Decade-long time-monitoring of candidate Luminous Blue Variable dwarf galaxies DDO 68 and PHL 293B

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ABSTRACT
We have studied the spectral time variations of candidate luminous blue variable stars (cLBV) in two low-metallicity blue compact dwarf galaxies, DDO 68 and PHL 293B. The LBV in DDO 68, located in H ii region #3, shows an outburst, with an increase of more than 1000 times in Hα luminosity during the period 2008–2010. The broad emission of the H i and He i lines display a P Cygni profile, with a relatively constant terminal velocity of ∼800 km/s, reaching a maximum luminosity $L(\text{H} \alpha)$ of $\sim 2 \times 10^{38}$ erg/s, with a FWHM of $\sim 1000$–1200 km/s. On the other hand, since the discovery of a cLBV in 2001 in PHL 293B, the fluxes of the broad components and the broad-to-narrow flux ratios of the H i and He i emission lines in this galaxy have remained nearly constant over 16 years, with small variations. The luminosity of the broad Hα component varies between $\sim 2 \times 10^{38}$ erg/s and $\sim 10^{39}$ erg/s, with the FWHM varying in the range $500$–1500 km/s. Unusually persistent P Cygni features are clearly visible until the end of 2020 despite a decrease of the broad-to-narrow flux ratio in the most recent years. A terminal velocity of $\sim 800$ km/s is measured from the P Cygni profile, similar to the one in DDO 68, although the latter is 3.7 more metal-deficient than PHL 293B. The relative constancy of the broad Hα luminosity in PHL 293B suggests that it is due to a long-lived stellar transient of type LBV/SN IIn.

Key words: galaxies: dwarf – galaxies: starburst – galaxies: ISM – galaxies: abundances.

1 INTRODUCTION
During their evolution, massive stars are known to go through a very short and high luminosity important transitional phase, called the luminous blue variable (LBV) phase. During this phase, LBVs undergo significant variations in photometric magnitudes and spectral features, characterized in particular by the appearance of broad components in the hydrogen and helium emission lines and in some heavy element ion lines in the UV and optical ranges. The broad emission in the LBVs may be due to sharp eruptions of the massive stars, reaching a total mass loss of up to $\sim 30$ – $100 \, M_\odot$. It can also be caused by stellar winds and expanding dense circumstellar envelopes. In these cases, Hα luminosities are in the range of $10^{36}$ – $10^{39}$ ergs s$^{-1}$ (Izotov et al. 2007). The mass loss rate of hydrogen-rich layers through stellar winds is $\sim 10^{-6}$ – $\sim 10^{-3} \, M_\odot$ yr$^{-1}$ (Humphreys & Davidson 1994; Smith et al. 1994; Drissen et al. 1997; 2001). However, very strong broad emission (FWHM $> 1000$ km s$^{-1}$) can also be present in the spectra of objects other than massive stars, such as Type IIn Supernovae (SNe) and Active Galactic Nuclei (AGNs). In these objects, the luminosities of the broad Hα component are larger and can reach values up to $10^{46} - 10^{47}$ ergs s$^{-1}$ (Izotov et al. 2007; Sobral et al. 2020; Kokubo 2021; Burke et al. 2021).

LBVs frequently show recurring eruptive events through various evolution phases, during their transition from young massive main-sequence stars to WR stars, SN explosions or massive black holes (BHs). It is believed that stars with masses greater than $20$ – $30 \, M_\odot$ and luminosities $L \sim 10^3$ – $10^6 \, L_\odot$ go through the LBV phase (Crowther 2007; Smith et al. 1994; Drissen et al. 1997; 2001). Among all types of variable stars, only LBV stars show significant variability both in photometric brightness and spectroscopic features: rapidly ampli-
fied broad emission and blueward absorption lines, strongly enhanced continuum that becomes bluer in the UV and optical spectra.

To date, about a few hundreds LBVs and candidate LBVs (cLBVs) are known to show irregular cyclic quasi-periodic brightness variations of $\sim$0.5 - 2 mag on timescales from several years to decades. They are called S Dor LBVs (see e.g. Massacce et al. 2004, Humphreys et al. 2013, 2017, Humphreys 2014, Grassitelli et al. 2020, Weis & Bomans 2020). On the other hand, there exists a tiny number of LBV stars which show giant eruptions, with amplitudes more than 2.5 - 3 mag, on timescales of up to thousands years (Davidson & Humphreys 1997; Smith et al. 2016, 2019; Grassitelli et al. 2020; Weis & Bomans 2020). Well-known prototypes of this category are η Carinae and P Cygni with luminosities $\sim 10^{40}$ ergs s$^{-1}$ (Lamers et al. 1983, Davidson 1999). In some cases, the peak luminosity during the outbursts can reach $\sim 10^{42}$ ergs s$^{-1}$ (Kokubo 2021). Nearly all these known luminous LBVs are either in our Galaxy or in nearby galaxies.

High intensity broad and very broad components of emission lines, with P Cygni profiles, have also been observed in the integral spectra of star-forming galaxies (SFGs) underlying their strong narrow emission lines produced in H II regions (see e.g. Schaerer et al. 1999; Izotov & Thuan 2008, Guseva et al. 2000, Leitherer et al. 2001). The most prominent spectral features in SFGs with LBVs are broad components of hydrogen and often helium lines with blueward absorption, and Fe II emission.

To understand the physical mechanism responsible for the broad emission, time-monitoring of the broad spectral features is necessary. The reason is that, as said previously, broad emission occurs not only in LBV spectra but also in those of SNe and AGNs. It is difficult to distinguish between these different possibilities without a long-term time monitoring of the broad features. It has now been established that a significant number of the objects detected in supernova surveys are not true supernovae, but belong to a category of objects called "supernova impostors". Ordinary LBVs of the S Dor type or LBVs with giant eruptions, like η Car at maximum luminosity, appear among these "impostors". Despite the fact that many stars with LBV features have been discovered (Weis & Bomans 2020), only a few dozen of them are confirmed as genuine Galactic and extragalactic LBVs (Wofford et al. 2020). The remaining are cLBV which require time-monitoring to confirm their true nature. A genuine LBV would show a significant enhancement of the spectral and photometric features on a time scale of tens of years, followed by the disappearance of these features. This disappearance is necessary to rule out SNe, AGNs or other physical mechanisms (Kokubo 2021).

In addition, it is of particular interest to understand how LBV evolution in SFGs depends on the properties of the host galaxy, such as gas metallicity, interstellar medium density, star formation rate (SFR) and specific SFR (sSFR). Only very few LBVs are known up to date in metal-poor SFGs with strong star-forming activity (see e.g. Weis & Bomans 2020, and references therein). We discuss in this paper the time monitoring over two decades of the photometric and spectroscopic properties of cLBV stars in two extremely metal-deficient dwarf star-forming galaxies (SFG), DDO 68 (located in H II region #3) with 12 + log (O/H) = 7.15 and PHL 293B with 12 + log (O/H) = 7.72. These two SFGs are the lowest-metallicity galaxies where LBV stars have been detected, allowing the study of the LBV phenomenon in the extremely low metallicity regime, and shedding light of the evolution of the first generation of massive stars possibly born from primordial gas.

The paper is structured as follows: the LBT/MODS and 3.5m APO observations and data reduction are described in Sect. 2. In Sect. 3, we present the study of multi-epoch optical spectra of DDO 68 #3 and PHL 293B. Finally, in Sect. 4, we summarize our main results.

### 2 OBSERVATIONS AND DATA REDUCTION

Over the course of more than a decade, starting in October 2008, we have obtained a series of spectroscopic observations for the two SFGs DDO 68 (its H II region #3) and PHL 293B, using two different telescopes and instrumental setups.

#### 2.1 APO Observations

The first instrumental setup consisted of the Dual Imaging Spectrograph (DIS) mounted on the ARC 3.5m Apache Point Observatory (APO) telescope. The blue and red channels of the DIS permitted to simultaneously observe the objects over a wide range of wavelengths. A long slits giving medium resolution ($R = 5000$) was used during all APO observations. The B1200 grating giving medium resolution ($R = 5000$) with a central wavelength of $\sim$4800 Å and a linear dispersion of 0.62 Å pixel$^{-1}$ was used in the blue range. In the red range, we employ the R1200 grating with a central wavelength of $\sim$6600 Å and a linear dispersion of 0.56 Å pixel$^{-1}$. In this way, APO medium resolution spectra of the two SFGs DDO 68 #3 and PHL 293B were obtained, that

### Table 1. Journal of observations

| Date           | exposure (seconds) | slit width (arcsec) | airmass |
|----------------|--------------------|---------------------|---------|
| DDO 68 #3, 3.5m APO |
| 2008-10-27     | 2700               | 1.5                 | 1.24    |
| 2008-11-06     | 2400               | 1.5                 | 1.17    |
| 2009-02-22     | 1800               | 2.0                 | 1.53    |
| 2009-11-19     | 1800               | 2.0                 | 1.18    |
| 2010-02-06     | 2700               | 1.5                 | 1.36    |
| 2010-03-20     | 1800               | 1.5                 | 1.16    |
| 2010-10-31     | 1500               | 1.5                 | 1.13    |
| 2012-02-15     | 2700               | 1.5                 | 1.20    |
| 2012-05-16     | 1800               | 1.5                 | 1.27    |
| 2013-06-01     | 986                | 1.5                 | 1.42    |
| 2016-04-09     | 1800               | 0.9                 | 1.51    |
| 2018-04-07     | 1800               | 1.5                 | 1.06    |
| PHL 293B, 3.5m APO |
| 2010-10-06     | 1800               | 1.5                 | 1.56    |
| 2014-11-17     | 2700               | 0.9                 | 1.19    |
| 2015-11-06     | 1800               | 0.9                 | 1.21    |
| 2017-12-15     | 1800               | 0.9                 | 1.27    |
| PHL 293B, 2×8.4m LBT/MODS |
| 2020-11-18     | 2700               | 1.2                 | 1.19    |
Table 2. Parameters of Hα narrow and broad components in DDO 68 #3 spectra, observed with the 3.5m APO telescope and presented in Fig. 4.

| Date          | \(F_{\text{nar}}^a\) | FWHM\(_{\text{nar}}^b\) | FWHM\(_c\ \text{([O ii]4959)}\) | \(F_{\text{br}}^a\) | FWHM\(_{\text{br}}^b\) | \(v_{\text{term}}^d\) | \(L_{\text{br}}^e\) |
|---------------|---------------------|-----------------------|-------------------------------|---------------------|-----------------------|----------------|----------------|
| 2008-10-27    | 64.26               | 115(2.51)             | 2.42                          | 84.01               | 1072                  | 706            | 16.2           |
| 2008-11-06    | 59.32               | 70(1.74)              | 2.00                          | 66.86               | 1029                  | 722            | 12.9           |
| 2009-02-22    | 47.13               | 88(1.92)              | 2.33                          | 74.41               | 1006                  | 764            | 14.4           |
| 2009-11-19    | 56.61               | 87(1.91)              | 2.16                          | 93.66               | 1110                  | 808            | 18.1           |
| 2010-02-06    | 27.58               | 78(1.72)              | 1.94                          | 30.94               | 1251                  | 749            | 6.0            |
| 2010-03-20    | 34.85               | 78(1.72)              | 2.15                          | 49.48               | 1107                  | 819            | 9.6            |
| 2010-10-31    | 56.30               | 78(1.71)              | 2.55                          | 73.84               | 1130                  | 871            | 14.3           |
| 2012-02-15    | 48.22               | 69(1.52)              | 1.86                          | 29.10               | 742                   | ...            | 5.6            |
| 2012-05-16    | 73.16               | 78(1.72)              | 1.80                          | 31.87               | 734                   | ...            | 6.2            |
| 2013-06-01    | 45.34               | 74(1.61)              | 1.61                          | 35.82               | 560                   | ...            | 6.9            |
| 2014-04-09    | 13.43               | 63(1.39)              | 1.54                          | 24.44               | 326                   | ...            | 0.5            |
| 2018-04-07    | 8.48                | 86(1.87)              | 1.63                          | ...                 | ...                   | 0.0            |                |

\(\text{aFluxes of Hα narrow (}F_{\text{nar}}\text{) and broad (}F_{\text{br}}\text{) components in units of }10^{-16}\ \text{erg s}^{-1}\ \text{cm}^{-2}\.\)

\(\text{bFull widths at half maximum (FWHM) of Hα narrow and broad components in units of km s}^{-1}\,\text{, and in angstroms (in brackets).}\)

\(\text{cFWHM of [O ii]4959Å emission line in units of angstroms.}\)

\(\text{dTerminal velocity in units of km s}^{-1}\.\)

\(\text{eLuminosity of Hα broad component in units of} \times 10^{16}\ \text{erg s}^{-1}\.\)

\(\text{fDistance} D = 22.7\ \text{Mpc of PHL 293B, the same as that adopted by Izotov & Thuan (2009).}\)

Table 3. Parameters of Hα narrow and broad components in PHL 293B spectra, presented in Fig. 5.

| Date            | tel.\(^a\) | \(F^b\) | FWHM\(^c\) | FWHM\(^d\) \text{([O ii]4959)} | \(F^c\) | FWHM\(^c\) | \(F^c\) | FWHM\(^c\) | \(F^c\) | FWHM\(^c\) | \(F^c\) | FWHM\(^c\) | \(L^e\) | \(v_{\text{term}}^f\) | \(L^f\) |
|-----------------|------------|--------|-----------|-----------------------------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|----------------|--------|
| 2001-08-22      | SDSS       | 238.02 | 235(5.1)  | 3.8                         | 63.74  | 1379      | 7.86   | 2062      | 71.60  | 938       | 44.2   |
| 2010-10-06      | APO        | 261.50 | 71(1.6)   | 2.2                         | 27.13  | 181       | 42.99  | 999       | 70.12  | 702       | 43.2   |
| 2014-11-17      | APO        | 71.04  | 66(1.4)   | 1.6                         | 11.77  | 162       | 12.62  | 627       | 24.39  | ...       | 15.0   |
| 2015-11-06      | APO        | 471.20 | 74(1.6)   | 1.6                         | 45.96  | 180       | 95.08  | 705       | 141.04 | ...       | 87.0   |
| 2017-12-15      | APO        | 91.16  | 69(1.5)   | 1.6                         | 9.64   | 165       | 15.02  | 903       | 24.66  | ...       | 15.2   |
| 2020-11-18      | LBT        | 401.30 | 280(6.1)  | 4.0                         | 23.98  | 504       | 11.64  | 1320      | 34.72  | ...       | 21.4   |

\(\text{aTelescopes: 2.5m APO (labelled as SDSS), 3.5m APO (labelled as APO), 2\times8.4m LBT (labelled as LBT).}\)

\(\text{bFlux of narrow (}F_{\text{nar}}\text{), broad (}F_{\text{br}}\text{) and very broad (}F_{\text{v.br}}\text{) components of Hα in units of }10^{-16}\ \text{erg s}^{-1}\ \text{cm}^{-2}\.\)

\(\text{cFWHM of [O ii]4959Å emission line in angstroms.}\)

\(\text{dFWHM of the [O ii]4959Å emission line in angstroms.}\)

\(\text{eFlux of the whole broad bump (i.e. sum of the broad and very broad components) in units of }10^{-16}\ \text{erg s}^{-1}\ \text{cm}^{-2}\.\)

\(\text{fTerminal velocity in units of km s}^{-1}\.\)

\(\text{gLuminosity of the whole broad bump (i.e. the sum of broad and very broad components) in }10^{37}\ \text{erg s}^{-1}, \text{calculated with the distance }D=22.7\ \text{Mpc of PHL 293B, the same as that adopted by Izotov & Thuan (2009).}\)

span two wavelength ranges, from \(\sim 4150\) to 5400 Å in the blue range, and from \(\sim 6000\) to 7200 Å in the red range.

The journal of the APO observations, giving the observation dates, the exposure times, the slit widths and the airmasses, are shown in Table 1.

2.2 LBT Observations

For PHL 293B, one high signal-to-noise ratio spectroscopic observation was also carried out with the 2\times8.4m Large Binocular Telescope (LBT). We employ the LBT in the binocular mode utilizing both the MODS1 and MODS2 spectrographs, equipped with 8022×3088 pixel CCDs. Two gratings, one in the blue range, G400L, with a dispersion of 0.5Å pixel\(^{-1}\), and another in the red range, G670L, with a dispersion of 0.8Å pixel\(^{-1}\), were used. The LBT 293B spectrum was obtained in the wavelength range \(\sim 3150 – 9500\ \text{Å}\) with a 60×1.2 arcsec slit, giving a resolving power \(R \sim 2000\). The seeing during the observation was in the range 0.5 – 0.6 arcsec. Three subexposures were derived, resulting in an effective exposure time of 2\times2700 s when adding the fluxes obtained with both spectrographs, MODS1 and MODS2. The spectrum of the spectrophotometric standard star GD 71, obtained during the LBT observation with a 5 arcsec wide slit, was used for flux calibration. It was also used to correct the red part of the LBT 293B spectrum for telluric absorption lines. The journal of the LBT observation is also shown in Table 4.
2.3 Data reduction

The two-dimensional APO spectra were bias- and flat-field corrected, fixed for distortion and tilt of frame and background subtracted using IRAF routines. For the LBT observation, the MODS Basic CCD Reduction package MODSCCDRED (Pogge 2019) was used for flat field correction and bias subtraction. Wavelength calibrations of both LBT and APO observations were performed using spectra of comparison lamps obtained every night before and after the observations. Each two-dimensional spectrum was aligned along the brightest part of the galaxy. After wavelength and flux calibration and removal of cosmic particle trails, all subexposures were summed. One-dimensional spectra were then extracted along the spatial axis so that the entire bright part of the H II region falls into the selected aperture.

In summary, we have obtained twelve new APO observations of DDO 68 #3 and four new APO observations of PHL 293B, together with one new LBT spectrum of PHL 293B. To increase the time baseline for PHL 293B, we have also included in our analysis the Sloan Digital Sky Survey (SDSS) spectrum obtained with the 2.5m APO telescope on 22 August 2001 and available in the SDSS archive. This brings the total number of PHL 293B spectra to be analyzed to six. More details are given in Tables 2 and 3. The spectra are shown in Fig. 1 and Fig. 3, respectively. All spectra are displayed in the wavelength range around $H_\alpha$ to better emphasize the temporal changes of this line. In Fig. 2, we have also shown two spectra of PHL 293B over the whole wavelength range of observations, and that are most separated in time.

3 RESULTS

3.1 Profile decomposition

The most remarkable features in the DDO 68 #3 and PHL 293B spectra are the strong broad components with P Cygni profiles underlying the narrow nebular emission of the hydrogen and helium lines. For derive quantitative measurements of these features, we have decomposed the profiles of the hydrogen emission lines into the sum of several
Figure 2. The most time-separated spectra of PHL 293B. Panels a) and b) show blue and red parts of the SDSS spectrum obtained with the 2.5m APO telescope on August 22, 2001. Panels c) and d) show the spectrum obtained with LBT/MODS on November 18, 2018. Absorption features of P Cygni profiles for hydrogen and helium emission lines are indicated in the rest-frame spectra by red and blue arrows, respectively. Wavelengths are in Å and fluxes are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

Figure 3. The rest-frame H$\alpha$ emission line profiles in the PHL 293B spectra at the different epochs listed in Table 3. Wavelengths are in Å and fluxes are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

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Figure 4. Decomposition by Gaussians of the H\textalpha narrow (blue dotted lines) and broad emission (blue solid lines) profiles in the spectra of DDO 68 \#3, listed in Table 2 and shown in Fig. 1. The observed profile is shown by the black solid line whereas the summed flux of narrow+broad components is represented by the red solid line. Wavelengths are in Å and fluxes are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

Figure 5. The observed profile of H\textalpha in DDO 68 \#3 with an excess flux at high velocities in redward wings. This excess is seen only for the observations on 15 February and 16 May 2012 (see Fig. 4h and Fig. 4i). Three Gaussians were used to fit the narrow, broad and very broad components (blue dots, turquoise solid and blue solid lines, respectively). The total fitted profile is represented by a red solid line. Wavelengths are in Å and fluxes are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

Figure 6. The H\textalpha profiles in the PHL 293B spectra obtained with different telescopes during different epochs. The black lines represent the observed spectra. The fits of H\textalpha by three or four Gaussians are shown by blue dotted lines (narrow component), by turquoise solid lines (broad component), by blue solid lines (very broad component) and by magenta dashed lines (for absorption features of P Cygni profiles whenever possible). Note that, in contrast to Fig. 4 and Fig. 5, the y-axes have different scales, to better see the shape of the broad components. Fluxes are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and wavelengths are in Å.

Gaussian profiles: a high-intensity narrow component, and low-intensity broad and very broad (the latter when needed) components, using the IRAF/SPLOT deblending routine.

The fluxes and full widths at half maximum (FWHM) of the H\textalpha narrow and broad components, along with the terminal velocities and the total luminosities of the broad components in the two SFGs are given in Table 2 and Ta-
Izotov & Thuan 2009; Annibali et al. 2019a). It is likely to narrow Hα.

Figure 7. a) Temporal variations of the flux ratio of broad-to-narrow Hα when calculating this broad-to-narrow ratio was taken to be the sum of the broad and very broad emission components, and of the absorption component when appropriate) was shown by the red dashed line. Note that the total flux of the whole broad bump (i.e. the sum of the broad and very broad emission components, and of the absorption component when appropriate) was taken to be the broad component when calculating this broad-to-narrow ratio. b) Temporal variations of Hα fluxes in different components for DDO 68 #3. The thick black line shows the APO observations discussed here while the thin black line represents data by Pustilnik et al. (2003, 2008) and Izotov & Thuan (2009). The colored lines show the data for PHL 293B.

Table 3 for all spectra shown in Figs. 4, 5, 6. For luminosity determination, the observed fluxes of narrow and broad emission lines were corrected for the extinction and underlying stellar absorption taken from Izotov & Thuan (2004), derived in accordance with the prescription of Izotov et al. (1994). Note that the extinction coefficient C(Hβ) is nearly unchanged between the end of 2010 and the beginning of 2012, with small variations in the component fluxes. The width of the broad component remained unchanged until October 2010 with a FWHM of 1000–1200 km s⁻¹ (Table 2). After 2011 the flux and the velocity of the broad component markedly decreased. Furthermore, the absorption feature in the P Cygni profile disappeared toward the beginning of 2012. That disappearance together with the sharp decrease of the fluxes of the broad features are possibly due to the dense stellar envelope being destroyed and scattered.

Our more than a decade APO monitoring showed that the features characteristic of eruption in the LBV in DDO 68 #3 persist until the period somewhere between the end of 2010 and the beginning of 2012, with small variations in the component fluxes. The width of the broad component remained unchanged until October 2010 with a FWHM of 1000–1200 km s⁻¹ (Table 2). After 2011 the flux and the velocity of the broad component markedly decreased. Furthermore, the absorption feature in the P Cygni profile disappeared toward the beginning of 2012. That disappearance together with the sharp decrease of the fluxes of the broad features are possibly due to the dense stellar envelope being destroyed and scattered.

Broad spectral features with blueshifted absorption in the lines of the hydrogen series as well as in some He i lines were first noticed in DDO 68 by Pustilnik et al. (2008). Those authors attributed the broad features to the outburst of a LBV located in one of the H ii region of DDO 68 named Knot 3, and which we will designate by #3 in the remainder of this paper.

Based on photometric and spectroscopic observations, Izotov & Thuan (2009) dated the start of the strong LBV outburst in DDO 68 #3 to be between 2007 February and 2008 January. They confirmed the presence of P Cygni profiles in both the H i and He i emission lines and found that the Fe ii emission lines are not present, in contrast to “typical” LBVs (Pustilnik et al. 2008; Izotov & Thuan 2009). The absence of Fe ii could be due to extremely low metallicity and thus low optical depth precluding considerable radiative pumping. Pustilnik et al. (2017) described the state of the LBV in 2015-2016 as being in a fading phase. Observations carried out by Annibali et al. (2019a) with LBT/MODS1 and LBT/MODS2 in February 2017 do not show the characteristic signs of a LBV star. This led them to conclude that, by 2017, the LBV was back in a quiescent phase.

We provide here a more complete picture of the time evolution of the LBV in DDO 68 #3 by monitoring its spectrum. Our observations start from 2008, and occur as often and as regularly as possible afterwards, ending in 2018. We show in Fig. 1 the time evolution of the Hα line. We emphasize that all spectra were obtained with the same telescope and instrumental setup (3.5m APO/DIS) and reduced in an uniform manner, so they are directly comparable. We remark that, as seen in Figs. 4 and more clearly in Fig. 5, the [N ii] emission lines near Hα are nearly not detected, due to the low metallicity of DDO 68 #3.

Our new APO observations in the monitoring series of DDO 68 #3 reveal that the fluxes of the Hα broad components are nearly an order of magnitude higher at the end of October 2008 as compared to January 2008, when the LBV was discovered by Pustilnik et al. (2008) (Table 2 and Fig. 5, thick solid black line). The MMT observation of DDO 68 #3 on March 2008 of Izotov & Thuan (2009) is consistent with that trend. It showed a broad Hβ flux ~2 times lower than the one in the first observation in our APO monitoring series starting 6 months later, in October 2008.

Our more than a decade APO monitoring showed that the features characteristic of eruption in the LBV in DDO 68 #3 persist until the period somewhere between the end of 2010 and the beginning of 2012, with small variations in the component fluxes. The width of the broad component remains unchanged until October 2010 with a FWHM ~1000–1200 km s⁻¹ (Table 2). After 2011 the flux and the velocity of the broad component markedly decreased. Furthermore, the absorption feature in the P Cygni profile disappeared toward the beginning of 2012. That disappearance together with the sharp decrease of the fluxes of the broad features are possibly due to the dense stellar envelope being destroyed and scattered.

In addition to the presence of broad components with absorption components, observed during the period from 2008 up to 2012 (Fig. 4 a – g), a low-intensity high-velocity redward tail made its appearance in 2012. It can be seen
as a flux excess above the Gaussian fit to the broad component (Fig. 4 and 3). It should be noted, however, that the best fit to the 2012 profiles could only be obtained by including two Gaussians for the broad component (Fig. 5: a broad one and a very broad one). Thus, a supplementary broad component with a small FWHM = 300 – 500 km s\(^{-1}\) is present, in addition to the very broad component with a larger FWHM \(\sim 1000\) km s\(^{-1}\) (see Fig. 5: solid turquoise curves). Note the blueward shift in the broad components in Fig. 5 (solid turquoise curves). Likely, the appearance of the high-velocity tail and the subsequent disappearance of the P Cygni profile can be interpreted as the break-up of a dense circumstellar envelope by a rapid outflow. In 2013, the spectrum, despite being somewhat noisy, still clearly shows the broad blueward component (Fig. 4). By 2018, the broad components have completely gone from the spectra, suggesting that the LBV shell has disappeared. The outburst event has thus lasted from 2008 to 2013, for a duration of about 5 years.

Assuming that the broad components of the emission lines belong exclusively to the LBV, and that the narrow emission components are predominantly nebular, we can trace the decay of the LBV outburst by using the flux ratio of the broad-to-narrow components in each of the hydrogen and helium lines. This can be done most reliably for the brightest H\(\beta\) line. The temporal evolution of the H\(\alpha\) broad-to-narrow flux ratio is shown in Fig. 6. A maximum for this flux ratio is seen between 2009 and 2010. It is more pronounced than the maximum for the flux of the broad component (Fig. 5). However, in general, the variation of the broad-to-narrow flux ratio follows tightly the temporal evolution of the broad component.

To derive line flux luminosities for DDO 68, we need to know the distance of the dwarf galaxy. Based on the same imaging \textit{HST} observations of the dwarf galaxy (GO 11578, PI: Aloisi) Cannon et al. (2014); Sacchi et al. (2016); Annibali et al. (2019b) have applied the TRGB (Tip of the Red Giant Branch) method to derive distances \(D = 12.74, 12.65\) and 12.75 Mpc for DDO 68, respectively. New \textit{HST} observations of a stream-like system associated with DDO 68 by Annibali et al. (2019a) gives \(D = 12.8 \pm 0.7\) Mpc, using the same TRGB method. The mean of these values is \(D = 12.7\) Mpc, which we adopt. This distance is more than twice as large as the previous indirect distance determination of \(D \sim 5 - 7\) Mpc (NED) (see e.g. Pustilnik et al. 2005; Izotov & Thuan 2009).

With this distance, the luminosity of the H\(\alpha\) broad component at the maximum is \(\sim 2 \times 10^{38} \text{ ergs s}^{-1}\). This maximum luminosity and the FWHM (\(\sim 1000 - 1200\) km s\(^{-1}\)) of the broad component of the lines during the transient event are in the ranges of those observed for LBV stars. The data thus suggest that a LBV star in the H \(\alpha\) region DDO 68 \#3 has undergone an outburst during the period 2008-2013.

The terminal velocity \(v_{\text{term}}\) of the LBV stellar wind is an important parameter for confronting theory with observation. It is obtained from the wavelength difference between the maximum of the broad emission line profile and the minimum of the blue absorption line profile. The terminal velocity \(v_{\text{term}}\) in DDO 68 \#3 is of \(\sim 800\) km s\(^{-1}\) and does not change significantly over time (Table 2). It remains also unchanged during the “maximum” of the eruption, as well as during the decay period starting in 2013. Nearly the same value of the expanding wind terminal velocity was reported by Izotov & Thuan (2009) and Pustilnik et al. (2014).

To summarize, the new data suggest that the broad component fluxes of the hydrogen lines of the LBV reached a maximum during the time interval \(\sim 2008 - 2012\). The narrow component also reached a maximum during the same period, but less pronounced. The broad-to-narrow component flux ratio reached a maximum at about the same period. This also supports the hypothesis that the LBV star underwent an eruptive event. It can be seen in Fig. 4 that the H\(\alpha\) luminosity of the LBV star is now at a minimum or close to it.

### 3.3 PHL 293B

The situation with understanding the physical processes taking place in PHL 293B is more complex than in DDO 68 \#3. PHL 293B (JJ2230-0006) is a well known SFG with a moderately low metallicity \(12+\log O/H \sim 7.6 - 7.7\) (e.g., Papaderos et al. 2008; Izotov et al. 2011; Fernández et al. 2013; Izotov & Thuan 2009) first detected a broad component in the strong hydrogen emission lines with P Cygni profiles of PHL 293B in a VLT UVES spectrum obtained on 8 November 2002, and in a SDSS spectrum taken on 22 August 2001. Those authors suggested that these broad features are due to a transient LBV phenomenon. Earlier observations of PHL 293B by Kinnunen (1965) and French (1980) did not mention any broad emission. The broad component was again detected by Izotov et al. (2011) in a VLT X-Shooter observation on 16 Aug 2009. Later observations have been carried out, and various other hypotheses have been proposed to interpret them. Thus, Terlevich et al. (2014) have suggested that the observations of PHL 293B can be explained by a young dense expanding supershell driven by a stellar cluster wind and/or two supernova remnants or by a stationary wind. Hydrodynamic models have been built by Tenorio-Tagle et al. (2013).

On the basis of the 10.4m GTC (Gran Telescopio Canarias)/MEGARA observations performed in July 2017, Kehrig et al. (2020) found a flux ratio \(I_{\text{br}}/I_{\text{nar}} \sim 0.10\) in the H\(\alpha\) emission line of all integrated regions. They interpret this low value as due to a diminution of the broad H\(\alpha\) emission.

Allan et al. (2020), from spectroscopic observations including the 2019 VLT X-Shooter data and radiation transfer modeling, report the absence of the broad emission component since 2011 and conclude that the LBV was in an eruptive state during 2001 - 2011 that has ended. Burke et al. (2021) also report the decrease of the \(I_{\text{br}}/I_{\text{nar}}\) ratio from 0.41 (SDSS, 2001) to \(< 0.10\), using Gemini observations taken in December 2019. Despite the fact that a AGN-like damped random walk model works well to fit the observed light curve, those authors concluded that a long-lived stellar transient of type SN IIn can better explain all the data for PHL 293B.

On the other hand, Prestwich et al. (2013) have emphasized the lack of X-ray emission in the galaxy, establishing an upper limit of \(L_X \sim 3 \times 10^{35}\) erg s\(^{-1}\) (their table 6). This casts some doubt on the supernova model, thought to be the most probable one for explaining the PHL 293B phenomenon. Kehrig et al. (2020) have detected P Cygni profiles in the H\(\alpha\) and H\(\beta\) emission lines in July 2017, while those features
were not found by Burke et al. (2020) in Hα in December 2019. These variations suggest that long-time monitoring, such as the observations described here, is important for distinguishing between various models.

Contrary to the conclusions of Izotov & Thuan (2009), based on the archival VLT/UVES observations on 2002-11-08, that P Cygni profiles are seen only in the hydrogen lines, and those of Terlevich et al. (2014), our new PHL 293B observations, as well as a reconsideration of the SDSS archival data (2001-08-22) and the VLT/X-Shooter observation by Izotov et al. (2011) on 2009-08-16, show that blue-shifted absorption lines are detected not only in hydrogen emission lines, but also in He i lines (Fig. 2). In other words, the situation is the same as in the case of DDO 68 #3 which has a much lower metallicity. However, the permitted Fe ii emission lines, which generally originate in dense circumstellar envelopes and are usually seen in the spectra of LBV stars experiencing a giant eruption and creating an envelope, have not been detected in our new observations. Note that Terlevich et al. (2014) found blue-shifted Fe ii absorption with a terminal velocity of $\sim 800$ km s$^{-1}$. We did not detect permitted Fe ii lines in the LBT spectrum obtained in 2020. Only forbidden [Fe iii] $\lambda\lambda$4658, 4702, 4755, 4986, 5270Å emission lines were found in this spectrum, with no absorption features.

In the decomposition of the strong emission lines, we have always attempted to fit the broad component in the simplest way possible, i.e., with the smallest number (preferably one) of Gaussian profiles. We also tried to perform fitting with Lorentzian profiles. But the results were always not as good as the Gaussian profiles. We also tried to perform fit-

The P Cygni profile has persisted over some two decades, during the period 2001–2020, as is clearly seen in Fig. 6. The blueward absorption feature with wavelength $\sim 6545$Å is close to the nitrogen emission line [N ii] $\lambda 6548$Å so that in many cases decomposition of the absorption profile in Hα emission line is difficult. The absorption is likely present, but masked by strong and broad very broad components and the nitrogen emission line (Fig. 3 and Fig. 4).

We obtain a high terminal velocity $v_{\text{term}} \sim 800$ km s$^{-1}$ for the absorption component in the Balmer lines. This value is the same as the ones derived by Izotov & Thuan (2009), Izotov et al. (2011) and Terlevich et al. (2014) from X-Shooter observations made in Aug. 2009 and in Aug.-Sep. 2009, respectively. The luminosity of the broad bump (i.e. the sum of broad and very broad components) varies from $10^{38}$ erg s$^{-1}$ to $10^{39}$ erg s$^{-1}$.

The very broad component derived by us from the SDSS spectrum taken in August 2001 (Fig. 3) has nearly the same redshift as Terlevich et al. (2014)’s faint ultrabroad component measured from their 2009 observations and shown in their figure 2 but a flux that is $\sim 100$ times lower. Note that Terlevich et al. (2014) also fitted Hα in their X-Shooter observation by two broad components. At about the same redshift, Izotov et al. (2011) also saw an excess in their fit of the Hβ broad component (their figure 3).

In our subsequent series of observations of PHL 293B start-

ing in 2010, the very broad component does not show any redward shift. On the contrary, the broad and very broad components are centered practically at the systemic velocity of the galaxy. This means that, at least since 2010, there has been no large velocity outflows. We remark also that the broad components in the SDSS spectrum dated 2001 Izotov & Thuan (2009), and in the VLT X-Shooter spectra dated 2009 Izotov et al. (2011), Terlevich et al. (2014), have quite large FWHMs, $\sim 1500$, 1000 and 1000 km s$^{-1}$, respectively. After 2010, these components become much narrower, with FWHM $\sim 160 - 180$ km s$^{-1}$. This signifies the fact that the velocity dispersions of the moving and radiating matter have decreased, at least in the broad components.

If the ionization parameter is close to the limiting value of $\log U \lesssim -2$, the radiation pressure can prevail over the ionized gas pressure (Coppi et al. 2002), and some contribution of a radiation-driven wind (i.e. by LyC and/or Lyα) superwind from a young stellar cluster, producing a high-velocity very broad component, will be possible (Komarova et al. 2021).

To check this possibility, we use accurate oxygen abundance and an observational indicator of the ionization parameter, $O32 = \frac{[O ii] \lambda 4959,5007/\text{[O iii]} \lambda 4363,5007}$, for PHL 293B (12 + logO/H = 7.72 and O32 = 15.52 from Izotov & Thuan (2009) and 12 + logO/H = 7.71 and O32 = 14.21 from Izotov et al. (2011)) to estimate log$U$. We get (following Kobulnicky & Kewley (2004)) log$U = -2.2$ and log$U = -2.3$, respectively, which are close to the maximum value, but still below it. Note that it is higher than log$U = -2.9$ derived from the MMT observation by Izotov & Thuan (2009) for DDO 68 #3.

In general, the temporal variations of both the broad-to-narrow component flux ratios and of the Hα fluxes of the narrow and broad components for PHL 293B (Fig. 6) colored lines) are very different from those of DDO 68 #3 (Fig. 7, black lines). A strong variability of the Hα fluxes, simultaneously in both the narrow and broad and very broad components, from 2011 to 2018, is seen in PHL 293B (Fig. 7, black lines). Flux jumps by a factor of $\sim 6$ are observed in both the narrow and the sum of the broad and very broad components (Table 3). We have checked the logs of the observations and have determined that all observations were carried out in photometric conditions, so that the flux variations cannot be attributed to sky variability. The flux variations, both in the narrow and broad and even very broad components (a sharp flux decrease in 2014 followed by a rise at the end of 2015, followed by another decrease in 2017) can be explained by inaccurate pointing when observing with a narrow slit of 0.9 arcsec. However the variations are likely to be real because the light curves derived by Burke et al. (2021) from SDSS and DES (Dark Energy Survey) imaging between 1998 and 2018 (their figure 2) also show small-amplitude variability in the $g$ and $r$ bands during the same years. The synchronicity in the variability of fluxes in the narrow and broad components does not hold anymore starting 2018 (see also the fading of the broad component in Allan et al. 2021).

In contrast to the outburst nature of the variability over time of the broad-to-narrow flux ratio in DDO 68 #3, which manifests itself in the form of a peak (Fig. 7, black line), PHL 293B does not undergo such a type of variation. Its broad-to-narrow flux ratios depend weakly on time, at least over the past two decades. However, a decrease in the broad-
to-narrow flux ratio can be seen starting from the very end of 2017 and continuing to 2020 (Fig. 4). This decrease can be partly explained by an increase of the narrow component relative to the broad one (Fig. 4), blue and red dashed and green solid lines).

In the case of PHL293B, the behavior of the broad component may be explained by several effects. Enduring broad hydrogen Balmer P Cygni profiles with absorption feature blue-shifted by \( \sim \) 800 km s\(^{-1}\), can indicate the presence of fast moving ejecta. The persistent luminosity of the broad Balmer emission and the possibility that the Balmer emission could be due to a long-lived stellar transient, like LBV/SN, motivate additional follow-up spectroscopy to distinguish between these effects.

### 3.4 LBVs in other SFGs

We now compare the behavior of the candidate LBVs in DDO 68 #3 and PHL293B with those in other SFGs.

The LBV in the relatively low-metallicity galaxy Mrk 177 = UGCA 239 at the post-merger stage, with 12 + logO/H = 28.9 Mpc, has undergone multiple outbursts during the last 20 years (Kokubo 2021). The luminosity of the broad H\(\alpha\) component of Mrk 177 varies from a maximum of 10\(^{39}\) erg s\(^{-1}\) during the strongest explosion to 10\(^{38}\) erg s\(^{-1}\) during the next two strong explosions. This is an order of magnitude higher than the corresponding values of \(L(\text{H}\alpha)\) (broad) = (2 – 9)\times10\(^{38}\) erg s\(^{-1}\) in PHL293B. As for the H\(\alpha\) broad-to-narrow flux ratio for the LBV in Mrk 177, it varies in the interval 3.4 – 4.5 during last two outbursts. This is in the same range as the LBV outburst maximum in DDO 68 #3, but one order of magnitude higher than in PHL293B. The strongest outburst in Mrk 177 during 2001 is characterised by a H\(\alpha\) broad-to-narrow ratio that is approximately 10 times higher than during subsequent explosions, i.e. \(\sim\) two orders of magnitude higher than in PHL293B.

On the other hand, the luminosity \(L(\text{H}\alpha)\) \(\sim\)10\(^{38}\) erg s\(^{-1}\) (Drissen et al. 2001) of the LBV-V1 in the low-metallicity (12 + logO/H = 7.89, Izotov et al. 1997) galaxy Mrk 71 (NGC 2363A) is lower than that of the cLBV in PHL293B, with a similar metallicity.

### 4 CONCLUSIONS

Over nearly two decades, we have monitored the time variation of the broad component fluxes and of the broad-to-narrow flux ratios of the strong hydrogen and helium emission lines in two low metallicity star-forming galaxies (SFG), DDO 68 (12 + logO/H = 7.15) and PHL293B (12 + logO/H = 7.72). These two SFGs have the particularity of harboring candidate luminous blue variable (cLBV) stars. We have carried out this monitoring by obtaining over time spectra of these two objects with the 3.5m Apache Point Observatory (APO) telescope and the 2\times8.4m Large Binocular Telescope (LBT).

Our main results are the following:

1) The broad emission with a P Cygni profile of the H\(\alpha\) line emitted by the DDO 68 H \(\alpha\) region \#3 shows a marked increase of its luminosity during the period 2005 to 2017, reaching a maximum \(L(\text{H}\alpha)\) of \(\sim\)10\(^{38}\) erg s\(^{-1}\) in 2008 – 2011, adopting the distance derived from brightness of the Tip of the Red Giant branch (TRGB). The absorption feature of the P Cygni-like profile and the broad component rapidly decayed and disappeared in 2018. These properties are characteristic of an eruptive event in a LBV star.

The derived H\(\alpha\) luminosity and the FWHM \(\sim\)1000–1200 km s\(^{-1}\) of the broad component during the eruption event are in the range of those observed for LBV stars. A terminal velocity \(v_{\text{term}}\sim\)800 km s\(^{-1}\) is measured from the absorption profile. It does not change significantly over time. These observations are also consistent with the earlier findings of Pustilnik et al. (2017) who described the LBV in DDO 68 #3 as going through a fading phase during 2015–2016, and with those of Annibali et al. (2019a) who did not find any characteristic sign of a LBV star at the beginning of 2017. Thus, our spectroscopic monitoring indicates that the LBV has passed through the maximum of its eruption activity and is now in a fairly quiet phase.

2) The situation is quite different in the BCD PHL293B. Since the discovery of the cLBV in it on the basis of SDSS 2001 observations, the fluxes of the broad component and the broad-to-narrow flux ratios of the hydrogen emission lines in PHL293B have remained nearly constant, with small variations, over 16 years, at least until 2015. A decrease of the broad-to-narrow flux ratio in recent years (2017–2020) can partly be attributed to an increase of the narrow component flux relative to that of the broad component. The luminosity of the broad H\(\alpha\) component varies from \(\sim\)2\times10\(^{38}\) erg s\(^{-1}\) to \(\sim\)10\(^{39}\) erg s\(^{-1}\), and the FWHM varies in the range \(\sim\)500–1500 km s\(^{-1}\) over the whole period of monitoring of PHL293B, from 2001 to 2020.

Unusually persistent P Cygni features with broad and very broad components of hydrogen emission lines and blueward absorption in the H\(\alpha\) and He\(\alpha\) emission lines are clearly visible, even at the very end of 2020, despite the several decreases of the broad-to-narrow flux ratio in the most recent years (2017–2020). A terminal velocity \(v_{\text{term}}\sim\)800 km s\(^{-1}\) is measured in PHL293B, similar to the one obtained for DDO 68 #3, although the latter is 3.7 times more metal deficient than the former. The terminal velocity does not change significantly with time. The near-constancy of the H\(\alpha\) flux suggests that the cLBV in PHL293B is a long-lived stellar transient of type LBV/SN IIn. However, other mechanisms such as a stationary wind from a young stellar cluster, cannot be ruled out. Further spectroscopic time monitoring of the BCD is needed to narrow down the nature of the phenomenon in PHL293B.

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5 DATA AVAILABILITY

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

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