

SN 2017fgc: A Fast-expanding Type Ia Supernova Exploded in Massive Shell Galaxy **NGC 474**

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Abstract

We present extensive optical photometric and spectroscopic observations of the high-velocity (HV) Type Ia supernova (SN Ia) 2017fgc, covering the phase from \sim 12 days before to \sim 389 days after maximum brightness. SN 2017fgc is similar to normal SNe Ia, with an absolute peak magnitude of $M_{\text{max}}^B \approx -19.32 \pm 0.13$ mag and a postpeak decline of $\Delta m_{15}(B) = 1.05 \pm 0.07$ mag. Its peak bolometric luminosity is derived as $(1.32 \pm 0.13) \times 10^{43}$ erg s⁻¹, corresponding to a ⁵⁶Ni mass of $0.51 \pm 0.03 M_{\odot}$. The light curves of SN 2017fgc are found to exhibit excess emission in the UBV bands in the early nebular phase and pronounced secondary shoulder/maximum features in the RrIi bands. Its spectral evolution is similar to that of HV SNe Ia, with a maximum-light Si II velocity of $15,000 \pm 150$ km s⁻¹ and a post-peak velocity gradient of $\sim 120 \pm 10$ km s⁻¹ day⁻¹. The Fe II and Mg II lines blended near 4300 Å and the Fe II, Si II, and Fe III lines blended near 4800 Å are obviously stronger than those of normal SNe Ia. Inspecting a large sample reveals that the strength of the two blends in the spectra, and the secondary peak in the i/r-band light curves, are found to be positively correlated with the maximum-light Si II velocity. Such correlations indicate that HV SNe Ia may experience more complete burning in the ejecta and/or that their progenitors have higher metallicity. Examining the birthplace environment of SN 2017fgc suggests that it likely arose from a stellar environment with young and high-metallicity populations.

Unified Astronomy Thesaurus concepts: Supernovae (1668); Type Ia supernovae (1728)

Supporting material: data behind figure, machine-readable tables

1. Introduction

Type Ia supernovae (SNe Ia) are widely believed to originate from thermonuclear runaway explosions of carbon-oxygen white dwarfs (WDs) in binary systems (e.g., Nomoto et al. 1997; Hillebrandt & Niemeyer 2000; Maoz et al. 2014; Livio & Mazzali 2018; Soker 2019), and they have a typical absolute V-band peak magnitude of \sim -19 mag (e.g., Phillips 1993; Perlmutter et al. 1999; Wang et al. 2006). One of the main applications of SNe Ia is that they can be utilized as extragalactic distance indicators

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(e.g., Riess et al. 1996; Guy et al. 2005; Wang et al. 2005; Howell et al. 2006; Howell 2011; Burns et al. 2018; Scolnic et al. 2018), leading to the discovery of the accelerating expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999).

Two prevailing ideas for the progenitor systems are the doubledegenerate (DD) scenario (Iben & Tutukov 1984; Webbink 1984) and the single-degenerate (SD) scenario (Whelan & Iben 1973; Nomoto et al. 1984; Podsiadlowski et al. 2008). The former scenario involves the dynamical merger of two WDs with an accretion phase (Rasio & Shapiro 1994; Yoon et al. 2007; Pakmor et al. 2012; Sato et al. 2015) or the violent/third-body-induced

collision of a binary WD (Thompson 2011; Pakmor et al. 2012; Raskin et al. 2014; Sato et al. 2015), while explosion in the latter case is triggered by accretion onto a WD from its nondegenerate companion (Whelan & Iben 1973; Iben & Tutukov 1984; Webbink 1984). However, details of the progenitor systems and explosion mechanisms of SNe Ia are still controversial (Wang et al. 2013; Maoz et al. 2014; Jha et al. 2019; Han et al. 2020). Some tentative evidence presented for the absence of companion stars in some SNe Ia favors the DD scenario (González Hernández et al. 2012; Schaefer & Pagnotta 2012; Olling et al. 2015; Tucker et al. 2019), while the possible detections of circumstellar material (CSM) support the SD scenario for at least a portion of SNe Ia (Hamuy et al. 2003; Wang et al. 2004, 2019b; Aldering et al. 2006; Pastorello et al. 2007; Blondin et al. 2009; Sternberg et al. 2011; Dilday et al. 2012; Taddia et al. 2012; Silverman et al. 2013; Bochenek et al. 2018), though some theoretical studies show that the CSM could also be produced in the DD scenario (Raskin & Kasen 2013; Shen et al. 2013; Levanon & Soker 2017).

Observations show that $\sim 70\%$ of SNe Ia are members of the spectroscopically normal subclass (Branch et al. 1993; Li et al. 2011), while the others are classified as peculiar, including the overluminous SN 1991T-like (Filippenko et al. 1992b; Ruiz-Lapuente et al. 1992; Filippenko 1997), the subluminous SN 1991bg-like (Filippenko et al. 1992a; Leibundgut et al. 1993), and the low maximum-light velocity with low luminosity SN Iax 2002cx-like (Filippenko 2003; Li et al. 2003; Foley et al. 2013). Benetti et al. (2005) divided normal SNe Ia into three subclasses: high velocity gradient (HVG), low velocity gradient (LVG), and faint, according to the temporal velocity gradient of the Si II line. Based on the equivalent width (EW) of Si II $\lambda 6355$ and Si II $\lambda 5972$ measured at B-band maximum, Branch et al. (2006) proposed that SNe Ia could be classified into core-normal, broad-line, cool, and shallow-silicon subgroups. According to the Si II $\lambda 6355$ velocity measured at B-band maximum, Wang et al. (2009a) suggested that the "Branch-normal" SNe Ia could be classified into normalvelocity (i.e., $v < 12,000 \text{ km s}^{-1}$; NV) and high-velocity (i.e., $v \ge 12,000 \text{ km s}^{-1}$; HV) subclasses. Although various classification schemes have been proposed to classify SNe Ia, there are overlaps between different classifications as demonstrated by different samples (Blondin et al. 2012; Silverman et al. 2012b). For example, HV SNe Ia are usually found to have large velocity gradient and broad line profiles (Barbon et al. 1989; Benetti et al. 2004: Wang et al. 2009a: Yamanaka et al. 2009: Silverman & Filippenko 2012). Moreover, after the analysis of the birthplace environments of SNe Ia in their host galaxies, Wang et al. (2013) suggest that the HV and NV subclasses of SNe Ia may come from progenitor systems with different metallicities.

Studies by Pan et al. (2015) and Li et al. (2021) suggest that HV SNe Ia tend to reside in massive galaxies and likely have metal-rich progenitor environments. Through an investigation of a large set of the host galaxies, Pan (2020) found that HV SNe might arise in massive host galaxies with metal-rich environments. Based on an analysis of Na I absorption lines in the spectra and the late-time light curves in the *B* and *V* bands, Wang et al. (2019b) show that HV SNe Ia likely have more abundant circumstellar dust around their progenitors, and they may originate from progenitor systems with nondegenerate companions.

SN 2017fgc is a fast-expanding SN Ia that exploded in the nearby shell galaxy NGC 474 at a distance of 29.51 ± 2.09 Mpc (Cappellari et al. 2011). Note that the host is a lenticular galaxy with prominent gas shell and bridge structures at its outskirts,

suggestive of the merging process (Lim et al. 2017; Alabi et al. 2020; Fensch et al. 2020). Burgaz et al. (2021) studied the photometric properties of this SN and proposed the presence of a prominent *RI*-band secondary shoulder/maximum. Here we present extensive photometric and spectroscopic observations of SN 2017fgc, and we report an additional discrepancy between the NV and HV subclasses in a well-observed sample of SNe Ia.

In this paper, the optical observations and data reduction are presented in Section 2. Section 3 discusses the light curve, color curves, and quasi-bolometric light curve, while Section 4 presents the spectroscopic evolution. The properties of SN 2017fgc and its host galaxy are discussed in Section 5. We summarize in Section 6.

2. Observations and Data Reduction

2.1. Discovery and Host Galaxy

SN 2017fgc was discovered at $\alpha = 01^{h}20^{m}14^{8}.440$, $\delta = 03^{\circ}24'09''.96$ (J2000) on 2017 July 9.29 (UT dates are adopted throughout this paper) by the Distance Less Than 40 Mpc (DLT40; Tartaglia et al. 2018) survey at r = 17.32 mag (Valenti et al. 2017b). At that time, the DLT40 survey operated with a ~24 hr cadence, and the last nondetection of the SN was on 2018 July 8.29 with a limiting magnitude of $r \approx 19.5$ mag. A spectrum taken ~1.4 hr after the discovery classified it as a normal SN Ia (Valenti et al. 2017a). The host galaxy of SN 2017fgc is NGC 474 with a redshift of $z = 0.00772 \pm 0.00002$ (Hernández-Toledo et al. 2011), which corresponds to a distance modulus of $\mu = 32.51 \pm 0.11$ mag assuming a Hubble constant of 73.5 km s⁻¹ Mpc⁻¹ (Riess et al. 2018).

2.2. Photometry

Our photometric observations of SN 2017fgc were obtained with several telescopes, including the 0.8 m Tsinghua-NAOC telescope (TNT; Huang et al. 2012), the Las Cumbres Observatory (LCO) Telescope network (Brown et al. 2010), the 0.76 m Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory (Filippenko et al. 1999, 2001), and the 1 m Nickel reflector²² at Lick Observatory. The TNT and the Nickel telescope monitored SN 2017fgc in the *BVRI* bands, KAIT observed it in the *BVRI* and Clear bands, and the LCO 1 m telescopes sampled the light curves in the *UBVgri* bands. Figure 1 shows color images of SN 2017fgc synthesized from observations in *gri* bands. The left panel shows a color image synthesized from CFHT²³ observations in *gr* bands processed by J.-C. Cuillandre and G. Anselmi, based on data from the MATLAS program (Duc et al. 2015), while the right panel shows a color image synthesized from TNT observations.

For photometric images obtained from the LCO during the Global Supernova Project, *lcogtsnpipe* (Valenti et al. 2016) was employed for image reduction. The point-spread function (PSF) implemented in *Photutils* (Bradley et al. 2020) was utilized to extract instrumental magnitudes of SN 2017fgc from images obtained by LCO. Photometric images from KAIT and Nickel were reduced with LOSSPhotPypeline²⁴ (Stahl et al. 2019, 2020a). The DLT40 images were reduced using a dedicated difference-imaging pipeline (Tartaglia et al. 2018), which calibrates the Open filter data to the *r* band utilizing the

²² https://www.ucolick.org/public/telescopes/nickel.html

²³ https://www.cfht.hawaii.edu/HawaiianStarlight/images.html

²⁴ https://github.com/benstahl92/LOSSPhotPypeline



Figure 1. Left: a color image synthesized from observations in gr bands obtained by the CFHT before the discovery of SN 2017fgc. The red circle marks the position of SN 2017fgc and the gas bridge can be clearly seen here. Right: a color image synthesized from TNT observations in the gri bands after the explosion of SN 2017fgc; the SN is marked with a red circle while the reference stars are labeled by numbers.

AAVSO Photometric All-Sky Survey (APASS²⁵) catalog. PSF photometry was performed on the difference images. As SN 2017fgc was located far away (\sim 18.90 ± 0.01 kpc) from the center of its host galaxy, we did not apply image-subtraction techniques for the photometry.

The color-transformation method introduced by Jordi et al. (2006) was employed to convert gri magnitudes from Sloan Digital Sky Survey (SDSS) DR12 (Alam et al. 2015) to Landolt UBVRI (Landolt 1992) magnitudes. The local standard stars with SDSS gri magnitudes and the transformed UBVRI magnitudes are listed in Table 1. The instrumental magnitudes obtained from TNT and KAIT in BVRI are calibrated to the Johnson UBVRI system (Landolt 1992; Stetson 2000). The unfiltered magnitudes from KAIT are calibrated to the standard Landolt *R*-band magnitudes, with a typical uncertainty of about 0.2-0.3 mag (Li et al. 2003; Zheng et al. 2017a). The LCO instrumental magnitudes in UBV are calibrated to the Johnson system (Landolt 1992; Stetson 2000), while the gri magnitudes are calibrated using the SDSS DR12 catalog (Alam et al. 2015). The final light curves are shown in Figure 2, and the fluxcalibrated magnitudes are listed in Table 2.

2.3. Spectroscopy

A total of 38 low-resolution spectra were obtained for SN 2017fgc with different instruments, including the FLOYDS spectrographs mounted on the LCO 2 m Faulkes Telescope North and South (FTN and FTS; Sand et al. 2011; Brown et al. 2013), the BFOSC mounted on the Xinglong 2.16 m telescope (XLT; Jiang et al. 1999; Fan et al. 2016; Zhang et al. 2016a), the YFOSC on the Lijiang 2.4 m telescope (LJT; Chen et al. 2001; Wang et al. 2019a) of Yunnan Astronomical Observatories, and the Kast spectrograph on the Lick 3 m Shane telescope (Filippenko et al. 1986; Vogt 1987; Stahl et al. 2020b). Three additional spectra of SN 2017fgc were obtained

with XSHOOTER (Vernet et al. 2011) mounted on the ESO Very Large Telescope (VLT), at $t \approx +149.7$ days, +383.9 days, and 388.9 days during ESO programs 0101.D-0242(A) and 0101.D-0443(A) (Graur et al. 2020). The journal of spectroscopic observations is presented in Table 3.

Standard IRAF²⁶ routines were used to reduce the spectra. Spectrophotometric standard stars observed at an airmass comparable to the target on the same night were used for flux calibration. The extinction curves at various observatories were utilized to correct for atmospheric extinction, and spectra of the standard stars were used to eliminate the telluric absorption lines.

3. Light Curves

3.1. Optical Light Curves

Figure 2 shows the optical light curves of SN 2017fgc, covering the phases from about two weeks before to over 200 days after *B*-band maximum light. Overall, they are similar to those of normal SNe Ia, characterized by a prominent shoulder or secondary maximum in the R/r and I/i bands. A small shoulder may also be detectable in the *V* and Clear bands. Applying a polynomial fit to the *B*-band light curves around maximum light yields a peak value of 13.07 ± 0.11 mag on MJD = 57,959.4 (2017 July 25.4 UT). The *V*-band light curve reached its peak of 12.91 ± 0.07 mag on MJD = 57,962.5, ~ 3.1 days after the *B*-band peak. The post-peak *B*-band decline rate $\Delta m_{15}(B)$ is measured as 1.05 ± 0.07 mag, and the color stretch (Burns et al. 2011, 2014) is determined to be $s_{BV} = 1.19 \pm 0.03$.

In Figures 3 and 4 the *UBVg* and *RrIi* light curves of SN 2017fgc are compared with those of well-observed normal SNe Ia having similar $\Delta m_{15}(B)$, including SNe 2002bo (Benetti et al. 2004; Krisciunas et al. 2004), 2003du (Stanishev et al. 2007), 2005cf (Wang et al. 2009b), 2006X (Wang et al. 2008b), 2007af (Stritzinger et al. 2011), 2007le (Ganeshalingam et al. 2010;

²⁵ https://www.aavso.org/apass

 $[\]frac{26}{10}$ IRAF is distributed by NOAO, which is operated by AURA, Inc., under cooperative agreement with the U.S. National Science Foundation (NSF).

Photometric Standards in the SN 2017fgc Field 1 ^a										
Star	α (J2000)	δ (J2000)	U (mag)	B (mag)	V (mag)	R (mag)	I (mag)	<i>g</i> (mag)	r (mag)	i (mag)
1	01:20:23.613	+03:20:23.698	16.631(011)	16.636(006)	16.087(006)	15.810(006)	15.406(008)	16.305(004)	15.947(004)	15.817(005)
2	01:20:00.124	+03:19:30.367	16.605(011)	16.792(006)	16.201(006)	15.899(006)	15.465(008)	16.446(004)	16.040(004)	15.884(005)
3	01:19:58.102	+03:27:56.473	16.538(012)	16.045(005)	15.200(005)	14.758(005)	14.216(006)	15.609(004)	14.914(004)	14.662(004)
4	01:20:02.123	+03:22:04.735	16.183(011)	15.993(006)	15.311(006)	14.963(006)	14.511(006)	15.615(004)	15.106(004)	14.934(004)
5	01:20:15.741	+03:27:27.932	14.593(007)	14.396(004)	13.664(004)	13.539(013)	13.904(013)	14.000(002)	13.434(004)	14.888(012)
6	01:20:24.708	+03:24:02.095	15.114(008)	15.032(006)	14.437(006)	14.207(005)	14.040(005)	14.685(004)	14.275(004)	14.597(003)
7	01:19:58.888	+03:28:12.706	17.790(021)	17.635(007)	16.934(007)	16.574(007)	16.102(010)	17.250(005)	16.720(005)	16.534(005)
8	01:19:55.296	+03:21:52.628	16.527(011)	16.420(006)	15.796(006)	15.478(006)	15.045(007)	16.062(004)	15.619(004)	15.465(004)
9	01:20:16.752	+03:27:05.422	17.123(015)	17.203(007)	16.646(007)	16.369(007)	15.983(009)	16.869(005)	16.503(005)	16.394(005)
10	01:19:52.090	+03:23:27.186	15.444(009)	15.191(006)	14.508(006)	14.230(005)	14.000(005)	14.812(004)	14.302(004)	14.597(003)
11	01:20:28.530	+03:24:20.902	16.748(012)	16.181(006)	15.351(006)	14.923(006)	14.420(006)	15.750(004)	15.073(004)	14.858(004)
12	01:20:04.722	+03:29:32.716	15.742(009)	15.545(005)	14.854(005)	14.497(005)	14.014(005)	15.164(004)	14.644(004)	14.447(004)
13	01:19:57.199	+03:27:11.729	17.634(018)	17.533(007)	16.874(007)	16.532(007)	16.070(009)	17.163(005)	16.679(005)	16.486(005)
14	01:20:31.904	+03:20:34.181	16.485(011)	16.426(006)	15.775(006)	15.439(006)	14.967(006)	16.059(004)	15.585(004)	15.393(004)
15	01:20:22.976	+03:28:34.205	14.711(011)	14.988(009)	14.325(009)	13.898(007)	13.041(006)	14.617(006)	14.129(007)	13.383(002)
16	01:20:53.340	+03:16:40.750	13.768(009)	12.763(001)	12.248(001)	11.994(001)	12.186(009)	12.444(001)	12.126(001)	12.026(001)
17	01:20:53.291	+03:26:42.976	13.709(010)	12.387(001)	11.927(001)	11.699(001)	11.956(008)	12.088(001)	11.831(001)	11.733(001)
18	01:20:44.339	+03:25:52.392	13.672(009)	12.566(001)	12.129(001)	11.913(001)	12.068(008)	12.275(001)	12.045(001)	11.949(001)
19	01:19:37.509	+03:17:06.781	14.010(021)	14.800(014)	14.010(014)	13.655(015)	11.016(011)	14.383(010)	13.751(010)	13.889(011)
20	01:19:56.437	+03:29:39.264	15.289(008)	15.176(005)	14.561(005)	14.268(005)	13.901(005)	14.821(004)	14.389(004)	14.363(003)

 Table 1

 notometric Standards in the SN 2017fgc Field 1

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^a Standard stars used for calibration of instrumental magnitudes.

MJD	Epoch ^a	U (mag)	B (mag)	V (mag)	<i>R</i> (mag)	I (mag)	g (mag)	r (mag)	i (mag)	Clear (mag)	Telescope
57,947.10	-12.30	15.304(100)	15.446(043)	15.381(040)	•••	•••	15.297(033)	15.223(033)	15.742(048)	•••	LCO
57,948.16	-11.24	14.743(076)	15.010(034)	14.928(034)			14.906(027)	14.857(027)	15.356(039)		LCO
57,954.72	-4.68	13.635(110)	13.948(051)	13.932(051)			13.893(056)	13.874(037)	14.420(063)		LCO
57,955.81	-3.59	13.571(052)	13.875(024)	13.820(022)			13.804(019)	13.868(021)	14.345(030)		LCO
57,956.81	-2.59	13.527(045)	13.838(019)	13.673(017)			13.716(015)	13.609(015)	14.316(023)		LCO
57,957.94	-1.46	13.545(054)	13.811(024)	13.699(022)			13.711(018)	13.644(019)	14.319(030)		LCO
57,959.49	+0.09		13.793(034)	13.596(030)	13.522(020)	13.889(031)					Nickel
57,959.82	+0.42	13.552(064)	13.801(028)	13.655(024)			13.688(023)	13.572(022)	14.337(054)		LCO
57,960.49	+1.09		13.819(065)	13.548(036)	13.566(048)	14.038(055)				13.609(054)	KAIT4
57,961.49	+2.09									13.589(051)	KAIT4
:	:	:	÷	÷	÷	÷	÷	÷	:	÷	:
58,134.25	+174.85		18.326(128)	18.276(101)	18.973(134)	19.131(196)					TNT
58,136.10	+176.70									18.341(135)	KAIT4
58,137.25	+177.85		18.408(112)	18.159(086)	18.790(104)	19.342(174)					TNT
58,144.11	+184.71		18.659(222)	18.446(136)			18.005(119)	19.192(102)	19.205(186)		LCO
58,146.14	+186.74									18.629(169)	KAIT4
58,150.11	+190.71									18.427(169)	KAIT4
58,152.25	+192.85		18.195(147)	18.446(108)	19.218(159)						TNT
58,154.12	+194.72		18.444(116)	18.660(182)	19.690(315)	19.112(242)				18.634(076)	KAIT4
58,162.12	+202.72									18.802(128)	KAIT4
58,164.12	+204.72									18.746(136)	KAIT4

 Table 2

 Photometric Observations of SN 2017fgc by Ground-based Telescopes

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^a Relative to the epoch of *B*-band maximum brightness (MJD = 57,959.4). Measurements are calibrated to the AB magnitude system.

(This table is available in its entirety in machine-readable form.)

 Table 3

 Spectroscopic Observations of SN 2017fgc

MJD	Epoch ^a	λ_{Start}	λ_{End}	Telescope
57,947.7	-11.7	3231	9918	LCO
57,952.5	-6.9	3616	10,400	Lick 3 m
57,952.6	-6.8	3226	9919	LCO
57,959.5	-0.1	3226	9919	LCO
57,960.5	+1.1	3622	10,400	Lick 3 m
57,961.5	+2.1	3226	9919	LCO
57,964.5	+5.1	3620	10,400	Lick 3 m
57,966.5	+7.0	3620	10,400	Lick 3 m
57,966.5	+7.1	3226	9920	LCO
57,972.6	+13.2	3226	9919	LCO
57,981.5	+21.1	3231	9919	LCO
57,987.5	+28.4	3473	9099	LJT
57,988.7	+29.3	3180	9919	LCO
57,992.5	+33.1	3622	10,400	Lick 3 m
57,997.7	+38.2	3374	9919	LCO
58,006.6	+47.2	3972	9919	LCO
58,010.5	+51.1	3632	10,400	Lick 3 m
58,011.5	+52.1	3634	10,400	Lick 3 m
58,013.6	+54.2	3226	9919	LCO
58,023.4	+64.0	3277	9918	LCO
58,023.5	+64.1	3632	10,400	Lick 3 m
58,023.6	+64.2	3276	9919	LCO
58,041.5	+82.1	3474	9224	LCO
58,045.4	+86.0	3620	10,400	Lick 3 m
58,051.4	+92.0	3620	10,400	Lick 3 m
58,053.1	+93.7	3701	8747	XLT
58,056.4	+97.0	3622	10,398	Lick 3 m
58,062.5	+103.1	3276	9919	LCO
58,083.1	+123.7	3725	8739	XLT
58,091.2	+131.8	3176	9918	LCO
58,101.2	+141.8	3227	9919	LCO
58,108.0	+148.6	5665	6963	LCO
58,109.1	+149.7	2990	24,790	ESO public
58,116.3	+156.9	3178	9902	LCO
58,131.2	+171.8	3226	9225	LCO
58,140.3	+180.9	5711	7002	LCO
58,343.3	+383.9	2990	24,790	ESO public
58,348.3	+388.9	2990	24,790	ESO public

^a Relative to the epoch of *B*-band maximum brightness (MJD = 57,959.4).

Hicken et al. 2012), 2009ig (Marion et al. 2013), 2011fe (Munari et al. 2013; Zhang et al. 2016b), 2013gs (Zhang et al. 2019), 2017hpa (Zeng et al. 2021), and 2018oh (Li et al. 2019). One can see that the light curves of SN 2017fgc are generally similar to those of comparison SNe Ia near the *B*-band maximum. We notice, however, that SN 2017fgc seems to have brighter tails in both *U* and *B* relative to those of NV SNe Ia, consistent with the tendency that HV SNe Ia have flatter evolution at $t \approx 1-3$ months after maximum light (e.g., Wang et al. 2008b, 2019b). For example, the magnitude decline measured within 60 days after peak brightness is 3.57 ± 0.08 mag in *U* and 2.96 ± 0.08 mag in *B*, similar to the evolution of the well-known HV SN 2006X. Figure 4 shows a comparison of the *RrIi* light curves. One can see that SN 2017fgc has a more significant secondary shoulder or peak in the *R*/*r* and *I*/*i* bands than the normal counterparts.

3.2. Reddening

The line-of-sight Galactic extinction of SN 2017fgc is estimated to be $A_V = 0.094$ mag (Schlegel et al. 1998;



Days from *B*-band Maximum

Figure 2. The optical light curves of SN 2017fgc. The different colors represent different observation bands, while data from different telescopes/instruments are indicated with different symbols. The vertical dashed line represents the time of the *B*-band maximum, relative to which all times are given in this paper. The light curves have been shifted vertically for clarity.

Schlafly & Finkbeiner 2011). Adopting $R_V = 3.1$ (Cardelli et al. 1989), this corresponds to a color excess of $E(B - V)_{Gal} = 0.030$ mag. After removal of the Galactic extinction, the B - V color of SN 2017fgc is estimated to be -0.03 ± 0.02 mag at t = 0 days and 1.62 ± 0.10 mag at t = +35 days relative to the *B*-band maximum, consistent with typical values of normal SNe Ia (Phillips et al. 1999; Wang et al. 2009a).

SuperNovae in object-oriented Python (SNooPy2; Burns et al. 2011, 2014) has also been employed to fit the multiband light curves of SN 2017fgc, and the model fitting results are shown in Figure 5(a). We adopt the *EBV* model with



Figure 3. Comparison of the optical light curves (in the *UBVg* bands) of SN 2017fgc with those of other well-observed SNe Ia having similar decline rates. The restframe light curves of the comparison SNe Ia have been normalized to match the peak magnitudes of SN 2017fgc. No *k*-corrections have been applied to the light curves, because both SN 2017fgc and the comparison sample have a redshift less than 0.01. The NV SNe Ia are marked with open symbols while the HV SNe are shown with filled symbols. The black dashed lines represent the polynomial fit to the NV SNe Ia, while the blue dashed lines represent the case for HV SNe Ia. The red dashed lines represent the best fit for the light curves of SN 2017fgc.

st-type and estimate the reddening due to the host galaxy as $E(B - V)_{\text{host}} = 0.17 \pm 0.07$ mag, suggesting an insignificant host-galaxy reddening for SN 2017fgc. This is consistent with the absence of Na I D absorption lines in the optical spectra of SN 2017fgc.

3.3. Color Curves

Figure 6 shows the color evolution of SN 2017fgc compared with that of several well-observed SNe Ia having similar $\Delta m_{15}(B)$. At early times, both the B - V and g - r color curves evolve toward the blue until they reach the blue peak at $t \approx 0$ days; then they evolve redward and reach the red peak at $t \approx 35$ days. The B - V and V - I color curves of SN 2017fgc show close resemblances to those of SN 2002bo, SN 2006X, and SN 2009ig, which all belong to the subclass of HV SN Ia (Benetti et al. 2004; Krisciunas et al. 2004; Wang et al. 2008b; Hicken et al. 2012; Silverman & Filippenko 2012). However, none of the comparison SNe Ia look perfectly the same as SN 2017fgc. While evolving redward, the g - r color curves of SN 2017fgc and other comparison SNe Ia show a clear jump at $t \sim 1$ week after maximum light, which is similar to that of the V - R color curves at similar phase (Cartier et al. 2014; Gutiérrez et al. 2016; Zhang et al. 2019). Both the V - I and g - i color curves show an evolution from red to blue until $t \approx 15$ days; then they evolve redward and reach the red peak at $t \approx 35$ days. Like other HV SNe Ia, SN 2017fgc also exhibited an overall bluer V - I color than the NV counterparts. The prominent Ca II near-infrared (NIR) absorption features shown in the spectra of HV SNe Ia are likely responsible for their bluer V - I colors.

3.4. First-light Time

The DLT40 survey intensely observed SN2017fgc at extremely early times, using a clear band (calibrated to the R band). The



Figure 4. Comparison of the optical light curves (in the *RrIi* bands) of SN 2017fgc with those of other well-observed SNe Ia having similar decline rates. The light curves of the comparison SNe Ia have been normalized to match the peak magnitudes of SN 2017fgc. The symbols are the same as in Figure 3.

photometric data are listed in Table 4. Both the expanding fireball model from Riess et al. (1999) and the broken power-law model from Zheng et al. (2018) are adopted to fit the early light curve of SN 2017fgc (as shown in Figure 7). The observed data at $t \leq -10$ days from the *R*-band peak are adopted to fit the fireball model while those obtained at $t \leq +15$ days are used for the broken power-law model fitting, and the estimated first-light time (FLT) of the light curve is 57941.1 \pm 0.3 days and 57,941.7 \pm 0.7 days, respectively. The results of these two estimations are in good agreement. The average fitted first-light time is estimated as $57,941.4 \pm 0.4$ days, hence the rise time of SN 2017fgc is estimated as 18.0 ± 0.4 days. The multicolor observations of SN 2017fgc are conducted at \sim 6 days after the FLT, \sim 12 days before the B-band maximum. A flux excess seems to exist for the first detection point, i.e., brighter than the fitting result by $\sim 0.23 \pm$ 0.07 mag (see the bottom panel of Figure 7). This excess flux detected in the early phase could be due to interaction of SN ejecta with a nondegenerate companion (Kasen 2010), surrounding CSM (Gerardy et al. 2004; Piro & Morozova 2016), or even the

radioactive decay of nickel synthesized on the surface of the exploding WD (Piro & Morozova 2016; Noebauer et al. 2017). A further analysis of early-time light curves including SN 2017fgc will be presented as part of a larger study (J. Burke et al. 2021, in preparation).

According to Zhang et al. (2010), the rise time of the *r*-band light curve of SNe Ia shows an anticorrelation with $\Delta m_{15}(B)$ (see Figure 8). For given $\Delta m_{15}(B)$, the rise time of NV SNe Ia seems to be on average longer than that of the HV ones. A similar trend has been reported in other studies (e.g., Pignata et al. 2008; Ganeshalingam et al. 2011; Zheng et al. 2017b). As shown in Figure 8, SN 2017fgc is also in line with this trend. As the *R*-band and clear-band light curves have similar rise times. The *R*-band rise time of SN 2017fgc is thus estimated as 18.0 ± 0.4 day by fitting its clear-band light curve. Given that the *R*-band light curve of SN 2017fgc reached its peak (~57,961.3 \pm 0.2) ~1.9 \pm 0.4 days later than the *B*-band light curve (~57,959.4 \pm 0.4), the *B*-band rise time can be thus



Figure 5. Best-fit light-curve model from SNooPy2 (left panel) and SALT 2.4 (right panel). The light curves are shifted vertically for clarity. The dashed lines represent the 1σ uncertainty of the best-fit light-curve templates.

inferred as 16.1 ± 0.4 days assuming that the SN photons in these two bands diffuse out simultaneously. The *B*-band rise time speculated for SN 2017fgc is also obviously shorter than the mean value for SNe Ia (Zheng et al. 2017b). The relatively shorter rise time seen in HV SNe Ia than in NV ones might be related to the fact that their ejecta become optically thin at a faster pace because of more rapid expansion (Zhang et al. 2010).

3.5. Quasi-bolometric Light Curve

According to Tully et al. (2013), based on the Tully–Fisher relation, the distance modulus measured for the host galaxy NGC 474 is 32.35 ± 0.14 mag. From fitting to the multicolor light curves of SN 2017fgc, SNooPy2 gives an average $\mu = 32.44 \pm 0.11$ mag (see left panel of Figure 5), while SALT 2.4 (Guy et al. 2010; Betoule et al. 2014) gives $\mu = 32.39 \pm 0.07$ mag (see right panel of Figure 5). These three estimates agree well with each other. The average value of 32.39 ± 0.06 mag is thus adopted in the following analysis. Assuming $R_V = 3.1$, the absolute *B*-band peak magnitude of SN 2017fgc is estimated to be $M_{\text{max}}(B) = -19.32 \pm 0.13$ mag after correcting for both Galactic and host-galaxy extinction, which agrees well with that of normal SNe Ia (i.e., $M_{\text{max}}(B) \approx -19.3$ mag for an SN Ia with $\Delta m_{15}(B) \approx 1.1$ mag; Phillips et al. 1999; Wang et al. 2009a).

Following the procedure used for SN 2018oh (Li et al. 2019), SNooPy2 is employed to establish the spectral energy distribution (SED) and thus the quasi-bolometric light curve of SN 2017fgc based on the *U*, *B*, *g*, *V*, *R*, *r*, *I*, and *i* light curves. According to Wang et al. (2009b) and Zhang et al. (2016b), the ultraviolet (UV)/optical ratios of SN 2005cf and SN 2011fe (normal SNe Ia) are measured as 0.095 and 0.085, while their NIR/optical ratios are measured as 0.058 and 0.059, respectively. The converted ratios relative to the bolometric luminosity are 0.082 and 0.074 respectively for SN 2005cf and SN 2011fe in UV bands, while those ratios in NIR bands are 0.050 and 0.052, respectively. Based on the SED of SN 2009ig (Marion et al. 2013; Chakradhari et al. 2019) near the maximum light, the UV/NIR to bolometric ratios of these HV SN Ia are estimated as 0.058 ± 0.010 and 0.054 ± 0.019 , respectively. Assuming that the average UV and NIR contributions are 7% and 5% for SN 2017fgc, the maximum-light luminosity is estimated as $L_{\text{peak}} = (1.32 \pm 0.13) \times 10^{43}$ erg s⁻¹, reached at ~0.96 days prior to the *B*-band maximum. This peak luminosity is larger than that of SN 2011fe (~1.13 × 10⁴³ erg s⁻¹; Zhang et al. 2016b) but smaller than that of SN 2018oh (~1.49 × 10⁴³ erg s⁻¹; Li et al. 2019).

The Minim Code (Chatzopoulos et al. 2013), utilizing a modified radiation diffusion model of Arnett (Arnett 1982; Chatzopoulos et al. 2012; Li et al. 2019), is used to fit the quasibolometric light curve with a constant-opacity approximation (see Figure 9). This fitting allows us to derive the following parameters, including the "first light" t_0 , the model timescale of the light curve $t_{\rm lc}$, the leaking timescale of gamma-rays t_{γ} , and the mass of radioactive ⁵⁶Ni ejecta $M_{\rm Ni}$ (see Chatzopoulos et al. 2012 for details), with the respective values being 57,941.4 \pm 0.4, 13.51 ± 0.08 days, 38.59 ± 2.28 days, and $0.51 \pm 0.03 M_{\odot}$. The dark phase was presented as the delay between the explosion and the emergence of the radioactivity-powered light curve in several models of SNe Ia (Piro & Nakar 2013). Assuming the initial diffusion wave reached the surface at t = 0, the framework of the Arnett model does not take a dark phase into account (Li et al. 2019). Piro & Morozova (2016) proposed that the length of the dark phase could be less than 2 days. The first light t_0 from the Arnett model is ~ 2.1 days later than that estimated from the fireball model or the broken-power-law model. Considering the model-dependent uncertainties in the estimation, we interpreted that the difference in the two estimated starting moments could be related to the dark phase in SN 2017fgc (Piro & Morozova 2016; Li et al. 2019). The first-light time of 57,941.4 \pm 0.4 days is used in the following analysis.



Figure 6. The B - V, V - I, g - r, and g - i color curves of SN 2017fgc are compared with those of SNe 2002bo, 2003du, 2005cf, 2006X, 2007af, 2009ig, 2011fe, 2013gs, 2017hpa, and 2018oh. All color curves, including those of SN 2017fgc, have been dereddened using SNooPy2 (Burns et al. 2011, 2014).

4. Optical Spectra

4.1. Temporal Evolution of the Spectra

The optical spectral evolution of SN 2017fgc is displayed in Figure 10. The early-time spectra are characterized by prominent absorption lines of intermediate-mass elements (IMEs) and ionized iron-group elements (IGEs), including Ca II H&K, Fe II $\lambda\lambda$ 4404, 5018, Mg II λ 4481, Si II λ 5051, Fe III λ 5129, S II $\lambda\lambda$ 5468, 5654, Si II λ 6355, and the Ca II NIR triplet. About two weeks before the *B*-band maximum, the absorption line near 4300 Å could be due to blended Fe II λ 4404 and Mg II λ 4481, while the broad absorption near 4800 Å could be a blend of Fe III λ 5129, Fe II $\lambda\lambda$ 4924, 5018, 5169, and Si II λ 5051. The distinct absorption features near

3700 Å and 7800 Å can be identified as Ca II H&K and the Ca II NIR triplet, respectively.

After about one week before maximum light, the "W"shaped S II absorption features near 5400 Å and Si II λ 5972 near 5800 Å begin to emerge in the spectra. The minimum of the Si II λ 6355 absorption line shifted redward gradually with the decreasing photospheric velocity, while the IGEs and sulfur gradually gain strength. At around the *B*-band maximum, the spectra are still dominated by the "W"-shaped S II absorption features and distinct absorption lines of Ca II H&K, Si II λ 6355, and the Ca II NIR triplet. The blended absorption lines of Fe III λ 5129, Fe II $\lambda\lambda$ 4924, 5018, 5169, and Si II λ 5051, as well as the blended absorption lines of Fe II λ 4404 and Mg II λ 4481, are also notable. At about ten



Figure 7. Fit to the observed clear-band light curve using the ideal fireball model (Riess et al. 1999) and the analytic function introduced by Zheng et al. (2017b). The black triangle represents the earliest limiting magnitude from the DLT40 survey, which is ~ 0.6 days after the fitted first-light time.

 Table 4

 DLT40 Photometry of SN 2017fgc in the Clear Band

MJD	Epoch ^a	Clear (mag)	Telescope
57,942.3	-17.1	19.183()	Prompt5
57,943.3	-16.1	17.324(086)	Prompt5
57,944.4	-15.0	16.550(040)	Prompt5
57,945.3	-14.1	16.096(030)	Prompt5
57,946.4	-13.0	15.532(020)	Prompt5
57,947.3	-12.1	15.196(027)	Prompt5
57,952.3	-7.1	14.130(016)	Prompt5
57,953.3	-6.1	14.015(016)	Prompt5
57,955.3	-4.1	13.854(016)	Prompt5
57,956.3	-3.1	13.779(016)	Prompt5
:	:	÷	:
58,098.1	138.7	17.728(056)	Prompt5
58,099.1	139.7	17.830(064)	Prompt5
58,100.1	140.7	17.687(060)	Prompt5
58,101.1	141.7	17.814(057)	Prompt5
58,102.1	142.7	17.961(063)	Prompt5
58,103.1	143.7	17.857(060)	Prompt5
58,108.1	148.7	18.137(075)	Prompt5
58,110.1	150.7	17.998(070)	Prompt5
58,111.6	152.2	18.123(067)	Meckering
58,124.5	165.1	18.593(079)	Meckering

^a Relative to the epoch of *B*-band maximum (MJD = 57,959.4).

(This table is available in its entirety in machine-readable form.)

days after maximum light, the "W"-shaped S II absorption line becomes very weak, while the features of Si II λ 6355 and the Ca II NIR triplet still remain prominent. At about one month after maximum, the Ca II NIR triplet and Ca II H&K absorption lines are still the dominant spectral features. By



Figure 8. *R*-band rise times of several well-observed SNe Ia are plotted against the light-curve decline rate $\Delta m_{15}(B)$. The data are taken from Zhang et al. (2010), and SN 2017fgc is overplotted as a black dot. The HV SNe Ia are plotted as red dots while the NV ones are blue open circles.



Figure 9. Quasi-bolometric light curve (dots) with an Arnett (1982) radiation diffusion model (blue curve).

the time when the SN enters the early nebular phase, features of IGEs start to emerge in the spectra.

The spectra of SN 2017fgc at four selected epochs are compared with those of several well-observed SNe Ia having similar $\Delta m_{15}(B)$, as illustrated in Figure 11. Panel (a) shows the comparison of the $t \approx -12$ days spectra, including SNe 2017fgc (this paper), 2002bo, 2003du, 2005cf, 2006X, 2011fe, and 2013gs. One can see that both SN 2017fgc and the comparison SNe Ia have strong absorption features due to Ca II H&K and Si II λ 6355. The three HV objects (with pseudo-equivalent width (pEW) being 211.1 \pm 19.2 Å for SN 2002bo, 211.6 \pm 26.0 Å for SN 2006X, and 188.7 \pm 15.6 Å for SN 2017fgc) are found to have systematically stronger ~4800 Å absorption than three NV ones (with pEW being 86.8 \pm 10.1 Å for SN 2003du, 146.8 \pm 3.3 Å for



Figure 10. Optical spectral evolution of SN 2017fgc. All of the spectra have been corrected for the redshift of the host galaxy and reddening. The epochs shown on the right represent the phases in days relative to *B*-band maximum light. The dashed line marks the center of the Si II λ 6355 line profile at +0.04 days from *B*-band maximum. The colors of the spectra represent data from different instruments.

(The data used to create this figure are available.)

SN 2005cf, and 122.2 ± 4.0 Å for SN 2011fe) at similar phases. pEW is measured to be 142.5 ± 24.4 Å for SN 2013gs (HV), which is comparable to that measured for SN 2005cf (NV). Previous studies suggest that the absorption near 4800 Å could be due to a blend of Fe III λ 5129, Fe II $\lambda\lambda$ 4924, 5018, 5169, and Si II λ 5051 lines.

Figure 11(b) shows the comparison at $t \approx 1$ week before maximum light. The absorption-line strengths of IMEs are enhanced in the spectra of SN 2017fgc and the comparison

SNe Ia. At this phase, the "W"-shaped S II absorption features near 5400 Å start to emerge in spectra of all SNe Ia in our sample. However, we notice that the Fe II and Mg II blended feature near 4500 Å is stronger in SNe 2002bo, 2006X, 2013gs, and 2017fgc than in the three objects in the NV SN Ia subclass.

The spectra near maximum light are displayed in Figure 11(c). At this phase, the blended features near 4800 Å of SN 2017fgc (with pEW being 227.9 ± 3.5 Å) are comparable to those of HV objects (with pEW being 204.2 ± 14.1 Å for SN 2002bo, 213.4 ± 6.4 Å for SN 2006X, and 156.6 ± 9.3 Å for SN 2013gs), but they are obviously stronger than those of the NV counterparts (with pEW being 121.1 ± 13.6 Å for SN 2003du, 130.1 ± 3.2 Å for SN 2005cf, and 125.1 ± 3.2 Å for SN 2011fe). A similar situation is found for the blended features near 4300 Å, with pEW being 106.5 ± 9.6 Å for SN 2002bo, 102.2 ± 4.0 Å for SN 2006X, 100.6 ± 6.1 Å for SN 2013gs, 110.7 ± 2.4 Å for SN 2017fgc, 86.4 ± 10.0 Å for SN 2003du, 92.6 ± 2.4 Å for SN 2005cf, and 85.0 ± 2.3 Å for SN 2011fe. The velocity measured for SN 2017fgc from the absorption-line minimum of Si II λ 6355 at maximum light is $15,000 \pm 150$ km s⁻¹, which is about 2000 $\text{km}\,\text{s}^{-1}$ faster than that of SN 2002bo (i.e., ~13,200 $\text{km}\,\text{s}^{-1}$ ¹). R(Si II), defined as the line-strength ratio of Si II λ 5972 to Si II $\lambda 6355$ (Nugent et al. 1995), is measured to be 0.04 ± 0.01 for SN 2017fgc, noticeably smaller than that of the NV SN 2005cf $(R(Si II) = 0.28 \pm 0.04; Wang et al. 2009b)$, perhaps suggesting a relatively higher photospheric temperature of SN 2017fgc around maximum light. In Figure 12, the line ratios R(Si II) of a few representative SNe Ia of different subclasses are plotted versus their decline in *B*-band magnitude $\Delta m_{15}(B)$. As expected, the fast decliners tend to have larger R(Si II) ratio and vice versa. Compared to the NV SNe Ia with similar decline rates, the HV ones have systematically smaller values of R(Si II), which provides additional evidence for different properties between these two subclasses. A systematically lower R(Si II) ratio indicates that the HV SNe Ia might have higher photospheric temperature and experienced more complete burning or they suffered from interaction of ejecta with CSM or companion stars (Zhao et al. 2015, 2016).

Figure 11(d) shows the spectral evolution at $t \approx 30$ days after maximum light. The absorption profiles of SN 2017fgc and the comparison SNe Ia are well developed and tend to have uniform morphologies. From the $t \sim 1$ month spectra, pEW of the Ca II NIR triplet of SNe 2002bo, 2006X, 2017fgc, 2005cf, and 2011fe are measured as 479.0 ± 17.5 Å, 475.6 ± 9.0 Å, 492.2 ± 13.2 Å, 73.9 ± 2.9 Å, and 9.5 ± 0.5 Å, respectively. We see that the Ca II NIR absorption lines in the spectra of HV SNe 2002bo, 2006X, and 2017fgc are much stronger than those of NV SNe 2005cf and 2011fe. By $t \approx 1$ month, the Fe II features gain strength and gradually dominate the wavelength region 4700–5000 Å.

Nebular spectra at $t \approx 170$ days and $t \approx 400$ days after maximum light are shown in Figures 13(a) and (b), respectively. The spectra of SN 2017fgc are well developed at such late phases and characterized by the forbidden lines of singly and doubly ionized IGEs, such as the [Fe II] and [Fe III] features at ~4700, ~5000, ~6500, and ~7000 Å, as well as [Co II] and [Co III] at ~5800 and ~6500 Å. The same lines are commonly seen in the comparison SNe Ia at similar phases. We notice that the emission profile of [Fe II]/[Fe III] at ~5000 Å is stronger in the NV SNe Ia (i.e., with pEW being measured as 63.8 ± 2.3 Å and 62.8 ± 1.6 Å for SN 2003du and SN 2011fe, respectively) than in HV ones (i.e., with pEW being measured as 24.8 ± 7.3 Å and 26.0 ± 1.9 Å



Figure 11. Spectra of SN 2017fgc at $t \approx -12$, -7, +0, and +30 days relative to *B*-band maximum, compared with spectra of SNe 2002bo (Benetti et al. 2004), 2003du (Stanishev et al. 2007), 2005cf (Wang et al. 2009b), 2006X (Wang et al. 2008b), 2011fe (Zhang et al. 2016b), and 2013gs (Zhang et al. 2019) at comparable phases. The spectra of HV SNe Ia are represented with solid lines while those of the NV ones are denoted with dashed lines. All of the above spectra have been corrected for reddening and redshift of the host galaxy.

for SN 2017fgc and SN 2006X, respectively). From the $t \approx +384$ days spectrum, we measured the velocity shifts of [Fe II] λ 7155 and [Ni II] λ 7378 as $+2220 \pm 260$ km s⁻¹, and that measured from the $t \approx +389$ days spectrum is $+1640 \pm 580$ km s⁻¹; these are consistent with the trend that HV SNe Ia tend to have redshifted Fe II/Ni II velocity in the nebular phase (Maeda et al. 2010; Maguire et al. 2018).

4.2. Ejecta Velocity

The methods described by Zhao et al. (2015, 2016) were utilized to measure the ejecta velocity from the absorption lines, such as S II $\lambda\lambda$ 5460, 5640, Si II λ 5972, Si II λ 6355, and the Ca II NIR triplet; the results are shown in Figure 14. The

photospheric velocity measured from Si II $\lambda 6355$ at $t \approx -11.7$ days is ~18,900 km s⁻¹, comparable to that of the Si II $\lambda 5972$ line (~18,000 km s⁻¹) and S II line (~19,000 km s⁻¹), but much slower than the velocity of the high-velocity feature (HVF) inferred from the Ca II NIR triplet (~32,000 km s⁻¹). At the time of *B*-band maximum, the velocity of Si II $\lambda 6355$ is measured as 15,000 \pm 150 km s⁻¹, significantly larger than the typical value (i.e., ~11,800 km s⁻¹) of NV SNe Ia. We thus put SN 2017fgc into the HV subclass according to the classification criteria proposed by Wang et al. (2009a).

Applying a linear fitting to the velocities of Si II $\lambda 6355$ measured during the period $t \approx 0$ days to $t \approx +10$ days, we derive the velocity gradient as 120 ± 10 km s⁻¹ day⁻¹, suggesting that SN 2017fgc belongs to the HVG subclass.



Figure 12. Line ratio R(Si II) of several well studied SNe Ia vs. luminosity indicator $\Delta m_{15}(B)$. Some data are taken from Benetti et al. (2004) and Blondin et al. (2012), while others are taken from Stanishev et al. (2007) for SN 2003du, Wang et al. (2009b) for SN 2005cf, Zeng et al. (2021) for SN 2017hpa, Li et al. (2019) for SN 2018oh, Wang et al. (2008b) for SN 2006X, Zhang et al. (2010) for SN 2007gi, Zhang et al. (2019) for SN 2013gs, and Kawabata et al. (2020) for SN 2019ein. The R(Si II) ratios for SNe 1998bp, 1998es, 1999gp, 2001eh, and 2011fe are calculated using the code respext with the spectra near maximum light (Stahl et al. 2020b). The HV SNe Ia are represented by red dots while the NV ones are shown by blue open circles. The peculiar objects SNe 1991bg and 1991T are plotted as red and blue dots, respectively, while SN 2017fgc is overplotted as a black dot.

Figure 14 shows the velocity evolution of some IMEs, including S II, Si II, and Ca II. The velocities of Si II λ 5972 and the Ca II NIR triplet photospheric component show similar evolution, while Si II λ 6355 exhibits slightly higher velocities. The HVF of the Ca II NIR triplet has the highest velocity. The evolution of the photospheric velocity of SN 2017fgc, as derived from the minimum of Si II λ 6355 absorption, is shown in Figure 15, together with that of the comparison SNe Ia, including SNe 2002bo, 2005cf, 2006X, and 2011fe. As can be seen, SN 2017fgc exhibits a velocity evolution similar to that of SN 2006X. The basic photometric and spectroscopic parameters of SN 2017fgc are listed in Table 5.

5. Discussion

5.1. Velocity and Velocity Gradient

The large velocity ($\sim 15,000 \pm 150 \text{ km s}^{-1}$) and velocity gradient ($\sim 120 \pm 10 \text{ km s}^{-1} \text{ day}^{-1}$) clearly put SN 2017fgc into the subclasses of both HV and HVG. In general, most HV SNe Ia belong to the HVG subclasses, while the NV SNe Ia correspond to the LVG ones (Wang et al. 2009a; Silverman et al. 2012b), as shown in Figure 16(a). However, there are also outliers such as SN 2017hpa, which has a normal velocity around maximum light ($\sim 9550 \text{ km s}^{-1}$) but a large velocity gradient ($\sim 130 \text{ km s}^{-1}$) (Zeng et al. 2021). This indicates that HVG SNe Ia could have multiple physical origins. This is also demonstrated by the correlation between velocity gradient and $\Delta m_{15}(B)$ (Phillips 1993), as shown in Figure 16(b), where no obvious correlation exists between velocity gradient and the luminosity indicator $\Delta m_{15}(B)$, while only the LVG sample possibly shows a weak correlation between these two observables.

Previous studies have shown that the difference in velocity gradient may be related to the different nature of the explosions or the mixture of SN Ia ejecta (e.g., Benetti et al. 2004; Sahu et al. 2013). Different viewing angles in an off-center ignition during the explosion of SNe Ia will lead to variations in the observed velocity gradient (Maeda et al. 2010). However, this idea has difficulty explaining the observed fact that HVG (HV) SNe Ia preferentially occur in the inner region of the galaxy (Wang et al. 2013). Woosley et al. (2009) and Blondin et al. (2012) found that varying the criterion of the deflagration-todetonation transition (DDT) will cause velocity gradients to vary over a wide range. The HVG subclass may result from adequate mixing of heavy elements in the SN ejecta, while their counterparts with low velocity gradient may suffer less mixing in the ejecta (Blondin et al. 2012; Sahu et al. 2013). As suggested by Zeng et al. (2021), the large velocity gradient seen in SN 2017hpa could be caused by the effective mixing of heavy elements in the SN ejecta.

5.2. Light-curve Features

During their study of the typical HV object SN 2006X, Wang et al. (2008a) noticed that it exhibited relatively flat tail evolution starting around +40 days after maximum light. A recent statistical study based on a large sample indicates that the excess blue flux is common for the HV group of SNe Ia (Wang et al. 2019b; Li et al. 2021). For SN 2017fgc, the decline from peak brightness measured at $t \approx 60$ days is 2.96 mag in B and 2.34 mag in V. The corresponding values are much smaller than in NV SNe Ia with similar $\Delta m_{15}(B)$, but are consistent with the behavior of HV SNe Ia. Figure 17 shows the results measured for SN 2017fgc and the comparison sample from Wang et al. (2019b). For the NV sample of SNe Ia, more luminous objects tend to have brighter tails and slower decline rates, while this tendency shows large scatter in the *B* band owing to the abnormally bright tails exhibited by the HV subsamples (Wang et al. 2019b). This is primarily due to the fact that HV SNe Ia tend to show excess emission in the early nebular phase, which can be caused by light scattering by the surrounding CSM (Wang et al. 2019b). This scenario is favored by the detections of nearby light echoes around SN 2006X (Wang et al. 2008a) and SN 2014J (Yang et al. 2018).

Besides the flatter bluer-band light-curve evolution in the early nebular phase, HV SNe Ia seem to share another lightcurve feature: a stronger secondary shoulder or maximum in the R/r and I/i bands. This seems to apply for SN 2017fgc. Following Stahl et al. (2020b), the Gaussian-process lightcurve fitting implemented in SNooPy2 is employed to obtain the secondary peak magnitudes of SN Ia light curves in the R/rand I/i bands. The resulting absolute *RrIi*-band secondary peak magnitudes of 92 SNe Ia (26 HV and 66 NV) are plotted as a function of Si II velocity in Figure 18. The black line with square symbols represents the binned average (i.e., a bin of 1000 km s^{-1} is used to calculate the average value). The Pearson coefficient is estimated as -0.94 and -0.88 for the binned r-band and i-band data, respectively. The corresponding p-values are 0.02 and 0.04, respectively, suggesting that the shoulder/secondary peak features could be correlated with the Si II velocity at a confidence level of $\sim 2\sigma$.



Figure 13. Nebular-phase spectra of SN 201fgc at $t \approx +170$ days and +384 days relative to *B*-band maximum, compared with spectra of SNe 2003du (Stanishev et al. 2007), 2005cf (Wang et al. 2009b), 2006X (Wang et al. 2008b), 2011fe (Zhang et al. 2016b), and 2013gs (Zhang et al. 2019) at comparable phases. The HV SNe Ia are represented with solid lines while the NV ones are dashed lines. All of the spectra have been corrected for reddening and redshift of the host galaxy.



Figure 14. Velocity evolution of different elements measured from spectra of SN 2017fgc. Note that for Ca II, both the detached high-velocity feature (HVF) and photospheric-velocity feature (PVF) are shown for comparison.

The NIR light curves of SNe Ia have been occasionally studied theoretically. Several delayed-detonation models have been applied by Höflich (1995) to reconstruct the *I*-band and NIR light curves. They described the double-peaked behavior as a temperature effect, in which the drop in temperature of the ejecta is compensated by the expansion of the photosphere. Pinto & Eastman (2000) explained the secondary maximum in the NIR bands as the release of trapped radiative energy owing to the decrease in the flux mean opacity. Kasen (2006) found that the NIR secondary maximum of SNe Ia could be due to the



Figure 15. Evolution of the expansion velocity of SN 2017fgc as derived from the minimum of the Si II λ 6355 absorption line, compared with those of the HV sample of SNe Ia, including 1984A, 2002bo, and 2006X, and the NV sample including SN 2003du, SN 2005cf, and SN 2011fe. The average velocity curves obtained for SN 1991T-like and SN 1991bg-like SNe are overplotted with red and blue dashed lines, respectively. The normal subclass of SNe Ia is plotted with a black solid line. The shaded region represents the 1 σ uncertainty for the mean velocity curve of NV SNe Ia. The values of SN 1984A are taken from Barbon et al. (1989), SN 2002bo from Benetti et al. (2004), SN 2005X from Wang et al. (2008b), SN 2005cf from Wang et al. (2009b), and SN 2011fe from Zhang et al. (2009a).

ionization transition of IGEs in the ejecta from doubly to singly ionized, which in turn leads to a weakening of Fe III and Co III lines and a strengthening of Fe II and Co II lines (see also



Figure 16. The spectroscopic subclassification of SN 2017fgc (as marked with a black dot) based on the scheme of Benetti et al. (2005). (a) Scatter plot of the Si II velocity vs. the velocity gradient. The velocity gradients of SN 2005cf and SN 2018oh are taken from Wang et al. (2009b) and Li et al. (2019), respectively, and those of the other objects are from Benetti et al. (2005) and Folatelli et al. (2013). The velocities are taken from Silverman et al. (2012b) and Wang et al. (2019b). The horizontal dashed line in the right panel marks the boundary between HVG and LVG, which is 70 km s⁻¹ day⁻¹ as defined by Benetti et al. (2005), while the vertical dashed line represents the boundary between the HV and NV SNe Ia as defined by Wang et al. (2009b). (b) $\Delta m_{15}(B)$ is plotted vs. the velocity gradient measured from the Si II $\lambda 6355$ absorption line in the near-maximum-light spectra.

Table 5Parameters of SN 2017fgc

Parameter		Value
	Photometric	
B _{max}		$13.07\pm0.11~\mathrm{mag}$
$B_{\rm max} - V_{\rm max}$		$0.16\pm0.13~\mathrm{mag}$
$M_{\rm max}(B)$		-19.32 ± 0.13 mag
$E(B-V)_{\rm host}$		$0.17\pm0.07~\mathrm{mag}$
$\Delta m_{15}(B)$		$1.05\pm0.07~\mathrm{mag}$
S_{BV}		1.19 ± 0.03
$t_{\max}(B)$		57,959.4 \pm 0.4 days
t_0		$57,941.4 \pm 0.4$ days
$\tau_{\rm rise}$		18.0 ± 0.4 days
$L_{\rm bol}^{\rm max}$		$(1.32 \pm 0.13) \times 10^{43} \text{ erg s}^{-1}$
M ⁵⁶ Ni		$0.51\pm0.03~M_{\odot}$
	Spectroscopic	
v ₀ (Si II)	1 1	$15,000 \pm 150 \text{ km s}^{-1}$
v(Si II)		$120 \pm 10 \ { m km \ s^{-1} \ day^{-1}}$
R(Si II)		0.04 ± 0.01

Jack et al. 2012; Dessart et al. 2014; Blondin et al. 2015). They suggested that the properties of the secondary maximum are related to $\Delta m_{15}(B)$ (and hence the peak luminosity), being more prominent in the brighter SNe Ia. Moreover, a small fraction of stable IGEs may be produced depending on the metallicity of the progenitor WD during the burning to nuclear statistical equilibrium (Kasen 2006; Kasen & Woosley 2007). The peak magnitude of the secondary maximum increases with the growth of the stable iron core, while the increase in metallicity of the progenitor increases the size of the iron core. In comparison NV SNe Ia, the more pronounced shoulder/ secondary peak features of HV SNe Ia seen in R/r and I/ibands might be related to the fact that the latter subclass has more metal-rich progenitor populations (Wang et al. 2013; Pan 2020).

5.3. Absorption of Intermediate-mass and Iron-group Elements

It is common that HV SNe Ia also show stronger absorption of Si II λ 6355, as evidenced by the fact that this subclass overlaps greatly with the broad-line subclass. According to Kasen (2006), the SN ejecta becomes very effective in redistributing the blue/UV photons to longer wavelengths when the iron-rich layers of the SN ejecta cool down to \sim 7000 K, which leads to the rebrightening of the NIR light curves. Jack et al. (2012) also found that the recombination of Fe III to Fe II is responsible for the second maximum features in NIR bands. Silverman et al. (2012a) suggested that pEW of Mg II complex and that of Fe II complex are correlated to the SALT2 color, with the HV SNe being redder and having larger pEW (see also Nordin et al. 2011; Walker et al. 2011). To further investigate the discrepancy between HV and NV SNe Ia (including 66 NV and 26 HV ones), we examine pEW of the blended absorption near 4400 Å (including Fe II λ 4404 and Mg II λ 4481) and that near 4900 Å (including Fe III λ 5129, Fe II $\lambda\lambda$ 4924, 5018, 5169, and Si II λ 5051), respectively dubbed pEW(Mg II) and pEW(Fe II). The samples are the same as those used by Wang et al. (2019b). The code respext²⁷ (Stahl et al. 2020b) is employed to estimate pEW of Fe II λ 4404/Mg II λ 4481 and Fe II/Fe III blends from the spectra around maximum light, and linear fitting is utilized to infer pEW at B-band maximum.

Figures 19(a) and (b) show the correlations between pEW (Mg II)/pEW(Fe II) and $\Delta m_{15}(B)$. One can see that HV SNe Ia have on average larger pEW(Mg II) and pEW(Fe II) than NV SNe Ia. The *p*-values from the *T*-test of pEW measured for

²⁷ https://github.com/benstahl92/respext



Figure 17. Tail brightness of SNe Ia, measured as the magnitude decline at $t \approx 60$ days from the peaks of the (a) *B* and (b) *V* light curves, vs. the luminosity indicator $\Delta m_{15}(B)$ that is measured as the magnitude decline within the first 15 days after *B*-band maximum (Phillips 1993). The data are taken from Wang et al. (2019b), while SN 2017fgc is overplotted as a black dot.



Figure 18. Left: the absolute secondary peak magnitude in the *r* band is plotted as a function of the Si II velocity of SNe Ia. The velocities are taken from Wang et al. (2019b). The black open square with black line represents the binned average, and *cc* and *p* are the correlation coefficient and *p*-value from Pearson statistics (with significance level $\sim 2\sigma$), respectively. Right: the same, but in the *i* band. The HV SNe Ia are represented with red dots and the NV ones with blue open circles. The vertical dashed lines represent the boundary between the HV and NV SNe Ia as defined by Wang et al. (2009b).

HV and NV SNe Ia are 0.07 and 0.09, corresponding to a significance of $\sim 2\sigma$. This indicates that HV and NV SNe Ia may have different ejecta properties that might be related to the explosion mechanism or progenitor system. Inspection of Figures 19(c) and (d) reveals that both pEW(Fe II) and pEW (Mg II) have a positive correlation with the Si II velocity. The difference in absorption features of IMEs and IGEs suggests that the outer ejecta of the HV SNe Ia may have experienced more complete burning than the NV subclass. This seems to be

consistent with the delayed-detonation model, which involves an initial subsonically propagating mode of nuclear burning followed by a supersonically moving detonation front with some time delay (Khokhlov 1989). Several three-dimensional models based on delayed-detonation Chandrasekhar-mass explosions have also been proposed in variants of DDT models (Khokhlov 2005; Röpke & Niemeyer 2007; Bravo & García-Senz 2008; Röpke et al. 2012). The reduced burning densities resulting from energy release in the subsonic propagation mode



Figure 19. (a) and (b): the pseudo-equivalent widths (pEW) of blended absorptions of Fe III λ 5129, Fe II $\lambda\lambda$ 4924, 5018, 5169, and Si II λ 5051 measured in the nearmaximum-light spectra plotted vs. the luminosity indicator $\Delta m_{15}(B)$ for 92 SNe Ia from Wang et al. (2019b). *p* represents the *p*-value (with significance level $\sim 2\sigma$) from the *T*-test statistics. (c) and (d): pEW of the blended absorptions of Fe II λ 4404 and Mg II λ 4481 plotted as a function of Si II velocity obtained around *B*-band maximum. The HV SNe Ia are represented by red dots while the NV subclass are blue open circles. For comparison, SN 2017fgc is shown with a black dot. The Si II velocities of SNe Ia are taken from Wang et al. (2019b). The black open square with black line represents the binned average, and *cc* and *p* are the correlation coefficient and *p*-value from Pearson statistics (with significance level $\sim 3\sigma$), respectively. The vertical dashed lines represent the boundary between the HV and NV SNe Ia as defined by Wang et al. (2009b).

of nuclear burning lead to extensive burning of the remaining fuel (Seitenzahl et al. 2013). In addition, larger off-center distances of DDT models might lead to more silicon at high velocities (Höflich et al. 2002, 2006). For a given $\Delta m_{15}(B)$, the asymmetric detonation can aspherically push Si outward and make the Si II features form in the regions at higher velocities (Höflich et al. 2006; Wang et al. 2007; Yang et al. 2018; Cikota et al. 2019).

As an alternative, the larger pEW seen in HV objects might be related to the metallicity of their environment, which could affect the observed properties of SNe Ia (Domínguez et al. 2001; Timmes et al. 2003; Silverman et al. 2012b). Higher metallicity for HV SNe Ia is favored by the study of their birthplace environments (Wang et al. 2013; Pan 2020). According to Wang et al. (2013), HV SNe Ia likely have younger massive and metal-rich progenitor systems than NV ones. The increase in stellar metallicity of progenitors could partially cause the higher Si II velocity seen in HV SNe Ia. The metal-rich stars could produce stronger outflows and more abundant CSM than their metal-pool counterparts (Wang et al. 2013), which is consistent with the observations that those showing blueshifted Na I D absorptions are more likely to be HV SNe Ia (Sternberg et al. 2011; Foley et al. 2012; Wang et al. 2019b). The strong absorption lines of Fe II and IMEs seen in the spectra of SN 2017fgc could thus originate from the metal-rich progenitor system, which will be further addressed below.

5.4. Explosion Environment and its Metallicity

In order to study the properties of the host galaxy NGC 474, a total of 13 bands of photometric data ranging from the UV to



Figure 20. The stellar population synthesis fit for the SED of NGC 474. The red open squares represent the observed AB magnitudes, while the synthesized magnitudes from the best-fit spectrum template (green curve) are overplotted as black diamonds.

the IR (the NUV band from Galaxy Evolution Explorer, five broad bands from SDSS, three NIR bands from the Two Micron All Sky Survey, and four NIR and mid-IR bands from Spitzer and the Wide-field Infrared Survey Explorer) from the NASA/IPAC Extragalactic Database (NED²⁸) have been downloaded to construct its SED. The stellar population synthesis code BC03 (Bruzual & Charlot 2003) was employed to construct the spectral models with the adopted parameter configurations, including the initial mass function (IMF; Chabrier 2003) and the Padova 1994 evolutionary tracks and delayed-exponential star formation history. The adopted SEDfitting method is described in Wei et al. (2021), while a χ^2 minimization is used to fit the total stellar mass of NGC 474 (see also Lin et al. 2013). The observed SEDs and the best-fit templates of NGC 474 are shown in Figure 20. The logarithmic stellar mass of NGC 474 is estimated to be 10.72 ± 0.02 by fitting the observed SED with the stellar population synthesis model. Utilizing the Spitzer observations at 3.6 μ m, Alabi et al. (2020) derived a similar logarithmic stellar mass of NGC 474 of ~10.6.

According to Wu & Boada (2019), the relation between host-galaxy stellar mass and metallicity can be characterized empirically as

$$Z = -1.492 + 1.847 \log(M_*/M_{\odot}) - 0.08026[\log(M_*/M_{\odot})]^2,$$
(1)

where Z is the oxygen abundance $12 + \log(O/H)$. Using this relation, a supersolar oxygen abundance of 9.08 ± 0.12 can be derived for NGC 474. From Figure 21, one can see that SN 2017fgc is consistent with the finding that HV SNe Ia tend to occur in more massive and metal-rich host galaxies. Also, the spectral survey for NGC 474 by Alabi et al. (2020) shows that the outer shell of this galaxy is slightly more metal-rich than its center. Recently, the detailed study by Fensch et al. (2020) showed that NGC 474 merged with a young metal-rich galaxy during its evolution.

Although a higher metallicity may help explain the properties observed in SN 2017fgc and some HV SNe Ia, we notice that SN 2017fgc is located far away (\sim 18.90 ± 0.01 kpc) from



Figure 21. Scatter plot of the Si II λ 6355 velocities and the corresponding hostgalaxy stellar mass (M_{stellar}). The HV SNe Ia are shown as red dots, and the NV SNe Ia are shown as blue circles. The horizontal and vertical dashed lines represent the criteria used to split the sample in velocity (Wang et al. 2009a) and M_{stellar} (Pan 2020) space, respectively. The data are taken from Pan (2020), and SN 2017fgc (this paper) is overplotted as a black dot.

the center of its host galaxy. Wang et al. (2013) initially found that HV SNe Ia tend to occur in more massive galaxies and explode near the center of the host galaxy, which was later confirmed by the Palomar Transient Factory (PTF) and the Berkeley SN Ia program sample (Pan et al. 2015; Pan 2020). It seems that SN 2017fgc is an outlier and does not follow this trend of HV SNe Ia. However, closer inspection of the host galaxy NGC 474 reveals that it is a massive lenticular galaxy that experienced a merger ~ 2 Gyr ago (Alabi et al. 2020; Fensch et al. 2020). SN 2017fgc is located in a gas bridge (see the left panel of Figure 1) connecting the gas shell and the massive galaxy. We speculate that SN 2017fgc could have

²⁸ https://ned.ipac.caltech.edu/

been ejected from the inner part of the companion galaxy NGC 470 as the merger took place ~ 2 Gyr ago, or that it formed as a result of some cold gas remaining in the companion disk.

We attempted to measure the metallicity of the explosion site from both the multicolor photometry and MUSE IFU (Laurent et al. 2010) spectra but failed because no spectra near SN 2017fgc are available. According to Alabi et al. (2020), the center of galaxy NGC 474 is dominated by slightly lower mass-weighted metallicity $[Z/H] = -0.14 \pm 0.08$ dex (corresponding to 0.72) times the solar metallicity) while the outer shell has a solar metallicity $[Z/H] = -0.03 \pm 0.09$ dex (corresponding to 0.93) times the solar metallicity). Thus, it is very likely that SN 2017fgc has a metal-rich progenitor system. Higher-metallicity WDs could produce relatively more stable and less radioactive nucleosynthetic products owing to the overabundance of neutrons (Timmes et al. 2003), which is consistent with the observed evidence that relatively small amounts of ⁵⁶Ni are found to be synthesized in the explosion of some HV SNe Ia (Polin et al. 2019; Li et al. 2021). Moreover, a higher-metallicity companion will produce more abundant CSM, consistent with recent studies (Wang et al. 2013; Pan 2020; Li et al. 2021).

6. Conclusion

In this paper, we present extensive optical photometric and spectroscopic observations of the fast-expanding Type Ia SN 2017fgc. This object can be put into the categories of both HVG and HV SNe Ia according to the classification schemes proposed by Benetti et al. (2005) and Wang et al. (2009a). It has a post-peak decline rate $\Delta m_{15}(B) = 1.05 \pm 0.07$ mag and an absolute *B*-band magnitude $M_{\text{max}}(B) = -19.32 \pm 0.13$ mag. Using the radioactive-decay-driven radiation diffusion model (Arnett 1982), we find that SN 2017fgc has a peak luminosity of $L_{\text{peak}} = (1.32 \pm 0.13) \times 10^{43} \text{ erg s}^{-1}$ and a synthesized nickel mass of $M_{\text{Ni}} = 0.51 \pm 0.03 M_{\odot}$.

The evolution of the light curve and color curve of SN 2017fgc are similar to those of other HV SNe Ia such as SN 2002bo and SN 2006X. The relatively bright tails in the *U* and *B* light curves observed in SN 2017fgc may be indicators of CSM around the progenitor system. Its spectral evolution is similar to those of SN 2002bo, SN 2006X, and SN 2013gs, with an unusually high Si II velocity near maximum light (~15,000 ± 150 km s⁻¹) as well as stronger absorptions of Fe II/Mg II blends near 4400 Å and Fe III/Fe II/Si II blends near 4900 Å. Moreover, SN 2017fgc and other HV SNe Ia are found to have more pronounced secondary maximum peaks in the *li* bands. All of the above features indicate that SN 2017fgc and other HV SNe Ia likely have experienced more complete burning, or their progenitors have higher-metallicity environments.

Inspection of its birthplace environment indicates that SN 2017fgc was born in a gas bridge with young and metal-rich stellar populations. However, the fact that it was located far away from the center of its host galaxy indicates that its progenitor cannot be metal-rich. A possible scenario is that the progenitor of SN 2017fgc could have been ejected from the inner part of the companion galaxy during the merger ~ 2 Gyr ago, or formed as a result of some cold gas remaining in the companion disk (Alabi et al. 2020; Fensch et al. 2020). Detailed study of the host environment of SN 2017fgc is needed. Also, more observations and further modeling are essential to reveal the origin of the strong absorption of Fe II and IMEs seen in SN 2017fgc and the nature of the fast-expanding subclass of SNe Ia.

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