Observations of the luminous red nova AT 2021biy in the nearby galaxy NGC 4631*:
Forbidden hugs in pandemic times – III

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ABSTRACT

We present an observational view of the luminous red nova (LRN) AT 2021biy in the nearby galaxy NGC 4631. The field of the object was routinely imaged during the pre-eruptive stage by synoptic surveys, but the transient was detected only at a few epochs from ~ 231 days before maximum brightness. The LRN outburst was monitored with unprecedented cadence both photometrically and spectroscopically. AT 2021biy shows a short-duration blue peak, with a bolometric luminosity of ~ 1.6 × 10^41 erg s^-1, followed by the longest plateau among LRNe to date, with a duration of ~ 210 days. A late-time hump in the light curve was also observed, possibly produced by a shell-shell collision. AT 2021biy exhibits the typical spectral evolution of LRNe. Early-time spectra are characterised by a blue continuum and prominent H emission lines. Then, the continuum becomes redder, resembling that of a K-type star with a forest of metal absorption lines during the plateau phase. Finally, late-time spectra show a very red continuum (T eff ~ 2050 K) with molecular features (e.g. TiO) resembling those of M-type stars. Spectroscopic analysis indicates that AT 2021biy has local dust properties similar to those of V838 Mon in the Milky Way Galaxy. Inspection of archival Hubble Space Telescope data taken on 2003 August 3 reveals a ~ 20 M⊙, progenitor candidate with log (L/L⊙) = 5.0 dex and T eff = 5900 K at solar metallicity. The above luminosity and colour match those of a luminous yellow supergiant. Most likely, this source is a close binary, with a 17–24 M⊙ primary component.

Key words. binaries: close — stars: winds, outflows — stars: individual: AT 2021biy

1. Introduction

Modern wide-field surveys have discovered a large number of transients with intrinsic luminosities that are similar to those of core-collapse supernovae (CC SNe) and classical novae (i.e. −15 ≤ M V ≤ −10 mag). Transients are often called "gap transients" (e.g. Kulkarni & Kasliwal 2009; Kasliwal et al. 2012; Pastorello & Fraser 2019; Fraser 2020). They have heterogeneous observational properties, arising from different progenitor types, and are likely triggered by diverse physical mechanisms.

Luminous red novae (LRNe; e.g. Martini et al. 1999; Munari et al. 2002; Tyranda 2005; Ivanova et al. 2013b; Kochanek et al. 2014; Williams et al. 2015; Goranskij et al. 2016; Pejcha et al. 2016a; Smith et al. 2016; Blagorodnova et al. 2017; Lipunov et al. 2017; MacLeod et al. 2017; Pejcha et al. 2017; Cai et al. 2019; Pastorello et al. 2019a; Stritzinger et al. 2020a; Pastorello et al. 2021a,b; Blagorodnova et al. 2021) are a subclass of gap transients showing well-constrained observational features. They usually have a composite light curve (e.g. Kankare et al. 2015) and dramatic spectral evolution. In particular, LRNe show a long-lasting, slow luminosity rise before the outburst, followed by a double-peaked light curve, with the second peak sometimes resembling a sort of plateau. Their early-time optical spectra are similar to those of Type IIn supernovae (SNe IIn; Schlegel 1990; Filippenko 1997) and are characterised by a blue continuum with superposed narrow H emission lines. In contrast, spectra taken during the second peak exhibit a redder continuum and a forest of metal lines in absorption, along with much weaker Balmer lines. At late times, spectra of LRNe transition to those of M-type stars, showing broad molecular absorption bands (e.g. TiO; see Kamitski et al. 2009; Mason et al. 2010; Barsukova et al. 2014; Cai et al. 2019; Pastorello et al. 2021a,b).

* Photometric tables are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/
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These well-defined observables allow us to discriminate LRNe from another subclass of gap transients, the so-called intermediate-luminosity red transients (ILRTs; e.g. Botticella et al. 2009; Thompson et al. 2009; Berger et al. 2009; Cai et al. 2018, 2021; Stritzinger et al. 2020b; Valerin et al. in prep.). ILRTs display single-peak light curves, with slowly-evolving spectra dominated by H and Ca features. ILRTs are proposed to be electron-capture SN explosions (e.g. Nomoto 1984, 1987; Pofahl et al. 2008; Pumo et al. 2009; Moriya et al. 2014; Doherty et al. 2015, 2017; Leung et al. 2020) from super-asymptotic giant branch (SAGB) stars (e.g. Prieto et al. 2008, 2009; Thompson et al. 2009; botticella et al. 2009; Adams et al. 2016; Cai et al. 2018, 2021). Nonetheless, controversial objects are occasionally observed, such as M85-2006OT1 and AT 2018hso, sharing transitional properties with both LRNe and ILRTs (Kulkarni et al. 2007; Pastorello et al. 2007; Rau et al. 2007; Cai et al. 2019).

The LRN phenomenon can be interpreted as the result of a common-envelope ejection, likely followed by a stellar merger (e.g. Metzger & Pejcha 2017; Mauerhan et al. 2018; Segev et al. 2019; Tylenda et al. 2011; Ivanova et al. 2013b; Soker & Kashi 2016). The progenitor systems of LRNe span a wide range of masses, from massive binaries of a few tens of M⊙ to low-mass systems down to ~ 1 M⊙. By studying a sample of LRNe, a correlation between their luminosity and the mass of the progenitor systems has been established, with higher-mass progenitors producing more-luminous outbursts (e.g. Kochanek et al. 2014; Blagorodnova et al. 2021).

Although ongoing surveys have significantly increased the available LRN sample in recent years, only a limited number of events have good data covering all evolutionary stages. In particular, pre-outburst detections, a high-cadence light curve, and well-sampled spectra are fundamental to properly compare LRNe with theoretical models. This motivated us to conduct an aggressive follow-up campaign for a new object, AT 2021biy, discovered in the nearby galaxy NGC 4631.

In this paper, we report the results of our observations of AT 2021biy in the optical and near-infrared (NIR) domains, and our analysis of the progenitor and its environment from pre-discovery archival images. The paper is structured as follows. The discovery, distance, reddening, and host-galaxy properties are reported in Sect. 2 while the photometric and spectroscopic evolution are respectively illustrated in Sect. 3 and 4. Sect. 5 investigates the quiescent progenitor system of AT 2021biy. A discussion and our conclusions are presented in Sect. 6.

2. Discovery, distance, reddening, and host galaxy

AT 2021biy was discovered by the Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018a,b; Smith et al. 2020) on 2021 January 29.56 (UT dates are used throughout this paper; that epoch corresponds to MJD = 59243.56), at an ATLAS orange-filter (o) brightness o = 18.12 ± 0.14 mag (Smith et al. 2021; Tonry et al. 2021). Soon after its discovery, it was classified as an LRN (Cai et al. 2021b) in the framework of the Nordic-optical-telescope Unbiased Transient Survey 2 (NOT2) collaboration. Its J2000 coordinates are α = 12°42′55.153″, δ = +32°32′07.388″, placing it 21.6″ south and 50.4″ west of the core of the SBd galaxy NGC 4631. The localization of the transient within the host galaxy is shown in Figure 1 while the main properties of NGC 4631 are reported in Table 1.

Table 1: General properties of NGC 4631.

| α (J2000) | 12°42′08.0″ |
| δ (J2000) | +32°29′4″ |
| Morphological Type | SB(s)d edge-on |
| B Magnitudea | 9.75 ± 0.16 mag |
| Redshiftb | 0.002035 ± 0.000007 |
| Distance Modulusc | 29.36 ±0.15 mag |
| MW extinction (AVMW)d | 0.047 mag |
| 12 + log(O/H) (K = 0)e | 8.39 ± 0.06 dex |

References: 1 = de Vaucouleurs et al. (1991); 2 = Kennicutt et al. (2008); 3 = Wolfinger et al. (2013); 4 = Monachesi et al. (2016); 5 = Schlafly & Finkbeiner (2011); 6 = Pilyugin et al. (2004, 2014).

The adopted distance of NGC 4631 is d = 7.46 ± 0.50 Mpc (μ = 29.36 ± 0.15 mag), based on the tip of the red giant branch (TRGB) method (Monachesi et al. 2016). The Galactic reddening toward AT 2021biy is very small, E(B − V)MW = 0.015 mag (Schlafly & Finkbeiner 2011). To estimate the host-galaxy extinction, we measured the equivalent width (EW) of the narrow interstellar NaI D λ5890,5896 absorption at the redshift of NGC 4631 in our earliest spectrum with good signal-to-noise ratio (S/N; see Sect. 4.1), and found it to be EW = 1.6 ± 0.6 Å. Poznanski et al. (2012) provides an empirical relation between NaI D EW and dust extinction, however, it saturates at EW beyond 0.8 Å. Therefore, following Turatto et al. (2002), we infer a host-galaxy reddening of E(B − V)host = 0.256 ± 0.096 mag; thus, the total colour excess is E(B − V) = 0.271 ± 0.096 mag.

1 We remark that the EW of NaI D was measured in the earliest spectrum of the transient within the host galaxy is shown in Figure 1 while the main properties of NGC 4631 are reported in Table 1.

2 http://nuts2.sn.ie/
toward AT 2021biy. As a consistency check, we measured the Balmer decrement in the earliest spectra of AT 2021biy after correction for the above reddening amount, and found a value of 2.86 (e.g. Weedman 1977).

### 3. Photometry

#### 3.1. Facilities and data reduction

Follow-up images in the Johnson-Cousins $UBV$, Sloan $ugriz$, and NIR $JHK$ filters were obtained using a number of facilities available to our collaboration. Their setups are summarised as follows: The Las Cumbres Observatory (LCO; Brown et al. 2013) global telescopes located at different sites (two 1 m telescopes) at McDonald Observatory, Texas, USA; secondly, TFC (two 0.4 m telescopes and one 1 m telescope) at Teide Observatory, Tenerife, Spain; The 0.8 m Tsinghua-NAOC Telescope (TNT) at Xinglong Observatory, China; The 0.67 m/0.92 m Schmidt telescope with a Moravian camera at Padova Astronomical Observatory, Istituto Nazionale di Astrofisica (INAF), Asago, Italy; The 1 m Zeiss telescope of the Special Astrophysical Observatory (SAO), Russian Academy of Sciences (RAS), Russia; The 1.82 m Copernico Telescope with the Asiago Faint Object Spectrograph and Camera (AFOSC), hosted by INAF – Padova Astronomical Observatory, at the Asiago site, Italy; The 2.0 m Liverpool telescope (LT) equipped with the IO:O camera, located at Observatorio Roque de Los Muchachos, La Palma, Spain; The 2.56 m Nordic Optical Telescope (NOT), at Observatorio Roque de Los Muchachos, La Palma, Spain, with the Alhambra Faint Object Spectrograph and Camera (ALFOSC) and the Nordic Optical Telescope near-infrared Camera (NOTCam); The 2.5 m Caesar telescope with the IR camera ASTRIANIRCAM (Nadip et al. 2017), hosted by the Caucasian Observatory of the Sternberg Astronomical Institute (SAI) of Lomonosov Moscow State University; The 3.5 m telescope with the Omega-2000 NIR imager at the Calar Alto Observatory, Spain; The 6 m telescope (BTA – Big Telescope Altazimuth) equipped with the SCORPIO-1 and SCORPIO-2 instruments, located near Mt. Pastukhova of the Special Astrophysical Observatory, Russia; The 10.4 m Gran Telescopio Canarias (GTC), at Observatorio Roque de Los Muchachos, La Palma, Spain, with the Espectrógrafo Multiobjeto Infra-Rojo (GTC), at Observatorio Roque de Los Muchachos, La Palma, Spain; The Isaac Newton Telescope (INT; $UBV$ images in 2003) for Johnson-Cousins filters.

Specifically, the instrumental magnitudes were measured through the PSF-fitting technique. A PSF model was built by fitting the profiles of bright, isolated stars in the field of the transient. Then, the fitted source was removed from the original images, and the residuals at the object’s location were used to evaluate the quality of the fits. If the target source was not detected, a magnitude limit was estimated.

We used zero points (ZPs) and colour terms (CTs) of individual instruments to calibrate the instrumental magnitudes, which were determined through observations of standard photometric fields during photometric nights. Specifically, Johnson-Cousins-filter images were calibrated via the Landolt (1992) catalogue, while Sloan-filter data were retrieved from the SDSS DR 13 catalogue (Albareti et al. 2017). In order to improve the calibration accuracy, a local sequence of stars in the transient’s field was used to correct the instrumental ZPs during nonphotometric nights. Their catalogue Sloan magnitudes were directly taken from SDSS, while the Johnson-Cousins magnitudes of the reference stars were derived from the Sloan magnitudes after applying the conversion relations of Chonis & Gaskell (2008).

Photometric errors were estimated through artificial-star simulations, in which several fake stars with known magnitudes (similar to that of the transient) were placed near the position of AT 2021biy. The magnitudes of the simulated stars were also measured with the PSF procedure. The standard deviation of the magnitudes of the artificial-star experiment was combined (in quadrature) with the PSF-fit and ZP calibration errors, hence providing us with the total photometric uncertainties. The resulting optical magnitudes are reported in electronic form at the CDS.

NIR data were reduced following similar prescriptions as the optical ones. Raw images were prereduced with flat fielding, distortion correction, and sky subtraction, and then combined to increase the S/N. Instrumental magnitudes were measured via the PSF-fitting technique, and finally, the apparent magnitudes were calibrated using the catalogue of the Two Micron All Sky Survey (2MASS) (Skrutskie et al. 2006). The resulting NIR magnitudes are given at the CDS.

#### 3.2. Multiband light curves of AT 2021biy

Although AT 2021biy was discovered by ATLAS on MJD = 59243.56 (~ 7 days before maximum brightness), we searched for earlier survey data from the forced-photometry servers of ATLAS (Smith et al. 2020) and Pan-STARRS (Chambers et al. 2016; Magnier et al. 2020). This allows us to constrain the pre-discovery evolution of AT 2021biy. ATLAS provides magnitudes in the cyan and orange filters, while Pan-STARRS gives $iz$ (very close to Sloan $iz$ filters) and $y$-band data. In this paper, the above magnitudes are maintained in their original photometric systems. The ATLAS and Pan-STARRS magnitudes are made available at the CDS.
ATLAS monitored the site of AT 2021biy on MJD = 57364.61 (∼1886 days prior to maximum brightness), providing a first upper limit of $m_o > 19.2$ mag. Pan-STARRS DR1 (PS1) reported an observation ($y > 19.7$ mag) on MJD = 56475.26 (∼2776 days before maximum). By inspecting these prediscovey data, no detections are reported above the 3$\sigma$ threshold from about 2776 to 231 days before maximum. The earliest detection of AT 2021biy in PS1 is in fact on MJD = 59020.26 (∼231 days before maximum) at $z = 20.70 \pm 0.35$ mag (Fig. 2). An earlier detection (MJD = 58931.46; about ∼320 days) is recovered in archival images from the 3.6 m Canada-France-Hawaii Telescope (CFHT; equipped with MegaPrime), with $g = 21.88 \pm 0.08$ mag and $r = 21.13 \pm 0.11$ mag.

Afterward, several additional detections were registered during the pre-outburst phase (Fig. 2); there is little, if any, evidence of variability, in contrast with what was found for the Galactic LRN V1309 Sco (Tylenda et al. 2011). Soon after the discovery, we started a high-cadence follow-up campaign lasting over 400 days. In addition, the subsequent outburst of AT 2021biy was well monitored by ATLAS and PS1. The multiband light curves of AT 2021biy, including pre-outburst data extending up to ∼1 yr before the LRN discovery, are shown in Figure 2. Similar to other LRNe, AT 2021biy rapidly rises to the light-curve peak in all bands in ∼7 days. We performed a fifth-order polynomial fit to the early-time r-band light curve to derive the time of $r$-max on MJD = 59251.0 ± 1.0 ($r_{\text{max}} = 16.28 \pm 0.03$ mag), which will be used throughout this paper. The peak is followed by a rapid decline (with a rate of $4.58 \pm 0.29$ mag (100 d)$^{-1}$ in $r$) lasting about 50 days and reaching a shallow minimum at $r_{\text{min}} = 18.04 \pm 0.01$ mag. A plateau is then observed with an average magnitude of $r_{\text{plateau}} = 17.19 \pm 0.14$ mag and a duration of 210 days. Note that a plateau or a broad second peak are typical features of LRNe (see, e.g. the sample of Pastorello et al. 2019b). After the plateau, AT 2021biy shows a rapid drop in all optical bands (of ∼2 mag in $B$), followed by a short-duration bump in optical light curves. The NIR light curves, although lacking early-time observations, appear to evolve similar to the optical light curves, with a plateau duration of ∼210 days. After a modest decline, ∼310 days from $r_{\text{max}}$ the NIR light curves have another pseudo-plateau lasting until our latest observations at ∼470 days. The slopes, fitted with a linear function, at different sections of the light curve are reported in Table A.1.
3.3. Light-curve comparison with other LRNe

The colour evolution of AT 2021biy, along with that of comparison LRNe including AT 2017jfs (Pastorello et al. 2019a), AT 2018hso (Cai et al. 2019), and the Galactic V838 Mon event (Goranskii et al. 2002; Munari et al. 2002; Tylenda 2005), is shown in Figure 3. At the earliest epochs (about 7 days), the intrinsic (B − V)0 and (r − i)0 colours of AT 2021biy are ∼ 0.5 and ∼ 0.1 mag, respectively. Then, the object evolves to bluer colours, with (B − V)0 ∼ −0.2 mag and (r − i)0 ∼ −0.4 mag at about +10 days. These colour minima are followed by a new rise from +10 to +50 days, and then by a flattening with a duration of ∼ 260 days, reaching colours of (B − V)0 ∼ 1.0 mag and (r − i)0 ∼ 0.5 mag at about +310 days. This slow colour evolution is also consistent with that of the temperature (see Sect. 3.4). Accompanied by the late-time light-curve rebrightening, the colours of AT 2021biy show a short-duration (∼ 1 month) red bump starting at ∼ 330 days. After the rebrightening phase, (r − i)0 rapidly reddens again, rising up to ∼ 1.2 mag at ∼ 420 days. The (J − K)0 colour evolution is similar to that of (B − V)0 and (r − i)0, getting steadily redder from 0.3 mag to 1.6 mag up to 470 days. As shown in Figure 3, the colour evolution of AT 2021biy resembles that of the comparison LRNe but with different timescales. A diverse flattening duration in the colour curves can be comfortably explained with different timescales in the hydrogen recombination front moving across the expanding gas (e.g. Ivanova et al. 2013b; Lipunov et al. 2017).

In Figure 4, we show the absolute light curves of AT 2021biy and the comparison LRNe. All show a similar morphology, with the double-hump light curves being the most characteristic LRN feature. However, a diversity of luminosity peaks (both first and second peaks during the outburst phase) and plateau durations is observed in LRNe (see a sample of LRNe in Pastorello et al. 2019b, 2021a; Stritzinger et al. 2020a). During the major outburst, AT 2021biy reaches \( M_r = -13.92 \pm 0.23 \) mag, comparable to \( M_r \approx -13.93 \) mag for AT 2018hso, while it is fainter than AT 2017jfs with \( M_r \approx -15.74 \) mag. We note that AT 2021biy shows a long-lasting plateau of ∼ 210 days (with \( M_r = -13.12 \pm 0.23 \) mag) resembling that of Type IIP SNe (Popov 1993), rather than a broad, red second peak observed as in most LRNe of our sample (see Fig. 4). This variety is likely due to the different masses of the involved ejecta and/or surrounding circumstellar envelope (e.g. Stritzinger et al. 2020a; Pastorello et al. 2021a,b).

After the plateau, AT 2021biy displays a rapid luminosity drop in the optical domain (e.g. \( \gamma_r(\tau) = 7.94 \pm 0.70 \) mag (100 d)^−1, while a significantly slower decline is observed in the NIR bands (e.g. \( \gamma_i(H) = 2.08 \pm 0.32 \) mag (100 d)^−1). Remarkably, a late rebrightening of AT 2021biy is visible both in the optical and NIR domains, analogous to that observed in V838 Mon. Late-time fluctuations in the light curve of V838 Mon were tentatively associated with the effect of the fragmentation of the dusty envelope and the emerging light of the merger outcome (Munari et al. 2002). This explanation appears to be less plausible for AT 2021biy, where a short-lived light-curve hump can also be produced by a collision of ejected material with a relatively thin gas shell.

3.4. Bolometric light curve, temperature, and radius

The evolution of the spectral energy distribution (SED) of AT 2021biy is constructed from the observed light curves, adopting the distance and extinction values reported in Sect. 2 and following the procedures implemented for other published LRNe (e.g. AT 2018hso; Cai et al. 2019). In order to study the evolution of the bolometric luminosity, we fitted the SEDs at some representative epochs with single black-body (BB) functions (see the left panel of Fig. 5). The bolometric luminosity for each SED is computed by integrating the BB flux over the entire electromagnetic spectrum. The resulting bolometric light curve, along with the inferred evolution of the BB temperature and radius, is shown in the right panel of Figure 5, while their values are reported in Table A.2.

At the first blue peak, AT 2021biy has a bolometric luminosity of \( \sim 1.6 \times 10^{40} \) erg s^−1, which is a factor of 3.4 fainter than AT 2017jfs (∼ 5.5 \times 10^{41} \) erg s^−1) but slightly brighter than AT 2018hso (∼ 1.1 \times 10^{41} \) erg s^−1; see the top-right panel of Figure 5. After a fast post-peak decline with a minimum luminosity of \( \sim 1.9 \times 10^{40} \) erg s^−1, AT 2021biy rises to a plateau at \( \sim 5.0 \times 10^{40} \) erg s^−1, while AT 2017jfs and AT 2018hso reach their second red maximum at \( \sim 3.2 \times 10^{41} \) erg s^−1 and \( \sim 4.4 \times 10^{40} \) erg s^−1, respectively. After the plateau (or the second peak), the luminosities of all objects decline again. Later, AT 2021biy exhibits a short-duration hump in the bolometric light curve, also observed in V838 Mon.

The BB temperature of AT 2021biy rapidly rises to a peak of 11,450 K (middle-right panel of Fig. 5), but soon after maximum brightness, it drops very quickly to 4500 K at +50 days. Later, the temperature evolves slowly, cooling to 4050 K at +315 days, supporting the H recombination explanation for the light-curve plateau. The comparison LRNe show a similar evolution trend with AT 2021biy during this stage; however, AT 2017jfs (\( T_{BB} \approx 7000 \) K) and AT 2018hso (\( T_{BB} \approx 8000 \) K) are much cooler at
their maxima. After the plateau, the temperature of AT 2021biy initially declines to a local minimum of $T_{\text{BB}} \approx 2850$ K and then rises again to $T_{\text{BB}} \approx 3150$ K at +371 days. Finally, it declines again to $T_{\text{BB}} \approx 2300$ K at our last observations around +467 days. In contrast, the Galactic LRN V838 Mon shows a very slow temperature rise at very late phases, going from $\sim 1750$ K to $\sim 2000$ K.

Figure 4 (bottom-right panel) shows the radius evolution of the four LRNe, which are inferred through the Stefan-Boltzmann law ($L = 4\pi R^2 \sigma T^4$, where $\sigma$ is the Stefan-Boltzmann constant) using the luminosity and temperature parameters estimated above. LRNe show relatively homogeneous radius evolution before the rebrightening phase, which is suggested to be a diagnostic tool to discriminate LRNe from the so-called ILRTs (see the discussion by Cai et al. 2019). At maximum light, AT 2021biy has the smallest photospheric radius ($1.1 \times 10^{14}$ cm = $1580 R_\odot$) among the comparison LRNe: AT 2017jfs ($5.4 \times 10^{14}$ cm = $7760 R_\odot$) and AT 2018hso ($1.9 \times 10^{14}$ cm = $2730 R_\odot$). After maximum brightness, the photospheric radius of AT 2021biy initially remains roughly constant, then steadily rises to $4.9 \times 10^{14}$ cm ($7040 R_\odot$) at +131 days; it expands at $\sim 335$ km s$^{-1}$. This is followed by a relatively slow evolution, with $R \approx 4.5 \times 10^{14}$ cm ($6470 R_\odot$) until +315 days. The radius then reaches a local maximum of $6.4 \times 10^{14}$ cm ($9200 R_\odot$) at +341 days and evolves to $R \approx 6.5 \times 10^{14}$ cm ($9340 R_\odot$) at the latest monitored epoch. In this phase, the SED peak appears to be shifted from the optical to the IR domains. According to current observations, AT 2021biy is showing an opposite trend in comparison with the very late-time radius evolution of V838 Mon, as the latter had a slow radius decline up to $R \approx 8.6 \times 10^{13}$ cm ($1240 R_\odot$) at +470 days.

### 4. Spectroscopy

High-cadence spectroscopic observations of AT 2021biy were performed using multiple instrumental configurations. Information on the obtained spectra is reported in Table A.3. The spectra were reduced following standard procedures in IRAF. After the traditional prereduction steps, such as bias and overscan corrections, trimming, and flat fielding, we extracted one-dimensional spectra from the two-dimensional frames. Wavelength and flux calibrations were performed using spectra of comparison lamps and spectrophotometric standard stars, respectively. The calibration images were taken during the same night and with the same
instrumental configuration as the LRN spectra. The spectral flux was improved by checking the coeval broadband photometry, and the telluric absorption bands (e.g. O$_2$ and H$_2$O) were removed using the spectra of standard stars. Spectra obtained with the 6 m BTA equipped with the SCORPIO-1 and SCORPIO-2 multimode focal reducers were calibrated following the descriptions by Afanasiev & Moiseev (2005) and Afanasiev & Moiseev (2011).

A series of optical spectra of AT 2021biy was obtained with the Kast Double Spectrograph (Miller & Stone 1993) mounted on the 3 m Shane telescope at Lick Observatory. The spectra were taken at or near the parallactic angle to minimise slit losses caused by atmospheric dispersion (Filippenko 1982). Data reduction followed standard techniques for CCD frame processing and spectrum extraction (Silverman et al. 2012) using IRAF routines and custom Python and IDL codes. In addition, spectra were obtained with Ekar 1.82 m/AFOSC, 3.6 m DOT/ADFOSC, NOT/ALFOSC, and GTC/OSIRIS were reduced using the dedicated pipeline Foscgui developed by E. Cappellaro, while the Keck i-LRIS spectra were processed with the pipeline LPipe written by Perley (2019). The OGG2 m/FLOYDS spectra were taken as part of the Global Supernova Project. The resulting AT 2021biy spectral series is shown in Figure 6.

4.1. Spectroscopic evolution

We collected 31 optical spectra of AT 2021biy, covering about 13 months and all crucial phases of its evolution. They exhibit the typical evolution of LRNe (e.g. Pastorello et al. 2019a,b, 2021a). We identify four distinct phases: Phase 1 – at early times, around the blue peak; Phase II – an intermediate phase during the plateau; Phase III – at late times, during the fast post-plateau decline; and Phase IV – during the late-time light-curve hump.

Phase I: At early epochs (until +29.5 days after the light-curve maximum), spectra of AT 2021biy show a blue continuum with superimposed prominent Balmer emission lines. Several Fe III emission lines are also observed, along with Ca II H&K in absorption and the barely visible Ca II NIR triplet (see the top panel of Fig. 7). The BB temperature, inferred from the spectral continuum, decreases from $\sim$ 10,800 K (at +1.5 days) to $\sim$ 5850 K (at +29.5 days).

In the NOT/ALFOSC spectrum at −5.9 days, the H$\alpha$ profile is dominated by an unresolved narrow component super-
Fig. 6: Spectral evolution of AT 2021biy. The spectra have been corrected for redshift and reddening. The symbol $\oplus$ marks the locations of strong telluric absorption bands. The phases extend from $-6.6$ to $+391.6$ days.
posed on a broader base (Fig. 5). We thus measure the full width at half-maximum intensity (FWHM) of the Hα emission line through a double-component fit: a narrow Lorentzian and a broader one. The resulting FWHM velocity of Hα, accounting for the instrumental resolution, has a narrow component with an upper limit of \( \sim 640 \text{ km s}^{-1} \) and a broader component of \( \sim 1680 \text{ km s}^{-1} \). Soon after maximum brightness, the broader component disappears and the Hα profile is well-reproduced by a single Lorentzian function fit with \( \text{FWHM} \approx 430 \text{ km s}^{-1} \) (close to the Shane/Kast instrumental resolution).

As mentioned in Sect. 2, we used the early, good-S/N spectrum at phase \( -5.9 \text{ days} \) to measure the EW of the narrow Na D feature that we attribute to line-of-sight gas within the host galaxy. While \( EW = 1.6 \pm 0.6 \text{ Å} \) in that spectrum, the EW of Na D seems to change with time. For this reason, we measure the temporal evolution of the EW of Na D absorption (Fig. 7), it clearly increases up to a factor of four during the first \( -50 \text{ days} \), remaining nearly constant during the following 8 months.

While the EW and the overall profile of the interstellar Na D absorption has been observed to change in other types of stellar transients (see, e.g., Patat et al. 2007; Wang et al. 2019), to our knowledge it has never been observed in LRNe. While we cannot rule out that this is due to changes in the ionisation stage of the line-of-sight interstellar medium or an increased dust condensation (Byrne et al. in prep.), the apparent evolution of this feature in the spectra of AT 2021biy may have a very simple explanation: the increasing contamination of the Na D absorption component of the expanding LRN ejecta. The increasing strength of other metal-line absorption seems to support this scenario.

Phase ii: At later phases, the spectra experience a remarkable change. The spectral continuum initially becomes rapidly redder, from \( T \approx 5850 \text{ K} \) at \( +29.5 \text{ days} \) to \( T \approx 4800 \text{ K} \) at \( +101.5 \text{ days} \); then the temperature decreases more slowly down to \( T \approx 3950 \text{ K} \) at \( +302.5 \text{ days} \). During the plateau phase, the Balmer emission lines are less prominent than in the early-time spectra (see Fig. 8) and are similar to those of LRN AT 2020kog (Pastorello et al. 2021b). We note that in most LRNe, the Balmer emission is barely detectable during the plateau, as one can see in the middle panel of Figure 7.

In the medium-resolution spectra taken with Keck-I/LRIS (at +60.5 days) and BTA/SCORPIO-1 (at +129.4 days), the Hα profiles show a double P Cygni feature in absorption, with minima blueshifted by \( \sim 350 \text{ km s}^{-1} \) and \( \sim 500 \text{ km s}^{-1} \), respectively. In addition, a forest of metal lines, such as Fe II, Sc II, Ba II, and...
NaI D, are observed during this phase (see the middle panel of Fig. 7).

Phase III: Spectra taken during the rapid post-plateau decline of the light curve show the classical features of old LRNe. The temperature of the spectral continuum further decreases from $T \approx 3950$ K (at $+302.5$ days) to $T \approx 3350$ K (at $+326.1$ days), evolving to that of a late M-type star. Hα becomes prominent again (see Fig. 8) with a $\text{FWHM}$ limit of 730 km s$^{-1}$ in the $+326.1$ day spectrum. Typical broad molecular absorption bands (mostly TiO, but also VO and CN) emerge in the late-time spectra, which are marked and identified in the bottom panel of Figure 8. This late-time metamorphosis is consistent with that observed in other LRNe (e.g., Kaminski et al. 2009; Cai et al. 2019; Pastorello et al. 2019a,b; 2021a,b).

Phase IV: Soon after the fast luminosity decline, we obtained two spectra during the late-time bumpy phase with LBT/MOSFIRE and Keck-I/LRIS. This is the first opportunity to spectroscopically follow the late bumpy phase for an extragalactic LRN. As seen in the bottom panel of Figure 7, these two spectra still show molecular features superposed on a very red continuum, with $T \approx 3550$ K (at $+372.5$ days) and $T \approx 2950$ K (at $+391.6$ days). The clear detection of a P Cygni Hα profile in the medium-resolution LBT spectrum at $+372.5$ days indicates a velocity of about 130 km s$^{-1}$ for an external shell or even the common envelope (see also in Fig. 8). The prominent Hα emission line in the Keck-I/LRIS spectrum (at $+391.6$ days) is well reproduced by two Gaussian components, narrow and broad, with $\text{FWHM} \approx 250$ km s$^{-1}$ and $\text{FWHM} \approx 1450$ km s$^{-1}$ (after correcting for instrumental resolution), respectively. The inspection of the two spectra taken during the late-time curve hump (at around $+370$ days; see Fig. 6 and bottom panel of Fig. 7) does not unequivocally reveal new features that can be attributed to shock interaction, such as the narrow high-ionization emission lines observed in some strongly interacting supernovae, or broader boxy features typical of shocked regions (Chevalier & Fransson 1994). This is probably due to the fact that in LRNe the shocked regions are deeply embedded within the envelope (e.g., Metzger & Pejcha 2017; Aydi et al. 2020). We note, however, that the broader Hα wings (with $\text{FWHM} \approx 1450$ km s$^{-1}$) observed in the $+391.6$ day spectrum are a plausible signature that higher velocity, shocked material emerged at very late phases.

We also collected two NIR spectra of AT 2021biy at very late phases ($+338.7$ days and $+371.1$ days), one with the Keck-I telescope equipped with MOSFIRE and the other with the GTC plus EMIR. This is the second extragalactic LRN published in the literature that has NIR spectroscopy (the first being AT 2018bwo, Blagorodnova et al. 2021). As shown in Figure 10, water (H$_2$O) vapour and CO are the strongest absorption features, which are similar to those of V838 Mon at late times (Lynch et al. 2007). By analogy with the optical spectra, molecular absorption features (e.g., AIO, VO) are also detected in the NIR spectra. However, VO absorption is not securely identified in the NIR spectrum. The CO(3ν) and OH(2ν) overtone absorption bands are clearly detected at $\sim 1.6$ μm in the H-band spectrum (Fig. 10), which are attributed to the decrease in opacity of the expanding gas. In addition, we identify H emission lines of the Paschen and Brackett series along with the atomic transitions of He1.

### 4.2. Spectropolarimetry

Using the Kast spectrograph on the 3 m Shane telescope at Lick Observatory, we obtained two nights of spectropolarimetry of AT 2021biy, $+1$ d and $+12$ d. Observations and data reduction were carried out as described by Patra et al. (2022). For instrumental calibration, we observed the low-polarization standard star HD 57702 to confirm the low instrumental polarization on each night. The average fractional Stokes $q$ and $u$ parameters were found to be $<0.05\%$. We also observed the high-polarization standard stars HD 43384 and HD 58624, and constrained the polarization and position angle to within $0.1\%$ and $3^\circ$ of the published values, respectively (e.g., Mathewson & Ford 1970; Hsu & Breger 1982). Figure 11 shows both epochs of spectropolarimetry of AT 2021biy.

The observed continuum polarization of AT 2021biy is $\sim 1\%$. However, it is unclear how much of it is intrinsic to AT 2021biy and how much is due to dust in the interstellar medium. The âskerowski lawâ puts an upper limit on the percent interstellar polarization (ISP) as $9 \times (E(B/V) - V)$, where $E(B/V)$ is given in magnitudes (Serkowski et al. 1975). In the direction of AT 2021biy, the Milky Way extinction is low ($E(B/V) = 0.015$ mag; Schlafly & Finkbeiner 2011), constraining Galactic ISP to $<0.14\%$. By observing an intrinsically unpolarized star (the probe star) that is located within $1'$ of the line of sight to AT 2021biy and at a distance $\sim 700$ pc away from Earth (to probe a sufficient column of Galactic interstellar medium), we estimated the Milky Way contribution to the interstellar polarization. The probe star was polarized at $<0.12\%$. This value is consistent with the upper limit derived above using the âskerowski law. Therefore, we conclude that the Milky Way contribution to ISP is low compared to the observed polarization.

As done previously for the LRN V838 Mon (Desidera et al. 2004), we fit the polarization spectrum taken on 2021 February 7 with a âskerowski curve to calculate host-galaxy ISP.
We note that, being extragalactic, the spectropolarimetry of AT 2021biy has much lower S/N compared to the Galactic LRN V838 Mon. We found a maximum polarization $p_{\text{max}} = 0.93 \pm 0.13\%$ for AT 2021biy, compared with $p_{\text{max}} = 2.48 \pm 0.10\%$ for V838 Mon. The wavelength at $p_{\text{max}}$ was determined to be $\lambda_{\text{max}} = 5360 \pm 910$ Å, consistent within 1σ of $\lambda_{\text{max}} = 5750 \pm 50$ Å for V838 Mon. However, we note that the constraint on $\lambda_{\text{max}}$ for AT 2021biy is weaker owing to the low-S/N data. The relative similarity of the values of $\lambda_{\text{max}}$ suggests that the dust properties in the vicinity of AT 2021biy are similar to those of dust in the Milky Way in the direction of V838 Mon. The polarization and position angle are consistent at both epochs, but as a consequence of the lack of additional epochs of polarimetry, we are unable to confidently calculate the intrinsic polarization of AT 2021biy.

5. Progenitor analysis

We examined archival data for NGC 4631 in order to search for the progenitor of AT 2021biy. While the *Spitzer Space Telescope* has observed this galaxy on multiple occasions between 2004 and 2019, these data unfortunately do not have sufficiently high spatial resolution to search for a progenitor, or even place meaningful limits on one. No point source is visible at the position of AT 2021biy, and only diffuse emission is seen. In addition, we checked the images taken by *WISE* from 2010 to 2020. The final released *WISE* images for AT 2021biy produced by the archival images taken by *WISE* in May 2020. The record status about half year before the major outburst of AT 2021biy. However, there is no signal from a pre-nova outburst.

The *Hubble Space Telescope (HST)* data are more useful. We downloaded 2 × 350 s F814W and 2 × 338 s F606W images of NGC 4631 taken on 2003 August 3 from the Mikulski Archive for Space Telescopes. We also briefly examined earlier data taken with WFPC2 in the F336W and F606W filters, but as these provided shallower images in the same filter as the ACS data (F606W) or the position of AT 2021biy was on the very edge of a detector (F336W), they were not further pursued.

A deep (15 × 60 s) stack of i-band images taken with LT+IO:O on 2021 July 16 was used to identify AT 2021biy in our pre-outburst data. The LT images were taken under good conditions, and the final stack has a FWHM of 0.9″. Ten point-like sources were identified in both the LT image and the pipeline-drizzled *HST*+ACS F606W image. Using the matched coordinates of these sources in both frames, we derived a geometric transformation between the pre-outburst and post-outburst images with a root-mean-square scatter of only 0.09″.

We measured the position of AT 2021biy in the LT image, and use our transformation to determine its corresponding po-
We plot the matching models in Figure 13. A large number of models match our photometry, and these are also consistent with the luminosity inferred from the YBC database. We note that detailed MESA (Modules for Experiments in Stellar Astrophysics; Paxton et al. 2018) modeling in Blagorodnova et al. (2021) for the common envelope phase in AT 2018bwo shows a drop in luminosity. While a similar drop is also observed in many of our matching BPASS models, we caution that significant uncertainties exist in the treatment of the common envelope phase in BPASS (and probably in all stellar evolution codes). Encouragingly, we also see that a 20 $M_\odot$ single-star model from BPASS is consistent with the observed photometry. Turning to the binary models, we find that the majority of matching models have a primary with a ZAMS mass of 17–24 $M_\odot$. The mass of the secondary is less constrained. However, we note that weighting for the initial mass function (IMF), most models seem to have lower mass secondaries ($\lesssim 60\%$ have $M_2$ below $\sim 5$ $M_\odot$).

We also determined the binary separation for each of the matching models. Figure 13 indicates models where the semimajor axis of the binary is less than the combined radius of the primary and secondary. We find that, again, the progenitor candidate is consistent with a close binary where the primary has 17–24 $M_\odot$.

While the overall result from our HST data analysis is that the progenitor of AT 2021biy is consistent with either a $\sim 20$ $M_\odot$ single star or a 17–24 $M_\odot$ ZAMS primary with a binary companion, we must stress several caveats. First, the progenitor candidate may be an erroneous identification. Attempting to perform differential astrometry between relatively wide-field, low-resolution, ground-based data and HST images with a small number of reference stars is subject to error. If the progenitor of AT 2021biy is not the star we have identified, then it is necessarily fainter and likely has lower mass than our candidate.

We also determined the binary separation for each of the matching models. Figure 13 indicates models where the semimajor axis of the binary is less than the combined radius of the primary and secondary. We find that, again, the progenitor candidate is consistent with a close binary where the primary has 17–24 $M_\odot$.

6. Discussion and concluding remarks

AT 2021biy is one of the best-observed LRNe, with extensive optical and NIR datasets during the major outburst phase. Although AT 2021biy shares a number of common properties with other LRNe, it shows an unprecedentedly long plateau, and a pronounced hump in the late-time (post-plateau) light curve.

The field of AT 2021biy was imaged for $\sim 7.6$ yr prior to the outburst by the ATLAS and Pan-STARRS surveys. However, a weak source is observed at the LRN location only from about $\sim 230$ days to $\sim 200$ days before the outburst onset. The subsequent observational gap lasts for about 165 days. For this reason, the timing of the onset of the common-envelope phase is not well constrained.

AT 2021biy shows a very fast initial rise lasting $\sim 7$ days, reaching the first blue peak at a luminosity of $1.6 \times 10^{41}$ erg s$^{-1}$. This short-duration peak can be comfortably explained by the outflow of material ejected by the stellar core coalescence (e.g.
The duration of an LRN plateau is set by a rapid luminosity decline and then by a long plateau of ~210 days. This is the longest plateau observed so far among LRNe.

By analogy with SNe IIP, the plateau (or the equivalent second peak commonly observed in LRNe) is likely powered by hydrogen recombination, during which the largest fraction of the radiated energy in LRNe is emitted. The peak is followed by a rapid luminosity decline and then by a long plateau of ~210 days. This is the longest plateau observed so far among LRNe.

As discussed by Matsumoto & Metzger (2022), the plateau duration is mostly determined by the timescale of the H recombination, which occurs at $T \approx T_i$. With this $T_i$, the characteristic density ($\rho_i$) is approximately a constant of $10^{-11}$ g cm$^{-3}$ in the Saha equation. Therefore, the duration of an LRN plateau is set by $\rho_i$ and other parameters, following the relation

$$t_{pl} \approx \left( \frac{3 M_{ej}}{4 \pi \rho_i \bar{v}_E} \right)^{1/3} \approx 140 \times \rho_i^{1/3} \left( \frac{M_{ej}}{M_\odot} \right)^{1/3} \left( \frac{\bar{v}_E}{300 \, \text{km s}^{-1}} \right)^{-1},$$

(1)

where $\rho_i = \rho_i / 10^{-11}$ g cm$^{-3}$, $M_{ej}$ is the total ejecta mass, and $\bar{v}_E$ is the mean ejecta velocity. Here, we estimate $M_{ej}$ following Eq. 1. In the case of AT 2021biy, the plateau duration is obtained from the light curve with $t_{pl} = 210$ days, and the ejecta velocity ($\bar{v}_E = 430 \, \text{km s}^{-1}$) is estimated through the FWHM velocity of H$\alpha$ in the +177.2 day Shane/Kast spectrum taken during the plateau phase (see Sect. 4.1). We find $M_{ej} = 9.9 M_\odot$.

Note that this result should be considered only as an indicative value, because the above relation is highly sensitive to the ejecta velocity which was estimated through our moderate-resolution spectrum. This should be improved by future efforts in both theoretical modeling and high-resolution spectral observations.

Furthermore, we follow Matsumoto & Metzger (2022) to infer the luminosity at plateau phase (see their Eq. 18). Adopting the above parameters ($\bar{v}_E = 430 \, \text{km s}^{-1}$ and $M_{ej} = 9.9 M_\odot$), the plateau luminosity results to be $L_{pl} \approx 3 \times 10^{39} \, \text{erg s}^{-1}$, which is about one order of magnitude smaller than the observed one ($\sim 5 \times 10^{40} \, \text{erg s}^{-1}$, see the top-right panel of Fig. 5). This discrepancy can be attributable to the crude assumption that the LRN plateau is solely powered by H recombination (Matsumoto & Metzger 2022). This tension can be relaxed by invoking an extra heating source, such as embedded shock-interaction between the ejecta and the circumbinary material (e.g. Metzger & Pejcha 2017).

Similar to other LRNe, the plateau of AT 2021biy is followed by a rapid luminosity decline. However, the decline abruptly stopped 11 months after maximum brightness, and the light curve showed a short-lived hump in all bands, likely due to gas shell collisions. Similar short-lived fluctuations in the light curve are frequently observed in some SNe whose ejecta interact with circumstellar material, and are normally interpreted as ejecta collisions with relatively thin circumstellar shells (e.g. Pastorello et al. 2008, 2015; Smith et al. 2012; Martin et al. 2015; Reguitti et al. 2019).

From the spectroscopic point of view, AT 2021biy shows the canonical evolution of LRNe. Early-time spectra are characterised by a blue continuum with prominent H lines. During the plateau phase, the spectra become redder and are dominated by a forest of narrow metal lines in absorption. Finally, all spectra at late times are extremely red and with prominent molecular features, resembling those of M-type stars.
LRNe are expected to produce dusty environments (e.g. Nicholls et al. 2013; Zhu et al. 2013; Goranskij et al. 2020; Moe­been et al. 2021; Woodward et al. 2021). Spectropolarimetric analysis reveals that the size distribution of the interstellar dust grains in the vicinity of AT 2021biy resembles that around V838 Mon in the Milky Way.

Many authors suggest that physical parameters of LRNe are correlated (e.g. Pejcha et al. 2016b; Mauerhan et al. 2018; Pastorello et al. 2019b; 2021b; Blagorodnova et al. 2021). In particular, the light curve luminosity seems to be correlated with some spectral parameters, such as the Hα luminosity (LHα) and the FWHM velocity (vFWHM). They inferred a general trend according to which brighter events have higher LHα and vFWHM (Hα) (see the analysis in Pastorello et al. 2022 and their Fig. 17).

Within this LRN sample, SNHunt248 should be regarded as an LRN progenitor. The detection of a source at the LRN location in archival HST images allows us to constrain its progenitor to be either a luminous yellow supergiant or, most likely, a binary system with a primary of 17–24 M⊙, placing AT 2021biy in the small group of LRNe with very massive progenitors, although still a factor of 2–3 less than the most massive progenitor of an LRN observed so far for SNHunt 248 (Mauerhan et al. 2018).

Future facilities, such as the China Space Station Telescope (CSST; Cao et al. 2022a,b), the Vera C. Rubin Observatory (e.g. Rubin et al. 2021; Gezari et al. 2022) will help refine the relation.

The full acknowledgments are available in Appendix B.

Acknowledgments

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second peak/plateau depends on the mass of the recombin­ing hydrogen (which is likely correlated with the total systemic mass). Therefore, we use the magnitude at the second peak/plateau as the reference. 15 Within this LRN sample, SNHunt248 should be regarded as an LRN candidate; its nature is still debated (Kankare et al. 2015).

Within this LRN sample, SNHunt248 should be regarded as an LRN candidate; its nature is still debated (Kankare et al. 2015).
Appendix A: Supplementary materials

Appendix A.1: Photometric data for AT 2021biy

Optical and NIR photometric measurements of AT 2021biy are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr(130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/ while other photometric materials are reported here. Our observations will be made public via the Weizmann Interactive Supernova Data Repository (WISeREP; Yaron & Gal-Yam 2012).

Table A.1: Decline rates of the light curves of AT 2021biy (mag (100 day)$^{-1}$) with their uncertainties.

| Filter | Phase 1 ($\gamma_1$) | Phase 2 ($\gamma_2$) | Phase 3 ($\gamma_3$) | Phase 4 ($\gamma_4$) | Phase 5 ($\gamma_5$) | Phase 6 ($\gamma_6$) |
|--------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
|        | ~ 0–50 d             | ~ 50–100 d           | ~ 100–310 d          | ~ 310–340 d          | ~ 340–370 d          | ~ 370–430 d          |
| u      | 10.87 (2.54)         | –                    | –                    | –                    | –                    | –                    |
| B      | 6.90 (0.36)          | −1.70 (0.13)         | 0.17 (0.02)          | 8.82 (0.84)          | –                    | –                    |
| g      | 6.37 (0.29)          | −1.97 (0.08)         | 0.13 (0.01)          | 8.13 (1.02)          | −2.27 (0.06)         | 6.15 (0.12)          |
| c      | 4.69 (0.55)          | −1.75 (0.30)         | 0.28 (0.07)          | –                    | –                    | 5.72 (1.55)          |
| V      | 4.55 (0.30)          | −1.50 (0.09)         | 0.21 (0.03)          | 7.25 (1.15)          | −2.23 (0.51)         | –                    |
| r      | 4.58 (0.29)          | −1.67 (0.06)         | 0.20 (0.02)          | 7.94 (0.70)          | −2.25 (0.35)         | 5.58 (0.48)          |
| o      | 3.52 (0.83)          | −1.64 (0.07)         | 0.18 (0.02)          | 7.51 (0.23)          | −2.35 (0.23)         | 3.39 (0.15)          |
| i      | 4.79 (0.41)          | −1.69 (0.09)         | 0.10 (0.01)          | 6.19 (0.61)          | −2.26 (0.27)         | 5.29 (0.30)          |
| z      | 2.69 (0.37)          | −1.22 (0.07)         | 0.13 (0.05)          | 5.76 (0.47)          | −1.58 (0.15)         | 4.18 (0.33)          |
| y/Y    | –                    | –                    | 0.06 (0.03)          | 3.47 (0.41)          | −1.99 (0.16)         | 2.24 (0.60)          |
| J      | –                    | −1.09 (0.18)         | 0.01 (0.04)          | 2.78 (0.39)          | −0.59 (0.29)         | 1.47 (0.17)          |
| H      | –                    | −1.08 (0.11)         | 0.01 (0.06)          | 2.08 (0.32)          | −0.22 (0.14)         | 1.04 (0.14)          |
| K      | –                    | −1.23 (0.23)         | 0.02 (0.03)          | 1.43 (0.24)          | −0.14 (0.09)         | 0.63 (0.10)          |
Table A.2: Parameters of black-body fit to the $uBgcVrizyYJHK$ bands of AT 2021biy. Uncertainties are given in parentheses.

| Date       | MJD    | Phase$^a$ (days) | Luminosity ($10^{39}$ erg s$^{-1}$) | Temperature (K) | Radius ($10^{14}$ cm) |
|------------|--------|------------------|-------------------------------------|-----------------|------------------------|
| 20210131   | 59245.10 | -5.9             | 4.97 (2.17)                         | 9450 (390)      | 0.94 (0.20)            |
| 20210202   | 59247.17 | -3.8             | 9.78 (4.03)                         | 9615 (565)      | 1.27 (0.26)            |
| 20210203   | 59248.20 | -2.8             | 11.50 (4.53)                        | 10080 (565)     | 1.25 (0.25)            |
| 20210205   | 59250.45 | -0.6             | 15.91 (13.04)                       | 11430 (1410)    | 1.14 (0.47)            |
| 20210210   | 59255.09 | +4.1             | 12.54 (8.91)                        | 10305 (1055)    | 1.25 (0.44)            |
| 20210216   | 59261.12 | +10.1            | 7.66 (1.80)                         | 9190 (260)      | 1.23 (0.14)            |
| 20210219   | 59264.80 | +13.8            | 5.78 (1.81)                         | 8685 (395)      | 1.19 (0.19)            |
| 20210227   | 59272.11 | +21.1            | 3.21 (0.92)                         | 6630 (225)      | 1.53 (0.28)            |
| 20210303   | 59276.08 | +25.1            | 2.49 (0.88)                         | 5980 (255)      | 1.65 (0.29)            |
| 20210313   | 59285.99 | +35.0            | 2.16 (0.59)                         | 5255 (145)      | 1.99 (0.27)            |
| 20210319   | 59292.05 | +41.0            | 2.02 (0.62)                         | 4950 (155)      | 2.17 (0.33)            |
| 20210327   | 59300.43 | +49.4            | 2.06 (0.76)                         | 4495 (170)      | 2.66 (0.49)            |
| 20210403   | 59307.98 | +57.0            | 1.86 (0.48)                         | 4780 (140)      | 2.24 (0.29)            |
| 20210414   | 59318.99 | +68.0            | 2.32 (1.16)                         | 4585 (250)      | 2.71 (0.68)            |
| 20210429   | 59333.10 | +82.1            | 2.76 (0.66)                         | 4655 (115)      | 2.87 (0.34)            |
| 20210508   | 59342.01 | +91.0            | 3.48 (2.00)                         | 4630 (280)      | 3.26 (0.92)            |
| 20210519   | 59353.91 | +102.9           | 4.41 (1.43)                         | 4555 (155)      | 3.79 (0.61)            |
| 20210530   | 59364.98 | +114.0           | 4.94 (2.06)                         | 4325 (190)      | 4.45 (0.93)            |
| 20210616   | 59381.93 | +130.9           | 5.07 (1.78)                         | 4145 (145)      | 4.91 (0.86)            |
| 20210626   | 59391.22 | +140.2           | 4.67 (1.19)                         | 4340 (155)      | 4.05 (0.52)            |
| 20210709   | 59404.89 | +153.9           | 4.96 (1.19)                         | 4355 (100)      | 4.40 (0.53)            |
| 20210725   | 59420.85 | +169.8           | 4.43 (0.91)                         | 4340 (80)       | 4.18 (0.43)            |
| 20210800   | 59434.88 | +183.9           | 4.18 (0.89)                         | 4400 (95)       | 3.96 (0.42)            |
| 20210820   | 59446.89 | +195.9           | 3.97 (0.85)                         | 4360 (95)       | 3.92 (0.42)            |
| 20210911   | 59468.78 | +217.8           | 4.17 (0.82)                         | 4230 (75)       | 4.27 (0.42)            |
| 20211105   | 59523.16 | +272.2           | 4.50 (1.10)                         | 4090 (90)       | 4.74 (0.58)            |
| 20211120   | 59550.48 | +299.5           | 4.31 (0.88)                         | 4185 (75)       | 4.44 (0.45)            |
| 20211128   | 59566.18 | +315.2           | 3.87 (0.84)                         | 4055 (80)       | 4.48 (0.49)            |
| 20211225   | 59573.17 | +322.2           | 3.04 (0.86)                         | 3590 (100)      | 5.07 (0.71)            |
| 20220102   | 59581.19 | +330.2           | 1.93 (0.71)                         | 3090 (105)      | 5.44 (1.00)            |
| 20220113   | 59592.11 | +341.1           | 1.88 (1.23)                         | 2825 (165)      | 6.44 (2.11)            |
| 20220123   | 59602.26 | +351.3           | 1.89 (0.56)                         | 3030 (80)       | 5.62 (0.83)            |
| 20220204   | 59614.18 | +363.2           | 2.26 (0.53)                         | 3140 (65)       | 5.71 (0.67)            |
| 20220212   | 59622.37 | +371.4           | 2.18 (0.45)                         | 3170 (50)       | 5.50 (0.56)            |
| 20220214   | 59624.02 | +373.0           | 2.16 (0.48)                         | 3105 (55)       | 5.71 (0.64)            |
| 20220228   | 59638.23 | +387.2           | 1.91 (0.45)                         | 2815 (55)       | 6.53 (0.78)            |
| 20220409   | 59678.90 | +427.9           | 1.11 (0.58)                         | 2055 (95)       | 9.35 (2.43)            |
| 20220414   | 59683.98 | +433.0           | 0.87 (0.47)                         | 2380 (140)      | 6.16 (1.66)            |
| 20220424   | 59693.93 | +442.9           | 0.98 (0.38)                         | 2330 (90)       | 6.83 (1.31)            |
| 20220518   | 59717.94 | +466.9           | 0.85 (0.41)                         | 2300 (110)      | 6.54 (1.58)            |

$^a$Phases are relative to $r$-band maximum brightness (MJD = 59251.0 ± 1.0).
Appendix A.2: Log of the spectroscopic observations of AT 2021biy.

Table A.3: General information on the spectroscopic observations of AT 2021biy.

| Date       | MJD     | Phase (days) | Telescope+Instrument | Grism+Slit | Spectral range (Å) | Resolution (Å) | Exp. time (s) |
|------------|---------|--------------|----------------------|------------|--------------------|----------------|---------------|
| 20210130   | 59244.45| −6.6         | OGG 2m+FLYODS        | red/blu+2.0" | 3500-10000        | 13             | 2700          |
| 20210131   | 59245.12| −5.9         | NOT+ALFOSC           | gm+1.0"    | 3400-9680         | 14             | 2700          |
| 20210201   | 59246.48| −4.5         | OGG 2m+FLYODS        | red/blu+2.0" | 3500-10000        | 13             | 3600          |
| 20210202   | 59246.77| −4.2         | LJT+yy01             | grism3+2.0" | 3500-8740         | 21             | 2000          |
| 20210203   | 59248.73| −2.3         | LJT+yy01             | grism3+2.0" | 3500-8740         | 21             | 2000          |
| 20210207   | 59252.46| +1.5         | Shane+Kast           | 300/7500+2.0" | 3620-10700     | 9.3            | 2160/2100     |
| 20210210   | 59255.68| +4.7         | LJT+yy01             | grism3+2.0" | 3500-8740         | 21             | 2200          |
| 20210214   | 59259.86| +8.9         | DOT+ADFOSC           | GR676R+1.5" | 3800-8900         | 12             | 900           |
| 20210216   | 59261.13| +10.1        | Ekar1.82m+AFOSC      | VPH6+1.69" | 5000-9290         | 16             | 2400          |
| 20210218   | 59263.41| +12.4        | Shane+Kast           | 300/7500+2.0" | 3620-10730     | 9.3            | 2160/2100     |
| 20210307   | 59280.52| +29.5        | Shane+Kast           | 300/7500+2.0" | 3620-10730     | 9.3            | 3060/3000     |
| 20210323   | 59296.02| +45.0        | NOT+ALFOSC           | gm+1.0"    | 3400-9680         | 14             | 1800          |
| 20210403   | 59307.95| +57.0        | NOT+ALFOSC           | gm+1.0"    | 3400-9680         | 14             | 3600          |
| 20210518   | 59322.26| +71.3        | Shane+Kast           | 300/7500+2.0" | 3630-10740     | 9.3            | 3060/3000     |
| 20210615   | 59380.90| +129.9       | BTA+SCORPIO-1        | VPHG1200R+1.2" | 5660-7375     | 5.6            | 2700          |
| 20210615   | 59380.99| +130.0       | NOT+ALFOSC           | gm+1.0"    | 3400-9650         | 14             | 2700          |
| 20210703   | 59398.26| +147.3       | Shane+Kast           | 300/7500+2.0" | 3630-10750     | 9.3            | 3660/3600     |
| 20210705   | 59400.96| +150.0       | TNG+LRS              | LRB/LRR+1.0" | 3500-10370     | 11/10          | 1200/1200     |
| 20210716   | 59411.19| +160.2       | Shane+Kast           | 300/7500+2.0" | 3630-10750     | 9.3            | 3660/3600     |
| 20210717   | 59412.91| +161.9       | GTC+OSIRIS           | R1000/R1000+1.0" | 3640-10140 | 7/8            | 1500/1500     |
| 20210802   | 59428.18| +177.2       | Shane+Kast           | 300/7500+2.0" | 3630-10750     | 9.3            | 3660/3600     |
| 20210819   | 59445.88| +194.9       | NOT+ALFOSC           | gm+1.0"    | 3400-9650         | 14             | 2400          |
| 20211103   | 59521.52| +270.5       | Shane+Kast           | 300/7500+2.0" | 3630-10750     | 9.3            | 3660/3600     |
| 20211104   | 59522.07| +271.1       | BTA+SCORPIO-2        | VPHG1200@540+1.0" | 3800-7330 | 4             | 3600          |
| 20211205   | 59555.53| +302.5       | Shane+Kast           | 300/7500+2.0" | 3630-10750     | 9.3            | 4890/4800     |
| 20211214   | 59562.10| +311.1       | BTA+SCORPIO-2        | VPHG1200@540+1.0" | 3800-7330 | 4             | 4200          |
| 20211228   | 59577.14| +326.1       | NOT+ALFOSC           | gm+1.0"    | 3520-9360         | 14             | 3600          |
| 20220110   | 59589.69| +338.7       | Keck-1-MOSFIRE       | JHK+0.7" | 9000-25000         | 32700          | 120/12/120    |
| 20220210   | 59622.09| +371.1       | GTC+EMIR             | YJ/HK+1.3" | 9000-25000         | 9873          | 1440/2880     |
| 20220213   | 59623.52| +372.5       | LBT+MODS             | G400L/G670L+1.0" | 3500-10000 | 3.3            | 5×600         |
| 20220304   | 59642.60| +391.6       | Keck-1-LRIS          | 600/4000&400/8500+1.0" | 3150-10280 | 4.7/9.0        | 900/900       |

*Phases are relative to r-band maximum light (MJD = 59251.0 ± 1.0).

Appendix A.3: Parameters of the sample of LRNe

Table A.4: $M_V$ at second peak (or plateau) and progenitor mass used to derive Eq. 2.

| Name          | Progenitor mass (M$_\odot$) | $M_V$ (mag) |
|---------------|-----------------------------|-------------|
| V4332 Sgr     | 1.00 ± 0.5                  | −5.21 ± 1.33|
| V1309 Sco     | 1.54 ± 0.5                  | −5.48 ± 1.04|
| M31-LRN2015   | 4 ± 1                       | −9.13 ± 0.42|
| V838 Mon      | 8 ± 3                       | −9.43 ± 0.22|
| AT 2018bwo    | 13 ± 2.5                    | −10.14 ± 0.45|
| AT 2015di     | 18 ± 1                      | −11.46 ± 0.31|
| AT 2021biy    | 20.5 ± 3.5                  | −12.65 ± 0.16|
| NGC 44900T    | 30 ± 22                     | −14.54 ± 1.00|
| SNhunt248     | 58 ± 2                      | −14.07 ± 0.36|

*See Pastorello et al. (2022) for references for the values of each object.
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