Multiple giant eruptions and X-ray emission in the recoiling AGN/LBV candidate SDSS1133

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ABSTRACT

We present a comprehensive analysis of 20 years worth of multi-color photometric light curves, multi-epoch optical spectra, and X-ray data of an off-nuclear variable object SDSS1133 in Mrk 177 at z = 0.0079. The UV-optical light curves reveal that SDSS1133 experienced four outbursts in 2001, 2014, 2019, and 2021. The persistent UV-optical luminosity in the non-outbursting state is \( \sim \) \( 10^{41} \) erg s\(^{-1}\) with small-scale flux variations, and peak luminosities during the outbursts reach \( \sim \) \( 10^{42} \) erg s\(^{-1}\). The optical spectra exhibit enduring broad hydrogen Balmer P-Cygni profiles with the absorption minimum at \( \sim -2,000 \) km s\(^{-1}\), indicating the presence of fast moving ejecta. Chandra detected weak X-ray emission at a \( 0.3-10 \) keV luminosity of \( L_X = 4 \times 10^{38} \) erg s\(^{-1}\) after the 2019 outburst. These lines of evidence suggests that SDSS1133 is an extreme luminous blue variable (LBV) star experiencing multiple giant eruptions with interactions of the ejected shell with different shells and/or circumstellar medium (CSM), and disfavors the recoiling Active Galactic Nuclei (AGN) scenario suggested in the literature. We suggest that pulsational pair-instability may provide a viable explanation for the multiple energetic eruptions in SDSS1133. If the current activity of SDSS1133 is a precursor of a supernova explosion, we may be able to observe a few additional giant eruptions and then the terminal supernova explosion or collapse to a massive black hole in future observations.

Key words: galaxies: active – stars: mass-loss – stars: variables: general – stars: individual (SDSS J113323.97+550415.8)

1 INTRODUCTION

SDSS J113323.97+550415.8 (hereafter SDSS1133) has long been recognised as an unusually persistent extragalactic variable object (see also López-Corredoira & Gutiérrez 2006; Zhou et al. 2006; Keel et al. 2012; Reines et al. 2013; Koss et al. 2014; Burke et al. 2020; Ward et al. 2021). SDSS1133 is a point source with a quasar-like optical color, located at the outskirt of a blue compact dwarf galaxy Mrk 177 (UGCA 239) at the galactocentric distance of 5.8′ = 0.81 kpc (Figure 1). By analysing historic photometry data of SDSS1133, Koss et al. (2014) show that SDSS1133 is optically detected over 63 yr since 1950. The absolute magnitude of SDSS1133 is in between \( M_B \sim -13 \) mag and \(-14 \) mag in its non-outbursting phase (before 1999 and after 2003), and it got two orders of magnitude brighter (\( M_B \sim -16 \) mag) in the outbursting phase in 2001 – 2002. The optical spectrum obtained in 2003 by the Sloan Digital Sky Survey (SDSS) reveals complex hydrogen Balmer line profiles, where the broad emission component has a full-width at half maximum (FWHM) greater than \( \sim 2,000 \) km s\(^{-1}\), and the SDSS pipeline classifies SDSS1133 as a quasi-stellar object (QSO). The narrow line redshift is consistent with that of the Mrk 177’s nucleus (z = 0.0079; see Section 2.12). Mrk 177 exhibits a disturbed morphology, suggesting that it is a post-merger galaxy (Koss et al. 2014).

It is suggested that SDSS1133 could be a recoiling type 1 Active Galactic Nuclei (AGN) with extreme variability (Koss et al. 2014). Under the recoiling AGN scenario, SDSS1133 is explained as an offset AGN ejected from the center of recently-merged galaxy Mrk 177, kicked by a gravitational wave recoil after the coalescence of the supermassive black hole binary (SMBHB) (e.g., Komossa 2012, and references therein). The absolute magnitude of SDSS1133 is consistent with that of the low-luminosity AGNs in the lo-

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cal Universe (e.g., Ho et al. 1997; Greene & Ho 2007; Reines et al. 2013). The large variability amplitude of \( \sim 2 \) mag is rarely seen in AGNs, but can be achieved by a rare population of extremely variable AGNs (e.g., MacLeod et al. 2010, 2012; Graham et al. 2017). The broad emission line profile can be interpreted as complex virial motions of broad line region clouds surrounding the AGN. The optical and near-infrared colors remain roughly constant over the observed periods and are redder than the stellar locus, being consistent with the recoiling AGN interpretation (Koss et al. 2014).

However, other observational properties suggest that SDSS1133 is a kind of stellar activity-related variables. The absolute magnitude and temporal behavior of SDSS1133 are more consistent with gap transients or SN impostors (namely giant eruptions of extragalactic luminous blue variable stars; hereafter LBV), or faint supernovae (SN) (e.g., Van Dyk et al. 2000; Smith et al. 2011; Smith 2017b; Pastorello & Fraser 2019; Perley et al. 2020). Also, the broad Balmer line profile of SDSS1133 exhibits blue-shifted P-Cygni-like absorption features up to \( \sim -5,000\) km s\(^{-1}\), which is reminiscent of those observed in SNe II and some giant eruption LBVs (e.g., Smith 2008; Pastorello et al. 2010, 2013; Mauerhan et al. 2013; Koss et al. 2014; Ward et al. 2021). SDSS1133 exhibits narrow/intermediate width Fe II and Ca II emission lines (Koss et al. 2014), which are rarely seen in AGNs while sometimes observed in SNe and LBVs (e.g., Smith et al. 2010; Foley et al. 2011; Taddia et al. 2013; Koss et al. 2014; Smith et al. 2018; Ward et al. 2021).

Recently, Ward et al. (2021) report another outburst event of SDSS1133 detected by the Zwicky Transient Facility (reported as a transient ZTF19aamfjfw, also known as Gaia19bwn) beginning on 2019 April 7, peaked on 2019 June 5, and faded again by 2019 December 1 (see also Stanek et al. 2019; Pursimo et al. 2019a,b). Moreover, the Gaia all-sky photometry reveals that SDSS1133 experienced another outburst peaked on 2021 June 21. Although Koss et al. (2014) and Burke et al. (2020) suggested a scenario that SDSS1133 is a LBV erupting for decades since 1950 and then followed by a terminal explosion observed as a SN IIn after 2001, the detection of these new outburst events rules out this possibility of terminal explosion and any other one-off event scenarios for SDSS1133 such as SNe, tidal disruption events, or binary mergers. Based on the detection of the recurrent outbursts and its peculiar enduring spectroscopic properties, Ward et al. (2021) suggest that SDSS1133 is likely to be an erupting LBV with the progenitor still alive, but the AGN scenario cannot be completely ruled out.

Although a lot of observational data are available and discussed in the literature, there is still no consensus on the nature of SDSS1133. The purpose of this paper is to present a comprehensive analysis of the multi-wavelength data of SDSS1133 to conclude the true nature of this enigmatic object. In Section 2, we present analysis for multi-epoch imaging and spectroscopic data of SDSS1133, including already published and unpublished X-ray, ultraviolet (UV), and optical data. In Section 3, we compare the observational properties of SDSS1133 with known LBVs as well as AGNs and SNe, and we conclude that SDSS1133 is one of the brightest extragalactic giant eruption LBV, akin to \( \eta \) Carinae’s Great Eruption and known SN progenitor LBV outbursts. We suggest that the X-ray-to-radio emission of SDSS1133 is mediated by interactions of an ejected shell with different shells and/or circumstellar medium (CSM), where the CSM is formed by enduring stellar wind and the ejecta are produced via multiple episodes of non-terminal explosions (e.g., pulsational pair-instability). Conclusions are summarized in Section 4.

2 DATA ANALYSIS

In this Section, we describe details of the analysis of the multi-wavelength data of SDSS1133 retrieved from various publicly-available data archives. The X-ray, UV, and optical imaging data from the SDSS, PanSTARRS1 (PS1), ZTF, Palomar Transient Factory (PTF), Mayall and Bok Legacy Surveys, Swift, XMM-Newton, and Chandra data archives are described in Sections 2.1–2.8, respectively. A part of the Swift and optical imaging data (SDSS and PS1) have already been published by Koss et al. (2014), but here we re-analyse all the data in a consistent manner using GALFIT version 3.0.5 (Peng et al. 2011) to derive host-subtracted Point Spread Function (PSF) magnitude light curves of SDSS1133 (see Section 2.9 for details). Other historic measurements for SDSS1133 reported in the literature are summarised in Sections 2.10 and 2.11. The optical and X-ray broad-band photometries of SDSS1133 derived in this work are tabulated respectively in Tables 1 and 2. Figures 2 and 3 show the broad-band light curves. The data analysis of the SDSS spectrum and unpublished Keck/LRIS spectra retrieved from the Keck Observatory Archive (KOA) is described in Section 2.12.

Following Koss et al. (2014), we use \( d_L = 28.9\) Mpc (distance modulus \( \mu = 32.30\) mag) as a luminosity distance to Mrk 177 (taken from NASA/IPAC Extragalactic Database (NED); Tully 1988, 1994) to calculate luminosities and absolute magnitudes of SDSS1133\(^1\). Since SDSS1133 is a low-redshift object \( (z = 0.0079)\), \( K\)-correction is negligible in

\(^1\) NED reports an uncertainty on the distance as \( d_L = 28.9 \pm 8.9\) Mpc \( (\mu = 32.30 \pm 0.80\) mag\). Throughout this paper we do not include the uncertainty on the distance, but it should be kept in mind that the derived luminosity is uncertain by 0.27 dex due to this distance uncertainty.
Figure 2. Top: the optical light curves of SDSS1133. The PSF magnitudes obtained by the GALFIT modelling are shown, except for the synthesized SDSS magnitudes from the SDSS spectrum in 2003 and Gaia G band light curve. Galactic extinction is corrected. Four outbursts observed in 2001, 2014, 2019, and 2021 are labelled. Epochs of optical spectroscopic observations (Section 2.12) are indicated by vertical bars. Middle: UV and NIR photometric measurements. The Keck/NIRC2 measurements are taken from Koss et al. (2014), and the Swift/UVOT and XMM-Newton/OM PSF measurements are analysed in this work. Bottom: the unabsorbed 0.3 – 10 keV X-ray flux light curve. The arrows indicate the 90% upper limits on the X-ray flux.

Table 1. UV-optical PSF photometry for SDSS1133 obtained by the GALFIT modelling.

| MJD       | Date (YYYY-MM-DD) | mag.  | error in mag. | Telescope | Filter |
|-----------|-------------------|-------|----------------|-----------|--------|
| 56701.96  | 2014-02-13        | 20.26 | 0.03           | Swift     | UVW2   |
| 58631.43  | 2019-05-28        | 18.61 | 0.03           | Swift     | UVW2   |
| 58631.44  | 2019-05-28        | 18.26 | 0.03           | Swift     | UVM2   |
| 56531.44  | 2013-08-27        | 20.14 | 0.02           | Swift     | UVW1   |
| 57358.55  | 2015-12-02        | 20.52 | 0.05           | XMM       | UVW1   |
| 57360.53  | 2015-12-04        | 20.44 | 0.04           | XMM       | UVW1   |
| 58631.44  | 2019-05-28        | 18.10 | 0.02           | Swift     | UVW1   |
| 52261.37  | 2001-12-18        | 16.35 | 0.01           | SDSS      | u      |
| 52365.14  | 2002-04-01        | 16.79 | 0.01           | SDSS      | u      |
| 52261.37  | 2001-12-18        | 16.34 | 0.01           | SDSS      | g      |

MJD indicates the mean epoch of each observation run. Galactic extinction is uncorrected. All magnitudes are listed as AB magnitude. The statistical photometric errors are reported (systematic errors are not included). The full table is only available in electronic form.
Figure 3. Top: the same as Figure 2, but the plot range is restricted from 2018 March 23 to 2020 July 10 (58200 < MJD < 59040), where the densely-sampled ZTF data are available. The optical and UV data points are shown simultaneously. Epochs of optical spectroscopy and X-ray observations (Swift and Chandra) are indicated by vertical bars. Middle: the $g-r$ colors at the epochs when quasi-simultaneous ZTF $g$ and $r$ band measurements are available. The large symbols are the mean colors of each of the observing period indicated by the horizontal lines ($g-r = 0.29, 0.26,$ and $0.42$ mag in 2018, 2019, and 2020, respectively). Bottom: the $g-i$ colors. The mean colors are $g-i = 0.18$ and $0.19$ mag in 2018 and 2019, respectively.

Table 2. Swift/XRT, XMM-Newton/EPIC, and Chandra/ACIS unabsorbed $0.3-10$ keV X-ray flux and luminosity ($L_{0.3-10}$ keV) of SDSS1133.

| MJD     | Date       | Flux        | Luminosity $L_{0.3-10}$ keV (SMC, LMC, MW) | Luminosity $L_{0.3-10}$ keV (10$^{39}$ erg s$^{-1}$) | Telescope |
|---------|------------|-------------|-------------------------------------------|--------------------------------------------------|-----------|
| 56531.4 | 2013/08/26-28 | < 1.018     | < 1.018                                   | < 2.756, 2.602, 1.891                              | Swift     |
| 56702.0 | 2014/02/06-25 | < 1.340     | < 1.339                                   | < 3.626, 3.423, 2.488                              | Swift     |
| 57359.6 | 2015/12/02-04 | < 0.337     | < 0.337                                   | < 1.098, 0.949, 0.671                              | XMM       |
| 58631.4 | 2019/05/27-29 | < 2.706     | < 2.705                                   | < 7.319, 6.910, 5.024                              | Swift     |
| 58708.9 | 2019/08/13-14 | 0.393$^{+0.116}_{-0.116}$ | 0.393$^{+0.116}_{-0.116}$ | 0.669$^{+0.198}_{-0.198}$ 0.644$^{+0.190}_{-0.190}$ 0.522$^{+0.154}_{-0.154}$ | Chandra   |

MJD indicates the mean epoch of each observation run. An absorbed power-law model with $\Gamma = 2$ and $N_H = 2 \times 10^{20}$ cm$^{-2}$ is assumed. Swift/XRT and XMM-Newton/EPIC data are non-detection, thus the 90% upper limits are shown. The reported uncertainty of the Chandra/ACIS luminosity is ±1σ.

The 4th column is the $0.3-10$ keV X-ray luminosity corrected for the host galaxy X-ray absorption assuming (SMC, LMC, MW)-like extinction, where the additional gas column of $N_{H, host} = (2.84, 1.46, 0.31) \times 10^{22}$ cm$^{-2}$ in the host galaxy is included in the X-ray spectral modelling, respectively (Section 3.4.4).
most cases. The magnitudes are reported in the AB magnitude unit. The Galactic extinction toward the direction of SDSS1133 is very low, $E(B - V) = 0.010$ mag (Fitzpatrick 1999; Schlafly & Finkbeiner 2011). The Galactic extinction coefficients for the SDSS and PS1 systems are taken from NED, and those for other photometric bands are derived by assuming a $A_V = 10,000$ K black body spectrum at $z = 0.0079$ and using the Fitzpatrick (1999)’s extinction curve and filter transmission curves.

### 2.1 SDSS imaging (2001-2002)

SDSS u, g, r, i, and z band images were obtained on 2001 December 18 and 2002 April 1 (MJD=52261.4 and 52365.1, respectively; Figure 1). We downloaded the SDSS corrected frames and calibration files from the SDSS Data Release (DR) 7 Data Archive Server. Photometric zero points were calculated from global zero points and airmass values 2, and PSF model images were reconstructed using the calibration files 3.

The background variance maps were calculated by using SExtractor version 2.25.0 (Bertin & Arnouts 1996; Bertin 2011), and variance maps were created by adding the background variance and objects’ Poisson variance. The PSF and the variance maps were used for the GALFIT modelling to perform the PSF photometry of SDSS1133, as described in Section 2.9.

### 2.2 PanSTARRS1 (2010-2015)

PanSTARRS1 (PS1) 3π survey started observing the entire northern sky since 2010 (Chambers et al. 2016). The PS1 data obtained before 2015 are now publicly available as PS1 DR2. We downloaded PS1 g, r, i, z, and y band 6000 × 6000 pixels (25′.8 × 25′.8) single-epoch warp and variance images at the position around SDSS1133 (sky-cell1.2375.070 of the PS1 sky tessellation) from the PS1 DR2 Image Cutout Service. The publicly available single-epoch images as of DR2 are spanning from 2010 February 27 to 2015 February 12. Several g and i band images were visually identified to be affected by chip and readout cells gaps or telescope tracking errors, and were excluded from the analysis. PSF models of the single-epoch images at the position of SDSS1133 were created using SExtractor and PSFEx version 3.21.1 (Bertin & Arnouts 1996; Bertin 2011). Photometric zero points calculated by the PS1 data analysis pipeline (written in the image headers) were directly used (Waters et al. 2020; Magnier et al. 2020).

### 2.3 PTF (2012-2015)

Palomer Transient Factory (PTF) was a wide-field optical time-domain survey using the Samuel Oschin 48-inch Schmidt telescope at Palomar Observatory (Law et al. 2009). PTF observed SDSS1133 in g and Mould-R bands in 2012, 2014, and 2015. Calibrated PTF images were downloaded from the IPAC database (Laher et al. 2014). As in Sections 2.1 and 2.2, image background variance maps were calculated by using SExtractor, and PSF models were created by using PSFEx photometric zero points defined by a 8 pixel diameter aperture taken from the image header (Laher et al. 2014) were rescaled by using the PSF models to represent infinite-aperture zero point magnitudes.

### 2.4 ZTF (2018-2020)

Zwicky Transient Facility (ZTF) has been conducting a time-domain survey using a wide-field camera with 47 square degree field of view mounted on the Samuel Oschin 48-inch Schmidt telescope at Palomar Observatory since 2017.
Northern Sky Public Survey is a three-day cadence survey of the Northern Sky with ZTF-g and ZTF-r bands, and other private programs are also obtaining g, r, and i band images over a fraction of the sky (Graham et al. 2019). As described by Ward et al. (2021), ZTF detected the 2019 outburst event of SDSS1133 and reported a transient detection alert on 2019 April 23 (MJD=58596), and recorded the transient as ZTF19aafmjfw (see Patterson et al. 2019, for details of the ZTF alert system) 4

The pipeline-processed data both from public and private surveys are made public via the ZTF Public Data Release. ZTF DR4 pipeline-processed g, r, and i band single-epoch images (sciimg.fits; primary science image of database field = 788) and associated PSF model images (sciimgdlaopsfent.fits; PSF estimate at science image center) were downloaded from the Science Data System at IPAC (Masci et al. 2019). Color terms in the g band during the period of 2018 March 25 - 2020 June 29, loaded from the Science Data System at IPAC (Masci et al. 2019), were obtained on 2014 February 6-25 are available (target ID = 00032905). Then, several follow-up observations were triggered after the 2019 outburst; Swift observed SDSS1133 on 2019 May 27 (MJD=58630.1) and 29 (MJD=58632.8) for 2.4 and 2.0 ks, respectively, with the XRT and UVOT in the UVW2, UVM2, and UVW1 filters (target ID = 00011418). We performed the Swift data analysis with HEAsoft software packages (Version 6.25; HEASARC 2014), using calibration datasets in the High Energy Astrophysics Science Archive Research Center (HEASARC)’s calibration database (CALDB; accessed 2020 December 17). Hereafter each of the Swift data in 2013, 2014, and 2019 were separately binned into a single measurement.

2.5 Mayall and Bok Legacy Imaging Surveys (2015-2018)

The sky region of SDSS1133 was imaged by the DESI Legacy Imaging Surveys (Zou et al. 2019; Dey et al. 2019), specifically by Mayall z band Legacy Survey and by Bok 90Prime g and r band Survey projects, during the period between 2016 and 2018. The Mayall Survey is using a mosaic camera (Mosaic-3) mounted on the 4-m Mayall telescope, and Bok 90Prime survey is using the 90Prime camera at the prime focus of the Bok 2.3-m telescope. Also, since the sky region of SDSS1133 is located inside the spring Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) field, two Mayall g band images obtained in 2015 March 15-16 during the course of an imaging survey for the HETDEX (NOAO program ID = 2015A-0075; PI: Robin B. Ciardullo) are available.

Mayall and Bok g, r, and z band imaging data (community pipeline (CP) ooi_v1 products before being processed by Tractor; Dey et al. 2019) containing SDSS1133 and Mrk 177 were downloaded from the NOAO Science Archive5. We used SExtractor and PSFEx to estimate PSF models of the images. The zero-point AB magnitudes were evaluated by comparing instrumental PSF magnitudes of three field stars around SDSS1133 to the PS1 PSF magnitudes taken from the PS1 DR2 MeanObject View table (Chambers et al. 2016), with color transformations given in Dey et al. (2019).

2.6 Swift (2013-2019)

Swift (Gehrels et al. 2004) X-ray Telescope (XRT) and UV-Optical Telescope (UVOT) have targeted SDSS1133 several times. Koss et al. (2014) carried out Target-of-Opportunity XRT and UVOT UVW1 observations for SDSS1133 on 2013 August 26, 27, and 28. Also, unpublished Swift UVW2 data obtained on 2014 February 6-25 are available (target ID = 00032905). Then, several follow-up observations were triggered after the 2019 outburst; Swift observed SDSS1133 on 2019 May 27 (MJD=58630.1) and 29 (MJD=58632.8) for 2.4 and 2.0 ks, respectively, with the XRT and UVOT in the UVW2, UVM2, and UVW1 filters (target ID = 00011418). We performed the Swift data analysis with HEAsoft software packages (Version 6.25; HEASARC 2014), using calibration datasets in the High Energy Astrophysics Science Archive Research Center (HEASARC)’s calibration database (CALDB; accessed 2020 December 17). Hereafter each of the Swift data in 2013, 2014, and 2019 were separately binned into a single measurement.

2.6.1 Swift/XRT

We downloaded pipeline-processed Swift XRT Level 1 products from the HEASARC Archive. Calibrated and cleaned event files in the XRT photon counting mode were produced using xrtpipeline with standard screening criteria.

Each of the 2013, 2014, and 2019 XRT datasets (18.6 ks, 13.8 ks, and 4.3 ks, respectively) was coadded separately. Spectral extraction and coadding of the event files were performed by using xselect. A circular aperture of 47″ in radius centered on the SDSS1133’s optical coordinate was used for the source count extraction, and an annular aperture with the inner and outer radii of 100″ and 200″ centered on the SDSS1133’s optical coordinates was used for the background count extraction. As shown in Section 2.8, not only SDSS1133 but also the Mrk 177’s nuclear X-ray emission contribute to the X-ray counts in the r = 47″ circular aperture. Thus, precisely speaking, the luminosity upper limits obtained above should be interpreted as the limits for the total luminosity of SDSS1133 and Mrk 177, giving a conservative upper limits on the SDSS1133’s luminosity.
xrtmkarf was used to create aperture-corrected (un-corrected) auxiliary response files (ARF) for the source (background) spectra, and an exposure time-weighted mean response file for each visit was created by using addarf. A common response matrix file (RMF; swxpc0to12s6_20130101v104.rmf) taken from CALDB was used for the subsequent analysis.

We found that the X-ray counts of SDSS1133 are quite low, thus the spectral bins were grouped into a single full band (0.3 – 10 keV) by using xspec/grppha. The background-subtracted full band net count rates were calculated to be −0.991(±1.941) × 10−4, −1.312(±2.141) × 10−4, and 4.383(±5.268) × 10−4 count s−1 in 2013, 2014, and 2019, respectively. We conclude that all of these measurements were non-detection. Under the assumption of Gaussian statistics with zero mean, 90% upper limits on the count rates are 2.488 × 10−4, 2.745 × 10−4, and 6.754 × 10−4 count s−1, respectively. The corresponding 90% upper limits on the 0.3 – 10 keV band flux and luminosity were evaluated by assuming an absorbed power-law model (phabs*powerlaw

4 https://antares.noao.edu/alerts/data/14589650; https://lasair.roe.ac.uk/object/ZTF19aafmjfw/
5 http://archive1.dm.noao.edu/
in XSPEC) with a fixed power-law photon index of $\Gamma = 2$ (in the form of $f_\nu \propto \nu^{-1-\Gamma}$) and a Galactic HI column density of $N_H = 2 \times 10^{20}$ cm$^{-2}$, and the results are summarized in Table 2. The Swift non-detection suggests that the X-ray luminosity of SDSS1133 is less than $3 \times 10^{39}$ erg s$^{-1}$ even at around the peak epoch of the 2019 outburst (Figure 3).

Our re-analysis of the Swift/XRT data shows that the “marginal” Swift/XRT X-ray detection on 2013 August 26–28 reported by Koss et al. (2014) was actually non-detection. As described in Section 2.8, this conclusion is further confirmed by the Chandra/ACIS data which indicate that the X-ray luminosity of SDSS1133 is just below the Swift/XRT’s detection limit.

2.6.2 Swift/UVOT

Swift/UVOT observed SDSS1133 through UVW1 (2600 Å), UVM2 (2246 Å), and UVW2 (1928 Å) bands. We downloaded pipeline-processed Swift UVOT Level 2 products from the HEASARC Archive. For each filter, each of the 2013, 2014, and 2019 data was combined into a single image using wrotimea.

Time dependent sensitivity corrections (several tens percent)$^6$ and small deadtime and coincidence loss corrections (at most 2%) were calculated by using deadtime, and applied for the measured fluxes (Poole et al. 2008; Breeveld et al. 2011). The zero point AB magnitudes for the source count rates for the standard aperture are 18.95, 18.54, and 19.11 mag for UVW1, UVM2, and UVW2 band, respectively$^7$. Using tables of encircled energy curves for the UVOT PSFs in the CALDB, we estimated zero point AB magnitudes for the infinite aperture (defined to be 30″ in radius) to be used for the PSF photometry as 19.11, 18.72, and 19.24 mag for UVW1, UVM2, and UVW2 band, respectively. The PSF models of the UVOT images were created with PSFEx. When reporting the Swift/UVOT photometric measurements, the errors on the magnitudes only include statistical errors. We should note that, in addition to the statistical errors, the reported magnitudes can be affected by various systematic errors; e.g., the Swift/UVOT photometric zero-point estimates induce $\sim 0.03$ mag errors on the magnitudes.

2.7 XMM-Newton (2015 December)

XMM-Newton (Jansen et al. 2001) X-ray and UV imaging data were obtained on 2015 December 2 and 4 (Obs. ID=0762960201 and 0762960301; PI: Michael Koss), which is unpublished in the literature. We downloaded the two XMM-Newton datasets (Observation Data File; ODF) from the XMM-Newton Science Archive. The Current Calibration Files (CCF) were downloaded from the CCF ftp server (accessed 2020 October 28). The data analysis was performed by using the XMM-Newton Science Analysis System (SAS version 18.0.0; Gabriel et al. 2004).

2.7.1 XMM-Newton/EPIC

Filtered photon counting event files of European Photon Imaging Camera (EPIC) MOS and PN cameras were generated by using standard SAS tasks emproc, eproc, and evselect. The exposure times of the MOS1, MOS2, and PN data are 8.2, 8.4, and 4.1 ks on 2015 December 2, and 11.3, 11.5, 7.2 ks on 2015 December 4, respectively. MOS and PN spectra of the two datasets were extracted and then combined into a single source spectrum, background spectrum, and response matrix (RSP) by using SAS/multiespecget. Here the combined RSP file was defined by summing up RSP files (=RMF×ARF) of all of the MOS and PN data, and the effective exposure time of the combined dataset was calculated to be 8.5 ks. A circular aperture of 32″ in radius centered on the optical position of SDSS1133 was used for the source spectral extraction, and an offset circular aperture of 72″ in radius was used for the background spectral extraction. As described in Section 2.6.1, the source extraction aperture of 32″ contains not only SDSS1133 but also the Mrk 177’s nuclear X-ray emission (see Section 2.8), thus the luminosity upper limit obtained here only provide a conservative upper limit on the SDSS1133’s luminosity.

The same analysis as Section 2.6.1 was applied for the XMM-Newton combined spectral data. The effective background-subtracted 0.3 – 10 keV net count rate was calculated to be 2.981 ($\pm 2.266) \times 10^{-3}$ count s$^{-1}$, thus we conclude that SDSS1133 is undetected in the XMM-Newton data. The 90% upper limit on the effective count rate is 2.905 $\times 10^{-3}$ count s$^{-1}$. Assuming the same absorbed power-law spectral model (phabs*powerlaw in XSPEC), we obtained an 90% upper limit on the unabsorbed X-ray flux in the 0.3 – 10 keV band as $3.370 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an 90% upper limit on the 0.3 – 10 keV luminosity of $L_{0.3–10\text{ keV}} = 3.367 \times 10^{38}$ erg s$^{-1}$, as summarized in Table 2.

2.7.2 XMM-Newton/OM

Both of the two XMM-Newton/Optical Monitor (OM; Mason et al. 2001) imaging mode datasets were obtained through the UVW1 band (2010 Å) with the pre-defined EPIC Imaging mode configuration, where the total on-source exposure times were 10.9 and 11.8 ks, respectively. Astrometrically-aligned mosaiced sky images ($\sim 16' \times 16'$, 2 $\times$ 2 binning, 0.953 pixel$^{-1}$) of the two datasets were separately generated from the ODFs by using SAS/omichain. Since SDSS1133 is faint, the coincidence-loss is negligible. The dead time fraction (0.017), sensitivity degradation correction factor (1.126), and large-aperture zero point in AB system (18.566 mag)$^8$ were directly taken from the CCF. We applied the same analysis as Section 2.6.2 to the XMM-Newton/OM data; SExtractor and PSFEx were respectively

$^6$ The most up-to-date UVOT sensitivity calibration file (included in CALDB ver.20201215) was used.

$^7$ These photometric zero-points convert count rates into AB magnitudes, where the count rates are corrected for deadtime, coincidence-loss, aperture corrections, large-scale sensitivity variations, and detector sensitivity variations.

$^8$ The UVW1-filter zero point is defined by an aperture of 35 unbinned pixels (10″.7) radius, and for count rates corrected for the coincidence-loss, dead time, and sensitivity degradation.

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show that SDSS1133 dimmed by \( \sim \) unpublished in the literature. Since the optical light curves (58 ks) with the Advanced CCD Imaging Spectrometer, ACIS observations put

**Figure 5. Chandra/ACIS 0.5 – 8 keV co-added count image centered on SDSS1133 (\( \sim 15'' \times 15'' \), 0.492 arcsec pixel\(^{-1} \)) obtained on 2019 August 13 and 14 (74.2 ks; Obs. ID = 21434 and 22684). The colorbar indicates the X-ray counts. North is up and East is to the left. The source extraction aperture (4'' in radius) centered on SDSS1133 is shown as a dotted line. The X-ray source located \( \sim 6'' \) North West from SDSS1133 corresponds to the nucleus of the host galaxy Mrk 177. The SDSS optical coordinates of SDSS1133 and Mrk 177’s nucleus are indicated by + and \( \times \) symbols, respectively.**

used to subtract global background from the images and create PSF models.

### 2.8 Chandra (2019 August)

Chandra (Weisskopf et al. 2002) observed SDSS1133 on 2019 August 13 (MJD=58708.4, 16 ks) and 14 (MJD=58709.3, 58 ks) with the Advanced CCD Imaging Spectrometer, ACIS (Obs. ID = 21434 and 22684; PI: David Pooley), which is unpublished in the literature. Since the optical light curves show that SDSS1133 dimmed by \( \sim 2 \) mag compared to the peak of the 2019 outburst by the end of 2019 June (Figure 3; Pursimo et al. 2019b), the Chandra observations put a constraint on the X-ray emission of the SDSS1133 in its post-outburst phase.

We used CIAO v4.12.1 (Fruscione et al. 2006) to download and analyse the archival ACIS data. Figure 5 shows a 0.5 – 8 keV co-added clipped count image centered on SDSS1133 (\( \sim 15'' \times 15'' \)) created by using CIAO/merge_obs. SDSS1133 is clearly detected in this image, and also the nucleus of the host galaxy Mrk 177 is detected at a similar count rate.

The event files, ARFs, and RMFs, reprocessed with CIAO/chandra_repro using CALDB 4.9.2.1, were input to CIAO/speceXtract to extract count rate spectra, where a circular aperture of 4'' in radius and annular aperture with 10'' inner and 40'' outer radii were used for the source and background extraction, respectively. The optical position of SDSS1133 was used to extract the spectra. Aperture corrections were applied for the ARFs for the source. Then, the spectra from the two exposures were summed by using CIAO/combine_spectra to create a 74.2 ks spectrum.

The background-subtracted full-band (0.5 – 8 keV) net count rate was calculated to be 2.327 (\( \pm 0.688 \times 10^{-4} \) count s\(^{-1} \)) with the signal-to-noise ratio of \( S/N = 3.380 \), under the assumption of the Gaussian statistics. The number of the observed X-ray counts is too small for the spectral analysis (see Figure 5), thus here we report integrated quantities in a 0.5 – 8 keV band. By using CIAO/modelflux with the ARFs and RMFs, and assuming a power-law spectral model with a fixed power-law photon index of \( \Gamma = 2 \) (xpowlaw) and a Galactic HI column density of \( N_H = 2 \times 10^{20} \) cm\(^{-2} \) (xphabs), we obtained an unabsorbed X-ray flux in the 0.5 – 8 keV band as 3.109 (\( \pm 0.919 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \)), or 0.5 – 8 keV luminosity of \( L_{0.5\text{--}8 \text{ keV}} = 3.107 (\pm 0.918) \times 10^{38} \) erg s\(^{-1} \). The corresponding 0.3 – 10 keV luminosity is 3.929 \( \times 10^{38} \) erg s\(^{-1} \) (Table 2). As already mentioned in Section 2.6.1, this faint X-ray luminosity suggests that the Swift/XRT observations were not sensitive enough to detect X-ray emission from SDSS1133.

Under the assumption that SDSS1133 is a LBV, an optically-thin thermal plasma model may be a more adequate reference model (e.g., Nazé et al. 2012). By using a thin thermal plasma emission model xspec (Smith et al. 2001) in CIAO/modelflux, and fixing the temperature to \( k_BT = 0.6 \) keV (following Nazé et al. 2012), Galactic HI column density to \( N_H = 2 \times 10^{20} \) cm\(^{-2} \), and metal abundance to \( Z_\odot \), we obtained an unabsorbed X-ray flux in the 0.5 – 8 keV band as 3.425 (\( \pm 0.103 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \)), or 0.5 – 8 keV luminosity of \( L_{0.5\text{--}8 \text{ keV}} = 3.423 (\pm 0.102) \times 10^{38} \) erg s\(^{-1} \). The difference of the estimated luminosity between the power-law model and thermal plasma model is small, suggesting that the luminosity estimates are not very sensitive to the choice of the spectrum models. In the subsequent sections, we only refer to the X-ray luminosities obtained under the assumption of the absorbed power-law model summarised in Table 2.

By applying the same analysis on the nucleus of Mrk 177, the count rate was evaluated as 1.770 (\( \pm 0.634 \times 10^{-4} \) count s\(^{-1} \)). We obtained an unabsorbed X-ray flux in the 0.5 – 8 keV band as 2.339 (\( \pm 0.838 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \)), or 0.5 – 8 keV luminosity of \( L_{0.5\text{--}8 \text{ keV}} = 2.337 (\pm 0.837) \times 10^{38} \) erg s\(^{-1} \). The corresponding 0.3 – 10 keV luminosity is 2.957 \( \times 10^{38} \) erg s\(^{-1} \). Coincidentally, this luminosity is very similar to that of SDSS1133. Since the separation between SDSS1133 and Mrk 177’s nucleus is 5.8, the low spatial resolution X-ray telescopes (Swift and XMM-Newton) cannot resolve the two X-ray components, as already pointed out in Sections 2.6.1 and Sections 2.7.1.

### 2.9 UV-optical structural decomposition of SDSS1133 and Mrk 177 with GALFIT

For each of the UV-optical imaging datasets (SDSS, PS1, PTF, ZTF, Mayall, Bok, Swift/UVOT, and XMM-Newton/OM), we performed structural decomposition of SDSS1133 and Mrk177 using GALFIT to obtain host-subtracted PSF magnitudes of SDSS1133. A 2-component model was adopted, where SDSS1133 was modelled by a PSF and Mrk 177 was modelled by a Sérsic profile (see Figure 4 for an example of the GALFIT modelling for a ZTF image). Specifically, GALFIT \( \chi^2\)-minimization was performed leaving
The fitting was performed on 10 parameters as free parameters, and then formed again with the 4 Sersic parameters (first light curves of each dataset, we performed a two-step fitting procedure for each image leaving all the 10 parameters as free parameters, and then GALFIT was performed again with the 4 Sersic parameters \((R_e, n, b/a, PA_{\text{Sersic}})\) being fixed to mean values of the fitted parameters. After the fitting, multiple measurements obtained on the same day were combined into a single measurement by taking a weighted mean. In total, the PanSTARRS data have 5, 7, 11, 9, and 10 data points for the \(g, r, i, z,\) and \(\gamma\) band, the PTF data have 1 and 7 data points for the \(g, r, i, z,\) and \(\gamma\) band, the ZTF data have 223, 210, and 28 data points for the \(g, r, i, z,\) and \(\gamma\) band, the Mayall data have 2 and 4 data points for \(g, r, i, z,\) and \(\gamma,\) and the Bok data have 5 and 4 data points for \(g, r, i, z,\) and \(\gamma,\) respectively.

The results of the PSF photometry for SDSS1133 are summarized in Table 1. For the SDSS data, the PSF magnitudes derived here are consistent with the values reported in Koss et al. (2014), who derived host-subtracted PSF magnitudes of SDSS1133 by fitting a PSF-linear background model for \(5'\times5'\) images centered on SDSS1133. The UVW1 magnitude of SDSS1133 on 2013 August 27 reported by Koss et al. (2014) was 21.41 ± 0.30 mag, which differs from our result (20.14 mag) by ∼ 1.27 mag. We speculate that the difference may be due to overestimation of the host galaxy flux contribution in Koss et al. (2014)’s analysis, where the a 5’ region around SDSS1133 was fitted with a PSF model and a linear background model. For reference, we measure the 3’ radius aperture flux of SDSS1133 on 2013 August 27 (with aperture correction applied by using urosource and without host galaxy subtraction) as 19.29 ± 0.05 (stat.) ±0.03 (sys.) mag, which is close to our PSF magnitude estimate (20.14 mag). This indicates that the host galaxy contamination is small in the UV bands.

Table 3 shows the mean structural parameters of Mrk 177 obtained by the GALFIT modelling. We can see that the derived Sersic parameters are consistent among the various survey datasets, except for the Swift UVM2 band (specifically the Sersic index \(n\)); this deviation is probably because the single Sersic component does not provide a good fitting to the patchy appearance of the galaxy in the shallow UV image. Since the accurate structural modelling is beyond the scope of this paper and it does not necessarily improve the PSF photometry of SDSS1133 in the UV band, we did not perform further fine-tuned refit. Actually, we confirmed that the UVM2 band PSF magnitude of SDSS1133 changes only by 0.15 mag when fixing the Sersic index to be \(n = 1\).

2.10 Gaia (2015-2022)

The Gaia mission (Gaia Collaboration et al. 2016) has been observing SDSS1133 in Gaia’s G band since 2015 January 18, including the period of the second flare event in 2019. The Gaia G band is a white-light filter covering entire optical wavelengths (Weiler 2018). We downloaded Gaia light curve data of SDSS1133 (recorded as Gaia19bwn; Pursimo et al. 2019a) from the Gaia Photometric Science Alerts Database webpage (accessed 2022 May 24), excluding ‘null’ and ‘untrusted’ data points. In total 141 data points are available between 2015 January 18 and 2022 March 14 as of 2022 May. The Gaia light curve is plotted in Figure 2, but we should note that the Gaia photometry is host-unsubtracted.

2.11 Other UV-optical, NIR, and radio measurements

Historic photometric measurements for SDSS1133 based on Photographic Digital Sky Survey (DSS) plates from the POSS I and II surveys are reported by Koss et al. (2014). Although the detections of SDSS1133 are not significant (see Figure 1 of Koss et al. 2014), the visual magnitudes on 1950 March 20, 1994 April 14, and 1999 April 25 are measured as 18.6 ± 0.7, 18.4 ± 0.4, and 18.8 ± 0.5 mag, where the observations were carried out with 103aO (u and g band), GG395 (g band), and IIaF emulsion (i band), respectively.

In addition, a g band upper limit is reported by Zhou et al. (2006) on January 2005; the observation using the 2.16-m telescope of the Beijing Observatory failed to detect the source within 3 mag of the 2002 SDSS observation, providing a rough limit on the g band brightness as \(g > 19.4\) mag (Koss et al. 2014).

Koss et al. (2014) carried out \(J\) and \(K_s\) band Adaptive Optics assisted imaging observations for SDSS1133 with Keck/the Near Infrared Camera 2 (NIRC2) on 2013 June 16 (MJD=56459.3) These observations put constraints on the
size of the SDSS1133’s emission region to be < 12 pc, and J- and Kp band AB magnitudes are estimated as 19.02 ± 0.18 and 18.92 ± 0.16 mag, respectively.

GALEX All-sky Imaging survey provides a NUV band (1750 – 2800 Å; λ_eff ~ 2267 Å) magnitude on 2004 March 6 as 21.62 ± 0.40 mag (Koss et al. 2014), though the detection significance is not high and it can be a false detection.

At a radio band, Perez-Torres et al. (2015) report a non-detection by 5.0 GHz electronic European VLBI Network (eEVN) radio observations for SDSS1133 on 2014 December 12 provides a 3σ upper limit of 150 microJy beam⁻¹, corresponding to a 5.0 GHz luminosity of 5.2 × 10²⁴ erg s⁻¹ Hz⁻¹. Archival FIRST radio observations at 1.4 GHz also provides a 3σ upper limit of about 450 microJy beam⁻¹, corresponding to a luminosity of 1.6 × 10²⁵ erg s⁻¹ Hz⁻¹.

2.12 Optical spectra

Koss et al. (2014) present multi-epoch spectra of SDSS1133; the SDSS spectrum on 2003 March 9 (MJD=52707), Keck/DEIMOS spectrum on 2013 December 13 (MJD=56639), and the Multiple Mirror Telescope (MMT) spectrum on 2014 January 3 (MJD=56660). Pursimo et al. (2019a,b) conducted optical spectroscopic follow-up observations for the 2019 outburst event of SDSS1133 (referred to as Gaia19bwn in their Fig. 2) with ALFOSC on Nordic Optical Telescope (NOT) on 2019 May 29 (MJD=58632), near the light curve maximum epoch (Figure 3). Ward et al. (2021) present an optical spectrum taken on 2019 May 29 with the Lowell Discovery Telescope, the same date as the Pursimo et al. (2019a)’s observation.

Other than these already published data, there are unpublished Keck/LRIS spectroscopic data of SDSS1133 obtained on 2015 July 17 (MJD=57220; 500 s × 2) and 2019 March 10 (MJD=58552; 500 s) in the KOA. The second Keck/LRIS was obtained just before the 2019 outburst event, probing the pre-outburst gradually rising phase (Figure 3). Below we describe the data reduction of the Keck/LRIS spectra (Section 2.12.1), and spectral decomposition analysis of the Keck/LRIS and SDSS spectra (Section 2.12.2). The comparisons of the multi-epoch spectra are presented in Section 2.12.3.

2.12.1 Keck/LRIS spectra (2015, 2019)

We downloaded the raw Keck/LRIS spectral data of SDSS1133, spectrophotometric star (H24), and associated calibration data from KOA (PI: Fiona Harrison, program ID: C280LA, C300). All the LRIS data were obtained with a 1.0′-width long-slit, 600/4000 (blue arm) and 400/8500 (red arm) grisms, and on-chip 2 pixel binning in the slit direction was applied (the pixel scale is 0″.27 pixel⁻¹). The observations were carried out under non-photometric (variable seeing and atmospheric extinction) conditions. The PSF FWHM were evaluated as ~ 8 pixel (2″.2) on 2015 July 17 and ~ 11 pixel (3″.0) on 2019 March 10 from the standard star’s spatial profiles on the dispersed images.

Standard IRAF\textsuperscript{10} data reduction was performed on the LRIS data, where overscan, split-illumination flat, wavelength calibration, and image distortion corrections were applied. Pixels affected by cosmic-rays were identified and masked by using lacos_spec (van Dokkum 2001). The object spectra were extracted by using IRAF/apall’s aperture extraction task with a 8 pixel (2″.16) aperture. The host galaxy component was not subtracted, and telluric absorption correction was not applied. The Galactic extinction was corrected by using Fitzpatrick (1999)’s extinction curve. The relative flux offset between the blue arm and red arm spectra of each epoch was corrected by requiring the fluxes at around λ_{Hα} = 5500 Å to be consistent with each other. Then, the absolute fluxes of the spectra were roughly calibrated by scaling the spectra to match the g band photometric magnitudes at the epochs of the spectroscopic observations, where the g band photometric magnitudes were evaluated by linearly interpolating the Galactic extinction-corrected g band light curve in Figure 2. The Galactic-extinction corrected g band magnitudes were estimated as 19.95 and 19.38 mag on 2015 July 17 and 2019 March 10, respectively, which are respectively 1.39 and 0.82 mag fainter than the g = 18.56 mag estimated from the SDSS spectrum on 2003 March 9.

The Keck/LRIS spectra and publicly available SDSS spectrum of SDSS1133 are shown in Figure 6. We can see that overall spectral properties of SDSS1133 are unchanged during the periods of these spectroscopic observations. The P-Cygni profile is detected in all of the hydrogen Balmer series and possibly in He I λ5877, with the velocity width of about a few 1000 km s⁻¹ (see also Koss et al. 2014; Ward et al. 2021). Many narrow-to-intermediate width metal emission lines (e.g., Fe II, Ca II, and O I) are clearly detected especially in the Keck/LRIS spectra.

By applying a supernova spectral classification software GELATO (GEneric cLAssification TOol v.2.0; Harutyunyan et al. 2008)\textsuperscript{11} to the SDSS and LRIS spectra, we find that SDSS1133 is reminiscent of interacting transients; the SDSS and LRIS 2019 spectra are consistently best-fitted by a spectrum of a pre-SN eruption of a type IIn SN 2009ip obtained on 2011 September 24 (Pastorello et al. 2013), and the LRIS 2019 spectrum is best-fitted by a late-phase (+664.5 d) spectrum of a type IIn SN 1995G obtained on 1996 December 19 (Pastorello et al. 2002). In Figure 6, a VLT/X-Shooter optical spectrum of the 2011 event of SN 2009ip downloaded from the ESO Science Archive Facility Phase 3 (boxcar smoothed by 5 Å and arbitrarily scaled) is plotted for comparison. A more detailed analysis of the spectral properties is given below.

2.12.2 Spectral decomposition

The most remarkable feature of the optical spectra of SDSS1133 is the broad Balmer P-Cygni profile. The spectral decomposition including the broad P-Cygni absorption feature is not performed by Koss et al. (2014), thus we conducted spectral decomposition analysis of the Hβ and Hα P-Cygni profile for the SDSS and Keck/LRIS spectra. Each spectrum at the wavelength range of λ_{Hβ} = 4000–5500 Å, was best-fitted by a late-phase spectrum of a type IIn SN 2009ip.

\textsuperscript{10} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

\textsuperscript{11} https://gelato.tng.iac.es

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4400 – 5400 Å was fitted with a power-law continuum, broad and very broad Gaussian Hβ lines, and narrow Gaussian Hβ and OIII emission lines, where the power-law continuum and broad and very broad Hβ were absorbed by a factor of $e^{-\tau}\lambda$ where $\tau\lambda$ was modelled as a Gaussian. Since the optical spectra of SDSS1133 clearly show Fe II line forest (Koss et al. 2014), we also included a Fe II pseudo-continuum template spectrum in the model. Since no template spectrum for SNe/stellar objects is available in the literature, we adopted the Fe emission template spectrum of Boroson & Green (1992) which is created from a spectrum of the narrow line Seyfert 1 galaxy PG0050+124 (I Zw 1). The Fe emission template spectrum has the intrinsic FWHM of I Zw 1 of 900 km s$^{-1}$, and we directly used the Fe II spectrum without further Gaussian convolution. The Fe template spectrum has a flux density of $1.38 \times 10^{-15}$ erg s$^{-1}$ Å$^{-1}$ at $\lambda_{\text{rest}} = 5000$ Å, and the flux scaling factor to the Fe template spectrum and its redshift are fitting parameters.

The same model fitting was also performed at the wavelength range of $\lambda_{\text{obs}} = 6200 – 7100$ Å where the [NII], [SII], and [OI] narrow emission lines were included in the model. The narrow emission lines were assumed to have the same redshift and line velocity width.

$\chi^2$ minimization model fitting was performed by using the Levenberg-Marquardt algorithm implemented as optimize.least_squares in SciPy. The fitting was performed in the observed-frame. Uncertainties on the best-fitting parameters were evaluated by 10,000 trials of Monte Carlo resampling, where 10,000 mock spectra were generated by adding Gaussian flux noise to the original spectrum using the calculated standard deviations of the flux density.

The fitting parameters are tabulated in Table 4, and the best-fitting model for the SDSS spectrum is shown in Figure 7. The narrow lines are only marginally spectrally-resolved, thus the narrow velocity widths reflect the instrumental broadening. The narrow emission line redshift is measured to be $z = 0.008$, being consistent with the redshift of Mrk 177. The Fe II emission template spectrum, though its velocity width does not match that of SDSS1133, well explains the pseudo-continuum bumps observed at the redward and blueward spectral regions of the Hβ emission line, while the Fe II emission at the Hα wavelength range is very weak and hard to be seen. The very broad component is not well constrained especially at the Hβ wavelength range, but is required to explain the extended wing of the Hα profile.

The asymmetric P-Cygni-like Balmer line profile can largely be explained by the combination of the variable broad blue-shifted absorption on the very broad symmetric Balmer line, and the broad blue-shifted absorption also account for the continuum absorption observed at the blueward spectral region of the Balmer lines. The best-fitting models for the SDSS and LRIS spectra are shown in Figure 8 as a function of rest-frame velocity from $-10,000$ km s$^{-1}$ to $10,000$ km s$^{-1}$ relative to the narrow Balmer emission lines. The best-fitting absorption model suggests that the absorption peaks at $\sim -2,000$ km s$^{-1}$ and the highest velocity component is $\sim -5,000$ km s$^{-1}$.

### 2.12.3 Time series of the Hβ line profile

Figure 9 summarises the multi-epoch Hβ spectra of SDSS1133 described at the beginning of Section 2.12. The
$g$ band magnitudes at the epochs of the SDSS, DEIMOS, MMT, LRIS 2015, LRIS 2019, and Lowell observations are evaluated by linearly interpolating the $g$ band light curve in Figure 2. $g = 18.66$ (SDSS 2003), 19.65 (DEIMOS 2013), 19.65 (MMT 2014), 19.95 (LRIS 2015), 19.38 (LRIS 2019), and 17.36 mag (Lowell 2019), respectively.

Figure 9 reveals that the P-Cygni absorption features of SDSS1133 have been persistent at least for 16 years since 2003, even during the outburst phase in 2019 at the epoch of the Lowell observation when SDSS1133 was $\sim 2$ mag brighter than the non-outbursting phase (Figure 3). The absorption minimum varies from $-2000$ to $-4000$ km s$^{-1}$, while the maximum velocity component is roughly kept constant at $\sim -5,000$ km s$^{-1}$. The persistent P-Cygni absorption feature suggests that the high velocity ejecta producing the P-Cygni absorption is not due to an one-off transient event but is due to continuous or multiple ejections (see Section 3.3.3 for details).

**2.12.4 Balmer decrement and dust extinction in the host galaxy**

The dust extinction toward SDSS1133 may be inferred by using the Balmer decrement, specifically the flux ratio of H$\alpha$ to H$\beta$. Figure 10 presents the H$\alpha$/H$\beta$ Balmer decrement for the narrow, broad, and very broad emission line components of SDSS1133. While the Balmer decrements of the broad and very broad components are not well constrained due to the line profile modelling uncertainties, the Balmer decrements of the narrow component constrain H$\alpha$/H$\beta$ to be $\sim 5 - 6$. By combining the three measurements of narrow Balmer decrements, the median and 68% percentile range is H$\alpha$/H$\beta = 5.49_{-0.51}^{+0.80}$.

The theoretically expected value of the Balmer decrement is 2.86 for Case B recombination H II region with $T = 10^4$ K and $n_e = 10^2$ cm$^{-3}$ (e.g., Osterbrock 1989; Domínguez et al. 2013). This means that the median value of the relative extinction at the H$\beta$ and H$\alpha$ wavelengths is $A_{H\beta} - A_{H\alpha} = 2.5 \log_{10}(5.49/2.86) = 0.71$ mag. Assuming Pei (1992)’s Small Magellanic Cloud (SMC)-like, Large Magellanic Cloud (LMC)-like, and Milky Way (MW)-like dust extinction curves ($R_V = A_V/E(B-V)$) = 2.93, 3.16, and 3.08, respectively), the Balmer decrement of the narrow component in SDSS1133 corresponds to

$$E(B-V)_{\text{host}} = 0.63^{+0.13}_{-0.09} \text{ (SMC)},$$  
$$0.61^{+0.13}_{-0.09} \text{ (LMC)},$$  
$$0.65^{+0.14}_{-0.10} \text{ (MW)},$$

in the unit of magnitude, respectively (Figure 10). Here $E(B-V)_{\text{host}} \equiv A_{B,\text{host}} - A_{V,\text{host}}$ indicates the color excess due to the dust extinction in the SDSS1133’s host environment. The hydrogen column density corresponding to
the derived value of $E(B - V)_{\text{host}}$ is $N_H_{\text{host}} = (2.84^{+0.60}_{-0.42}, 1.46^{+0.31}_{-0.22}, 0.31^{+0.07}_{-0.05}) \times 10^{22}$ cm$^{-2}$ for the SMC-like, LMC-like, and MW-like dust-to-gas ratios, respectively (Pei 1992). The inferred large dust extinction ($A_V = R_V E(B - V) = 1.8 - 2$ mag) may be attributed to dust grains either in the CSM like $\eta$ Carinae’s dusty Homunculus nebula (e.g., Smith 2012; Morris et al. 2017), or interstellar materials located along our line of sight towards SDSS1133.

$E(B - V)_{\text{host}}$ derived above assumes that the hydrogen Balmer line-emitting region is in the Case B recombination condition. The intrinsic Balmer decrements can be much larger than 2.86 when the collisional excitation becomes important and/or the line-emitting region is optically-thick to the hydrogen Balmer lines (e.g., Osterbrock 1989; Kokubo et al. 2019). In SDSS1133, the narrow Balmer lines may possibly have multiple origins, and the Balmer decrement measurements can be affected by the flux contaminations from the dense circumstellar photo-ionizing region where the intrinsic Balmer decrements are larger than 2.86.

Also, the assumptions of the dust extinction curves and $R_V$ directly affect the estimates of the dust extinction. Since the SDSS1133’s host galaxy Mrk 177 is a low-mass, low-metallicity galaxy (Section 3.1), the SMC-like dust extinction with $R_V = 2.93$ may provide a good approximation to the interstellar dust extinction in Mrk 177. However, we know little about the size distribution, dust composition, and dust-to-gas ratio of the circumstellar dust grains possibly surrounding SDSS1133. For example, the intense radiation from SDSS1133 may preferentially remove small dust grains and result in a flat extinction curve (e.g., Tazaki et al. 2020). Detailed discussion about the properties of the circumstellar dust grain of the SDSS1133 is beyond the scope of this paper, and will be discussed elsewhere.
**Table 4.** Best-fit model parameters and 68% percentile range derived from the spectral fitting.

| Parameters | SDSS 2003 March 9 | LRIS 2015 July 17 | LRIS 2019 March 10 |
|------------|------------------|------------------|------------------|
| $\lambda_{H\beta, \text{obs}}$ (Å) | 4901.25$^{+0.03}_{-0.03}$ | 4899.72$^{+0.02}_{-0.03}$ | 4900.43$^{+0.04}_{-0.04}$ |
| $\sigma_{H\beta, \text{rest}}$ (km s$^{-1}$) | 91.90$^{+1.86}_{-1.93}$ | 121.10$^{+1.63}_{-1.32}$ | 146.41$^{+2.65}_{-3.33}$ |
| $f_{H\beta, \text{obs}}$ (10$^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 102.09$^{+7.04}_{-7.20}$ | 39.43$^{+1.98}_{-2.37}$ | 64.55$^{+3.98}_{-4.43}$ |
| $\lambda_{H\beta, \text{obs}}$ (Å) | 4901.16$^{+0.73}_{-0.72}$ | 4899.72$^{+0.49}_{-0.49}$ | 4902.23$^{+0.41}_{-0.41}$ |
| $\sigma_{H\beta, \text{rest}}$ (km s$^{-1}$) | 609.44$^{+49.72}_{-50.72}$ | 721.74$^{+142.16}_{-141.56}$ | 825.22$^{+73.75}_{-74.56}$ |
| $f_{H\beta, \text{obs}}$ (10$^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 311.25$^{+18.59}_{-17.52}$ | 116.47$^{+21.47}_{-20.30}$ | 139.13$^{+10.76}_{-9.79}$ |
| $\lambda_{H\beta, \text{v}, \text{obs}}$ (Å) | 4912.29$^{+26.92}_{-26.36}$ | 4872.95$^{+4.87}_{-5.10}$ | 4887.42$^{+20.95}_{-21.34}$ |
| $\sigma_{H\beta, \text{v}, \text{rest}}$ (km s$^{-1}$) | 2197.98$^{+397.34}_{-681.36}$ | 3410.30$^{+585.59}_{-676.36}$ | 3706.91$^{+1092.25}_{-1137.54}$ |
| $f_{H\beta, \text{v}, \text{rest}}$ (10$^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 822.47$^{+244.33}_{-252.27}$ | 3250.40$^{+79.46}_{-79.46}$ | 174.84$^{+89.74}_{-89.74}$ |
| $f_{[O II](4959)}$ (10$^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 84.92$^{+6.02}_{-6.02}$ | 25.05$^{+1.01}_{-1.01}$ | 36.18$^{+2.29}_{-2.11}$ |
| $f_{[O II](5007)}$ (10$^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 242.94$^{+6.06}_{-6.06}$ | 68.74$^{+2.07}_{-2.07}$ | 110.44$^{+3.00}_{-2.99}$ |
| $\alpha$ | $-1.44^{+0.05}_{-0.05}$ | $-1.61^{+0.04}_{-0.04}$ | $-1.96^{+0.04}_{-0.04}$ |
| $\beta$ | $-0.10^{+0.10}_{-0.10}$ | $-3.79^{+0.03}_{-0.03}$ | $6.77^{+0.11}_{-0.11}$ |
| $\alpha_{H\beta, \text{obs}}$ (Å) | 4865.53$^{+2.45}_{-2.26}$ | 4853.99$^{+0.49}_{-0.49}$ | 4851.87$^{+0.30}_{-0.30}$ |
| $\sigma_{H\beta, \text{obs}}$ (km s$^{-1}$) | 2671.89$^{+247.49}_{-263.17}$ | 1941.97$^{+234.57}_{-220.17}$ | 1697.22$^{+663.85}_{-502.55}$ |
| $\tau_{H\beta, 0}$ & 24.77$^{+66.36}_{-74.21}$ & 46.82$^{+30.77}_{-29.41}$ & 13.91$^{+17.58}_{-17.58}$ |
| $\text{scale}_{Fp}$ & 1.34$^{+0.07}_{-0.06}$ & 0.51$^{+0.02}_{-0.02}$ & 0.54$^{+0.05}_{-0.05}$ |
| $z_{Fp}/z_{H\beta, n}$ & 1.06$^{+0.01}_{-0.01}$ & 1.06$^{+0.01}_{-0.01}$ & 1.07$^{+0.01}_{-0.01}$ |

The spectroscopic fitting was performed at the H$\beta$ and Ho spectral ranges independently. The Galactic extinction is corrected, but not the host galaxy extinction. $\lambda_{\text{obs}}$, $\sigma_{\text{rest}}$, and $f$ indicate the observed-frame central wavelength, rest-frame velocity standard deviation, and integrated flux of the narrow (n), broad (b), and very broad (vb) Gaussian line components. The narrow lines are only marginally spectrally-resolved. The continuum is assumed to have a power-law form of $I_{\lambda} = f_{\lambda} \lambda^{(1+z)}[1/(1+z)]^{1500}$, and the P-Cygni absorption strength is modelled as $e^{-\tau_{\lambda}}$ where $\tau_{\lambda} = \tau_{0}(2\pi\text{scale}_{\lambda, 0})^{-1}/z_{Fp}$, $z_{Fp}$, and $\text{scale}_{Fp}$ indicate the scaling factor to the Boroson & Green (1992) Fe template spectrum and relative redshift of the Fe template to the hydrogen Balmer narrow line. The details of the fitted spectral model is described in Section 2.12.2.

### 3 DISCUSSION

In this Section we discuss the nature of SDSS1133 inferred from the multi-epoch, multi-band photometric and spectroscopic measurements described in the previous Section. As mentioned in Section 1, SDSS1133 is suggested to be either an recoiling (offset) AGN or extragalactic outbursting LBV star (=SN impostor). The multiple outbursts and persistent emission rule out the possibility of an one-off transient event.

Following Koss et al. (2014) and Burke et al. (2020), we summarize the major observational properties of SDSS1133 discussed in this section and evaluate each scenario in Table 5. As summarized in Table 5, narrow line BPT diagr...
Table 5. Source properties discussed in this work and possible scenarios

| Source Property                                      | LBV | recoiling AGN | Sections |
|------------------------------------------------------|-----|---------------|----------|
| Offset from the galactic center                      | YES | Unusual       | 3.1      |
| Large-amplitude UV-optical outbursts                  | YES | Unusual       | 3.2.2    |
| Narrow line variability?                              | YES | NO            | 3.3.1    |
| Narrow line BPT diagnostics                           | YES | Unusual       | 3.3.1    |
| Ca II emission lines                                  | YES | Unusual       | 3.3.2    |
| Broad P-Cygni feature                                 | YES (Unusual) | NO          | 3.3.3, 3.3.4 |
| UV-optical luminosity                                 | YES (Unusual) | YES         | 3.4.1, 3.4.2 |
| Small X-ray/optical luminosity ratio                  | Unusual | Unusual     | 3.4.3, 3.4.4 |

YES indicates that the observational feature can be readily explained by the scenario. NO indicates it cannot be explained. Unusual indicates it can be explained but it is unusual of observed systems. The last column indicates the section numbers where the corresponding source properties are discussed.

Figure 9. Long-term time-series of the H$\beta$ velocity spectra of SDSS1133. Keck/DEIMOS and MMT spectra are taken from Fig. 9 of Koss et al. (2014), and Lowell Discovery Telescope/DeVeny spectrum is taken from Fig. 14 of Ward et al. (2021). The spectra are horizontally shifted so that the narrow H$\beta$ peaks correspond to 0 km s$^{-1}$, and the flux is arbitrarily shifted and scaled for the purpose of clarity. Dotted lines indicate continuum levels estimated by linear regression for relatively iron-free spectral windows at $-7,000\pm200$ km s$^{-1}$ and $+7,000\pm200$ km s$^{-1}$ (see Figure 8). Persistent blue-shifted broad absorption is clearly seen, with the maximum absorption velocity at $\approx -5,000$ km s$^{-1}$. The vertical bars indicate the flux-weighted mean absorption velocity measured using the flux values below the linear regression lines in the velocity range between $-5,000$ km s$^{-1}$ and 0 km s$^{-1}$.

Figure 10. The Balmer decrement for the narrow, broad, and very broad emission line components of SDSS1133. The median Balmer decrement for the narrow component, H$\alpha$/H$\beta = 5.49$, is indicated by the dot-dashed line. Theoretically expected value of H$\alpha$/H$\beta = 2.86$ for Case B recombination H II region with $T = 10^4$ K and $n_e = 10^2$ cm$^{-3}$ is indicated by the dotted line.

nastics, detection of the narrow line variability, presence of the broad P-Cygni absorption features in the hydrogen Balmer lines, and small X-ray/optical luminosity ratio observed in SDSS1133 all suggest that SDSS1133 is presumably an extragalactic LBV instead of a recoiling AGN. Although the high X-ray/UV/optical luminosity and high-velocity P-Cygni absorption features are unusual for a LBV, we point out several well-known giant eruption LBVs (e.g., $\eta$ Carinae and SN 2009ip) share the similar properties with SDSS1133. We conclude that SDSS1133 belongs to an extreme population of LBVs experiencing multiple non-terminal explosions and subsequent strong interactions of the ejected shell with different shells and/or CSM. Details of these source properties and comparisons with other giant eruption LBVs and SN impostors are discussed below.

3.1 Host galaxy properties

The SDSS1133’s host galaxy Mrk 177 is a dwarf galaxy with the g band absolute magnitude of $M_g = -16.6$ mag, which is comparable to the SMC. The total stellar mass of Mrk 177
is estimated to be $M_* \sim 10^{6.55} M_\odot$ (Koss et al. 2014). The disturbed morphology of Mrk 177 indicates that Mrk 177 is a post-merger galaxy (see Koss et al. 2014, for details). The gas-phase oxygen abundance is estimated to be $12 + \log(O/H) = 8.58$ from the SDSS optical spectroscopy of the Mrk 177’s nucleus. The low metallicity galaxies are preferred sites for massive star formation, thus the low metallicity in Mrk 177 may be consistent with the idea that the progenitor of SDSS1133 is a massive star like other LBVs.

Under the LBV scenario, SDSS1133 is a massive star and the local environment of SDSS1133 should be an active star-forming region. The local environment of SDSS1133 cannot be examined by current observations, and further high spatial resolution observations for the emission lines and dust emission around SDSS1133 are needed to judge the validity of the LBV scenario based on the host galaxy’s local environment.

Koss et al. (2014) estimate a star-formation rate of Mrk 177 at 0.05 $M_\odot$ yr$^{-1}$ using GALEX UV photometry. WISE magnitudes of Mrk 177 are 13.25, 13.20, 10.03, and 7.68 Vega mag at W1, W2, W3, and W4 band, respectively, and the WISE colors W1−W2=0.05 Vega mag and W2−W3=3.17 Vega mag are outside of empirical AGN selection windows (Hainline et al. 2016). The SDSS optical spectrum of the nucleus of Mrk 177 exhibits star-forming galaxy-like emission line ratio of [NII]/Hα and [OIII]/Hβ, indicating that Mrk 177 does not harbor a strong AGN at the galactic center (Koss et al. 2014; Toba et al. 2014). Also, the weak X-ray luminosity of $L_{0.3-10 \text{ keV}} \sim 3 \times 10^{38}$ erg s$^{-1}$ at the nucleus of Mrk 177 observed by Chandra (Section 2.8) is well below the empirical threshold luminosity to identify AGNs ($\sim 3 \times 10^{42}$ erg s$^{-1}$), and can be explained by integrated luminosities from X-ray binary populations in the galaxy without the need for AGN (e.g., Lehmer et al. 2016; Birchall et al. 2020; Schirra et al. 2021).

The recoiling AGN scenario requires that SDSS1133 is a merged SMBH that was ejected from the center of Mrk 177 at the time of the SMBHB coalescence, and it requires that the Mrk 177’s nucleus currently possesses no SMBH. The absence of an AGN in the nucleus of Mrk 177 is not inconsistent with the recoiling AGN scenario, though the observations do not exclude the possibility of the presence of an inactive SMBH in Mrk 177.

The narrow line redshift of SDSS1133 is consistent with that of Mrk 177’s nucleus, indicating that the line-of-sight velocity of SDSS1133 relative to the systemic velocity is currently much less than 100 km s$^{-1}$ (Section 2.12.2). Then it is safe to assume that the projected velocity is also smaller than 100 km s$^{-1}$. Assuming the recoiling AGN scenario for SDSS1133, in order to explain the current projected galactocentric distance of 0.81 kpc in terms of the recoil kick from the galactic center, the required life-time of the AGN activity of SDSS1133 is at least 0.81 kpc/100 km s$^{-1}$ $\sim$ 10$^5$ yrs. This time scale of 10$^5$ yrs is too long for a recoiling AGN to maintain the AGN activity (e.g., Blecha & Loeb 2008; Ward et al. 2021), and we conclude that the observed small velocity of SDSS1133 relative to the systemic velocity does not fit the recoiling AGN scenario.

### 3.2 Light curve evolution

#### 3.2.1 Long-term declining trend

Figure 11 shows the 70 years worth of absolute magnitude light curve of SDSS1133, which include the POSS-I and POSS-II photographic plate measurements in 1950, 1994, and 1999 (see Section 2.11). Except for the POSS data, Figure 11 shows $g$ band absolute magnitudes of SDSS1133; in addition to the $g$ band measurements between 2001 and 2021, $r$ and $i$ band measurements between 2010 and 2018 are used to calculate the synthetic $g$ band magnitudes assuming constant colors of $g − r = 0.29$ mag and $g − i = 0.18$ mag from the ZTF data in 2018 (Figure 3). Two light curves are shown; one is uncorrected and the other is corrected for the possible extinction in the host galaxy estimated from the Balmer decrement (Section 2.12.4).

SDSS1133 has been a bright variable object at least since 1950, as first noticed by Koss et al. (2014). In addition to the outbursts, SDSS1133 also exhibits small amplitude flux variations even in the non-outbursting phase. After 1994, SDSS1133 light curve probably shows a long-term declining trend since 1994. We calculated the long-term linear trend by fitting a straight line for the data points in Figure 11 between 1994 April 14 and 2020 June 29 (49456 $\leq$ MJD $\leq$ 59300), excluding the outbursting epochs between 2001 December 18 and 2002 April 1 ($52261 \leq$ MJD $\leq$ 52366), 2014 March 16 and 2014 May 10 ($56732 \leq$ MJD $\leq$ 56788), and 2018 October 31 and 2019 July 22 ($58422 \leq$ MJD $\leq$ 58687). This linear declining model provides a reasonable fitting to the long-term light curve in the non-outbursting phase, and we obtained the best-fitting decline rates of 0.058 mag yr$^{-1}$ and 0.051 mag yr$^{-1}$ for host extinction uncorrected and corrected light curves, respectively.

As reference models, consider simple SN light curve models. Late-phase SN luminosity can be powered either by radioactive decays in cobalt or SN ejecta-CSM shock interactions. The former light curve is approximately an exponential form of $L(t) \propto e^{-t/\tau_{56\text{Co}}}$ where $\tau_{56\text{Co}} = 111.3$ days is the decay time of $^{56}$Co, and the latter can be approximately a power-law form of $L(t) \propto t^{-3/2}$ (assuming a steady stellar wind CSM) where $n = 7$ – 12 depends on the radial density structure of the ejecta ($\rho_{ej} \propto r^{-n}$; e.g., Moriya et al. 2013b). In either case, a single SN exploded somewhere in the 20th century cannot explain the very slow decline trend of the long-term light curve of SDSS1133. For the same reason, we can conclude that the non-outbursting phase light curve of SDSS1133 cannot be attributed to a tidal disruption of a star by a SMBH ($L(t) \propto t^{-5/3}$; Phinney 1989), or in general to any other known one-off explosive events.

AGNs are known to show decades-long optical variability at amplitudes of a few 0.1 mag (e.g., MacLeod et al. 2012), thus the long-term light curve in the non-outbursting phase of SDSS1133 alone cannot exclude the possibility of the AGN origin. However, the co-existence of the decades-long trend and short time-scale large-amplitude outbursts is rarely seen in AGNs. As shown below, some giant eruption LBVs are observed to show long-lasting light curves with sporadic outbursts, and the observed light variations of SDSS1133 are not inconsistent with these LBVs.
3.2.2 Outbursts

As shown in Figures 2 and 11, we find that SDSS1133 experienced at least four optical outbursts since 2001; these four outbursts are referred to as 2001 outburst, 2014 outburst, 2019 outburst, and 2021 outburst, respectively.

SDSS1133 was in a very bright outbursting phase during the two SDSS imaging observations on 2001 December 18 and 2002 April 1 (Koss et al. 2014). In both observations (separated by 104 days), the brightness level was similar (g ≈ 16.3 mag). As pointed out by Koss et al. (2014), SDSS1133 was not detected on 2MASS images on 2001 January 10 (MJD=51553), suggesting that the first brightening event happened sometime between 2000 January 10 (2MASS non-detection) and 2001 December 18 (SDSS detection). Also, the SDSS spectrum taken on 2003 March 9 (MJD=52707) provides a rough estimate of the SDSS1133 brightness at this epoch; g = 18.70 ± 0.18, r = 18.28 ± 0.06, i = 18.65 ± 0.05, and z = 18.49 ± 0.08 mag (Koss et al. 2014), which are ~2 mag fainter than the that during the 2001 outburst. Therefore, the duration of the 2001 outburst is constrained to be less than 52707 – 51553 = 1154 days (3.2 yrs) and longer than 104 days (0.3 yrs). The absolute g-band magnitude peaks at Mg = −16.30 mag (Mg = −18.26 mag after correcting for the possible host galaxy extinction), thus the 2001 outburst event can be regarded as a SN impostor (Pastorello et al. 2013; Pastorello & Fraser 2019; Perley et al. 2020).

The PTF and PS1 photometry reveals that SDSS1133 experienced a brief optical outburst between 2014 March 8 (MJD=56738.5; PTF R = 18.99 mag) and 2014 July 8 (MJD=56846.3; PS1 y = 18.65 mag). The observed peak magnitude is PS1 i = 18.12 ± 0.01 mag on 2014 May 10 (MJD=56787.3). The duration of the 2014 outburst is roughly constrained to be 56846.3 – 56738.5 = 108 days (0.3 yrs), suggesting that this was shorter and fainter than the 2001 outburst. This event is also noted by Ward et al. (2021), who report the small flare detection detected by unpublished data from the Catalina Real-time Transient Survey (CRTS) between 2014 April 28 and 2014 June 5.
The ZTF $g$, $r$, and $i$ band observations provide the densely-sampled multi-band light curves for the 2019 outburst (Figure 3). The $g$ and $r$ band light curves peak on 2019 June 5 (MJD=58639.2) at $g = 17.03$ and $r = 16.81$ mag, about 3 mag brighter than the non-outbursting phase. The absolute $g$-band magnitude at the peak is $M_g = -15.27$ mag ($M_g = -17.46$ mag after correcting for the possible host galaxy extinction), thus the 2019 outburst should be regarded as another SN impostor event in SDSS1133 after the 2001 outburst. We can see from Figure 3 that the duration of the entire 2019 outburst is about ~100 days (see also Ward et al. 2021), thus the 2019 outburst is at least ~0.6–0.7 mag fainter and is probably shorter-lived compared to the 2001 outburst.

The $Gaia$ photometry in 2021 reveals the fourth outburst event occurred between 2021 April 25 (MJD=59329.0; $G = 19.07$ mag) and 2021 August 14 (MJD=59440.3; $G = 20.22$ mag). The observed peak magnitude is $G = 17.87$ mag on 2021 June 21 (MJD=59386.3). The duration of the 2021 outburst is roughly constrained to be less than 59440.3 − 59329.0 = 111 days (0.3 yrs), which is similar to the 2014 and 2019 outbursts. We can say that the three outbursts in 2014, 2019, and 2021 had similar observational properties, and they were fainter and had shorter durations compared to the 2001 outburst.

The latter three outbursts have similar observational characteristics, but the outburst in 2001 was relatively brighter and had a longer duration.

Among the four outbursts, only the 2019 outburst is temporally resolved thanks to the high cadence ZTF observations. The outburst light curve is more complex than a simple rise and fall, exhibiting small bumps on the outburst profile (see Figure 3). Following the definition in Perley et al. (2020), the rise time and fade time of the 2019 outburst are calculated as the time durations between the peak and the point where the light curve drops to 0.75 mag below peak (equivalent to half the peak flux); by using the linearly-interpolated ZTF g-band light curve, we obtain $t_{\text{rise}} = 23.9$ days and $t_{\text{fade}} = 3.6$ days, and the duration is $t_{\text{rise}} + t_{\text{fade}} = 27.5$ days. The long rise and short fall light curve behavior of the 2019 outburst is very different from normal SNe or Galactic variable stars (see Fig. 3 of Perley et al. 2020).

The multi-band optical light curves during the 2019 outburst (and also the 2001 outburst) do not show significant color evolution, and there is little difference in the color between the outbursting and non-outbursting phases (Figure 3; see also Ward et al. 2021). This suggests that the effective temperature of SDSS1133 is kept constant (see Section 3.4 for further details), and that the outburst event cannot be explained by an adiabatically-cooling expanding ejecta as observed in SNe.

The long-term and outburst light curve behaviors of SDSS1133 are suggested to be consistent with LBV outbursts (Koss et al. 2014; Ward et al. 2021), but the constant temperature may indicate that the outbursts are due not to normal LBV eruptions. As pointed out by Humphreys et al. (1999), LBV eruptions can largely be classified into two subclasses; S Doradus (S Dor)-type “normal” eruptions and η Carinae analog giant eruptions (see also Smith et al. 2011; Smith 2017b, and references therein). The optical outbursts in the S Dor-type LBV eruptions are associated with the decrease of the temperature so that the bolometric luminosity is unchanged while the photospheric radius increases (Figure 15; Wolf 1989; Vink 2011; Smith et al. 2011; Pastorello et al. 2013; Smith 2014, 2017b; Kilpatrick et al. 2018, and references therein), which is not the case for SDSS1133’s outbursts. Instead, we suggest that the flux variations in SDSS1133 are due to the intrinsic increase in the bolometric luminosity as observed in some of η Carinae analog giant eruption LBVs = SN impostor, e.g., pre-SN outbursts of SN 2009ip (e.g., Humphreys et al. 1999; Smith et al. 2011; Pastorello et al. 2013; Davidson 2020; Weis & Bomans 2020, and references therein). We will return to this point in Section 3.4.

As mentioned in Section 1, the large variability amplitude of ~2 mag may be achieved by a rare population of extremely variable AGNs. Further quantitative evaluation of the light curve properties is needed to discuss the differences/similarities with the AGN variability, which is beyond the scope of this paper, but at least we can say that multiple short-duration outbursts observed in SDSS1133 are likely to be unusual for an AGN.

3.2.3 Comparisons with other LBV giant eruptions

In Figure 11, the absolute $g$-band magnitude light curve of SDSS1133 is compared with the historical $V$ band light curve of the 19th century Great Eruption of η Carinae’s compiled by Frew (2004) and Smith & Frew (2011). The original light curve is shifted by 0.02 mag to match the AB magnitude system, and the absolute magnitude is calculated by assuming a distance to η Carinae as 2.3 kpc ($\mu = 11.81$ mag), and $A_V = 1.4$ mag (Davidson & Humphreys 1997; Smith 2006; Smith & Frew 2011). The absolute $V$-band magnitude of η Carinae had been in a range between −9 and −11 mag before 1822 and reached ~−14 mag during the Great Eruption during 1822–1864 (peaked at ~−14.2 mag in 1845). The short durations of the 2019 outburst of SDSS1133 is comparable to η Carinae’s brief precursor eruptions in 1838 and 1843 just before the final brightening in 1844 December (see Smith & Frew 2011). Figure 11 suggests that SDSS1133 remains to be brighter than the η Carinae’s Great Eruption over the period since 1950. Since the total mass-loss from η Carinae during the Great Eruption is estimated to be about ~10 $M_\odot$ (Smith & Frew 2011), the mass-loss from SDSS1133 should be much larger than 10 $M_\odot$ if we assume the mass-loss rate (C kinetic energy) is roughly in proportion to the radiation energy. Also this may possibly mean that the SDSS1133’s current mass is more massive than η Carinae, i.e., > 100 $M_\odot$ (e.g., Smith 2008).

We also show a $R$ band absolute magnitude light curve of SN 2009ip (Smith et al. 2010; Mauerhan et al. 2013; Pastorello et al. 2013) in Figure 11. It is constructed from R band, F606W band, and unfiltered data between 1999 June 29 and 2009 August 28 in Smith et al. (2010) and the R band data between 2009 August 30 and 2012 October 16 in Pastorello et al. (2013). The absolute magnitude is calculated by assuming a distance modulus to SN 2009ip as $\mu = 31.55$ mag, and $A_R = 0.05$ mag (Mauerhan et al. 2013; Pastorello et al. 2013), and the light curve is shifted by 0.21 mag to match the AB magnitude system. SN 2009ip is believed to have exploded as a terminal SN (namely SN IIn) in 2012 September (but see Pastorello et al. 2013), and before that
there were multiple precursor eruptions. The first identified eruption was in 2009 August–September whose peak was on 2009 August 28 (MJD=55071.75; $m_R = 17$ mag; Smith et al. 2010). The second eruption was observed in 2011 May–October, and then in 2012 there were two large eruptions (2012a event from August 8 to September 24, and 2012b event from September 24 to December; Smith et al. 2010; Pastorello et al. 2013; Margutti et al. 2014). The 2012b event is considered to be the terminal SN explosion of SN 2009ip, and the pre-SN eruptions (observed as SN impostor) are suggested to be originated from the LBV giant eruptions of the progenitor star (Mauerhan et al. 2013; Smith et al. 2014a; Graham et al. 2014). The peak absolute magnitude of SN 2009ip during the eruptions (2009 and 2012a events) is similar to that of η Carinæ’s giant eruptions, and thus very close to the brightness of SDSS1133 (Figure 11).

Another interesting object to be compared with SDSS1133 is iPTF14hls, which is a hydrogen-rich optical transient at $z = 0.0344$ ($d_L = 156$ Mpc), exhibiting multiple peaks before and after the maximum epoch, and lasting for 2 years (Arcavi et al. 2017; Yalinewich & Matzner 2019; Sollerman et al. 2019). The spectrum shows broad hydrogen Balmer P-Cygni absorption features at $-6000$ km s$^{-1}$ but no signs of narrow P-Cygni features (Arcavi et al. 2017), similar to SDSS1133. Although the absolute magnitude reaches over $-18$ mag, the peculiar light curve shape of iPTF14hls is inconsistent with normal SNe. There is a suggestion that iPTF14hls is not a terminal SN explosion; specifically, Moriya et al. (2020) suggest that iPTF14hls is a suggestion that iPTF14hls is not a terminal SN explosion; nevertheless, if SDSS1133 is a binary system, the binary orbital period may be inferred from the recurrence timescale of the observed outbursts.

We observed four large outbursts from SDSS1133 in 2001, 2014, 2019, and 2021; specifically, the observed peak epochs are 2001 December 18 (SDSS, MJD=52261.4), 2014 May 10 (PS1 i band, MJD=56787.3), 2019 June 5 (ZTF, MJD=58639.2), and 2021 June 21 (Gaia, MJD=59386.3), respectively. The observations before 2014 were scarce, and we may have missed other outbursts between 2003 and 2014. The time interval between the 2001 and 2014 outbursts is $\Delta t_{2001-2014,obs} = 4525.9$ days, 2014 and 2019 outbursts is $\Delta t_{2014-2019,obs} = 1851.9$ days, and 2019 and 2021 outbursts is $\Delta t_{2019-2021,obs} = 747.1$ days. Interestingly, the outburst interval looks decreasing as a function of time, which may be related to an orbital evolution due to significant mass-loss episodes, if the binary scenario is true for SDSS1133 (e.g., Smith & Frew 2011; Smith 2011). Alternatively, the decreasing outburst interval could be related to the increasing pair-instability toward the end of the stellar evolution (e.g., Yoshida et al. 2016; Woosley 2017).

The linear regression relationship that predicts the time of the next outburst (MJD) from the time of the previous outburst (MJD$_{-1}$) can be expressed by a linear recurrence relation as

$$\text{MJD}_i - \text{MJD}_{i-1} = -0.59 \times (\text{MJD}_{i-1} - 60000) - 55.36. \quad (2)$$

Based on the well-determined observed peak of the 2019 outburst (MJD = 58639.2), Equation 2 predicts outburst epochs as MJD$_{pred} = 52369$ (in 2002), 56816.0 (in 2014), 59386.7 (in 2021), which are close to the observed outburst epochs. Equation 2 also predicts multiple outbursts in 2022 and converges to MJD$_{pred} = 59906.2$ (2022 November 23). Further intensive monitoring observations are definitely needed to examine the possible temporal pattern.

### 3.3 Spectroscopic features

#### 3.3.1 Narrow emission lines and BPT diagnostic diagrams

The results of the spectral decomposition analysis in Table 4 indicate that the low-ionization nebular narrow lines ([OIII],[NII], and [SII]) seem to display flux variations over the spectroscopic periods (see also Purismo et al. 2019a). The narrow [SII] doublet ratio $[SII]/[OIII]$ is consistent at $\sim 1.4$, indicating that the electron density of the narrow emission line region is consistent with typical electron densities for local galaxies, $n_e = 10 - 100$ cm$^{-3}$ (Osterbrock 1989). Figure 12 presents the Baldwin-Phillips-Terlevich (BPT) narrow line diagnostic diagrams for SDSS1133 (Baldwin et al. 1981; Kewley et al. 2001, 2006; Kauffmann et al. 2003). The [NII] narrow emission lines of SDSS1133 are much weaker compared to the Hα narrow line in SDSS1133, while the narrow line ratio of log([OIII]/Hβ) is relatively high compared to typical star-forming galaxies. Also, the [OII]6300/Hα and [SII]6717,6731/Hα narrow line ratios are much less than 1.

AGN narrow line flux variability is rarely observed since the narrow line region in AGNs is extended over $\sim$ kpc

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**MNRA** **000**, 1–30 (2022)
Figure 12. BPT classification diagrams for the narrow emission line ratios of SDSS1133. The SDSS and two Keck/LRIS measurements are indicated by filled circles, open circles, and filled squares, respectively. The extreme starburst lines (solid lines; Kewley et al. 2001), pure star-formation line (dotted line; Kauffmann et al. 2003), and Seyfert-LINER (low-ionization nuclear emission-line region) classification lines (dot-dashed lines; Kewley et al. 2006) are shown.

Figure 13. The SDSS and Keck spectra at the Ca II IR lines (dot-dashed lines; Kewley et al. 2006) are shown. Star-formation line (dotted line; Kauffmann et al. 2003), and Seyfert-LINER classification indicated by filled circles, open circles, and filled squares, respectively. The extreme starburst lines (solid lines; Kewley et al. 2001), pure star-formation line (dotted line; Kauffmann et al. 2003), and Seyfert-LINER (low-ionization nuclear emission-line region) classification lines (dot-dashed lines; Kewley et al. 2006) are shown.

According to the BPT diagrams, the narrow line ratios of SDSS1133 are consistent with low-mass star-forming galaxies, and suggest that the narrow emission line region of SDSS1133 has a high ionization parameter and low-metallicity (e.g., Kewley et al. 2013; Simmonds et al. 2016). The BPT diagnostics for SDSS1133 do not support the standard AGN ionization and thus the reciling AGN scenario, as already pointed out by Koss et al. (2014) and Simmonds et al. (2016). However, we should note that, since the narrow emission lines are not spectrally-resolved, they are probably originated from multiple regions, such as the host galaxy H II region and photo-ionized circumstellar region. If the AGN narrow emission lines are unusually weak, the emission lines from the star-forming region can dominate the observed emission. Actually, a fraction of X-ray bright AGNs is observed to exhibit BPT line ratios similar to SDSS1133 (e.g., Smith et al. 2014b; Agostino & Salim 2019). In that case, the interpretation of the BPT diagnostics is ambiguous.

3.3.2 Calcium and iron emission lines

As shown in Figure 7, the optical spectra of SDSS1133 are heavily contaminated by iron emission line forests. In addition to the iron emission lines, another interesting spectroscopic feature of SDSS1133 is intermediate-width or narrow calcium emission lines clearly detected in the optical spectra, as already reported by Koss et al. (2014) and Ward et al. (2021). In the LRIS spectra, [Fe II]λλ7155, λ7324, O I λ8446 and Ca II IR triplet λλ8498, 8542, 8662 are clearly detected, while adjacent Paschen lines (e.g., P14 at 8598Å) are much weaker. The Ca II H+K emission lines at 3968 and 3933 Å are not detected. The [Fe II]λ7155 and [Ca II]λ7291, 7324 forbidden lines are unobserved in the SDSS spectrum while they are clearly detected in the LRIS spectra (see Figure 10 of Koss et al. 2014, for the Fe II, Ca II, and O I line profile fitting to the SDSS and Keck/DEIMOS spectra of SDSS1133), probably implying that the electron density of circumstellar materials exhibits time-evolution around $n_e \sim 10^5$ cm$^{-3}$ (e.g., Humphreys et al. 2013).

Figure 13 shows a power-law + Gaussian emission line model fitting to the SDSS and LRIS spectra at the Ca triplet
soups, etc. The rest-frame velocity widths are 386.45, 172.67, and 170.43 km s\(^{-1}\) for the SDSS and two LRIS spectra (the latter two are spectrally-unresolved), respectively, suggesting that the line widths of these lines are variable. The Ca II triplet line ratios are roughly 1:1:1 rather than the theoretically predicted value of 1:9:5, suggesting that the line-forming region is optically-thick (e.g., Apparao & Tarafdar 1988; Banerjee et al. 2021). The resemblance between the Ca II and Fe II line widths in the SDSS spectrum implies that Ca II and Fe II emission region is separated from the same, high density photo-ionization region. The broader line widths of Ca II and Fe II compared to the other H, N, S, and O nebular narrow lines in the SDSS spectrum (Table 4) suggest that the Ca II and Fe II emission region is separated from the low density, low velocity dispersion nebular responsible for the nebular narrow lines, and is located in closer vicinity to SDSS1133. The narrow Ca II lines are occasionally seen in stellar explosion events and LBVs (e.g., Smith et al. 2010; Foley et al. 2011; Ward et al. 2021), while they are rarely seen in AGNs (though not exclusively; Persson 1988; Marinello et al. 2016). The presence of the temporally variable intermediate-width Ca II lines makes SDSS1133 even more unusual for an AGN (e.g., Koss et al. 2014; Ward et al. 2021).

### 3.3.3 The broad P-Cygni absorption feature due to high velocity ejecta

As shown in Section 2.12.2, the hydrogen Balmer lines in SDSS1133 exhibit multi-component line profiles, composed of an unresolved narrow component, FWHM = 1,000 – 2,000 km s\(^{-1}\) broad component, and FWHM \(~\sim 4,000\) km s\(^{-1}\) very broad component. Moreover, the broad and very broad components exhibit blue-shifted broad P-Cygni absorption feature. The spectral changes in the broad line profile can be reproduced by the model where large variations in the absorption component are allowed. As shown in Figure 9, the spectroscopic properties of the H\(^\alpha\) and He\(^I\) profiles of SDSS1133 remain essentially unchanged during the epochs of the spectroscopic observations since 2003.

The P-Cygni absorption feature is clearly detected with the absorption peak at \(~\sim -2,000\) km s\(^{-1}\), and the absorption feature continuously extends from \(~\sim 0\) km s\(^{-1}\) up to \(~\sim -5,000\) km s\(^{-1}\) (Figure 8).

The optical spectra of SDSS1133 resemble those of type II SNe (Pursimo et al. 2019a), but the long-duration light curve and multiple outbursts observed in SDSS1133 rule out the possibility that SDSS1133 is an one-off event, and are in favor of the LBV scenario (see also Ward et al. 2021). Under the assumption that SDSS1133 is a LBV star, the persistent broad absorption feature implies that the ejected materials are moving at a high velocity of \(~\sim -2,000\) km s\(^{-1}\) (up to \(~\sim -5,000\) km s\(^{-1}\)). Observations for giant Eruption LBVs (namely \(\eta\) Carinae and SN 2009ip’s pre-SN eruptions) have revealed that at least a fraction of outflowing materials ejected during the LBV giant eruptions can have a velocity higher than 5,000 km s\(^{-1}\) (see Figure 6; e.g., Smith 2008; Foley et al. 2011; Pastorello et al. 2013; Mauerhan et al. 2013). Moreover, the time variations of the absorption minimum observed in SDSS1133 (Figure 9) resemble those observed in the SN 2009ip’s pre-SN eruptions (see Figure 8 of Pastorello et al. 2013). The persistent broad P-Cygni absorption seen in SDSS1133 suggests that the mass-loss in SDSS1133 is one of the most energetic among the known examples of the LBV giant eruptions (Pastorello et al. 2013). Such high velocity mass ejections (moving faster than the star’s escape velocity) are hard to be explained solely by the radiation-driven winds of the star, and they imply the existence of non-terminal explosions in the stellar core inducing outward blast waves into the envelope, which are observed like scaled-down SNe (e.g., Smith 2008; Pastorello et al. 2013; Smith 2013, 2014, 2017b; Smith et al. 2014a, 2018; Strotjohann et al. 2021); see Section 3.3.4.

### 3.3.4 Interpretations of the broad emission line component

Most LBVs generally exhibit narrow hydrogen Balmer emission lines from the stellar winds with the velocity of a few 100 km s\(^{-1}\), reflecting the low escape speed of blue supergiants stars (Smith 2014; Davidson 2020). In contrast to the normal LBVs, the line width of the broad emission lines in SDSS1133 is much broader than 1,000 km s\(^{-1}\); the FWHM of the broad component is FWHM\(_b\) = 2\(\sqrt{2}\ln 2\)\(\sigma_b\) \(~\sim 1,500 – 2,000\) km s\(^{-1}\), and very broad component is FWHM\(_{b^*}\) \(~\sim 5,000 – 10,000\) km s\(^{-1}\), which are comparable to the line widths observed in SNe.

As with the broad P-Cygni absorption, the broad Balmer emission lines of SDSS1133 are in common with the pre-SN outbursts of SN 2009ip (e.g., Smith 2008; Foley et al. 2011; Pastorello et al. 2013; Mauerhan et al. 2013; Ward et al. 2021). The broad P-Cygni absorption feature implies the presence of the high velocity outflowing materials (Section 3.3.3), and the broad emission lines are presumably emitted from the same high velocity materials. As already mentioned in Section 3.3.3, although the relatively narrow lines (\(~\lesssim 1,000\) km s\(^{-1}\)) observed in typical LBV eruptions can be attributed to stellar winds (e.g., Smith 2014; Davidson 2020), the broad lines of \(>1,000\) km s\(^{-1}\) observed in SDSS1133 and pre-SN outbursts of SN 2009ip are too broad to be explained by the same wind mechanism (e.g., Smith 2008; Pastorello et al. 2013; Smith 2014), suggesting that the broad line-emitting fast materials are originated from the non-terminal explosions (Smith 2008, 2013; Smith et al. 2018; Fransson et al. 2022).

It is known that SNe IIn exhibit broad/very broad emission lines and absorption features originated from ejecta-CSM interaction regions, where the ejecta kinematics and electron scattering broaden the emission lines up to ~

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10,000 km s\(^{-1}\) (e.g., Chugai 2001; Kokubo et al. 2019). The blue optical continuum and broad and narrow emission lines produced by the ejecta-CSM interactions in SNe IIn are known to closely resemble those of type 1 AGNs (Filippenko 1989; Baldassare et al. 2016), as observed in SDSS1133. We can expect that a similar mechanism can produce broad emission and absorption features in the case of mass-loss ejecta-CSM interactions or collisions between shells of matter ejected from a LBV (e.g., Woosley et al. 2007; Dessart et al. 2009; Pastorello et al. 2010; Yoshida et al. 2016; Woosley 2017). Smith (2013) suggests a model for the 19th century eruption of \(\eta\) Carinae where a strong wind blowing for 30 yrs and subsequent non-terminal \(\sim 10^{50}\) erg explosion occurring in 1844 result in ejecta-CSM interactions like a scaled-down SN IIn (see also Smith 2008; Smith et al. 2018). If SDSS1133 is an event similar to these \(\eta\) Carinae analog giant eruptions, the persistent blue UV-optical continuum and broad emission lines from SDSS1133 can naturally be explained by these non-terminal explosions and subsequent shock interactions. The shock interactions also produce X-ray photons (Chevalier 1982; Chevalier et al. 2006; Dessart et al. 2009; Dwarkadas & Gruszo 2012; Smith 2013), and X-ray emission escaped from the shock region can naturally explain the observed X-ray luminosity of SDSS1133 (see Section 3.4.4). We will discuss the energetics of this non-terminal explosion scenario in detail in Sections 3.5.

SDSS1133 shows no signs of narrow P-Cygni absorption features. SNe IIn with strong ejecta-CSM interactions typically show the narrow P-Cygni absorption, which is attributed to unshocked pre-SN stellar wind components (e.g., Taddia et al. 2013). But observationally, some SNe IIn lack narrow P-Cygni absorption features (e.g., Kokubo et al. 2019), which is probably due to viewing angle effects caused by asphericity in the CSM matter distribution. Therefore, under the scaled-down SN IIn scenario, the absence of narrow P-Cygni absorption may imply the aspherical CSM interactions in SDSS1133.

### 3.4 Spectral Energy Distribution

#### 3.4.1 Black body model for the UV-optical emission

The UVOT data obtained on 2014 February 6–25 (non-outbursting phase) and 2019 May 27–29 (during the 2019 outburst) are useful to constrain the UV-to-optical SED of SDSS1133. While the 2019 data cover the full UV wavelength range with the UBV2, UVM2, and UVW1 bands, the 2014 data are obtained only with the UVW2 band. Since simultaneous optical broad band photometries were not available at the epochs of the UVOT observations, ZTF \(g, r, i\) and PS1 \(z\) and \(y\) band magnitudes in 2019 and PS1 \(z\) and \(y\) band magnitudes in 2014 at the epochs of the UVOT observations were estimated by linearly-interpolating the light curves; the time differences between the Swift/UVOT and the closest optical measurements are 1.78, 0.75, and 5.84 days for the ZTF \(g, r, i\) band measurements in 2019, and 24.38 and 24.37 days for the PS1 \(z\) and \(y\) and measurements in 2014, respectively.

Assuming a spherical black body radiator with a radius \(R\), the observed flux is modelled as

\[
f_{\nu, \text{obs}} = \left(\frac{\nu}{d_L}\right)^2 (1 + z) \pi B_{\nu, \text{eff}}(T_{\text{eff}}).
\]

Figure 14. UV-optical SEDs of SDSS1133 on 2014 February 6–25 (non-outbursting phase) and 2019 May 27–29 (outbursting phase). The best-fitting black body spectra are overplotted. The host galaxy extinction-corrected SEDs assuming the extinction curves determined by the Balmer decrement (Figure 10) are also shown; the extinction-corrected SEDs are consistent with Rayleigh-Jeans power-law (\(\lambda L_\lambda \propto \lambda^{-3}\)), for which the black body fitting was not available.

There are two free parameters; \(T_{\text{eff}}\) and overall scaling factor \(C \equiv (r/d_L)^2\). The bolometric luminosity \(L\) can be evaluated from \(T_{\text{eff}}\) and \(C\):

\[
L = 4\pi R^2 C \sigma_{\text{SB}} T_{\text{eff}}^4,
\]

from the Stefan-Boltzmann law, \(f \pi B_{\nu}(T_{\text{eff}})d\nu = \sigma_{\text{SB}} T_{\text{eff}}^4\), where \(\sigma_{\text{SB}}\) is the Stefan-Boltzmann constant and \(B_{\nu}\) is the black body intensity. Therefore, there are two fitting parameters, \(T_{\text{eff}}\) and \(L\). The SED fitting was performed with the \(\chi^2\) minimization, where the model broad band magnitudes calculated by the filter convolution were compared to the observed magnitudes.

Figure 14 shows the UV-optical SEDs of SDSS1133 on 2014 February 6–25 (non-outbursting phase) and 2019 May 27–29 (outbursting phase). The SEDs corrected for possible host galaxy extinction assuming the extinction curves determined by the Balmer decrement (Figure 10; Section 2.12.4) are also shown. The best-fitting black body spectra are overplotted. The best-fitting black body parameters for the SEDs with no host galaxy extinction correction are \(T_{\text{eff}}\) and \(L\). The corresponding black body radius is \(R = 10^{3.17} R_\odot\) and \(10^{3.92} R_\odot\), respectively. This fitting may imply that the effective temperature of SDSS1133 did not vary significantly between the outbursting and non-outbursting phases. Even considering the uncertainty on the intrinsic dust extinction this fitting may imply that the effective temperature of SDSS1133 did not vary significantly between the outbursting and non-outbursting phases.
specifcally the effective temperature never drops well below \( \sim 10,000 \) K.

As already discussed in Section 3.2.2, the constant temperature is in contrast to normal LBV eruptions or S Dor-type variables. The eruptions in the normal LBVs can be explained by the outward motion of the photosphere either due to a true increase in the star’s hydrostatic radius or the radius of a pseudo-photosphere in the opaque wind; the optical outbursts are accompanied with lowering of effective temperature so that the bolometric luminosity remains nearly constant (see Figure 15; Vink 2011; Smith 2011; Smith et al. 2011; Van Dyk & Matheson 2012; Humphreys et al. 2014). The constant effective temperature during the eruptions in SDSS1133 is more similar to LBV giant eruptions, like the 19th century Great Eruption of \( \eta \) Carinae (e.g., Davidson & Humphreys 1997; Smith et al. 2011; Smith 2013, 2014, 2017b).

In terms of the recoiling AGN scenario, the UV-optical luminosity can be related to the Eddington luminosity of the recoiling SMBH. Considering the host galaxy stellar mass of \( 10^{10.55} \, M_\odot \) (Section 3.1), the SMBH mass may be \( \sim 10^6 \, M_\odot \) (Reines & Volonteri 2015), and the corresponding Eddington luminosity is \( L_{\text{Edd}} \sim 10^{38.5}\,L_\odot \). Therefore, the observed UV-optical luminosity of SDSS1133 is not inconsistent with the recoiling AGN scenario if the accretion rate is sub-Eddington (\( \sim 0.1 - 1\% \)).

Although the effective temperature and bolometric luminosity from the fitting for the host galaxy extinction-corrected SEDs are physically reasonable, the observed SED shape is much redder than the black body spectra, probably being consistent with the large Balmer decrements described in Section 2.12.4. Actually, as shown in Figure 14, the host galaxy extinction correction makes the SEDs consistent with Rayleigh-Jeans power-law (\( \lambda L_\lambda \propto \lambda^{-3} \)). If the host galaxy extinction coefficients are taken at their face values, the weak UV turnover (if any) in the SEDs in Figure 14 prevents us from determining the effective temperature. This implies that the true temperature of SDSS1133 is much higher than \( 10^4 \) K. In this sense, \( T_{\text{eff}} \) and \( L \) derived for the host galaxy extinction-uncorrected SEDs should be taken as the lower limits, as indicated in Figure 15. Also, taking into account the uncertainties in the host galaxy extinction estimates (Section 2.12.4), the host galaxy extinction-corrected SEDs shown in Figure 14 should be regarded as the upper limits.

We should note that the artificial excess emission in the UVM2 band seen in the host galaxy extinction-corrected SEDs in Figure 14 is due to the 2175\,Å bump in the extinction curves. Assuming that the intrinsic continuum SEDs should be smooth, the 2175\,Å extinction bump toward SDSS1133 should be suppressed than the MW, SMC, LMC extinction curves. Since the 2175\,Å extinction bump is considered to be caused by Polycyclic Aromatic Hydrocarbons (PAHs) and/or small graphite dust grains (e.g., Draine & Lee 1984; Taack et al. 2020), the weak 2175\,Å extinction bump may indicate that these small grains are eliminated toward the line of sight, probably due to the strong emission of SDSS1133.

3.4.2 H-R diagram and the energy source of SDSS1133

Figure 15 shows the Hertzsprung-Russell (H-R) diagram for SDSS1133 in 2014 (non-outbursting phase) and 2019 (outbursting phase), compared with known S Dor-type LBVs and giant eruption LBVs taken from Rest et al. (2012). Except for \( \eta \) Carinae, the same objects are connected with dotted lines. The S Dor instability strip (LBVs in quiescence) and constant temperature eruptive LBV strip (LBVs in outburst) are indicated by gray bands, and the empirical Humphreys–Davidson (HD) limit is indicated by a solid line. The dashed-dotted line indicates the Zero-Age Main Sequence (ZAMS) for stars with \( M = 25 - 120 \, M_\odot \) (no rotation and \( Z = Z_\odot \); Ekström et al. 2012). The temperatures and luminosities for SDSS1133 and SN 2009ip’s pre-SN eruption in 2009 are lower limits because of the possible effects of host galaxy reddening.

Figure 15. The H-R diagram for SDSS1133 in 2014 (non-outbursting phase) and 2019 (outbursting phase), compared with known S Dor-type LBVs and giant eruption LBVs taken from Rest et al. (2012). Except for \( \eta \) Carinae, the same objects are connected with dotted lines. The S Dor instability strip (LBVs in quiescence) and constant temperature eruptive LBV strip (LBVs in outburst) are indicated by gray bands, and the empirical Humphreys–Davidson (HD) limit is indicated by a solid line. The dashed-dotted line indicates the Zero-Age Main Sequence (ZAMS) for stars with \( M = 25 - 120 \, M_\odot \) (no rotation and \( Z = Z_\odot \); Ekström et al. 2012). The temperatures and luminosities for SDSS1133 and SN 2009ip’s pre-SN eruption in 2009 are lower limits because of the possible effects of host galaxy reddening.
sembling the decades-long 19th century Great Eruption of η Carinae (Figure 11; Smith & Drew 2011).

It is suggested that the giant eruption LBVs may be subdivided into two classes; ‘hot LBV’ subclasses exemplified by the SN impostors SN 2009ip and SN 2000ch, and ‘cool LBVs’ exemplified by UCG 2773-OT (e.g., Pastorello et al. 2010; Smith et al. 2010; Foley et al. 2011; Smith et al. 2011; Smith 2013; Ward et al. 2021). The hot LBVs have high temperature of > 10,000 K, high luminosity, and broad line profiles, while the cool LBVs have cooler 7,000 – 8,000 K spectra of F-type supergiants superseded with narrower emission/absorption features (Figure 15; e.g., Smith et al. 2010). SDSS1133 resembles SN 2009ip’s precursor (pre-SN) eruption (Figure 15), and thus belongs to the hot LBV subclass. Combined with the other observational evidence (high velocity P-Cygni profile and X-ray emission; Sections 3.3.3 and 3.3.4), we can speculate (as pointed out by Smith et al. 2010) that the hot LBVs (including SDSS1133) may be powered by ejecta-CSM or ejecta-ejecta interactions by a large fraction, while the cool LBVs are dominated by the photospheric emission of opaque radiation-driven outflows (e.g., Davidson 2020, and references therein).

### 3.4.3 X-ray emission

The dust extinction in the host galaxy of SDSS1133 inferred by the Balmer decrement also implies the presence of X-ray absorption. As mentioned in Section 2.12.4, the hydrogen column density in the host galaxy inferred from the color excess is $N_H, host = (2.84, 1.46, 0.31) \times 10^{22}$ cm$^{-2}$ under the assumption of the SMC-like, LMC-like, and MW-like extinction, respectively. The X-ray absorption due to the gas of the columns density of $N_H, host$ is estimated by adding xszvphabs (xzvphabs) component in the XSPEC (CIAO) X-ray spectral modelling, where the heavy-element abundances relative to MW are assumed to be 1/8, 1/3 for SMC and LMC, respectively (Pei 1992), the absorber’s redshift is fixed to 0.0079. Table 2 lists the X-ray luminosity corrected for the X-ray absorption in the host galaxy. By comparing the values in Table 2, we can see that the correction factor due to the X-ray absorption in the host galaxy is at most ~3. This mean that the uncertainty on the X-ray absorption strength in the host galaxy have only little influence on our order-of-magnitude discussion about the X-ray luminosity of SDSS1133.

Figure 16 shows the X-ray-to-NIR SED of SDSS1133 in the non-outbursting phase in 2014 and outbursting phase in 2019. The Elvis et al. (1994)’s template SED for luminous ($M_V < -22$ mag) radio-quiet AGNs is overplotted in Figure 16 for comparison. The Swift/XRT X-ray upper limits obtained simultaneously with the Swift/UVOT UV measurements reveal that the X-ray emission of SDSS1133 is much less than the X-ray emission expected from the typical X-ray-to-UV/optical luminosity ratio in AGNs (see also Simmonds et al. 2016). Moreover, the Chandra X-ray detection in the non-outbursting phase in 2019 (but this is just after the 2019 outburst) suggests that the X-ray luminosity is at least a thousand times smaller than the UV-optical luminosity. Such an low X-ray-to-optical luminosity ratio is unusual for an AGN (e.g., Hasinger 2008; Gibson et al. 2008; Liu et al. 2018). As shown in Figure 16, the corrections for the X-ray and UV-optical host galaxy absorption/extinction further decrease the X-ray-to-optical luminosity ratio. The weak X-ray emission of SDSS1133 is suggestive of the non-AGN nature. Actually, the X-ray luminosity of SDSS1133 is well below an empirical threshold luminosity to identify AGNs ($~10^{42}$ erg s$^{-1}$; Lehmer et al. 2016; Birchall et al. 2020; Schirra et al. 2021), thus SDSS1133 cannot be classified as an AGN based on the X-ray luminosity.

The UV-optical black body modelling for the host extinction-uncorrected SED in the non-outbursting phase in 2014 suggests that the UV-optical luminosity of SDSS1133 is $L \sim 10^{41}$ erg s$^{-1}$ (Section 3.4.1). By using the Chandra X-ray luminosity ($L_X = 4 \times 10^{39}$ erg s$^{-1}$), the X-ray-to-optical luminosity ratio is $log(L_X/L) \sim -2.4$. On the other hand, if the host galaxy extinction correction shown in Figure 16 is taken at its face value, the UV-optical luminosity of SDSS1133 can be as large as $L \sim 10^{43}$ erg s$^{-1}$, thus...
log$(L_X/L) \sim -4.4$. Nazé et al. (2012) show that the X-ray-to-optical luminosity ratio (log$(L_X/L)$) of known LBVs is at most $\sim -5$ and generally less than $-6$. We should note that the X-ray luminosity of SDSS1133 is at least 4 orders of magnitude larger than that observed in Galactic LBVs ($L_{0.5\text{-}8\text{keV}} < 10^{34}$ erg s$^{-1}$; Nazé et al. 2012; Koss et al. 2014). Therefore, we can conclude that SDSS1133 is extremely bright compared to normal LBVs. In summary, SDSS1133 is too faint to be a “typical” AGN, but too bright to be a “typical” LBV.

### 3.4.4 Multi-wavelength SED

The large discrepancy between the X-ray luminosities of SDSS1133 and other LBVs known to date (Nazé et al. 2012) is probably because the current LBV sample observed at X-ray is limited to normal S Dor-type LBVs, and essentially no detailed X-ray data is available for giant eruption LBVs or SN impostors.

As discussed in Sections 3.3.3 and 3.3.4, a population of LBV giant eruptions can be powered by shock interactions between ejecta materials and CSM (e.g., Smith 2008, 2013; Smith et al. 2010, 2018). As observationally confirmed in ejecta-CSM interacting SNe II, the interaction region can produce strong UV-optical, X-ray, and radio emission (Smith 2013, 2017a). It is naturally expected that the observational properties of the interaction-powered LBVs resemble the SNe II, and observed as scaled-down SNe II (Smith 2013).

In Figure 17, the X-ray and radio luminosities of SDSS1133 are compared with those of a sample of ejecta-CSM interacting SNe II compiled by Margutti et al. (2014). We should note that the Chandra X-ray observation was carried out just after the 2019 outburst (Figure 3), thus the X-ray luminosity may be an “afterglow” emission of the 2019 outburst event, while the radio luminosity reflects the emission in the non-outbursting phase before the 2014 outburst. In this figure, we can see that SDSS1133 may locate at the faint end of the X-ray vs. radio correlation space of the interacting SNe. The X-ray luminosity of SDSS1133 is about 2 orders of magnitude lower than the typical values of the interacting SNe II, suggesting that SDSS1133 is a scaled-down version of these objects. In terms of the multi-wavelength energetics, we can say that SDSS1133 is in between LBVs and interacting SNe. Also, the radio luminosity of SDSS1133 is at least two orders of magnitude below compared to the X-ray/radio correlation of low-luminosity AGNs at the given X-ray luminosity (e.g., Merloni et al. 2003; Grossová et al. 2022).

Koss et al. (2014) point out that the Keck/NIRC2 $K$ band measurement may indicate the presence of an IR excess emission at $λ \sim 20,000$ Å (see Figure 16). Since the hot dust emission of various strength is one of the observational features of interacting SN (e.g., Szalai et al. 2019; Kokubo et al. 2019), the IR excess in SDSS1133 can also be naturally explained by the above mentioned scaled-down SN II model. Future optical-NIR simultaneous observations are needed to confirm this weak NIR excess emission.

### 3.5 Energetics: LBV with CSM interactions?

In this Section we discuss the energetics of the UV-optical emission in the non-outbursting and outbursting phases of SDSS1133. Constructing models to reproduce the detailed structure of the multi-wavelength light curves is beyond the scope of this paper and will be presented elsewhere. Here we show that the required radiation energy to explain SDSS1133 can be generated within existing observational and theoretical frameworks; namely, some form of non-terminal explosions and subsequent efficient kinetic-to-radiation energy conversion by ejecta-CSM or ejecta-ejecta interactions.

The UV-optical luminosity of SDSS1133 is at least $L_{\text{non-outburst}} = 10^{38\text{–39}} L_\odot = 10^{41.67}$ erg s$^{-1}$ during the 2019 outburst (no host galaxy extinction correction; Section 3.4.1), that continued for more than 27.5 days (see Section 3.2.2). Thus, the total energy required to explain the 2019 outburst is at least

$$E_{\text{rad, outburst}} \sim 10^{48} \text{erg} \times \left(\frac{L_{\text{outburst}}}{10^{39} L_\odot}\right) \left(\frac{\Delta t}{27.5 \text{ days}}\right).$$

SDSS1133 experienced multiple outbursts of similar radiation energy at least four times since 2001. On the other hand, the persistent continuum luminosity in the non-outbursting phase since 1950 is roughly $L_{\text{non-outburst}} = 10^{37.49} L_\odot = 10^{31.67}$ erg s$^{-1}$, thus the total radiation energy released so far is

$$E_{\text{rad, non-outburst}} \sim 10^{50} \text{erg} \times \left(\frac{L_{\text{non-outburst}}}{10^{37.49} L_\odot}\right) \left(\frac{\Delta t}{70 \text{ yrs}}\right).$$

We should note that these estimates for $E_{\text{rad}}$ are lower-limit, as the possible host galaxy extinction is uncorrected correction in the above calculations.

The Eddington ratio or Eddington parameter $\Gamma$ given the luminosity $L$ and stellar mass $M$ is

$$\Gamma = \frac{\kappa_L L}{4\pi G M c} = 2.6 \times \left(\frac{L}{10^{37} L_\odot}\right) \left(\frac{M}{100 M_\odot}\right)^{-1}. \tag{7}$$
where \( \kappa_e = 0.34 \text{ cm}^2 \text{ g}^{-1} \) is the opacity due to Thomson scattering, and we assume \( M = 100 \, M_\odot \) (the current mass of \( \eta \) Carinae; e.g., Smith 2008) as a reference value. The luminosity of SDSS1133 (\( L > 10^7 \, L_\odot \)) implies that it exceeds the classical Eddington limit of \( \Gamma = 1 \) even in the non-outbursting phase at least for 70 yrs. This situation is reminiscent of the \( \eta \) Carinae’s Great Eruption, that had been luminous at \( \Gamma = 5 \) for over decades. Like the \( \eta \) Carinae’s Great Eruption, SDSS1133 is probably continuously launching inhomogeneous, porous super-Eddington (SE) continuum-driven winds (e.g., Smith & Owocki 2006; Owocki & Shaviv 2012; Dotan & Shaviv 2012). A dense CSM around SDSS1133 can be produced by these radiation-driven winds (e.g., Smith 2014). The radiation-driven wind mechanisms, however, cannot produce high velocity outflows of \( > 1,000 \, \text{km s}^{-1} \) (well beyond the star’s escape velocity) observed in SDSS1133 as the broad absorption, thus we need some form of non-terminal explosions and subsequent enhanced mass ejections (like scaled-down SN) to explain the high velocity materials observed in SDSS1133 (Sections 3.3.3 and 3.3.4).

The radiated energy of SDSS1133 is comparable to that of a single core-collapse SN (\( E_{\text{rad}} \sim 10^{49} \, \text{erg} \)). As suggested in Sections 3.3.3 and 3.3.4, the large radiation energy of SDSS1133 can be naturally explained by mass ejections due to non-terminal explosions (\( E_{\text{kin}} \sim 10^{50} - 10^{51} \, \text{erg} \), where \( E_{\text{kin}} \) is the kinetic energy of the explosion) and subsequent CSM interactions. Because the CSM interactions can have high efficiency of converting kinetic energy into radiation (a few 10%; e.g., Moriya et al. 2013a; Smith et al. 2014a), the shocks induced by the non-terminal explosions and propagating into the dense CSM can produce enough radiation energy to account for both the outbursting and non-outbursting phases of SDSS1133. In the same way as the CSM interactions, if massive shells ejected by the multiple explosion events have different velocities, collisions between the shells may produce distinct outbursts (e.g., Heger et al. 2003; Woosley et al. 2007; Dessart et al. 2009; Moriya et al. 2013a; Yoshida et al. 2016; Arcavi et al. 2017).

Consider a simple ejecta-CSM shock interaction model (e.g., Smith 2013; Moriya et al. 2013b). The CSM is assumed to be formed via a steady wind with a velocity of \( v_w \). The kinetic energy of the ejected massive shell is converted into radiation energy at the shocked region moving at a velocity of \( v_s \). The shocked shell velocity \( v_s \) is time-dependent, but here we replace it by the initial velocity of the ejecta: \( v_s \sim \sqrt{2E_{\text{kin}}/M_{ej}} \approx 1,000 \, \text{km s}^{-1} \times (E_{\text{kin}}/10^{50} \, \text{erg})^{1/2}(M_{ej}/10 \, M_\odot)^{-1/2} \), where \( M_{ej} \) is the ejected mass. A kinetic-to-radiation conversion efficiency, \( \epsilon \), is usually assumed to be in the range of 0.1 – 0.5 (e.g., Moriya et al. 2013a,b). The wind mass-loss rate \( \dot{M} \) can be related to the bolometric luminosity via \( \epsilon \) as:

\[
L = \frac{1}{2} \frac{\dot{M}}{v_w} v_s^2
\]

\[
= 10^{7.92} L_\odot \times \left( \frac{\epsilon}{0.1} \right) \left( \frac{\dot{M}}{100 \, M_\odot \, \text{yr}^{-1}} \right) \left( \frac{v_w}{100 \, \text{km s}^{-1}} \right)^{-1} \left( \frac{E_{\text{kin}}}{10^{50} \, \text{erg}} \right)^{3/2} \left( \frac{M_{ej}}{10 \, M_\odot} \right)^{-3/2}
\]

Although most of the parameters are uncertain in the case of SDSS1133, this estimate suggests that the luminosities in the non-outbursting and outburst phases can be produced by the CSM interactions if the persistent mass-loss of the order of \( \dot{M} \sim 1 \, M_\odot \, \text{yr}^{-1} \) and non-terminal explosions of \( E_{\text{kin}} \sim 10^{50} \, \text{erg} \) and \( M_{ej} \sim 10 \, M_\odot \). Such a large mass-loss rate is suggested to present in giant eruption LBVs (Smith 2014), and actually the mass-loss rate at the time of the \( \eta \) Carinae’s Great Eruption is estimated to be a few \( M_\odot \, \text{yr}^{-1} \) from observations for the Homunculus nebula (e.g., Humphreys 2005; Smith 2013). The large mass-loss rate also indicates that SDSS1133 is a massive star of the mass of \( 100 \, M_\odot \) like \( \eta \) Carinae.

While the dense CSM may be naturally formed via the SE winds (e.g., Smith 2014), it is unclear what mechanisms can trigger (multiple) non-terminal explosions in LBVs (e.g., Smith et al. 2014a). From the viewpoint of energy deposition, it is suggested that the non-terminal explosions of \( E_{\text{kin}} \sim 10^{50} \, \text{erg} \) may not be explained by the envelope instability, and require to transfer a large amount of extra energy from the stellar core into the outer envelope (e.g., Smith 2014; Smith et al. 2014a; Strotjohann et al. 2021).

Many mechanisms to generate the mass-loss episodes in the giant eruption LBVs or SN impostors have been suggested in the literature, including pulsational pair instability (PPI; e.g., Woosley et al. 2007; Woosley 2017; Arcavi et al. 2017), wave-driven mass loss (e.g., Quataert & Shiode 2012; Shiode & Quataert 2014), and stellar collisions or mergers in a binary system (e.g., Kashi & Soker 2010; Smith 2011; Hirai et al. 2021) (see Smith et al. 2011; Smith 2014, for a review). Although \( \eta \) Carinae is known to be a binary (or triple) system, currently there is no reason to consider that SDSS1133 is in a binary system and its eruptions are caused by binary interactions. Moreover, the binary interactions alone may not be enough to explain the highly-luminous multiple outbursts observed in SDSS1133. Among these scenarios, the PPI-driven mass ejection is of particular interest since this mechanism may possibly provide a natural explanation for the multiple giant eruptions (=non-terminal explosions) every few years with the explosion energy of \( \sim 10^{50} \, \text{erg} \), ejected mass of \( \sim 10 \, M_\odot \), and ejecta velocity of \( \sim 2,000 \, \text{km s}^{-1} \), as observed in SDSS1133 and other extreme LBV giant eruptions (e.g., Smith 2008; Yoshida et al. 2016; Woosley 2017; Arcavi et al. 2017; Fransson et al. 2022). An interesting possibility is that, since the PPI (as well as the wave-driven mass loss) is predicted to occur at the very late stage of massive star evolution, we may be able to observe the terminal SN explosion of SDSS1133 after a few additional pre-SN eruptions, like other precursor eruptions observed prior to SNe IIn (e.g., Gal-Yam & Leonard 2009; Smith et al. 2011; Langer 2012; Mauerhan et al. 2013; Moriya et al. 2014; Ofek et al. 2014; Arcavi et al. 2017; Smith 2017b; Strotjohann et al. 2021; Fransson et al. 2022). Another possibility is that SDSS1133 may end up with a collapse to a massive BH without a bright SN (e.g., Heger et al. 2003; Allan et al. 2020). Further multi-wavelength follow-up observations are encouraged to trace the evolution of SDSS1133.

3.6 Volumetric rate of SDSS1133-like objects

The volumetric rate of the SDSS1133-like LBV objects may roughly be estimated by the fact that there are only two objects found to be offset from the host galaxy nucleus among 3,579 broad Hα emission lines objects at \( z < 0.31 \).
targeted by the 8,032 deg² SDSS-I/II spectroscopic survey (> 1,000 km s⁻¹; Abazajian et al. 2009; Stern & Laor 2012; Koss et al. 2014). Among the two objects, one is SDSS1133, and another is Mrk 739, but Mrk 739 is confirmed to be a dual AGN (Koss et al. 2011). The comoving volume within redshift \( z = 0.31 \) is 7.8 Gpc³ \( \times (8,032/41,253) = 1.5 \) Gpc³, thus the volumetric rate of SDSS1133-like objects may be estimated as \( ~0.7 \) Gpc⁻³. The estimated rate of the SDSS1133-like LBV objects is much less than the core-collapse SN rate in the local Universe (\( \sim 100,000 \) Gpc⁻³ yr⁻¹; Perley et al. 2020). It may indicate that at most a few percent of core-collapse SN progenitors experience the SDSS1133-like long-lasting (>60 years) bright LBV eruption phase. This may be consistent with the scenario that LBVs with enhanced mass-loss end up with (super-luminous) SNe IIn, i.e., a rare population of core-collapse SNe (Ofek et al. 2014; Smith 2017b; Strotjohann et al. 2021).

The above volumetric rate estimate ignores several objects similar to SDSS1133 individually reported in the literature; for example, PHL 293B, which is found in a local blue compact dwarf galaxy at \( z = 0.00517 \), is suggested to be another example belonging to the same class of extragalactic transient variable as SDSS1133 (e.g., Izotov & Thuan 2009; Terlevich et al. 2014; Burke et al. 2020; Allan et al. 2020). Another similar object is recently reported by ZTF (AT2018kde at \( z = 0.013 \) with the peak absolute magnitude of \( M_g = -16.34 \); Perley et al. 2020), which is classified as an eruption of a LBV. It is worth noticing that the spectral resemblance between SDSS1133 and broad line AGNs suggests that many SDSS1133-like objects are missed by the current surveys; for example, a fraction of nuclear/off-nuclear AGN-like objects can actually be LBVs (e.g., Izotov et al. 2007; Izotov & Thuan 2008; Baldassare et al. 2016; Simmonds et al. 2016; Burke et al. 2021; Ward et al. 2021). In this sense, the volumetric rate of the SDSS1133-like objects could be higher than the above estimate, and more comprehensive survey is needed to quantify the true occurrence rate of the SDSS1133-like objects.

4 SUMMARY AND CONCLUSIONS

In this paper we have presented the comprehensive analysis of the multi-wavelength data of SDSS1133. As summarized in Table 5, our analysis reveals that the observational properties of SDSS1133 are unusual for an AGN, while consistent with several well-known giant eruption LBVs. SDSS1133 is an off-nuclear object, thus if it is an AGN it is already a very rare “recoiling AGN”, and it seems unreasonable to accept that such a special object simultaneously has many unusual observational properties for an AGN as discussed in this paper. Therefore, we conclude that SDSS1133 is not a recoiling AGN but is more likely to be an extragalactic giant eruption LBV.

The observed peak absolute magnitude of the outbursts reaches \( M_g \sim -16 \) mag (\( -18 \) mag after correcting for the possible host galaxy extinction), which places SDSS1133 as one of the brightest LBV giant eruptions of known Galactic and extragalactic LBVs and SN impostors. The observational properties of SDSS1133 (multiple outbursts, broad P-Cygni profile, UV-optical luminosity, high black body temperature of \( \sim 10,000 \) K) is reminiscent of pre-SN eruptions of SN 2009ip (Sections 3.2.2, 3.3.3, 3.3.4, and 3.4.1), suggesting that SDSS1133 belongs to the hot LBV subclass (Section 3.4.2). The persistent P-Cygni absorption feature seen in the hydrogen Balmer lines extends up to \( \sim 5,000 \) km s⁻¹. The fast ejected materials responsible for the P-Cygni absorption in SDSS1133 likely originate from multiple non-terminal explosive outbursts, rather than radiation-driven stellar winds (Section 3.3.3). We suggest that both of the bright persistent emission and UV-optical outbursts in SDSS1133 are produced by interactions of the ejected shell with CSM and/or different shells (Sections 3.3.4 and 3.5). The interaction model naturally explains the long-duration SN IIn-like multi-wavelength photometric and spectroscopic properties of SDSS1133 including X-ray luminosity, persistent broad emission/absorption lines, and blue UV-optical continuum (Sections 3.3.4, 3.4.4, and 3.5).

The origin of the non-terminal explosions is highly debated. Among the many theoretical possibilities, we suggest that pulsational pair-instability may provide a viable explanation for the multiple energetic eruptions in SDSS1133, in terms of the energetics and occurrence rate of the eruptions (Sections 3.2.2 and 3.5.1). If the current activity of SDSS1133 is a bona-fide precursor of a terminal SN explosion, we may be able to observe a few additional giant eruptions and then the terminal SN explosion or collapse to a massive BH in future observations (in a few years to a few thousand years).

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This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013). We used numpy (Harris et al. 2020), scipy (Virtanen et al. 2020), extinction (Barbary 2016), and speclite¹³ in the data analysis.

This research has made use of the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration. The Keck archival data (KOAIMD = LB.20150717.21554, LB.20150717.22197, LB.20190310.44548, LR.20150717.21508, LR.20150717.22257, LR.20190310.44557) obtained through the programs C280LA and C300 (PI: F. Harrison) were used.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/)

¹² ACDM cosmology of \( \Omega_L = 0.7, \Omega_m = 0.3, \) and \( H_0 = 70 \) km s⁻¹ Mpc⁻¹ is assumed

¹³ https://github.com/declhub/speclite
This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This research has made use of data obtained from the Chandra Data Archive and the Chandra Source Catalog, and software provided by the Chandra X-ray Center (CXC) in the application packages CIAO, ChIPS, and Sherpa.

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The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; NOAO Proposal ID # 2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NOAO Proposal ID # 2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall 4 meter Legacy Survey (MzLS; NOAO Proposal ID # 2016A-0453; PI: Arjun Dey); DECaLS, BASS and MzLS together include data obtained, respectively, at the Blanco telescope, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory (NOAO); the Bok telescope, Steward Observatory, University of Arizona; and the Mayall telescope, Kitt Peak National Observatory, NOAO. The Legacy Surveys project is honored to be permitted to conduct astronomical research on Iolkam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham Nation.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
