosities are computed at 230 and

345\,GHz for two types of circumstellar environments --- one with the wind-density with the same

parameterization as that adopted in Section \ref{subsec:flash} and the other with a constant-density

environment ($\rho = \,{\rm constant}$).

Adopting the explosion epoch found in Section \ref{subsec:fastrise}, our SMA observations were

obtained at 2.75\,day after explosion. Given the early time of these observations, we consider constant

shock velocities at 0.1--0.25$c$, as found to be typical in SNe Ibc \citep{Wellons2012}. We assume an

electron energy power law index of $p = 3$, a volume filling factor $f=0.5$, and that the electrons

and magnetic field in the post-shock region share constant fractions of the post-shock energy

density, i.e., $\epsilon\_e = \epsilon\_B = 0.1$.

The expected radio luminosity predicted by the \citealt{Chevalier1998} model in the two environments

at 230\,MHz are shown in Figure~\ref{fig:radio} by the color maps, and the black contours indicate our

$3\sigma$ limits. As can be seen, only small regions have expected luminosity higher than the

$3\sigma$ limits (indicated by the hatched regions), and thus our observations are not deep enough to

provide stringent constrains on the circumstellar properties. Compared with 230\,MHz, the parameter

space is more

poorly

constrained at 350\,GHz and are thus not shown.

\subsection{Radioactivity Powered Main Peak} \label{subsec:radioactivity}

After subtracting the shock cooling emission from the bolometric light curve, the remaining light curve

has a peak luminosity of $L\_{\rm peak}\approx 6\times 10^{41}\,{\rm erg \, s^{-1}}$ and a rise time of

$t\_{\rm peak}\approx 9\,{\rm d}$. In the shaded region of \citet[][Fig.~1]{Kasen2017}, this falls between

the $M\_{\rm Ni} = 0.1 M\_{\rm ej}$ and $M\_{\rm Ni} = 0.01 M\_{\rm ej}$ lines, indicating that the remaining

component can be powered by $^{56}$Ni decay. Apart from this, the moderate $t\_{\rm decay}$ of

\name\ (bottom panel in Figure~\ref{fig:compare\_mag}) is similar to a few Ca-rich transients, and

consistent with coming from radioactivity. Here we use two methods to estimate $M\_{\rm ej}$ and

$M\_{\rm Ni}$.

First of all, we use analytical models \citep{Arnett1982, Valenti2008, Wheeler2015} to constrain the

nickel mass ($M\_{\rm Ni})$, a characteristic photon diffusion timescale ($\tau\_{\rm m}$), and a

characteristic $\gamma$-ray escape timescale ($t\_0$). Details of the model fitting are illustrated in

Appendix \ref{subsec:arnettfit}. The dotted blue line in Figure~\ref{fig:Lbb} shows the best-fit model of

$M\_{\rm Ni} = 1.61\_{-0.03}^{+0.04}\times 10^{-2} M\_\odot$, $\tau\_{\rm m} = 6.35\pm 0.18$\,d, and $t\_0

= 24.04\_{-0.73}^{+0.76}$\,d. Thus, using Equation~(\ref{eq:taum}), the ejecta mass can

be estimated to be

\begin{align}

M\_{\rm ej} = 0.27^{+0.02}\_{-0.01}\, M\_\odot \frac{v\_{\rm ej}}{6000\,{\rm km\,s^{-1}}} \frac{0.07\,{\rm

cm^2\,g^{-1}}}{\kappa\_{\rm opt}} \notag

\end{align}

Here we adopt the ejecta velocity as the photospheric velocity measured in Section

\ref{subsubsec:spec\_middle} and the mean opacity of SNe Ibc found by \citet{Taddia2018}. The kinetic

energy is then calculated to be

\begin{align\*}

E\_{\rm kin} = \frac{3}{10}M\_{\rm ej} v\_{\rm ej}^2 = (5.7 \pm 0.3)\times 10^{49}\,{\rm erg}

\end{align\*}

Recently, \citet[][hereafter KK19]{Khatami2019} presents improved analytic relations (compared with

the original \citealt{Arnett1982} model) between $t\_{\rm peak}$ and $L\_{\rm peak}$. When $t<10$\,d,

$\varepsilon\_{\rm Ni}(t) \gg \varepsilon\_{\rm Co}(t)$ (see Equations~\ref{eq:heatNi}, \ref{eq:heatCo}),

and hence we have an exponential heating function

\begin{equation}

L\_{\rm heat}(t) = L\_0 e^{-t/\tau\_{\rm Ni}}

\end{equation}

where $L\_0 = M\_{\rm Ni}\times \epsilon\_{\rm Ni}$. In this case, KK19 (Eq.~21) shows that

the relation between peak time and luminosity is:

\begin{equation}

L\_{\rm peak} = \frac{2L\_0 \tau\_{\rm Ni}^2}{\beta^2 t\_{\rm peak}^2} \left[ 1 - (1 + \beta t\_{\rm

peak}/\tau\_{\rm Ni} ) e^{-\beta t\_{\rm peak}/ \tau\_{\rm Ni}} \right]

\end{equation}

where $\beta \sim 4/3$ gives a reasonable match to numerical simulations. With $L\_{\rm peak}\approx

6\times 10^{41}\,{\rm erg \, s^{-1}}$ and $t\_{\rm peak} \approx 9$\,d, we get an estimate of $M\_{\rm

Ni}\sim 0.017 M\_{\odot}$.

$M\_{\rm ej}$ can be estimated using Eq.~23 of KK19:

\begin{align}

\frac{t\_{\rm peak}}{t\_{\rm d}} = 0.11\,{\rm ln} \left( 1 + \frac{9\tau\_{\rm Ni}}{t\_{\rm d}} \right)+ 0.36,

\label{eq:kk19\_23}

\end{align}

where $t\_{\rm d}$ is the characteristic timescale without any numerical factors

\begin{align}

t\_{\rm d} = \left(\frac{\kappa\_{\rm opt} M\_{\rm ej}}{v\_{\rm ej}c}\right)^{1/2}. \label{eq:kk19\_12}

\end{align}

We derive $t\_{\rm d} \approx 15.4$\,d, which implies

\begin{align}

M\_{\rm ej} \approx 0.23 M\_\odot \frac{v\_{\rm ej}}{6000\,{\rm km\,s^{-1}}} \frac{0.07\,{\rm

cm^2\,g^{-1}}}{\kappa\_{\rm opt}} \notag

\end{align}

The kinetic energy of the ejecta is then $E\_{\rm kin} \approx 4.9\times

10^{49}\,{\rm erg}$.

In conclusion, the estimates derived from simplified model fitting and new analytic relations from

KK19 are roughly the same. Ejecta mass ($M\_{\rm ej}\sim 0.25M\_\odot$), nickel mass ($M\_{\rm Ni} \sim

0.017M\_\odot$), and total kinetic energy ($E\_{\rm

kin}\sim 5\times 10^{49}\,{\rm erg}$) from the explosion of

\name\ are very small.

\section{Interpretation} \label{sec:interpretation}

\subsection{A Core-Collapse Supernova}

At early time, the cooling emission from shock-heated surrounding material of $M\_{\rm

ext}\sim0.1\,M\_\odot$ and $R\_{\rm ext}\sim 3\times 10^{12}\,{\rm cm}$ ($40\,{ R\_\odot}$) corroborates

that the progenitor of \name\ is a star with an extended envelope. The \ion{He}{II} $\lambda4686$ flash

ionized emission comes from an optically thin material locating at $\sim 5\times 10^{13}\,{\rm cm}$

($700\,R\_\odot$). Such an extended envelope is predicted for stripped helium

stars at low metallicity \citep{Laplace2020}. Therefore, the early-time shock cooling light curve and

emission line serves as strong evidence that \name\ is the explosion of a star with inflated radius (not a

compact object).

The $^{56}$Ni mass of $\sim 0.017\,M\_\odot$ inferred from the radioactivity-powered decay

is much greater than that produced in electron-capture SNe ($\sim10^{-3}\,M\_\odot$,

\citealt{Moriya2014}), whereas the ejecta velocity of $v\_{\rm ej}\approx6000\,{\rm km\, s^{-1}}$ is much

larger than that expected in fallback SNe ($\sim3000\,{\rm km\,s^{-1}}$, \citealt{Moriya2010}).

Therefore, we conclude that \name\ is associated with the class of iron CCSNe.

\subsection{An Ultra-Stripped Progenitor}

As noted in the introduction, the majority of SNe Ibc, with $M\_{\rm ej}$ in the range of

1--5\,$M\_\odot$, are believed to come from binary evolution. The small amount of ejecta mass seen in

\name\ ($M\_{\rm ej}\sim 0.25\, M\_\odot$) requires extreme stripping prior to the explosion in a

binary system, which suggests an ultra-stripped progenitor \citep{Tauris2013}. Typical direct

progenitors are stripped helium stars with zero-age helium core masses within 2.5--3.2\,$M\_\odot$

\citep{Woosley2019}.

Compared with iPTF14gqr, where the second peak of the light curve suggests $M\_{\rm ej}\sim

0.2\,M\_\odot$, \name\ has a slightly higher ejecta mass. In particular, the helium-rich photospheric

spectra indicate that \name\ has a greater amount of helium in the ejecta. \ion{He}{I} emissions are

non-thermally excited by collisions with fast electrons, which result from Compton processes with

$\gamma$-rays from $^{56}$Ni decay \citep{Dessart2012, Hachinger2012}. On the other hand, the

weak absorption strength in the \ion{He}{I} P-Cygni profile (Figure~\ref{fig:spectra} and

Figure~\ref{fig:hst\_opt}) suggests that the helium envelope mass of \name\ is substantially lower than

that in a canonical Type Ib SN \citep{Fremling2018}. The stripping in \name\ is therefore less extreme

than iPTF14gqr. Nevertheless, the striking similarities between these two events indicate that they

probably originate from similar channels.

The photospheric and late-time spectra of \name\ signify interaction with a helium-rich extended dense

shell, which may consist of gas originally ejected by the progenitor as a

stellar wind or deposited by binary interaction. However, the mass loss rate constrained from

early-time spectroscopy ($\dot M \gtrsim 10^{-4}\,{ M\_\odot}\, \rm yr^{-1}$) is much higher than that

observed in Galactic Wolf-Rayet stars \citep{Smith2014}. The high mass loss rate and short ejection

timescale are similar to that expected in the final stages of stellar evolution where super-Eddington

energy deposition drives a powerful outflow \citep{Shiode2014,

Quataert2016}, which can happen during nonconservative mass transfer in binary evolution of the

ultra-stripped progenitor \citep{Tauris2015}.

\input{tables/tab\_p15fit\_comparion.tex}

\subsection{Stellar Evolution Pathways} \label{subsec:stellar\_pathways}

Here we discuss possible evolution paths of \name's progenitor.

We first consider the scenario where \name\ comes from a binary consisting of two massive stars.

\citet{Yoon2010} shown that stripping is very inefficient at subsolar metallicity of $Z\approx 0.004$

(similar to the $Z\approx 0.005$ calculated in Section \ref{subsec:host}), such that the final mass of

the primary at the time of core-collapse will be higher than 3.8\,$M\_\odot$. This will lead to $M\_{\rm

ej}\gtrsim 2.3\,M\_\odot$ assuming that the explosion forms a neutron star of 1.5\,$M\_\odot$. The

inferred ejecta mass is much higher than the observed ($M\_{\rm ej}\sim 0.3 \, M\_\odot$). We thus

conclude that this scenario is not consistent with observations of \name.

We next consider the possibility that the companion is a lower mass ($<10\,M\_\odot$) main sequence

star. \citet{Zapartas2017} performed population synthesis simulations, showing that for the pre-SN

helium star to reach $<2 M\_\odot$, a relatively high initial mass ratio is needed. Based on this result,

\citet{De2018} disfavored this scenario for the progenitor of iPTF14gqr, since a small mass ratio is

required to enable a narrow orbit where the helium star undergoes mass loss via

Roche-lobe overflow (RLO) to achieve extreme stripping. Their argument probably also applies here.

Finally, we consider scenarios where the progenitor resides in a tight helium star $+$ degenerate object

system, where the degenerate object can be a white dwarf, a neutron star, or a black hole. This

scenario is supported by the high efficiency of mass transfer to compact companions via Case BB/BC

RLO in the production of almost bare CO cores with little helium envelope \citep{Dewi2002,

Tauris2012}. We

note that in both iPTF14gqr and \name, the envelope radii extend to a few hundreds

of solar radii, which is even larger than the expected orbital separation required for

extreme stripping. Therefore, these large radii may instead represent a short-lived common envelope

phase just before the explosion where the companion gets engulfed by the expanded He star (see

Figure~6 of \citealt{De2018}).

The final mass of the helium

envelope depends on the initial mass of the helium star and the orbital period of the compact binary.

To reconcile with the ejecta mass observed in \name, one may expect small final envelope mass

($\lesssim0.3\,M\_\odot$) but large enough for optical helium features to be observed in the SN

explosion ($\gtrsim 0.06\, M\_\odot$, \citealt{Hachinger2012}). This can be achieved in a system where

the progenitor is a helium star in a compact binary with $0.1 \lesssim P\_{\rm orb} \lesssim 20$\,d

\citep{Tauris2015}. Therefore, we conclude that the observational characteristics of \name\ can be best

explained by a compact companion.

The outcome of \name\ --- an iron core-collapse ultra-stripped SN --- is a neutron star with mass

in the range 1.1--1.8\,$M\_\odot$ \citep{Tauris2015}. The small ejecta mass and the small binding energy

of the stripped envelope imply a small kick velocity ($\sim 50\,{\rm km\, s^{-1}}$) imparted onto the

newborn NS \citep{Tauris2015, Suwa2015, Bray2016, Muller2018}, which can prevent the binary system

from being disrupted or broken up, leaving a compact NS binary \citep{Tauris2017}. Ultra-stripped iron

CCSNe therefore serve as a natural formation channel for compact NS binaries with small eccentricities.

\subsection{Comparison with Other Ultra-Stripped SNe Candidates}

In addition to \name\ and iPTF14gqr, we search the literature for other subluminous fast-evolving

hydrogen-poor SNe whose light curves can potentially be well fitted by an early-time shock-cooling

component from an extended envelope and a radioactivity-powered second peak with small $M\_{\rm

ej}$. We recover iPTFF16hgs \citep{DeKC2018} and SN2018lqo \citep{De2020b} as ultra-stripped SNe

candidates. Here we apply our modelling approach described in Section \ref{subsec:fastrise} and

\ref{subsec:radioactivity} to iPTF16hgs and SN2018lqo to distill the physical parameters of these two

events. We show the results in Table \ref{tab:model\_compare}. The ejecta masses of

iPTF16hgs and SN2018lqo are greater than that in SN2018dge and iPTF14gqr by a factor of $\sim3$,

and falls inside the range of $M\_{\rm ej}$ expected in explosions of a helium star orbiting a compact

object, but is at the upper side of the limits \citep{Tauris2015}.

A full discussion of the progenitors of iPTF16hgs and SN2018lqo is beyond the scope of this paper.

Here we refer to a recent study conducted by \citet{De2020b}, which classify these two objects into

the ``green Ca-Ib'' subclass in the Ca-rich SNe category. This class of objects is spectroscopically

similar to SNe Ib at maximum light, and do not exhibit line-blanketed continua at

$\sim3500$--5500\AA. \citet{De2020b} proposed that pure helium-shell detonations or deflagrations

can explain their photometric and spectroscopic properties. In this scenario, the early-time peak might

be caused by radioactive decay from short-lived isotopes in the outermost ejecta, and the main

peak is powered by $^{56}$Ni decay.

\section{Rates} \label{sec:rates}

As progenitors of compact neutron star binaries, the volumetric rates

of ultra-stripped SNe have implications for our understanding of the evolutionary pathways leading to

these systems and the gravitational waves detected by existing and upcoming facilities such as

LIGO/VIRGO \citep{GW170817}.

Based on population synthesis calculation, \citet{Tauris2015} estimate

that the volumetric rates of ultra-stripped SNe should be $\sim 0.1$--1\% of the rate of Core-collapse

SNe. Using the properties of the promising ultra-stripped SN iPTF14gqr \citep{De2018},

\citet{Hijikawa2019} estimate the volumetric rates of iPTF14gqr-like ultra-stripped SNe to be $\sim 2

\times 10^{-7}\,{\rm Mpc^{-3}\, yr^{-1}}$, or $\sim 0.2$\% of the local CCSNe rate

\citep{Li2011a}. However, since existing ultra-stripped SN candidates were found outside of systematic

SN classification efforts, observationally constraining the rates of ultra-stripped SNe has not been

possible thus far.

\subsection{Simple Estimation}

\subsubsection{Using the BTS Sample} \label{subsubsec:BTS}

\name\ was followed up as a part of the ZTF Bright Transient Survey

\citep[BTS,][]{FremlingBTS2019} that aims to spectroscopically classify all extragalactic transients in

ZTF brighter than 18.5--19\,mag at peak. Since BTS only reads from the ZTF public alert stream

(highlighted with a greater marker size in Figure~\ref{fig:lc\_pid}), \name\ peaks between 18.5 and

19.0\,mag in the BTS sample. Thanks to the relatively high spectroscopic completeness ($\approx

89$\%) at the brightness limit of 19.0\,mag, we can directly place constraints on the rates of \name-like

ultra-stripped SNe using the BTS sample.

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/lc\_programids.pdf}

\caption{Un-binned P48 light curve of \name. We highlight observations obtained in the public

Northern Sky Survey in a greater marker size and high-opacity colors, while observations obtained in

the high-cadence survey are shown in semi-transparent.

\label{fig:lc\_pid}}

\end{figure}

\name\ peaked at an absolute magnitude of $-16.44$\,mag in $g$-band.

At the BTS peak brightness limit of 19.0\,mag, objects similar to \name\ would be detectable

out to 123\,Mpc. Thus, taking only the local 123\,Mpc volume within redshift of $z = 0.028$, we

compare the number of CCSNe brighter than 19.0\,mag at peak that were found in the BTS experiment

in its first 12 months of operations (between 2018-06-01 and 2019-06-01). In this time period, BTS

classified a total of 116 CCSNe in this volume. As such, the detection of one object in this sample

constrains the rate of ultra-stripped SNe to be $\sim$0.86\% of the CCSNe rate brighter than $M =

-16.44$\,mag in this volume.

Taking the observed luminosity function of CCSNe in the local universe \citep{Li2011b}, we find that

$\approx 50$\% of CCSNe are fainter than $M = -16.44$\,mag. The

luminosity function corrected rate of \name-like events is then $\sim$0.43\% of the local CCSNe rate.

The inferred rate is consistent with that estimated in

\citet{Tauris2015}, but higher than that inferred for iPTF14gqr-like events \citep{Hijikawa2019}.

Adopting the CCSNe volumetric rate of $0.7 \times 10^{-4}\,{\rm Mpc^{-3}\, yr^{-1}}$

\citep{Li2011a}, the volumetric rate of \name-like ultra-stripped SNe rate is $\sim$300\,${\rm Gpc^{-3}\,

yr^{-1}}$. This rate estimation is likely only a lower limit, since the

fast photometric evolution of objects similar to \name\ can be easily missed due to the slower 3-day

cadence of the ZTF public survey.

\subsubsection{Using the CLU sample}

The ZTF team also conducts a campaign to spectroscopically

classify all SNe within 200\,Mpc by filtering transients occurring in galaxies with

previously known redshifts within $z\leq0.05$ in the Census of the Local Universe (CLU) catalog

\citep{De2020b}. Hereafter we refer this experiment as CLU. The spectroscopic completeness of

transients in the CLU sample that had at least one detection brighter

than 20\,mag is 89\%. Since CLU reads from the whole ZTF alert stream (e.g., all data points shown in

Figure~\ref{fig:lc\_pid}), the higher-cadence sub-surveys allow it to better characterize fast-evolving

SNe. However, the uncertainty in this experiment is the incompleteness of the input galaxy catalog.

The redshift completeness factor (RCF) is $\approx80$\% at the lowest redshifts and decreases to

$\approx50$\% at $z=0.05$, as measured by the BTS experiment \citep{FremlingBTS2019}.

At the CLU peak brightness limit of 20.0\,mag, objects similar to \name\ would be detectable out to

195\,Mpc. Between 2018-06-01 and 2019-06-01, CLU classified a total of 273 CCSNe in this volume,

whereas no good ultra-stripped SNe candidates have been identified. This might be used to place an

upper limit of ultra-stripped SNe rate following the simple calculation described in

Section~\ref{subsubsec:BTS}. However, it is also susceptible to the fast evolution of \name-like SNe

being missed by the observation gaps. In Section \ref{subsec:cadence} we attempt to place robust

estimates of \name-like ultra-stripped SNe rate by running simulated surveys with the ZTF cadence.

\subsection{Estimation Based on Survey Simulations}\label{subsec:cadence}

We utilize \texttt{simsurvey} \citep{Feindt2019}, a \texttt{python} package designed for

assessing the rates of transient discovery in surveys like ZTF. To simulate the expected yield of a

specific type of transient given a volumetric rate, \texttt{simsurvey} requires three inputs: 1) A survey

schedule. We use the actual ZTF observing history in $g$- and $r$-band between 2018-06-01 and

2019-06-01 in any of the public or collaboration surveys as the input survey plan. 2) A transient model.

We construct a light curve template of \name\ (see details in Appendix \ref{subsec:gaussian}). Using

the template, we generate a \texttt{TimeSeriesSouce} model in the \texttt{sncosmo} package

\citep{Barbary2016}. 3) A function to sample the transient model parameters. Transients are injected

out to a redshift of $z=0.044$, since objects further out are not expected to peak birghter than

20.0\,mag.

We examine the expected number of detected \name-like SNe for a range of input rates from

$100\,{\rm Gpc^{-3}\,yr^{-1}}$ to 20,000\,${\rm Gpc^{-3}\,yr^{-1}}$. For each input rate, we performed

300 simulations of the ZTF observing plan. In order to select transient candidates that would have

passed the selection criteria of the BTS or CLU experiment and been flagged as an object with

photometric properties consistent with being a \name-like ultra-stripped SN, we apply cuts on the

simulated light curves as described below.

For the BTS filter, we only use public survey pointings, and reject SNe at low Galactic latitudes ($|b|\leq

7 \degree$) to be consistent with the BTS experiment \citep{FremlingBTS2019}. In either the $g$- or

$r$-band light curve, we identify peak light as the brightest detection in the simulated light curve, and

require:

\begin{enumerate}[label=(\roman\*)]

\item peak magnitude $<19.0$\,mag

\item within 4.1\,d before peak, there must be at least one detection or one upper limit

deeper than 1.5\,mag below peak

\item within 15\,d after peak, there must be at least three detections, and the measured decline rate

must be greater than $0.07\,{\rm mag\,d^{-1}}$.

\end{enumerate}

Criterion (ii) is set to require that the fast rise of the light curve can be recognized from the

observation. This is essential since if we only discover \name\ at the radioactive tail, we will

probably classify it as a low-velocity SN Ib. Criterion (iii) is

made to ensure that the rapid decline of the light curve can be captured, such that the small ejecta

mass can be inferred.

For the CLU filter, we use all ZTF pointings, and require that in either the $g$- or $r$-band light curve:

\begin{enumerate}[label=(\roman\*)]

\item peak magnitude $<20.0$\,mag

\item the light curve must satisfy at least one of the following criteria: 1) within 4.1\,d before peak,

there must be at least one detection or one upper limit deeper than 1.5\,mag below peak,

2) within 2.5\,d before peak, there must be at least one detection deeper than 0.75\,mag below

peak

\item same as criterion (iii) applied in the BTS filter.

\end{enumerate}

We apply the above criteria to the actual observations of CCSNe in the BTS and CLU sample. We

identify one other SN --- ZTF18abwkrbl (SN2018gjx) --- that pass our criteria. However, ZTF18abwkrbl

is a SN IIb that clearly shows hydrogen in the spectra, and can therefore be excluded as an

ultra-sttripped SNcandidate \citep{Tauris2015}.

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/SN2019dge\_rate\_pct.pdf}

\caption{The number of \name-like SNe passing criteria (descrived in text) as a

function of the input volumetric rate, in both the BTS and CLU experiments. The lines show the

mean of the 300 simulations, and the shaded boundaries indicate the 16th and 84th percentiles.

\label{fig:rate}}

\end{figure}

In Figure~\ref{fig:rate}, we show the number of transients that pass our selection criteria as a function

of the input volumetric rate. The solid line and shaded region indicate the mean and 68\% credible

region of the 300 simulations. In the actual BTS experiment, there was only \textit{one} detected

ultra-stripped SN. Therefore, we consider the range of volumetric rate where \textit{one} falls within

the shaded red region as a constraint on the rate of \name-like ultra-stripped SNe.

This gives $R\_{\rm 19dge}$ in the range of 1400--25,000\,${\rm Gpc^{-3}\,yr^{-1}}$.

Using the fact that there was \textit{zero} ultra-stripped SN detected in the actual CLU experiment, the

grey shaded region in Figure~\ref{fig:rate} might suggest $R\_{\rm 19dge}\lesssim 4500\,{\rm

Gpc^{-3}\,yr^{-1}}$. However, this upper limit needs to be corrected for offset

distribution and galaxy catalog incompleteness. First of all, as discussed in \citet{De2020b}, the CLU

experiment is restricted to trnasients coincident within 100$^{\prime\prime}$ of the host galaxy nuclei.

\name\ and iPTF14gqr are 0.5$^{\prime\prime}$ and 24$^{\prime\prime}$ from their host galaxies (all

within 100$^{\prime\prime}$). Although a large sample of ultra-stripped SNe is needed to examine the

host offset distribution of this class of objects, the fact that they arise from massive binary evolution

suggest that the correction due to this factor should be small. Secondly, the incompleteness of the

input galaxy catalog likely lead to an underestimation of ultra-stripped SNe rate by a factor of

55--80\%, as indicated by the RCF. We adjust for such an imcompleteness by increase the upper limit

from 4500 to 9000\,${\rm Gpc^{-3}\,yr^{-1}}$.

Combining results from the BTS and CLU experiments, we derive a \name-like ultra-stripped SNe rate of

1400--9000\,${\rm Gpc^{-3}\,yr^{-1}}$, corresponding to 2--13\% of CCSNe rate.

\subsection{Effects of Different Envelope Masses and Radii}

\label{subsubsec:physics}

Given the low mass of ultra-stripped progenitors, we expect to see shock cooling emission from the

inflated pre-explosion star, as has been clearly seen in the case of iPTF14gqr and SN2019dge in the

fast early-time evolution and blue colors of the optical light curve. As is shown by

\citet[][Fig. 2]{Nakar2014}, rise time of the shock cooling light curve is determined by mass of the

extended material $M\_{\rm ext}$, while the peak luminosity is mainly modulated by $R\_{\rm ext}$. We

demonstrate this dependence in Figure~\ref{fig:cooling}. We simulate shock cooling light curves by

varying $M\_{\rm ext}$ and $R\_{\rm ext}$, and at the same time setting $E\_{\rm ext}=1.15\times

10^{50}\,{\rm erg}$ (the value found in \name).

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/cooling\_trise.pdf}

\includegraphics[width=\columnwidth]{figures/cooling\_Mpeak.pdf}

\caption{Expected $r$-band rise time (upper panel) and $g$-band peak absolute luminosity (bottom

panel) as a function of shock cooling model parameters $R\_{\rm ext}$ and $M\_{\rm ext}$. Position of

\name\ is indicated by the black asterisks. In the upper panel, parameter space that could not pass

our criteria of ``rise from 1.5\,mag below peak to peak in less than 4.1\,d'' (Section

\ref{subsec:cadence}) is indicated by the hatched region. \label{fig:cooling}}

\end{figure}

In the upper panel, $t\_{\rm rise}$ is defined in the same

way as in Section \ref{subsubsec:compare\_mag} (rise time from half-max to max). The rising part of

the cooling light curve can be captured by a three-day, two-day, and one-day cadence optical survey

at $M\_{\rm ext}\gtrsim 0.14\,M\_\odot$, $\gtrsim 0.07\,M\_\odot$, and $\gtrsim 0.03\,M\_\odot$,

respectively. Transients with $M\_{\rm ext} \gtrsim 0.15\,M\_\odot$ will not pass our selection criteria in

Section \ref{subsec:cadence}. In the bottom panel, we show the expected absolute luminosity at

peak of the $g$-band cooling light curve. As is readily shown, for ultra-stripped progenitors with an

extended radius $\lesssim 2\times 10^{12}\,{\rm cm}$, a survey like ZTF is only sensitive to objects

in the local universe ($\lesssim 100$--150\,Mpc) for the subsequent evolution of the light curve to be

well-characterized. Taken together, we conclude that our estimation of the ultra-stripped SNe rate

does not include ultra-stripped progenitors with $M\_{\rm ext}\gtrsim 0.15\,M\_\odot$ or $R\_{\rm

ext}\lesssim 2\times 10^{12}\,{\rm cm}$.

\subsection{Other Uncertainties}

\label{subsec:companion}

The above estimation of ultra-stripped SNe rate should \textit{not} be directly compared with double

neutron star (DNS) local coalescence rate density ($R\_{\rm DNS}$) due to several reasons. First of all,

if the companion of the pre-explosion helium star is a white dwarf or a black hole, \name\ will

\textit{not} be the progenitor of a double neutron star system, and thus the inferred $R\_{\rm dge}$ is

not connected with $R\_{\rm DNS}$. Secondly, even in the case that the companion is a neutron star, if

the forming DNS binary has orbital periods less than $\sim1$\,d, it cannot merger within the age of the

Universe \citep{Tauris2015}. Future theoretical work is needed to establish the relationship between

orbital periods of the pre-explosion binary systems and SNe observational properties. Finally, as noted

in the introduction, apart from the ultra-stripped progenitors, DNSs can also form via dynamical

capture in a globular cluster \citep{East2012, Andrews2019}. As the fraction of DNSs formed from each

channel is not clear, this acts as another uncertainty in relating $R\_{\rm dge}$ to $R\_{\rm DNS}$.

\section{Conclusion} \label{sec:conclusion}

In this paper we have presented the discovery, observation and modeling of the transient \name. We

summarize the main characteristics of this object below:

\begin{enumerate}[label=(\alph\*)]

\item Peak absolute magnitudes are $M\_{g\rm , peak}\approx -16.5$\,mag and $M\_{r \rm ,peak }

\approx -16.3$\,mag. In $r$-band, rise time (half-max to max) is 2.0\,d and decay time (max to

half-max) is 8.6\,d. \name\ is one of the most rapidly rising subluminous SNe I known thus far.

\item Early-time spectra show a blue continuum and flash \ion{He}{II} features that indicate a

high mass loss rate of $\gtrsim 10^{-4}\, M\_\odot \, \rm yr^{-1}$.

\item Photosperic spectra indicate a helium-rich ejecta, and the prominent NUV \ion{Mg}{II} emission

suggests interaction between SN ejecta and CSM.

\item Late-time spectra show signatures of interaction with helium-rich CSM, similar to that observed

in Type Ibn SNe.

\item \name\ exploded only $0.2$\,kpc away from the nucleus of a compact low-metallicity

($Z\approx 0.005$) galaxy with small star formation rate (${\rm SFR}\approx 0.015\, M\_\odot\, \rm

yr^{-1}$) and stellar

mass ($M\_\ast \approx 2.5 \times 10^{8}\, M\_\odot$).

\item The bolometric light curve of \name\ peaks at $\sim 5 \times 10^{42}\,{\rm erg\, s^{-1}}$,

and can be explained by a combination of two components. The first component is consistent

with shock cooling from an envelope of $\sim 0.1\,M\_\odot$ located at $\sim 3\times 10^{12}\, \rm

cm$ ($40\, R\_\odot$) from the progenitor. The second component is powered by

$\sim 0.017\, M\_\odot$ of $^{56}$Ni.

\item We estimate the ejecta mass and kinetic energy of \name\ to be 0.25--0.35\,$M\_\odot$

and 5.5--7.3\,$\times10^{49}\,{\rm erg}$, respectively.

\end{enumerate}

Taken together, we interpret \name\ as the first helium-rich ultra-stripped envelope SN.

Based on the one event, we estimate the rate density of \name-like ultra-stripped SNe (with $M\_{\rm

ext}\lesssim 0.15\,M\_\odot$ and $R\_{\rm ext}\gtrsim 2\times 10^{12}\,{\rm cm}$) to be

1400--9000\,${\rm Gpc^{-3}\, yr^{-1}}$. If the companion of the

pre-explosion helium star is also a neutron star, and the orbital period of the formed DNS is short

enough to merge within a Hubble time, \name\ will represent the progenitors of DNS gravitational wave

systems. The first detection of gravitational waves from merging DNS binary GW170817 gave $R\_{\rm

DNS}=320$--$4740\,{\rm Gpc^{-3}\, yr^{-1}}$ \citep{GW170817}. Detection of GW190425 provides an

update of $R\_{\rm DNS}=250$--$2810\,{\rm Gpc^{-3}\, yr^{-1}}$ \citep{GW190425}. Based on an

archival search for EM170817-like transients (known as ``kilonovae'' or ``macronovae'') in the PTF

database, \citet{Kasliwal2017} reported an upper limit on the rate of $800\,{\rm Gpc^{-3}\, yr^{-1}}$,

which might be doubled if the typical kilonova is 50\% fainter than EM170817. In an order-of-magnitude

comparison, our constraint of $R\_{\rm 19dge}$ is thus similar to $R\_{\rm DNS}$ implied by the

LIGO/VIRGO experiment and the upper limit of kilonovae rate estimated from PTF.

It is important to compare ultra-stripped SNe rate and $R\_{\rm DNS}$ constrained by future GW

observations. This will help to anwer the question that, among the ultra-stripped SN and the dynamical

formation channel, which one is the major path for forming DNS systems. As such, further systematic

search for ultra-stripped SNe is requried to reduce the large uncertainties of the current estimation.

%The upcoming Large Synoptic Survey Telescope (LSST) at Rubin Observatory will have a typical

%cadence of 3--4 days \citep{Ivezic2008}, and is thus not ideal to find fast-evolving transients.

Moving forward, the discovery of ultra-stripped SNe will still reply on high-cadence

wide-field experiments such as ZTF. In particular, the upcoming ZTF-II, with a two-day cadence all

survey survey, coupled with higher cadence boutique experiments, is well-positioned to carry out this

task.

\acknowledgements

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teaching techniques in time-domain data analysis. This study made use of the open supernova catalog

\citep{Guillochon2017}.

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University, the University of Maryland, the University of Washington, Deutsches

Elektronen-Synchrotron and Humboldt University, Los Alamos National Laboratories, the TANGO

Consortium of Taiwan, the University of Wisconsin at Milwaukee, and Lawrence Berkeley National

Laboratories. Operations are conducted by COO, IPAC, and UW.

\software{

\texttt{astropy} \citep{Astropy-Collaboration2013},

\texttt{corner} \citep{Foreman-Mackey2016},

\texttt{emcee} \citep{Foreman-Mackey2013},

\texttt{Lpipe} \citep{Perley2019lpipe},

\texttt{matplotlib} \citep{Hunter2007},

\texttt{pandas} \citep{McKinney2010},

\texttt{pyneb} \citep{Luridiana2013},

\texttt{pyraf-dbsp} \citep{Bellm2016},

\texttt{scipy} \citep{Jones2001},

\texttt{simsurvey} \citep{Feindt2019},

\texttt{sncosmo} \citep{Barbary2016}

}

%% For this sample we use BibTeX plus aasjournals.bst to generate the

%% the bibliography. The sample63.bib file was populated from ADS. To

%% get the citations to show in the compiled file do the following:

%%

%% pdflatex sample63.tex

%% bibtext sample63

%% pdflatex sample63.tex

%% pdflatex sample63.tex

\appendix

\section{UV and Optical Data} \label{sec:appphot\_data}

\input{tables/tab\_phot.tex}

\input{tables/tab\_host\_phot.tex}

The full set of photometry of \name\ is listed in Table~\ref{tab:phot}. Photometry of the host

galaxy SDSS J173646.73+503252.3 is listed in Table~\ref{tab:host\_phot}.

\section{Modelling of \name}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/bbprior.pdf}

\caption{Posterior (solid lines) distribution of the blackbody temperature

$T\_{\rm bb}$ on Apr 7 (upper panels) and Apr 9 (bottom panels) using three different priors

(dotted

lines). \label{fig:bbprior}}

\end{figure}

\begin{figure\*}

\centering

\includegraphics[width = 0.9\textwidth]{figures/seds\_log.pdf}

\caption{Black data points are $Swift$/UVOT and optical photometry of \name. Solid lines show

model fits using estimated parameters, while 30 random draws from the MCMC posterior are

shown with dashed lines.

\label{fig:seds}}

\end{figure\*}

\input{tables/tab\_bbfit.tex}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/corner\_P15.pdf}

\caption{Corner plot showing the posterior constraints on ${\rm lg}R\_{\rm ext}$, ${\rm lg}M\_{\rm

ext}$, $t\_\mathrm{fl}$, and $E\_{\rm ext, 49}$. Marginalized one-dimensional distributions are

shown along the diagonal, along with the median estimate and the 68\% credible region (shown

with vertical

dashed

lines). \label{fig:pirocorner}}

\end{figure}

\input{tables/tab\_P15priors.tex}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/P15model.pdf}

\caption{Cooling emission model fit to the early light curve of \name.

Data excluded from the fitting are shown as transparent circles.

The maximum a posteriori model is shown via solid lines.

The vertical dashed line shows the median 1-D marginalized posterior value of

$t\_{\rm fl}$.

\label{fig:piromodel}}

\end{figure}

\input{tables/tab\_Nidecaypriors.tex}

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/corner\_arnett\_modified.pdf}

\caption{Corner plot showing the posterior constraints on $\tau\_{\rm m}$, ${\rm lg}M\_{\rm

Ni}$, and $t\_0$. Marginalized one-dimensional distributions are shown along the

diagonal, along with the median estimate and the 68\% credible region (shown with vertical

dashed

lines). \label{fig:Nidecaycorner}}

\end{figure}

\subsection{Modelling the Physical Evolution} \label{subsec:bbfit}

To model the multi-band light curve with a blackbody function, we utilized the Monte Carlo Markov

Chain (MCMC) simulations with \texttt{emcee} \citep{Foreman-Mackey2013}. We test the performance

of three types of model priors for

the blackbody radius ($R\_{\rm bb}$) and temperature ($T\_{\rm bb}$): (i) $T\_{\rm bb}$

and $R\_{\rm bb}$ are uniformly distributed in the range of [$10^3$, $10^7$]\,K and [$10$,

$10^6$]\,$R\_\odot$, respectively (ii) the two paramters are logarithmically uniformly

distributed in the same ranges (ii) the two paramters follow Jeffreys prior \citep{jeffreys1946invariant}

in the same ranges.

Within the ensemble, we use 100 walkers, each of which is run until convergence or 100,000 steps,

whichever comes first. The test for convergence follows steps outlined in \citet{Yao2019} and

\citet{Miller2020}. We adopt the 68\% credible region (i.e., $16^{\rm th}$ and $84^{\rm th}$ percentiles

of posterior probability distributions) as the model uncertainties quoted in Table~\ref{tab:bbfit}.

We examine the fitting results under different choice of priors in Figure~\ref{fig:bbprior}, which shows

the posterior distribution of $T\_{\rm bb}$ using data obtained on Apr 7 (top panels) and Apr 9 (bottom

panels). Early stages of SN evolution often feature extremely high temperatures. At an epoch where

both UV and optical data are available (Apr 9), the posterior does not depend on the particular choice

of prior, and the model parameter can thus be well constrained. However, at our first detection epoch

where only optical data is available (Apr 7), the posterior strongly depends on the prior. For a linearly

flat prior, high numbers receive a lot of ``weight'', making the ``multi-peaks'' shape posterior in the

upper left panel of Figure~\ref{fig:bbprior}. Log prior and Jeffreys prior generally give the same result.

Given that all models were run to converge using the log prior, whereas fitting of the first epoch did

not converge adopting Jeffreys prior, we adopt results using log prior in this study.

In Figure \ref{fig:seds} we show the photometry interpolated onto common epochs, and fit to a

blackbody function to derive the photospheric evolution. The resulting evolution in bolometric

lumonosity, photospheric radius, and effective temperatures is listed in Table \ref{tab:bbfit}.

\subsection{Modelling Early Light Curve} \label{subsec:p15fit}

We cast the P15 analytical expression for the shape of the early-time light curve in terms of $M\_{\rm

ext}$, $R\_{\rm ext}$, $E\_{\rm ext}$, and $E\_{51}$:

\begin{subequations}

\begin{align}

L(t) =& \frac{t\_eE\_{\rm ext}}{t\_p^2} {\rm exp} \left[ -\frac{t (t + 2t\_e)}{2t\_p^2}\right] \,{\rm erg\, s^{-1}}\\

t\_e =& 10^{-9} R\_{\rm ext} E\_{\rm ext,49}^{-1/2}

\left(\frac{M\_{\rm ext}}{0.01 M\_\odot}\right)^{1/2} \, {\rm s}\\

t\_p =& 1.1\times 10^{5} \kappa\_{0.34}^{1/2} E\_{51}^{-0.01 /

1.4} \notag \\

& \times E\_{\rm ext, 49}^{-0.17 / 0.7} \left(\frac{M\_{\rm ext}}{0.01 M\_\odot}\right)^{0.74} {\rm s}

\label{eq:tp}

\end{align}

\end{subequations}

where $t$ is time since explosion in seconds, $\kappa\_{0.34} = \kappa / (0.34\,{\rm cm^2\, g^{-1}})$,

$E\_{\rm ext, 49} = E\_{\rm ext} /

(10^{49}\,{\rm erg\,s^{-1}})$, $E\_{51} =E / (10^{51}\,{\rm

erg\,s^{-1}})$, and $E$ is energy of the explosion.

Following P15 we assume the emission is a blackbody at radius

\begin{align\*}

R(t) = R\_{\rm ext} + 10^9 \left( \frac{E\_{\rm ext}}{10^{49}\,{\rm

erg\,s^{-1}}} \right)^{1/2} \left(\frac{M\_{\rm ext}}{0.01 M\_\odot}\right)^{-0.5} t

\end{align\*}

and temperature

\begin{align\*}

T(t) = \left( \frac{L(t)}{4\pi R(t)^2 \sigma\_{\rm SB}} \right)^{1/4}

\end{align\*}

We fix $\kappa \approx 0.2\,{\rm cm^2\, g^{-1}}$ as

appropriate for a hydrogen-deficient ionized gas, and assign wide flat priors for all model parameters,

as summarized in Table~\ref{tab:P15priors}. We only include observations up to $\Delta t = 2$\,d in

the fitting. We found that this particular choice of $\Delta t$ --- 2\,d instead of 1\,d or 3\,d --- in

general does not affect the final inference for the model parameters. Figure~\ref{fig:pirocorner} shows

the corner plot of ${\rm lg}R\_{\rm ext}$, ${\rm lg}M\_{\rm ext}$, $t\_\mathrm{fl}$, and $E\_{\rm ext, 49}$.

For clarity, $E\_{51}$ is excluded as it does not exhibit strong covariance with the parameters shown

here. This can be understood by Eq.~\ref{eq:tp}, which gives $t\_p \propto E\_{51}^{-0.01/1.4}$,

suggesting that the shock cooling luminosity only weakly depends on $E\_{51}$.

The maximum a posteriori model is visualized by solid lines in Figure~\ref{fig:piromodel} color-coded in

different filters. Note that the fitting is not perfect at the UV bands since

the SED is not exactly a blackbody at peak (see Figure~\ref{fig:seds}). The rising part of the model

does not closely match to data due to the ignorance of the density structure of the stellar profile.

Nevertheless, the peak of the light curve is well captured by this model.

\begin{figure}[htbp!]

\centering

\includegraphics[width=\columnwidth]{figures/template\_g.pdf}

\includegraphics[width=\columnwidth]{figures/template\_r.pdf}

\caption{$g$- and $r$-band light curve templates for \name\ obtained from Gaussian process

fitting. \label{fig:template}}

\end{figure}

\subsection{Modelling the Main Peak}\label{subsec:arnettfit}

For $^{56}\rm Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ decay powered explosions, the energy

deposition rate is

\begin{align}

\varepsilon\_{\rm rad} =&\varepsilon\_{\rm Ni, \gamma} (t) + \varepsilon\_{\rm Co, \gamma} (t)

\label{eq:heatTotal} \\

\varepsilon\_{\rm Ni, \gamma} (t) =& \epsilon\_{\rm Ni}e^{-t/\tau\_{\rm Ni}} \label{eq:heatNi}\\

\varepsilon\_{\rm Co, \gamma} (t) =& \epsilon\_{\rm Co} \left( e^{-t/\tau\_{\rm Co}} - e^{-t/\tau\_{\rm

Ni}} \right) \label{eq:heatCo}

\end{align}

where $\epsilon\_{\rm Ni}= 3.90 \times 10^{10} \, {\rm erg\,g^{-1}\,s^{-1}}$, $\epsilon\_{\rm Co}=6.78\times

10^{9} \, {\rm erg\,g^{-1}\,s^{-1}}$, $\tau\_{\rm Ni}=8.8$\,d and $\tau\_{\rm Co}=111.3$\,d are the decay

lifetimes of $^{56}\rm Ni$

and $^{56}\rm Co$ \citep{Nadyozhin1994}. The effective heating rate is modified by the probability of

thermalization, and thus $\varepsilon\_{\rm heat} \leq \varepsilon\_{\rm rad}$.

The bolometric light curve can be generally divided into the

photospheric phase and the nebula phase. The photospheric phase can be modelled using Equations

given in \citet[][Appendix A]{Valenti2008}, with modifications given

by \citet[][Eq.~3]{Lyman2016},

\begin{align}

L\_{\rm phot} (t) =& M\_{\rm Ni} {\rm e}^{-x^2} \times \notag \\

& \Big[ (\epsilon\_{\rm Ni} - \epsilon\_{\rm Co}) \int\_0^x (2z {\rm e}^{-2zy+z^2}){\rm d} z \notag \\

& + \epsilon\_{\rm Co} \int\_0^x (2z {\rm e}^{-2zy+2zs + z^2}) {\rm d} z \Big]

\end{align}

where $x = t/\tau\_{\rm m}$, $y = \tau\_{\rm m} / (2\tau\_{\rm Ni})$,

\begin{align}

s &= \frac{\tau\_{\rm m} (\tau\_{\rm Co} - \tau\_{\rm Ni})}{2 \tau\_{\rm Co} \tau\_{\rm Ni}}, \notag \\

\tau\_{\rm m} &= \left( \frac{2\kappa\_{\rm opt} M\_{\rm ej}}{13.8 c v\_{\rm phot}}\right)^{1/2}

\label{eq:taum}

\end{align}

At the nebula phase the SN ejecta becomes optically thin, such that the delay between the energy

deposition from radioactivity and the optical radiation becomes shorter. The bolometric luminosity is

then equal to

the rate of energy deposition: $L\_{\rm neb}(t) = Q(t)$. At any given time, the energy deposition rate

$Q(t)$ is \citep{Wheeler2015, Wygoda2019}:

\begin{align}

Q(t) \approx Q\_{\gamma}(t) \left( 1 - e^{-(t\_0/t)^2}\right) % Q\_{\rm pos}(t),

\end{align}

where $Q\_{\gamma}(t) = M\_{\rm Ni}\varepsilon\_{\rm rad}$ is the energy release rate of gamma-rays,

$t\_0$ is the time at which the ejecta becomes optically thin to gamma rays. Here the difference

between energy deposition rate of gamma-rays and positrons is neglected.

%\begin{align}

%Q\_{\rm pos}(t) &= M\_{\rm Ni}\varepsilon\_{\rm Co, pos}(t)\\

%\varepsilon\_{\rm Co, pos}(t) &= 2.3\times 10^{8} \left( e^{-t/t\_{s, {\rm Co}}} - e^{-t/t\_{s, {\rm Ni}}}\right)

%\end{align}

To fit the shock cooling subtracted bolometric light curve with a simple radioactive decay model, we do

not divide the data into photosperic phase and nebula phase, but instead adopt the following formula

for the whole light curve:

\begin{align}

L(t) = L\_{\rm phot}(t) \left( 1 - e^{-(t\_0/t)^2}\right)

\end{align}

Priors or the model parameters are summarized in Table~\ref{tab:Nidecaypriors}, and Figure

\ref{fig:Nidecaycorner} shows the coner plot of $\tau\_{\rm m}$, lg$M\_{\rm Ni}$, and $t\_0$.

\subsection{Generating a Light Curve Template for SN2019dge} \label{subsec:gaussian}

To construct a template for SN2019dge in the ZTF $g$ and $r$ filters, we model the observed light

curve by a Gaussian process. We denote the measurements as $(\mathbf{x}, \mathbf{y})$, where

$\mathbf{x}$ is ${\rm MJD}-58583.2$, and $\textbf{y}$ is flux calculated as $10^{-0.4m}\times 10^8$

($m$ is magnitude). We choose a kernel in the form of Matern covariance function

\citep[][Eq.~4.17]{rasmussen2003gaussian}:

\begin{align}

k\_{3/2}(x, x^{\prime}) = A \left( 1 + \frac{\sqrt{3}r}{l}\right) {\rm exp} \left(-

\frac{\sqrt{3}r}{l} \right) \label{eq:mat32}

\end{align}

where $r = |x-x^{\prime}|$. $A$ and $r$ in Eq.~\ref{eq:mat32} are chosen to minimize the negative log

likelihood function (see, e.g., Eq.~2.43 of \citealt{rasmussen2003gaussian}).

We perform the fit from $x=-10$\,d to $x=+40$\,d, and the obtained templates are shown in

Figure~\ref{fig:template}.

\bibliography{at2019dge}{}

\bibliographystyle{aasjournal}

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