Discovery of a massive variable star with $Z=Z_\odot/36$ in the galaxy DDO 68

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ABSTRACT

The Local Volume dwarf galaxy DDO 68, from the spectroscopy of its two brightest HII regions (Knots 1 and 2) was designated as the second most metal-poor star-forming galaxy [12+log(O/H)=7.14]. In the repeated spectral observations in 2008 January with the 6-m telescope (BTA) of the HII region Knot 3 [having 12+log(O/H)=7.10±0.06], we find strong evidence of a transient event related to a massive star evolution. From the follow-up observation with the higher spectral resolution in 2008 February, we confirm this phenomenon, and give parameters of its emission-line spectrum comprising of Balmer HI and Hei lines. The luminosities of the strongest transient lines (Hα, Hβ) are of a few $10^{36}$ erg s$^{-1}$. We also detected an additional continuum component in the new spectrum of Knot 3, which displays the spectral energy distribution raising to ultraviolet. The estimate of the flux of this continuum leads us to its absolute $V$-band magnitude of $\sim$7.1. Based on the spectral properties of this transient component, we suggest that it is related to an evolved massive star of luminous blue variable type with $Z=Z_\odot/36$. We briefly discuss observational constraints on parameters of this unique (in the aspect of the record low metallicity of the progenitor massive star) event and propose several lines of its study.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: abundances – galaxies: individual: DDO 68 (UGC 5340) – stars: emission-line, Be – stars: variables: other

1 INTRODUCTION

The most metal-poor galaxies [or extremely metal-deficient, XMD, with 12+log(O/H)<7.65, e.g., review by Kunth & Ostlin (2000)] are considered as the best laboratories to study in great detail the processes related to galaxy evolution and star formation (SF) in young galaxies at high redshifts. Among several XMD galaxies with O/H near the bottom of dwarf galaxy distribution, namely those with parameter 12+log(O/H)<7.3, DDO 68 (UGC 5340) with its value of 7.14 is the nearest one (Pustilnik, Kniazev, & Pramskij 2005; Izotov & Thuan 2007, hereafter PKP and IT07). Its distance was accepted as 6.5 Mpc in PKP. However, for its $V_{\text{helio}}=502$ km s$^{-1}$, due to the large negative peculiar velocity correction in this space region (Tully et al. 2008), this can be as large as $\sim$10 Mpc. Nevertheless, this galaxy is one of the most perspective to study individual massive stars with the future Extremely Large Telescopes (ELTs) (e.g., Kniazev & Pustilnik 2006). In the recent papers DDO 68 was shown to be a likely result of a merger of two gas-rich dwarfs (Ekta, Chengalur, & Pustilnik 2008) and to show up colours on the SDSS images, which for the standard Salpeter IMF are consistent with no tracers of stars older than $\sim$1 Gyr (Pustilnik, Tepliakova, & Kniazev 2008). The current O/H value of DDO 68 is based on the direct measurements by the classic T$e$-method of two brightest HII regions in the Northern ring, called Knots 1 and 2 (PKP, IT07). In this Letter we present new BTA spectra of Knots 1 and 3. The latter displays transient emission lines and blue continuum, which we attribute to a massive variable star of luminous blue variable (LBV) type.

2 OBSERVATIONS AND DATA REDUCTION

The long-slit spectral observations of Knots 1 and 3 ($15''$ in between) were conducted with the multimode instrument SCORPIO (Afanasiev & Moiseev 2003) installed in the prime focus of the SAO 6 m telescope (BTA) on the nights of 2008 January 11 and February 4. The grism
VPHG550G was used with the 2K×2K CCD detector EEV 42-40 on 2008 January 11 and the grism VPHG1200G on 2008 February 4. These set-ups gave the range 3500–7500 Å with ~2.1 Å pixel^{-1} and the full width at half-maximum (FWHM) of ~12 Å and the range 3900–5700 Å with ~0.9 Å pixel^{-1} and FWHM of ~6 Å along the dispersion, respectively. The scale along the slit (after binning) was 0''36 pixel^{-1}. Six and five 15-min. exposures were obtained on nights 2008 January 11 and 2008 February 4, respectively, under the seeing of 1.2 and 1.3 arcsec. The objects spectra were complemented before or after by the reference spectra of He–Ne–Ar lamp for the wavelength calibration. Bias and flat-field images were also acquired to perform the standard reduction of 2D spectra. Spectral standard star Feige 34 [Bohlin 1996] was observed during the night for the flux calibration.

All data reduction for Knots 1 and 3 and emission line measurements for Knot 1 were performed similar to that described in PKP. Namely the standard pipeline with the use of IRAF[1] and MIDAS[2] was applied for the reduction of long-slit spectra, which included the next steps: cosmic ray hits removal, bias subtraction, flat-field correction, wavelength calibration, night-sky background subtraction. Then, using the data on spectrophotometry standard stars, all spectra were transformed to absolute fluxes. 1D spectra were extracted by summing up, without weighting, of 12 and 6 rows along the slit, in Knots 1 and 3, respectively. The emission lines with their errors were measured in the way described in details in [Kniazev et al. 2004].

### 3 RESULTS

In Fig. 1 the relevant new and old spectra, obtained with the same set-up, are shown. The bottom panel displays the spectrum of Knot 3 obtained on 2008 January 11 with FWHM~12 Å, while the middle panel shows the similar spectrum of Knot 3 obtained on 2005 January 13. Significant changes in relative line intensities have occurred during the past ~3 years. In the top panel, we show two spectra of Knot 1, obtained on 2008 January 11 (upper) and 2005 January 8. The latter spectrum is shifted down by 0.05 flux unit to allow better visual comparison of both spectra. They have very similar parameters of both relative line intensities and underlying continuum and show no evidences for systematic difference.

In Table I we present the line intensities of all relevant emission lines measured in the spectrum of Knot 1 of 2008 January 11, normalized by the intensity of Hβ and corrected for the foreground extinction C(H/β) and equivalent widths of underlying Balmer absorption lines (EW(abs)).

| Parameter | Value |
|-----------|-------|
| C(H/β) dex | 0.00±0.03 |
| EW(abs) Å | 2.50±0.14 |
| F(H/β) Å | 39.1±0.7 |
| EW(H/β) Å | 162±3.9 |
| Rad. vel. km s^{-1} | 476±33 |
| Te(O III)(10^{3} K) | 18.81±1.12 |
| Te(O I)(10^{4} K) | 15.31±0.86 |
| Te(S II)(10^{3} K) | 17.32±0.93 |
| Ne(S II)(cm^{-3}) | 378±294 |
| O^{+}/H^{+}(×10^{-5}) | 0.301±0.044 |
| O^{++}/H^{+}(×10^{-5}) | 1.192±0.167 |
| O^{++}/H^{+}(×10^{-5}) | 0.039±0.006 |
| O/H(×10^{-5}) | 1.532±0.173 |
| 12+log(O/H) | 7.19±0.05 |
| Ne^{++}/H^{+}(×10^{-5}) | 0.201±0.027 |
| ICF(Fe) | 1.285 |
| log(Ne/O) | -0.77±0.08 |
| S^{+}/H^{+}(×10^{-7}) | 0.527±0.058 |
| S^{++}/H^{+}(×10^{-7}) | 3.132±0.742 |
| ICF(S) | 1.601 |
| log(S/O) | -1.56±0.13 |

* in units of 10^{-16} ergs s^{-1} cm^{-2}.

1 IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation (NSF).

2 MIDAS is an acronym for the European Southern Observatory package – Munich Image Data Analysis System.

Abundances of oxygen, neon and sulphur (with respective ICFs - ionization correction factors), along with the total abundances derived for the above measured line intensities with the classic Te method as described in [Kniazev et al. 2004, 2005]. The latter are consistent with the results from both PKP and IT07. The relative line intensities of Knot 1, measured on the spectrum 2008 February 4 (not shown here due to the lack of space) with a higher resolution but with a

![Image](https://via.placeholder.com/150)
more narrow range, are consistent with those from Table [1]. However, they can not be used for the independent derivation of O/H since this spectrum does not include the line [O II]λ3727.

One of the aims of new observations of Knot 3 was an attempt to improve its element abundances determination. However, due to appearance in the spectrum of 20008 January 11 of additional ‘broad’ components and the difficulty due to low spectral resolution (FWHM~12 Å) to disentangle nebular emission lines from variable ‘broad’ components, we should postpone this task till getting the spectrum with a higher resolution. The same relates to the spectrum of 2008 February 4, with FWHM~6 Å. This appears also insufficient to get reliable line intensities of nebular emission lines. Before to return to analysis of lines of the variable component, we briefly describe one more estimate of O/H for Knot 3, derived from its old spectrum, which will be used in Discussion.

From the line intensities of Knot 3 in table 3 and fig. 2 of PKP (also shown in the middle panel of Fig. [1], with the use of direct T_e method for the observation with the better S-to-N ratio in I([OIII]λ4363)) (2005 January 13), the derived value of 12+log(O/H), assumed to be related to the metallicity of the variable star, discussed below, was 7.11±0.11. This motivates an attempt to improve the accuracy of O/H in Knot 3.

We apply below the so-called ‘semi-empirical’ method, suggested by IT07. It is intended for abundance determination in the case when the principal faint line [O II]λ4363 is too noisy or undetected. This uses the rather tight correlation between T(OIII) and the total intensity of the strong oxygen lines relative to I(Hβ) (Stasińska & Izotov 2003). After T(OIII) is estimated from the total intensity of [O II]λ3727, [O III]λ4959,5007 lines via the relation presented in IT07, all other calculations are made as in the classical T_e method, using measured line intensities. The robustness of the semi-empirical method in the very low-metallicity regime was tested in IT07 and by us, using all available data on the DDO 68 HII regions. These O/H estimates relative to those obtained by the direct T_e method, appeared very stable and showed a scatter consistent with the errors of the direct method determination and those for the semi-empirical method itself. Applying this method to the same data on line intensities, and ignoring the faint line [O II]λ4363, we obtain for Knot 3 the value of 12+log(O/H)=7.10±0.06, which is nicely consistent with the value derived from the direct T_e method.

We therefore accept for further discussion this value of O/H, which corresponds to 1/36 of (O/H)⊙ (Asplund et al. 2004). As the nearest of young star-forming regions (age of 5.0 Myr, PKP) with such a low metallicity, Knot 3 is certainly one of the most attractive targets for the future Extremely Large Telescopes (ELTs) to study individual massive stars with metallicities typical of very young galaxies in the early Universe.

Fortunately, by good luck, some tracers of the individual massive stars in nearby metal-poor galaxies can be found occasionally in the spectra of star-forming regions (Izotov, Thuan, & Guseva 2007). This allows to conduct their studies with modern large telescopes. DDO 68 appears to be one of such galaxies, but outstanding for its the record lowest metallicity. In Fig. [1] we display the old and new spectra of Knot 3, with resolution of FWHM~12 Å, in which pronounced differences have occurred during the past 3 yr. To better describe the variable component in the spectrum of Knot 3, including its continuum, we show its difference spectrum in the top panel of Fig. [2] The normalization of the old spectrum (by a factor of 0.85) was performed before the subtraction, in order to fully remove the (assumed) HII region nebular lines [O III]λ4959,5007.

In the bottom panel of Fig. [2] we show the spectrum of Knot 3 with resolution of FWHM~6 Å, in which broad components of Balmer and He I lines are more evident. The subtraction of nebular lines (shown in red) in this spectrum was performed by scaling the same lines in the spectrum of Knot 1, exposed on the same long slit, just ~15 arcsec a side. We present the parameters of ‘narrow’ and ‘broad’ components of the residual lines, shown in black, in Table 2 where the names of the columns are self-explaining. To determine parameters of ‘narrow’ and ‘broad’ components (index n and b for Balmer and He I lines) we performed the procedure of two-component Gaussian fitting in MIDAS. To understand the relative velocities of the transient emission and that of Knot 3 HII region, the heliocentric velocity of the latter, defined on the spectrum with FWHM=6 Å, is V(Knot 3)=564±27 km s⁻¹.

### Table 2. Parameters of residual lines in Knot 3

| λ_{obs} (Å) | λ_{Ion} (Å) | V_{hel} (km s⁻¹) | Flux | FWHM (km s⁻¹) |
|-------------|-------------|------------------|------|--------------|
| 5109.70     | 5101.74 HeII| 582±14           | 1.15±0.12 | 711±34     |
| 4126.82     | 4101.74 HeII| 1833±64          | 0.20±0.12 | 728±159    |
| 4349.27     | 4340.47 HeII| 608±14           | 2.58±0.19 | 803±39     |
| 4361.94     | 4340.47 HeII| 1483±380         | 0.84±0.53 | 3182±663   |
| 4479.51     | 4471.47 HeII| 539±39           | 0.47±0.16 | 732±114    |
| 4492.80     | 4471.47 HeII| 1430±345         | 0.41±0.23 | 1440±558   |
| 4723.16     | 4713.14 HeII| 638±50           | 0.35±0.16 | 1012±153   |
| 4871.65     | 4861.33 HeII| 636±14           | 5.46±0.45 | 805±42     |
| 4887.94     | 4861.33 HeII| 1641±608         | 0.91±0.38 | 1616±1007  |
| 4932.97     | 4921.93 HeII| 673±22           | 0.21±0.10 | 605±52     |
| 5023.99     | 5015.66 HeII| 498±66           | 0.65±0.16 | 777±145    |
| 5054.28     | 5015.66 HeII| 2308±410         | 0.29±0.29 | 1517±1044  |

* in units of 10⁻¹⁶ ergs s⁻¹cm⁻².

### 4 DISCUSSION

The natural interpretation of this transient emission-line component is the appearance of a luminous variable star. Some of the observed and derived parameters of this unique variable star and the related star-forming region are as follows. The integrated V-band magnitude of Knot 3, as measured on the respective image in PKP, is ~21.2. The latter is consistent with V calculated through convolving the 2008 January spectrum of this region with the V-filter bandpass, namely V=20.94. A similar convolution of the residual spectrum in the top panel of Fig. [2] allows us to estimate the V-magnitude of the transient to be 22.95. Its continuum, clearly rising to the ultraviolet (UV), indicates a hot star of OB spectral type. For the accepted distance module of DDO 68 µ=30.0 (D=10 Mpc) (see Pustilnik et al. 2008),
Figure 1. Top panel: The spectra of DDO 68 Knot 1 on 2005 January 8 and 2008 January 11, superimposed, with the former one shifted down in flux by 0.05 unit. The spectra look very similar, including both lines and continuum. Middle panel: Spectrum of Knot 3 in DDO 68 on 2005 January 13. Bottom panel: Spectrum of Knot 3 in DDO 68 on 2008 January 11. Pay attention on the significant enhancement in the latter spectrum of He\textsc{i} lines (λ4471, λ4713, λ5876, λ6678 and λ7065), the appearance of asymmetric broad wings in the strongest He\textsc{i} lines, and the change of relative intensities of [O\textsc{iii}]λ4959,5007 and Balmer lines.

Figure 2. Top panel: The difference spectrum of Knot 3 with resolution of ~12 Å, obtained by subtraction of the two spectra taken 3 years apart. The residual features represent the massive star wind emission lines, while the underlying continuum presumably indicates the spectral energy distribution of a variable hot star. The marked lines are H\textsc{ii}-He\textsc{i} 3889, H\textsc{e} 3970, H\textsc{e}i 4026, H\textsc{e} 4102, H\textsc{e} 4340, H\textsc{e} 4388, H\textsc{e}i 4471, H\textsc{e} 4713, H\textsc{beta} 4861, H\textsc{beta} 4922, He\textsc{i} 5016 (affected by subtraction of [O\textsc{iii}]λ5007), He\textsc{i} 5876, H\alpha, He\textsc{i} 6678. Bottom panel: The spectrum of Knot 3 with resolution of ~6 Å. Shown here are both the original spectrum (red) and a difference spectrum (black), obtained by the subtraction of scaled lines in the spectrum of Knot 1, registered on the same slit. Continuum remains original. Broad wings of both Balmer and He\textsc{i} lines are visible as well as an indication of P Cygni profiles in Balmer lines.

the absolute magnitudes, $M_V$, of Knot 3 and the variable star are ~9.1 and ~7.1, respectively.

For the estimated Knot 3 age of ~5 Myr (PKP), one can calculate the mass of its young stellar cluster, using, e.g., models for evolving stellar populations of PEGASE2 package (Fioc & Rocca-Volmerange 1999). Accounting for ~20 per cent light contribution of nebular emission and a small correction for the Galaxy extinction, with the accepted stellar metallicity of $z$=0.0004 and the standard Salpeter Initial Mass Function with $M_{\text{low}}$ and $M_{\text{up}}$ of 0.1 and 120 $M_\odot$, we obtain $M_{\text{cluster}} = 8.5 \times 10^3 M_\odot$.

To further address the type of a massive star related to the observed transient, we briefly describe its emission-line properties. In both spectra of the variable massive star in Fig. 2 only the Hydrogen Balmer series and He\textsc{i} emission lines are detected. This is in agreement with its extremely low metallicity of $Z_\odot/36$. The observed line profiles, with broad asymmetric wings and an indication of P Cygni profile resemble those of B-supergiant LBVs. These represent the short transition phase in the post-main-sequence evolution of massive stars with $M \lesssim 50 M_\odot$. The latter are exemplified by spectra of stars He3-519, AG Car, η Car and others in Kudritzki (1998) and Walborn & Fitzpatrick (2000). Their ‘narrow’ components are close in radial velocity to that of the related HII region. However, their widths (FWHM) of ~700 km s$^{-1}$ are clearly larger than the instrumental ones. The nature of both ‘narrow’ and broad components (FWHM~1000-2000 km s$^{-1}$) is not clear. For the accepted
DDO 68 distance of 10 Mpc, the Hβ line fluxes correspond to luminosities of $\sim 4.6$ and $\sim 0.8 \times 10^{36}$ erg s$^{-1}$ in 'narrow' and broad components, respectively. Both electron scattering in dense envelopes (Bernat & Lambert 1978) and stellar winds could contribute to their appearance. The asymmetry of the broad components can be partly due to absorption of the approaching region of the (non-spherical) wind. This has important implications, since in very low-metallicity stars the line-driven wind can be inefficient, and continuum-driven eruptions might be more significant (Smith & Owocki 2006).

The latter, in turn, will have important implications for evolution of Population III stars and the early metal enrichment of the Universe.

The hunting for the most metal-poor local galaxies as useful testbeds for models of young galaxies was rather successful during the last years, with the lowest HI-region oxygen abundance found so far in SBS 0335–052 W on the level of $12+\log(O/H)=7.12$ (Izotov, Thuan, & Guseva 2005). The star-forming region Knot 3 of a much closer galaxy DDO 68 appears to have very similar metallicity of $12+\log(O/H)=7.10$ (Izotov, Thuan, & Guseva 2007; Yoon, Cantiello, & Langer 2008). In particular, imaging with the HST of Knot 3 would help to localise this luminous star (King et al. 2008) and massive metal-poor objects. Monitoring of its several young star-forming regions could lead to interesting findings in extremely metal-poor environments and the properties of massive metal-poor stars, actively studied in recent years (e.g., Meynet et al. 2005; Yoon, Cantiello, & Langer 2008). In particular, imaging with the HST of Knot 3 would help to localise this luminous star ($V\sim 23$), and provide its spectral energy distribution in broad range from UV to NIR. This information will be helpful for spectral study of this star with the next generation space telescope JWST. Even its medium resolution spectra ($R\sim 5000$) would provide the important constraints on rotation of such stars, while NIR spectra might shed light on the properties of related wind/shells.

Massive low-metallicity stars are the main suppliers of energy, momentum and metals during the early evolution of galaxies in the young Universe (e.g., Barkana & Loeb 2001). Their properties and details of their evolution are important for estimating the effect of SF feedback on galaxy evolution and their effect on re-ionization of the Universe. Thus, the discovery and the study of such metal-poor massive stars with the next generation of ELTs is directly relevant to insights in the early Universe evolution.

Summarising the results and discussion above we draw the following conclusions:

(i) The spectrum of HII-region Knot 3 in the nearby XMD galaxy DDO 68 changed substantially during the period between 2005 January and 2008 January, displaying enhanced intensities and broad components of Balmer and HeI lines, as well as an additional continuum component typical of a hot star.

(ii) The luminosity, blue continuum and emission-line parameters of this variable emission resemble those expected for a LBV with metallicity of $Z=Z_\odot/36$ (as measured on nebular emission in Knot 3). This suggests the discovery of the first individual massive star with the record low metallicity and implies good prospects for study such stars with the future ELTs.

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