The disappearance of a massive star in the low metallicity galaxy PHL 293B*

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ABSTRACT

Our current understanding of the final stages of massive star evolution is largely incomplete, particularly in low metallicity environments. To improve upon this, we investigate the behavior of a suspected LBV in one of the most metal-poor dwarf galaxies, PHL 293B. Excitingly, we find the sudden disappearance of the LBV signature from our spectra obtained in 2019. Spectroscopic observations of PHL 293B between 2001 and 2009 consistently revealed both narrow and broad strong emission components in the hydrogen Balmer lines, with minimal variation between observations. These broad components combined with P Cygni profiles have been associated with a massive Luminous Blue Variable (LBV) star. However, such features are absent from our spectra obtained in 2019 with the ESPRESSO and X-shooter instruments of the ESO’s VLT, as well as archival data from 2011 and 2016. We compute radiative transfer models using CMFGEN that fit the observed spectrum of the LBV. This reveals that during 2001–2009 the LBV had a luminosity $L_B = 2.5 - 5.0 \times 10^5 L_\odot$, a mass-loss rate $M = 0.005 - 0.020 M_\odot$ yr$^{-1}$, a stellar wind velocity of 1000 km s$^{-1}$, and an effective temperature $T_{\text{eff}} = 6000 - 6800$ K. These values indicate an eruptive state. We consider two main hypotheses for the absence of the broad emission components from the spectra obtained since 2011. One possibility is that we are seeing the end of an LBV eruption of a surviving star, with a mild drop in luminosity, a shift to hotter effective temperatures, and some dust obscuration. Alternatively, the LBV could have collapsed to a massive black hole without the production of a bright supernova.

Key words. Stars: massive Stars: peculiar – Stars: supernovae – Stars: black holes – Stars: winds, outflows

1. Introduction

Massive stars are among the most important sources of ionising photons and chemical elements, having produced a large proportion of the elements currently present in the Universe through nuclear burning. They are instrumental to the understanding of a variety of astrophysical topics, including the link between supernovae (SNe) and gamma-ray bursts to the nature of their respective progenitors (e.g., Schulze et al. 2015), as well as the early evolution of the Universe.

Our current understanding of massive stars and their fates is incomplete in environments with metallicity $Z$ lower than the Small Magellanic Cloud. This is owed mainly to a scarcity of observations of massive stars at these very low $Z$. Efforts to advance our understanding are being made, with recent numerical stellar evolution models of low-metallicity stars revealing a surprising prediction. They indicate that the most massive stars end their lives as unstable stars called Luminous Blue Variables (LBVs; Groh et al. 2019a), as they fail to shed mass and become H-poor WR stars. The LBV phase is thought to occur late in the evolution of massive stars (Humphreys & Davidson 1994; Maeder & Meynet 2000; Meynet & Maeder 2000; Groh et al. 2014). LBVs show re-occurring eruptive events generating considerable mass loss (Smith & Owocki 2006), in addition to irregular photometric and spectroscopic variations of the S-Doradus type (van Genederen 2001). LBVs play a key role in the mass budget of very massive stars (Smith 2014) and regulate their final compact remnant masses, which in some cases can be a massive black hole (Groh et al. 2019b). LBVs are also thought to be immediate progenitors of some SN explosions (Kotak & Vink 2006; Gal-Yam & Leonard 2009; Smith et al. 2011; Boian & Groh 2018).

In an effort to improve our understanding of very massive stars at low $Z$, we have monitored the blue compact dwarf (BCD) galaxy PHL 293B. This galaxy lies at a distance of 23.1 Mpc (Mould et al. 2000), and has a metallicity of $Z \approx 0.1 Z_\odot$ (Izotov et al. 2007). Spectra obtained between 2001–2009 shows broad, strong emission components in the hydrogen Balmer lines, which are interpreted to originate in the LBV outflow (Izotov & Thuan 2009; Izotov et al. 2011). These spectra were remarkably similar, differing mainly in the strength of the narrow components, likely due to the different aperture sizes used. Photometric analysis of PHL 293B revealed no optical photometric variability at the level of 0.1 mag between 1988 and 2013 (Terlevich et al. 2014). Based on this, Terlevich et al. (2014) suggested that the blueshifted absorptions of H I and Fe II were not caused by an LBV, but instead by an expanding supershell generated by the cluster wind of PHL 293B. The substantial spectral variation reported in this Letter disfavors this hypothesis.

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Burke et al. (2020) also report the weakening of the hydrogen broad components based on 2019 Gemini data. In addition, they report photometric variability of 0.12 mag in the broad components based on 2019 Gemini data. In addition, which are also shifted for clarity.

The data were reduced with the ESO pipeline version xshoo3.3.5. The archival INT/IDS, WHT/ISIS, and 2009 X-shooter spectra were obtained without flux standards and flat fields. Therefore, we re-scaled the flux as to best match the equivalent width of the narrow component of the H-α line of a spectrum with a similar aperture size (UVES).

To constrain the parameters of the LBV in PHL 293B during the outburst, we fitted radiative transfer models to the high-resolution 2002 UVES spectrum. We use the line-blanketed atmospheric/wind radiative transfer code CMFGEN (Hillier & Miller 1998) to compute continuum and line formation in non-local thermodynamic equilibrium (NLTE) and spherical symmetry. We base our models on those of the LBV progenitor of the SN candidate SN 2015bh (Boian & Groh 2018), and refer the reader to that paper for details. In summary, we vary the luminosity $L_*$, mass-loss rate $M_*$, and set the stellar radius to $R_*$ = $6.93 \times 10^{10}$ cm (this has little effect on the results given the high optical depth of the outflow) and the Fe mass fraction to 1.7 $\times 10^{-4}$, i.e., ~0.1 of the solar value. We degraded the CMFGEN high-resolution synthetic spectra by convolving with a Gaussian function with FWHM of 33.3 km s$^{-1}$ to match the UVES spectral resolution. Because of the high wind density, we compute both a temperature $T_e$ at the stellar surface (at Rosseland optical depth $\tau_{Ross}=10$), as well $T_{eff}$ at the photosphere (where $\tau_{Ross}=2/3$).

Due to its distance of 23.1 Mpc, the LBV is spatially unresolved from the underlying stellar population of PHL 293B. Therefore, we created a grid of models with varying degrees of photometric correction from the LBV and (flat) background galaxy to the total flux. We then compare the equivalent width of the H-α, H-β, and Fe II 5169 Å emission lines to the 2002 spectrum, giving equal weights to each line when computing the fit error. We chose these lines as they are the only ones where the broad component is visible with enough signal-to-noise ratio. The white regions in Fig. 2 show the wavelength range considered in this calculation for the H-α and H-β lines. We neglect the narrow component of the Balmer lines as this is strongly affected by the background galaxy. Figure 2 shows the CMFGEN synthetic models around the Balmer lines as this is strongly affected by the background galaxy. Figure 2 shows the CMFGEN synthetic models with fit error $\leq 25\%$.

2. Observations and modelling of the LBV

We present new spectra of PHL 293B obtained in 2019 using the ESO/VLT instruments X-shooter and ESO/ULS spectrograph for Rocky Exoplanet- and Stable Spectroscopic Observation (ESPRESSO). We also compute radiative transfer models of stellar winds to interpret the spectroscopic observations. As we elaborate below, we find that the LBV was in an eruptive state at least between 2001–2009, which then ended, and may have been followed by a collapse into a massive black hole (BH) without the production of a SN.

Fig. 1. Spectroscopic evolution of PHL 293B between 2001–2019. The 2009 X-shooter spectrum (dashed grey) is overplotted to all spectra, which are also shifted for clarity.

We then compare the equivalent width of the narrow component to our best-fitting CMFGEN models. The blue region corresponds to models with a fit error $\geq 25\%$. The white regions show the wavelength ranges considered in the fit.

Fig. 2. Comparison of the 2002 UVES spectrum of PHL 293B (black) to our best-fitting CMFGEN models. The blue region corresponds to models with a fit error $\leq 25\%$. The white regions show the wavelength ranges considered in the fit.
The LBV had an eruption that ended sometime after 2009. This could have been followed by 1) a surviving star or 2) a collapse of the LBV to a BH without the production of a bright SN, but possibly with a weak transient.

One possibility is that we are seeing the end of an LBV eruption of a surviving star, with a mild drop in luminosity, a shift to higher effective temperatures, and some dust obscuration. The lack of variation of broad emission in the H-α and H-β in all spectra from 2001 to 2009 would require such an eruption to have persisted for a minimum of 8.5 years, and possibly longer. Considering the high mass-loss rate and relatively low temperatures for the outer wind from our model predictions, the dust obscuration scenario does also not necessarily require a sudden end of the eruption between the 2009 and 2011 observations. A combination of a slightly reduced luminosity and a thick dusty shell could result in the star being obscured. While the lack of variability between the 2009 and 2019 near-infrared continuum from our X-shooter spectra eliminates the possibility of formation of hot dust (≥ 1500 K), mid-infrared observations are necessary to rule out possible dust formation.

3. The fate of the massive star in PHL 293B
Based on our observations and models, we suggest that PHL 293B hosted an LBV with an eruption that ended sometime after 2009. This could have been followed by 1) a surviving star or 2) a collapse of the LBV to a BH without the production of a bright SN, but possibly with a weak transient.

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out a slowly expanding cooler dust shell. Photometric analysis of PHL 293B revealed no optical photometric variability at the level of 0.1 mag between 1988 and 2013 (Terlevich et al. 2014). Burke et al. (2020) detect optical variability of 0.12 mag. Their light curve shows a slight fading from 1999 to 2004, and again from 2013 to 2017. Unfortunately, no photometry is available in the period 2009 to 2011 when the spectral change occurred. The small change in brightness in the optical of only 0.1 mag between eruption and post-eruption would be surprising for an LBV eruption.

Smith & Owocki (2006) show that optically thick, continuum-driven outbursts could play a greater role in the mass loss of massive stars than steady, line-driven winds. Importantly, they suggest that such outbursts should be largely metallicity insensitive in comparison to line-driven winds. Our potential finding of such an outburst at a low metallicity could help confirm their hypothesis, implying that mass loss at low metallicities could be dominated by continuum-driven winds/eruptions. This conclusion would carry important implications for the final masses and SNe produced by the first stars of the Universe.

There is considerable debate on the end stages and fate of the most massive stars. Instead of surviving the eruption, the LBV in PHL.293 B could have instead collapsed to a black hole (BH), with perhaps the LBV eruption signalling the end of the stellar life. Assuming that a BH has been formed, we utilise low initial metallicity (Z=0.002 and Z=0.0004) stellar evolutionary models (Georgy et al. 2013; Groh et al. 2019a) to estimate the BH mass. We find that an initial mass between 85–120 $M_\odot$ best suits our determined parameters for the LBV. Based on these initial masses, a BH could have a mass between 40 and 90 $M_\odot$ through fallback, assuming no mass loss at that stage. The final BH mass depends on the rotation of the progenitor. Fast-rotating models within this initial mass range may produce a pair-instability SN rather than a core collapse to a BH. The non-detection of such a bright event, however, suggests that this was likely not the case for the LBV in PHL 293B. Evolutionary models predict that the lifetime of a star with initial mass of 120 $M_\odot$ is between 2.88 – 3.90 Myr, depending on the metallicity and rotation (Georgy et al. 2013; Groh et al. 2019a). The initial mass of the star could, however, have been significantly lower if the star was a mass gainer in a binary system. This would result in a drastically longer lifetime and lower BH mass. Determining the age of the stellar population surrounding the LBV could possibly discriminate between single and binary star evolutionary scenarios, see Smith & Tombleson (2015).

A spectroscopic observation of a star immediately preceding the collapse to a BH without a bright SN would be unprecedented. LBVs span a wide range of luminosities (Smith et al. 2019) and it would not be impossible for a low-luminosity, dust-reddened LBV to show eruptive behavior and perhaps collapse to a BH. This could have important consequences for N6946-BH1, for which a RSG progenitor was originally suggested (Adams et al. 2017).

An alternative explanation for the disappearance of the LBV in PHL.293B is an undetected SN explosion. Burke et al. (2020) favor this hypothesis, suggesting that an SN IIn event occurred between 1995 and 1998, during which no photometry is available. In this case, the broad components seen in the Balmer lines between 2001–2009 would come from interaction between the SN ejecta and a dense circumstellar medium. However, a decade-long SN interaction with a relatively constant spectrum would require large CSM mass, which implies a high luminosity with a broad lightcurve. This would be similar to events such as, e.g., 2005ip (Stritzinger et al. 2012), which decline slowly and are still much brighter at > 5 years. We consider unlikely that such a prolonged event would go unnoticed at early times, but we cannot rule out at this time a peculiar SN IIn.

Both pre- and post-explosion spectra have been reported for only one SN (SN 1987a: Walborn et al. 1989) and two SN candidates (SN 2009ip, e.g. Smith et al. 2014) and SN 2015bh, e.g. Boian & Groh (2018). An obvious difference between these and the PHL.293B case is the detection of a SN explosion rather than simply the fading of the star. Analysis of the pre-explosion spectra has revealed that the progenitor of SN 2015bh was an LBV star (Boian & Groh 2018). Interestingly though, the spectra and consequently the predicted parameters of its progenitor do not greatly differ from that of the LBV in PHL.293B.

Our best-fit models for the 2002–2009 spectra place the LBV in PHL.293B at the higher $L_\odot$ end of the HRD (Fig. 3), in proximity to very massive LBVs such as Eta Car, and in a $T_\ast$ range characteristic of LBVs. It should be noted that the wind properties are however stronger than those of Eta Car, with $\dot{M}_*$ being 5-20 times larger for PHL 293B. It is, however, remarkably similar to the quiescent LBV progenitor of SN 2015bh, in $L_\ast$, $M_\ast$, and $T_\ast$, the latter being only slightly hotter (Fig. 3). SN 2015bh (Boian & Groh 2018) is a SN candidate with a rare pre-explosion spectrum. SN 2009ip is part of the same category of events, and its progenitor also resides in a similar region of the HRD, however, slightly dimmer than PHL.293B, and with relatively poor $T_\ast$ constraints. Other LBV progenitors of luminous transients, such as SN 2010jl and Gaia16cfr, which have been identified in pre-explosion photometry, show much lower luminosities but consistent temperatures. An obvious difference between these transients and the PHL.293B case is the detection of a SN explosion rather than simply the fading of the star.

The case of PHL.293B is unique in the sense that several spectra were obtained shortly before its disappearance, which show spectral features that are consistent with stellar properties of an LBV in eruption. The low metallicity (~ 0.1 solar) of PHL.293B further amplifies its importance. Deep high-spatial resolution imaging is urgently needed to further discriminate be-
between the different scenarios that have been proposed. It will be highly beneficial to search for similar events in large scale surveys such as the Zwicky Transient Factory (ZTF) and the Large Synoptic Survey Telescope (LSST). Given that the majority of such events in deep surveys will be much fainter than PHL 293B and located much farther, a detailed analysis of this object in the local Universe provides an important benchmark for understanding the late-time evolution of massive stars in low metallicity environments and their remnants.

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