BLUE LUMINOUS STARS IN NEARBY GALAXIES—UIT 005: A POSSIBLE LINK TO THE LUMINOUS BLUE VARIABLE STAGE

M. A. Urbaneja$^1$, A. Herrero$^{2,3}$, D. J. Lennon$^4$, L. J. Corrau$^5$, and G. Meynet$^6$

$^1$ Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
$^2$ Instituto de Astrofísica de Canarias, Vía Láctea S/N, E-38200 La Laguna, Canary Islands, Spain
$^3$ Dpto. de Astrofísica, Universidad de La Laguna, Avda. Astrofísico Francisco Sánchez, E-38205 La Laguna, Canary Islands, Spain
$^4$ ESA, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
$^5$ Instituto de Astronomía y Meteorología, Universidad de Guadalajara, Avda. Vallarta 2602, Guadalajara, Jalisco, C.P. 44130, Mexico
$^6$ Geneva Observatory, Ch. des Maillettes 51, 1290 Sauverny, Switzerland

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ABSTRACT

A detailed study of the blue supergiant UIT 005 (B2-2.5Ia*) in M 33 is presented. The results of our quantitative spectral analysis indicate that the star is a very luminous (log $L/L_\odot \sim 5.9$ dex) and massive ($M \sim 50 M_\odot$) object, showing a very high nitrogen-to-oxygen ratio in its surface (N/O~8, by mass). Based on the derived Mg and Si abundances, we argue that this high N/O ratio cannot be the result of an initial low O content due to its location on the disk of M 33, a galaxy known to present a steep metallicity gradient. In combination with the He abundance, the most plausible interpretation is that UIT 005 is in an advanced stage of evolution, showing in its surface N enrichment and O depletion resulting from mixing with CNO processed material from the stellar interior. A comparison with the predictions of current stellar evolutionary models indicates that there are significant discrepancies, in particular with regard to the degree of chemical processing, with the models predicting a much lower degree of O depletion than observed. At the same time, the mass-loss rate derived in our analysis is an order of magnitude lower than the values considered in the evolutionary calculations. Based on a study of the surrounding stellar population and the nearby cluster, NGC 588, using Hubble Space Telescope/WFPC2 photometry, we suggest that UIT 005 could be in fact a runaway star from this cluster. Regardless of its origin, the derived parameters place the star in a region of the Hertzsprung–Russell diagram where luminous blue variables (LBVs) are usually found, but we find no evidence supporting photometric or spectroscopic variability, except for small Hα changes, otherwise observed in Galactic B-type supergiants. Whether UIT 005 is an LBV in a dormant state or a regular blue supergiant could not be discerned in this study. Subsequent monitoring would help us to improve our knowledge of the more massive stars, bridging the gap between regular and more exotic blue supergiants.

Key words: galaxies: individual (M33) – stars: abundances – stars: atmospheres – stars: early-type – stars: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

There is no doubt that massive stars, those born with masses above $\sim 8 M_\odot$, played, and still play, a fundamental role in shaping the universe as we observe it. Unmistakable signatures of their presence are imprinted in the spectra of star-forming galaxies, both nearby and at high redshift (Steidel et al. 1996). It is in fact because of their very existence that the physical properties of these distant galaxies can be investigated, through directly related stellar indicators such as stellar wind features (Rix et al. 2004), or indirectly related stellar signatures, such as the ionizing radiation field reprocessed by the gas and radiated in a few forbidden emission lines (Kobulnicky & Koo 2000; Pettini et al. 2001). Throughout their entire life, from the main sequence to their end in a supernova (SN) event, massive stars drive, to a significant extent, the evolution of galaxies via radiative, kinetic, and chemical feedback. Understanding their physical properties and their evolution in different environments is therefore a relevant issue for many different fields in modern astrophysics.

A proper understanding of these objects needs to be assessed by testing the level of agreement between the different theories involved, namely the atmosphere and interior structures. Predictions under different conditions have to be compared at any given evolutionary stage. This has not been a trivial task for the last two decades (see Maeder & Meynet 2000 or the review by Herrero 2008), and although in the last few years an increasingly better agreement has been reached, there are still some pending issues, such as the efficiency of rotational mixing or the presence of other phenomena affecting the stellar evolution (Trundle & Lennon 2005; Hunter et al. 2008; Maeder et al. 2009).

Particularly important in this context is the role that stars in nearby galaxies can play, where very different conditions can be found. Only a relatively small number of Galactic massive stars are available for these comparative studies, since the massive stellar population is basically concentrated in the Galactic plane, where thick clouds of dust keep them hidden. This small number makes the observation of short-lived evolutionary phases, which could be crucial as they are affected by strong episodes of mass loss and mixing (Massey 2003), even more difficult. The problem is less severe in nearby galaxies, such as M 33, where we can have access to a much larger number of massive stars and objects in these short-lived phases.

We came across a very interesting object in our spectroscopic survey of massive blue supergiants in M 33. It seemed quite probable that UIT 005 (R.A.: 01h32m42s89, decl.: +30°38’47”.2, J2000; Massey et al. 1996) could be in an advanced phase of evolution, one of those very short lived phases, and close to the luminous blue variable (LBV) stage. The aim of this paper is to
test the level of agreement between the results obtained from the model atmospheres and the theory of stellar evolution in such an object. This will provide us with clues about the consistency between these models in an environment and evolutionary stage different from the most studied cases.

The rest of this paper is organized as follows; we describe in Section 2 the observations and data reduction steps. The different aspects of the spectral analysis are presented in Section 3 and the results are discussed in Section 4. Finally, our conclusions are presented in Section 5. Throughout this work, metal abundances are expressed as $A(X) = \log(N(X)/N(H)) + 12$. Regarding the host galaxy, we adopt a distance modulus of $\mu = 24.56 \pm 0.1$ mag (Freedman et al. 2001), and $R_\phi = 28^\circ77$, a position angle of the line of nodes of $\phi = 22^\circ$ and an inclination of $i = 54^\circ$ (Vila-Costas & Edmunds 1992), with the galactic center located at R.A. $01^h33^m50^s9$ and decl. $+30^\circ39^\prime36^\prime\prime$ (J2000).

2. OBSERVATIONS

2.1. Photometry

Photometric information for UIT 005 is available in several bands from diverse sources. Its designation as UIT 005 originates from the work by Massey et al. (1996), where, along with fluxes in two ultraviolet bands, $U_-$, $B_-$, and $V$-band photometry was provided. Massey et al. (2006) published new $U$, $B$, $V$, $R$, and $I$-band photometric measurements in a recent epoch. In this work, UIT 005 can be identified as the source J013242.9+303847.0. A much fainter source, J013242.86+303847.0, is almost coincident with our star (see below).

The nearby giant H II region NGC 588 and its ionizing cluster were targeted with the WFPC2 on board the Hubble Space Telescope (HST) during Cycle 4 (program 5384), using a suite of five different filters: F170W, F336W, F439W, F469W, and F547M. Given its close proximity (both objects are separated by $\sim 30^\prime$, see Figure 1), UIT 005 was imaged by one of the three detectors of the Wide-Field Camera. The fainter source mentioned before is spatially resolved in the HST images. We have carried out photometry of these data using HSTphot (Dolphin 2000a). Magnitudes in the WFPC2 filter system can be transformed to the Johnson-Cousins system by applying the recipes presented by Holtzman et al. (1995) and Dolphin (2000b).

The contamination of Massey et al. (1996) photometry due to the faint source can be estimated, either by using Massey et al. (2006) or our WFPC2 photometry. Both sets indicate a contribution to the combined flux of $\sim2\%$ for the $U$, $B$, and $V$ bands. This is not the case for the $R$ band where, according to the values published by Massey et al. (2006), the faint source is only $\sim0.2$ mag fainter than UIT 005, which translates into a flux ratio of 1:0.78. This is unexpected, given the almost constant flux ratio in the bluer bands, and the fact that UIT 005 was detected in the $I$ band, while the faint source was not. Moreover, there is no indication of a second source in the red spectra (see later); if the $R$-band magnitudes are right, then we would overestimate the continuum by almost a factor of two, which would severely affect the measured equivalent widths of the metal lines around Hα. We conclude that the published $R$-band magnitude of the faint source is affected by some unknown problem and that it is not representative of its real value.

If we disregard for a moment the possibility of photometric variability for UIT 005 and combine the WFPC2/HST photometry with the previous ground-based values, we find for the mean values $V = 16.79 \pm 0.05$, $B-V = 0.014 \pm 0.014$, and $U-B = -0.942 \pm 0.099$ mag. The uncertainties associated with these values are an order of magnitude larger than the individual 1σ uncertainties quoted in the different photometric measurements. The small scatter in the $V$-band magnitude and almost constant $B-V$ color suggest a low level of photometric
variability within the expectations for blue supergiant stars. At the same time, the scatter in \( U - B \) is slightly higher, indicating perhaps photometric variations in the \( U \) band.

The combination of the different photometric observations could be affected in principle by the time elapsed between the measurements. Most unfortunately, the possibility of time-dependent variations could be affected in principle by the time elapsed between different epochs spanning 19 months from 2004 January to 2006 January, in the 3.6 and 4.5 \( \mu \)m channels can be found in this section (scale, 0.19 arcsec pixel\(^{-1}\)) centered at 4400 Å. The 1.2 arcsec slit was imaged with an EEV12 detector at approximately 1200 Å, centered at 6558 Å.

A third data set was collected from the Keck Observatory Archive. The star was observed in 2001 October 10 with the High Resolution Echelle Spectrometer (HIREs; Vogt et al. 1994) at Keck 1. This set contains four exposures of 3600 s each, covering the range \( \sim 4265-6630 \) Å at \( R \sim 65,000 \), with gaps in the coverage between some of the 30 orders. Unfortunately, the instrumental setup used during these observations was not optimal for B-type stars, and a number of key diagnostic lines, in particular the Si\( ii \) and Si\( iv \) lines that are required to determine the effective temperature, were not included. While an independent analysis of this spectrum is then not possible, we can still compare it with the ISIS spectra, to search for spectral variations.

**Table 1**

| Bandpass/Color | Magnitude \((\text{mag})\) | Date | Comment |
|----------------|--------------------------|------|---------|
| \( V \)         | 16.78                    | 1993 Nov 22 | Massey et al. (1996), ground |
| \( B - V \)     | 0.03                     | 1993 Nov 22 | Massey et al. (1996), ground |
| \( U - B \)     | −0.91                    | 1993 Nov 22 | Massey et al. (1996), ground |
| F170W           | 15.566 ± 0.013           | 1994 Oct 28 | This work, WFPC2/HST, no transformation |
| F336W           | 15.415 ± 0.004           | 1994 Oct 28 | This work, WFPC2/HST, \( U = 15.970 ± 0.004 \) |
| F439W           | 16.813 ± 0.004           | 1994 Oct 28 | This work, WFPC2/HST, \( B = 16.833 ± 0.004 \) |
| F469N           | 16.845 ± 0.014           | 1994 Oct 28 | This work, WFPC2/HST, no transformation |
| F547M           | 16.836 ± 0.003           | 1994 Oct 28 | This work, WFPC2/HST, \( V = 16.831 ± 0.003 \) |
| \( V \)         | 16.727 ± 0.003           | 2001 Sep 18 | Massey et al. (2006), ground |
| \( U - B \)     | −1.053 ± 0.003           | 2001 Sep 18 | Massey et al. (2006), ground |
| \( B - V \)     | 0.010 ± 0.003            | 2001 Sep 18 | Massey et al. (2006), ground |
| \( V - R \)     | 0.019 ± 0.003            | 2001 Sep 18 | Massey et al. (2006), ground |
| \( R - I \)     | 0.058 ± 0.013            | 2001 Sep 18 | Massey et al. (2006), ground |
| \( J \)         | 16.79 ± 0.135            | 1997 Dec 5 | Cioni et al. (2009), WFCAM/UKIRT |
| \( H \)         | 16.74 ± 0.011            | 2005 Sep 29–2005 Dec 16 | Cioni et al. (2009), WFCAM/UKIRT |
| \( K_s \)       | 16.77 ± 0.03             | 2005 Sep 29–2005 Dec 16 | Cioni et al. (2009), WFCAM/UKIRT |
| IRAC 3.6\( \mu \)m | 16.637 ± 0.078          | 2004 Jan 9–2005 Aug 25 | McQuinn et al. (2007), mean values |
| IRAC 4.5\( \mu \)m | 16.659 ± 0.145         | 2004 Jan 9–2005 Aug 25 | McQuinn et al. (2007), mean values |

The quantitative analysis presented in the following sections is mainly based on two observational runs with the 4.2 m William Herschel Telescope (WHT) equipped with the Intermediate dispersion System (ISIS). The blue wavelength range \( (3970–4850 \) Å) was acquired in 2000 September 7, using a 1200 lines mm\(^{-1}\) grating (dispersion, 0.23 Å pixel\(^{-1}\)) centered at 4400 Å. The 1.2 arcsec slit was used, imaged with an EEV12 detector (scale, 0.19 arcsec pixel\(^{-1}\)), providing a spectral resolution of \( \sim 0.9 \) Å FWHM. Two 3600 s exposures were secured under a seeing of 2 arcsec, for an airmass below 1.3.

The red spectrum was observed in 2003 October 15, using the ISIS red arm equipped with a 600 lines mm\(^{-1}\) grating (dispersion, 0.44 Å pixel\(^{-1}\)). A 1.2 arcsec slit was used, imaged with the MARCONI2 chip (scale 0.20 arcsec pixel\(^{-1}\)), providing the system a spectral resolution of 1.6 Å FWHM. Two exposures, one of 2200 s and another of 2000 s, were acquired, for a characteristic airmass below 1.4. The red spectrum expands approximately 1200 Å, centered at 6558 Å.

A third data set was collected from the Keck Observatory Archive. The star was observed in 2001 October 10 with the High Resolution Echelle Spectrometer (HIREs; Vogt et al. 1994) at Keck 1. This set contains four exposures of 3600 s each, covering the range \( \sim 4265–6630 \) Å at \( R \sim 65,000 \), with gaps in the coverage between some of the 30 orders. Unfortunately, the instrumental setup used during these observations was not optimal for B-type stars, and a number of key diagnostic lines, in particular the Si\( ii \) and Si\( iv \) lines that are required to determine the effective temperature, were not included. While an independent analysis of this spectrum is then not possible, we can still compare it with the ISIS spectra, to search for spectral variations.
The ISIS data were processed using standard IRAF\(^7\) routines for long slit spectroscopy (bias correction, flat-fielding, wavelength calibration, and optimal extraction). The archival HIRES data were fully processed with Tom Barlow’s MAKEE package. The final extracted spectra were continuum normalized using low-order polynomial fits to well-defined continuum points.

New service mode observations with ISIS/WHT were carried out on 2009 November 6, under clear sky conditions, for a seeing of \(\sim 1.2\) arcsec and a characteristic airmass of 1.7. On this occasion, both arms were fed simultaneously. The configuration of the blue arm was quite similar to the one used in the 2000 run, but with the spectrum centered at 4260 Å, hence covering the range 3868–4618 Å. For the red arm, we selected the R1200R grating, centered at 6800 Å, with the spectrum covering the range 6497–7190 Å at a spectral resolution of \(\sim 1\) Å FWHM for a projected slit width of 1.2 arcsec. Two exposures of 1800 s each were collected. This set was processed in the same way as explained above. The signal-to-noise ratio (S/N) achieved (S/N \(\sim 30–40\)) is well below the one in the 2000/2003 cases (S/N \(\sim 80\)); nevertheless, this new spectrum shows that the star has not changed.

We have carefully compared the spectra from the various epochs for radial velocity variations, finding no significant evidence for binarity. However, due to difficulties in assigning zero-point off-sets for the various observational configurations we are unable to detect radial velocity variations smaller than \(\pm 10\) km s\(^{-1}\).

3. SPECTRAL ANALYSIS

3.1. Qualitative Description of the Spectrum

The first noteworthy spectral characteristic is the narrow H Balmer profile, pointing to a high luminosity. This is supported by the 2003 H\(\alpha\) profile, fully in emission. In terms of metal features, the blue spectrum is characterized by the presence of strong N\(\text{ii}\) lines and the weakness of the O\(\text{ii}\) lines. Other prominent features present in the spectrum are the strong Si\(\text{ii}\) triplet lines at 4553-67-74 Å and the Mg\(\text{ii}\) doublet at 4481 Å. Three other strong N\(\text{ii}\) lines appear in the observed ISIS red domain, along with H\(\alpha\) and He\(\text{i}\) 6678 Å line, plus the C\(\text{i}\) doublet at 6578–82 Å.

The two H\(\alpha\) profiles, shown in Figure 2, are slightly different. In 2001, the profile (top panel in Figure 2) appears as a P Cygni line, while the 2003 observation (middle panel) shows a strengthening of the profile in pure emission. To better illustrate this change, we have included in the bottom panel of Figure 2 a comparison of both observations, with the HIRES 2001 profile degraded to the spectral resolution of the ISIS 2003 observation. By contrast, the few metal lines in the red range do not show any change within the noise level. In the same sense, there are no noticeable differences in the blue range between the ISIS 2000 and HIRES 2001 spectra.

By comparing the equivalent width ratios of Mg\(\text{ii}\) 4481 Å to the Si\(\text{ii}\) triplet lines with the sample of Galactic supergiant stars of Lennon et al. (1993) and the LMC sample of Fitzpatrick (1991), we tentatively locate the star in the spectral-type range of B2-2.5. Although the metallicity of UIT 005 could be different from that of these templates, the abundance ratio of these two elements remains fairly constant (see Urban et al. 2005).

Correspondingly, we assign a luminosity class of Ia\(^+\) due to the narrow H Balmer lines. This is a minor revision in luminosity class with respect to the classification previously provided by Massey et al. (1996) on the basis of low-resolution spectroscopy (see their Figure 5(b), displaying a spectrum covering the wavelength range \(\sim 3900–4900\) Å, obtained either in 1993 or 1995).

3.2. Methodology: Model Atmosphere/Line Formation Code and Main Assumptions

The model atmosphere/line formation code FASTWIND (Fast Analysis of STellar atmospheres with WINDs) was used to create a small set of models for the analysis. The code was first introduced by Santolaya-Rey et al. (1997). Meanwhile, a number of improvements have been incorporated. A complete description of the current status of the code as well as comparisons with alternative codes have been presented by Puls et al. (2005). Briefly, as used in this work, FASTWIND solves the radiative transfer problem in the comoving frame of the expanding atmospheres of early-type stars in a spherically symmetric geometry, subject to the constraints of statistical equilibrium and energy conservation. Steady state and homogeneous chemical composition are also assumed. The density stratification is set by the momentum equation (the advection term is not considered) along with the mass-loss rate and the wind-velocity field (a standard \(\beta\)-law) via the equation of continuity. A smooth transition between the wind regime and the pseudostatic photosphere, which is described by a depth-dependent pressure scale-height, is ensured.

Each model is defined by a set of parameters: effective temperature, surface gravity, and stellar radius (all these quantities are defined at \(r_{\text{Ross}} = 2/3\)), the exponent of the wind-velocity law (\(\beta\)), the microturbulence velocity, the mass-loss rate, the wind terminal velocity, and a set of chemical abundances. In order to reduce the number of parameters to be explored with our

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\(^7\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
grid of models, we follow the procedure described in Urban et al. (2005), with a modification in that the microturbulence velocity is fixed to 10 km s\(^{-1}\) for the calculation of the atmospheric structure. For specific information concerning the model atoms used in our calculations, the reader is referred to the last reference.

### 3.3. Stellar Parameters and Surface Chemical Composition

Table 2 summarizes the derived properties of UIT 005, with Figures 3 and 4 displaying, respectively, a comparison of the ISIS and HIRES data with our final model. The effective temperature is well constrained by using the Si \(\text{ii} \) line at 6379 Å, the weak lines at 4073-6 Å, and, particularly, the group of strong lines just redwards of the red wing of H\(\gamma\) (located at 4345, 4347, 4349, and 4351 Å). In general this group of lines forms on the red wing of H\(\gamma\), while due to the narrow H Balmer profiles, these lines appear out of the wing in this case.

Finally, the Mg abundance is based on the only one feature present in the spectrum, the Mg \(\text{ii} \) line at 4481 Å.

### 3.4. Error Analysis

Uncertainties affecting the determination of the effective temperature and the (effective) surface gravity basically depend on the quality of the observed spectrum (i.e., the S/N). In our case, \(T_{\text{eff}}\) can be constrained within a range of \(\pm 1000 \) K: any larger variation in this quantity would shift the \(\text{Si} \) ionization equilibrium in such a way that either \(\text{Si} \text{iv} \) or \(\text{Si} \text{ii} \) lines would become too strong relative to the observed ones.

The effective surface gravity is well determined by simultaneously fitting the H Balmer lines (H\(\delta\) and H\(\gamma\) in this case), from which we found an uncertainty of \(\pm 0.05 \) dex. To that, we have to add the contributions coming from the stellar wind parameters. In doing so, the total budget amounts to \(\pm 0.10 \) dex, taking into account very conservative errors for \(\beta\) and \(Q\) (the optical depth invariant, see, i.e., Kudritzki & Puls 2000, is defined as \(Q = M \beta^2 / f_1 / c_0 \)).

Concerning the N abundance, lines from single ionized N are used to determine its surface abundance. These are 3995, 4447, and 4601-07-14-21-30 Å along with the lines present in the red wavelength coverage, namely 6379, 6482, and 6610 Å. Other N \(\text{ii} \) lines can be identified at 4035-41-43 Å, but they involve high-energy terms, presently above the energy cutoff considered in our N \(\text{ii} \) model.

The derived carbon abundance is based on the three available lines: C \(\text{ii} \) 4267, 6578–82 Å. It must be noted that we regard our current C model atom as not fully reliable, and thus the quoted C abundance has to be considered carefully.

For the determination of the O abundance, we consider the single ionized oxygen lines located at 4072-76, 4317-19-66, 4414, 4591-96, and 4661 Å, neither of them known to present any blend with other species in the range of effective temperatures characteristic of our star. Other O \(\text{ii} \) lines, not directly used, are present in the spectrum, such as the lines around \(\sim 4000\) Å, the weak lines at 4673-6 Å, and, particularly, the group of strong lines just redwards of the red wing of H\(\gamma\) (located at 4345, 4347, 4349, and 4351 Å). In general this group of lines forms on the red wing of H\(\gamma\), while due to the narrow H Balmer profiles, these lines appear out of the wing in this case.

Finally, the Mg abundance is based on the only one feature present in the spectrum, the Mg \(\text{ii} \) line at 4481 Å.

### Notes

1. The characteristic metallicity \(Z\) is defined as the mean of the individual differences of Mg and Si abundances with respect to their solar values.

2. Presently, clumping is treated under the micro-clumping formalism: the wind consists of overdense clumps embedded in a void inter-clump medium; \(f_1\) measures the overdensity in the clumps.

### Table 2

| Properties                          | UIT 005              |
|-------------------------------------|-----------------------|
| Alt. ID                             | J013242.92±303847.0   |
| SpT                                 | B2-2.5IA              |
| \(T_{\text{eff}}\) (kK)             | 19.0 ± 1.0            |
| \(\log g\) (cgs)                    | 2.25 ± 0.10           |
| \(v_{\infty}\) (km s\(^{-1}\))     | 450                   |
| \(M\) (10\(^{-6}\) \(M_{\odot}\) yr\(^{-1}\)) | 1.42–1.00             |
| \(R\) (\(R_{\odot}\))              | 86.5 ± 6.0            |
| \(\beta\)                           | 2.20 ± 0.20           |
| \(n(\text{He})/n(\text{H})\)       | 0.15                  |
| \(v_{\text{turb}}\) (km s\(^{-1}\)) | 10 ± 3                |
| \(v\sin i\) (km s\(^{-1}\))        | \(\leq 50\)           |
| A(C)                                | 7.40 ± 0.20           |
| A(N)                                | 8.85 ± 0.15           |
| A(O)                                | 7.90 ± 0.22           |
| A(Mg)                               | 7.50 ± 0.16           |
| A(Si)                               | 7.35 ± 0.15           |
| Z (\(Z_{\odot}\))\(^{\alpha}\)     | 0.75                  |
| \(M_{\odot}\) (mag)                | 16.79 ± 0.05          |
| \(B - V\) (mag)                     | 0.01 ± 0.01           |
| \(E(B - V)\) (mag)                  | 0.18 ± 0.015          |
| \(M_{\odot}\) (mag)                | \(-8.33 ± 0.11\)      |
| BC (mag)                            | \(-1.79 ± 0.12\)      |
| Log (\(L/L_{\odot}\)) (cgs)        | 5.95 ± 0.16           |
| \(M_{\odot}^{\text{intr}}\) (\(M_{\odot}\)) | 48.6 ± 18.0          |

Notes: The mass-loss rates correspond to the values derived from each H\(\alpha\) profile.
Finding the stellar radius requires knowledge of the absolute magnitude, for which the distance to the star (840 kpc; Freedman et al. 2001) and photometric data in several bands are required. Along with $M_V$, the radius also depends on the SED provided by the models, and in particular on the flux in the Johnson $V$ band. The error in the absolute magnitude is dominated in our particular case by the uncertainty of the distance modulus to the galaxy, $\Delta \mu = \pm 0.10$ mag (see the previous reference), since in comparison the adopted error in the apparent magnitude $m_V$ is small, $\Delta m_V = \pm 0.05$ mag. This $\Delta M_V = 0.10$ mag translates into a contribution of $\Delta R(\mu) = 4 R_\odot$ due to the uncertainty in the distance. We can also estimate the contribution due to the differences in the theoretical SEDs (basically the uncertainties on $T_{\text{eff}}$) by computing the required radii to reproduce the absolute magnitude for our limiting models with $T_{\text{eff}} \pm \Delta T_{\text{eff}}$, resulting in $\Delta R(T_{\text{eff}}) = 4 R_\odot$. Considering both contributions, we estimate an uncertainty in the radius of $\Delta R = 6 R_\odot$.

In principle, it would seem feasible to estimate the wind terminal velocity from the H$\alpha$ P Cygni profile present in the HIRES spectrum. In doing so, the velocity at which the continuum level is recovered corresponds to $\sim 125$ km s$^{-1}$. However, the P Cygni profile is not saturated, therefore it is
Figure 4. Observed HIRES/Keck 1 spectrum (thin line, $R \sim 65,000$) of UIT 005 compared with our final model. Only selected windows are shown to illustrate the excellent agreement between the model based on the lower resolution ISIS/WHT spectra and the high-resolution HIRES spectrum.

(A color version of this figure is available in the online journal.)

unclear whether this is the actual terminal velocity; it could be that the opacity in the line beyond this point is negligible and it is not contributing to the formation of the line. Models computed for a broad range of terminal velocities (keeping $M v_{\infty}^{-2}$ constant) produced indistinguishable profiles, hence suggesting that the line should not be used to estimate this quantity. Without precise information of the wind terminal velocity, the goodness of our derived mass-loss rate $\dot{M}$ is uncertain. It is possible to assign formal errors to $\dot{M}$ by model comparisons, but it is important to understand that the derived mass-loss rate is anchored to the adopted wind terminal velocity, in the sense that two models with different $M$ and $v_{\infty}$ but keeping $M v_{\infty}^{-2}$ constant will show very similar H$\alpha$ profiles.

Recent UV studies of B-type supergiants in different metallicity environments (Bresolin et al. 2002; Urbaneja et al. 2002; Evans et al. 2004) as well as theoretical investigations (Puls et al. 2000; Vink et al. 2000; Kudritzki 2002; Krütsch 2006) indicate a weak metallicity dependence of the terminal velocity. On the other hand, observational studies of Galactic stars (see Kudritzki & Puls 2000 for a review) show a relatively large dispersion in wind terminal velocities within a given spectral type. For the sake of our analysis, we have adopted a terminal velocity given by the surface escape velocity and the $v_{\infty}-v_{\rm esc}$ relationship provided by Kudritzki & Puls (2000). The mass-loss rates quoted in Table 2 correspond to the values obtained from the two different H$\alpha$ profiles available, and, to avoid any overinterpretation, we do not include a precise estimation of their uncertainties.

Finally, at the spectral resolution used in this work, the S/N is the main contributor to the uncertainties in the chemical abundances. Other factors could increase the line-to-line scatter for each element, like the continuum normalization and the accuracy of the derived fundamental stellar parameters. The uncertainties presented in Table 2 result from the combination (quadratic sum) of two different contributions. The first one corresponds to the statistical error associated with the elemental abundances derived from our final model, based on a line-by-line analysis (see Table 3). For the second one, we consider the uncertainties related to the determination of the fundamental
Table 3
Equivalent Widths, Line-to-line Abundances and Statistical Uncertainties of the Mean Values

| Feature | EW (mÅ) | S/N | (AX) |
|---------|---------|-----|------|
| C II 4267 | 104 | 60 | 7.37 |
| C II 6578 | 154 | 70 | 7.44 |
| σ(C) | 0.07 |
| N II 3995 | 365 | 34 | 9.06 |
| N II 4447 | 117 | 57 | 8.25 |
| N II 4601 | 177 | 65 | 8.75 |
| N II 4607 | 173 | 62 | 8.85 |
| N II 4614 | 144 | 60 | 8.62 |
| N II 4621 | 189 | 86 | 8.91 |
| N II 4630 | 358 | 67 | 9.00 |
| N II 6380 | 123 | 84 | 8.75 |
| N II 6482 | 316 | 63 | 8.87 |
| N II 6610 | 140 | 99 | 8.51 |
| σ(N) | 0.08 |
| O II 4072 | 48 | 50 | 7.84 |
| O II 4076 | 87 | 50 | 7.54 |
| O II 4317 | 32 | 60 | 7.63 |
| O II 4319 | 93 | 60 | 8.40 |
| O II 4366 | 42 | 70 | 7.76 |
| O II 4414 | 81 | 65 | 7.97 |
| O II 4591 | 22 | 55 | 7.38 |
| O II 4596 | 22 | 50 | 7.53 |
| O II 4661 | 100 | 58 | 7.95 |
| σ(O) | 0.11 |
| Mg II 4481 | 176 | 74 | 7.50 |
| σ(Mg) | 0.09 |
| Si II 4552 | 272 | 68 | 7.32 |
| Si II 4567 | 217 | 75 | 7.31 |
| Si II 4574 | 155 | 80 | 7.38 |
| σ(Si) | 0.04 |

Note. Abundances derived for each line; SNR as measured in the continuum close to the line.

There is also no reason to assume that our object and the nearby faint source are physically related in any way. In the following, we consider that UIT 005 has evolved as a single star since this is the simplest assumption that can be made from the information at hand. Moreover, we adopt the characteristic metallicity of UIT 005 as given by the Si and Mg abundances, ~0.7 Z☉, i.e., a metallicity intermediate between that of the Milky Way and that of the LMC. This value, based on the abundances of two α-elements, is consistent with what would be inferred from the C+N+O by mass relative to the solar value, ~0.8 Z☉. We note here that this metallicity is higher than the corresponding value for the ionized gas in NGC 588 when using the gas phase O abundance (see below) as a proxy for metallicity, 0.4 Z☉. The population-synthesis-based study of the ionizing cluster of NGC 588 by Jamet et al. (2004) indicates an even lower metallicity, 0.2 Z☉. However, both these results are contradicted by Bianchi et al. (2004), who find near solar metallicity for UIT 008, one of the two known Wolf-Rayet stars in NGC 588.

Figure 5 locates UIT 005 in a log Teff–log g diagram, together with the sample of M 33 blue supergiant stars analyzed by Urbaneja et al. (2005), hereinafter UHK05, and evolutionary models for Galactic (Meynet & Maeder 2003) and LMC (Meynet & Maeder 2005) metallicities. The position of UIT 005 is consistent with models having initial masses between 40 and 60 M☉ for both metallicities. As the derived metallicity of UIT 005 lies between that of the Galaxy and the LMC, we conclude that its initial mass was also between these two values. Note that, unlike in the classic Hertzsprung–Russell (H-R) diagram (luminosity versus effective temperature), both Teff and log g are directly derived from the spectral analysis, without any assumption regarding the distance to the object. This figure also illustrates that UIT 005 is farther away from the...
main sequence phase than the M 33 B-type supergiant stars in the sample studied by UHK05. This point is stressed in Figure 6; our object appears clearly isolated in this N/O–$T_{\text{eff}}$ diagram, showing a much higher N/O ratio (by mass) than any of the other M 33 objects. The star presents an N/O~8 and an N/C~32 (this last value is highly uncertain because of the issues with our C model atom). In comparison, the object with the higher N/O ratio in the Galactic sample studied by Crowther et al. (2006; empty circles in Figure 6) is the well-known blue hypergiant HD 152236, for which these authors find N/O = 3. As we will discuss later, the apparent agreement with the predictions by the evolutionary models is misleading.

Even though the abundances are far from the expected values at (CNO) equilibrium, 20.5 and 64, respectively, the very high observed N/O ratio of UIT 005 is quite remarkable and, at a first glance, could be an indication of an advanced evolutionary status (enhanced N abundance). Alternatively, this could be a consequence of an initial low O abundance, because of the location of the star in the galaxy and its strong radial abundance gradient (UHK05; U et al. 2009). Or it could result from a combination of both.

The proposition of an initial low O content can easily be tested by using the information provided by the other two $\alpha$-elements for which we derived an abundance, Mg and Si. Figure 7 displays the O and Mg abundances of UIT 005 and the sample studied by UHK05. In the case of O (Figure 7, top panel), it seems that UIT 005 does not follow the gradient defined by the other B-type supergiants, while this is not the case for Mg (Figure 7, bottom panel). The same happens if we consider Si instead of Mg (not shown). Using the stellar O radial gradient obtained by UHK05, the O abundance that would correspond to the galactocentric distance of UIT 005 is log(O/H)+12 = 8.45 dex. Even if one argues that there is no particular reason for the gradient to behave smoothly, our expectation for the O abundance is supported by recent results for the giant H II region NGC 588, separated by ~30′′ (a de-projected distance of ~130 pc for the distance to the galaxy adopted in this work) of our star, with an O abundance in the range 8.45–8.32 dex (Crockett et al. 2006; Magrini et al. 2007; Rosolowsky & Simon 2008). It would seem then that the present low O content of UIT 005 is not related to its location in M 33.

We can further investigate this issue by removing the spatial dependence. Figure 8 presents the relation between the derived O abundance and the mean $\alpha$-element abundance defined by Mg and Si. Considering the sample of UHK05, it seems clear that there is a relation between the abundances of these three elements that is not followed by the abundances of UIT 005. Therefore, the relative stellar abundance of O to the two other $\alpha$-elements, Mg and Si, in combination with the previous paragraph, strongly supports the idea of UIT 005 having suffered significant evolution and presently exposing material processed by the CNO cycle.

Further constraints can be obtained from the evolutionary lifetimes of phases consistent with the effective temperature and gravity derived for UIT 005. Not all the possible models have the same likelihood, since in some cases the compatible stages are predicted to be extremely short. In fact, a close examination of the lifetimes indicates that for the rotating models these are always only a few hundred years, making

\footnote{Normalized distance to the galactic center, $R / R_{25} = 0.80$}
it extremely improbable that UIT 005 started its life with a high rotational velocity. On the other hand, non-rotating models at 50 and 60 $M_\odot$ spend, respectively, 6.7 and 6.2 $\times$ $10^4$ years in this phase at Galactic metallicity, while the 50 $M_\odot$ at LMC metallicity spends 3.8 $\times$ $10^4$ years, giving us a chance to observe such an object. Therefore, from the available set of evolutionary models, we are left with the non-rotating models at 50 $M_\odot$ (for both metallicities) and 60 $M_\odot$ (only for the solar metallicity, but note that the non-rotating 60 $M_\odot$ model was not available for LMC metallicity). For all three models, the evolutionary predicted masses are between 30 and 44 $M_\odot$, in agreement with the spectroscopic mass, within the error bars. At the same time, however, the observed surface enrichment is at odds with the ones provided by these evolutionary models; while N is within the uncertainties of the observed value, the models predict that the O surface abundance should be almost an order of magnitude higher than observed. Since, owing to rotation, one would expect a higher degree of evolution in N than in O, the observed values would not be explained by models with higher initial rotational velocity alone.

Because of the somewhat peculiar derived abundances, one might ask to what extent our results are conditioned by the necessary assumption incorporated in the model atmosphere/line formation code used for the analysis. During the course of our work, we calculated a number of models with the alternative code CMFGEN (Hillier & Miller 1998). These models were based on our FASTWIND solution for UIT 005; i.e., we did not perform an independent analysis using CMFGEN models in the same way as described in previous sections. We limited the calculations to a small region of the parameter space around the values obtained with FASTWIND instead. A discussion of the differences between both codes is clearly beyond the scope of our paper; this would require a larger sample of objects to investigate possible systematic differences. Nevertheless, the “best” solution found with CMFGEN ($T_{\text{eff}} \sim 18300$ K, log $g \sim 2.15$ dex) overlaps, within the errors of the analysis, with our parameters. Moreover, the chemical abundances derived with both codes are consistent. In particular, the O abundance obtained with CMFGEN, 7.85 dex, is in excellent agreement with our FASTWIND derived value of 7.90 dex.

Although somehow uncertain due to the lack of precise information about the wind terminal velocity, the mass-loss rates derived from the available He profiles ($\dot{M} \approx 1.0\text{--}1.4 \times 10^{-6} M_\odot$ yr$^{-1}$) are low when compared with the theoretical value predicted by Vink et al. (2000, 2001), $\dot{M} = 1.8 \times 10^{-5}$ $M_\odot$ yr$^{-1}$. We have not found firm indications of a structured wind in our admittedly limited set of observations, but even if the wind is clumped to some extent, this will not bring the observed and the theoretical values into better agreement. Rather, the situation would become even worse since a clumped wind would act in the opposite way, implying a smaller true mass loss (our derived mass-loss rates would be upper limits in that case). This is a significant point of disagreement with the evolutionary models since these apply the theoretical predictions by Vink et al. (2000, 2001) to prescribe the mass-loss rates during the blue supergiant phases. This discrepancy between theoretical predictions and He and radio continuum derived mass-loss rates for mid-B types has been previously reported for Small Magellanic Cloud (Trundle & Lennon 2005) and Galactic (Crowther et al. 2006; Markova & Puls 2008; Benaglia et al. 2008) supergiants. We refer the reader to Markova & Puls (2008), where this dilemma has been discussed at some length. In fact, in the case of UIT 005, the high theoretical mass-loss rate is also not consistent with the observed SED (see below).

The available H$\alpha$ profiles indicate a variation of $\sim$25% in the mass-loss rate from the 2001 to the 2003 observations. At the same time, the few He and metal lines available in the same wavelength range suggest that this change does not affect the structure of the star significantly. Changes in H$\alpha$ profiles at this level have been previously reported for Galactic early B-type supergiants (Rivinius et al. 1997; Crowther et al. 2006).

UIT 005 resides in a region of the H-R diagram (Figure 9) populated by extreme blue objects such as LBVs. In fact, if the distance to M 33 is larger than assumed here, as recently derived from several stellar indicators (see Bonanos et al. 2006; U et al. 2009, and references therein), then UIT 005 could be as luminous as log ($L$/L$_\odot$) $\sim$ 6.1 dex, well in the regime of the most luminous LBVs. Whether our star is a regular blue object or a dormant LBV is unclear. The observed SED from 0.44 to 4.5 $\mu$m (Figure 10) is very well matched by the synthetic SED of our final model (Figure 10, solid line), even though those photometric measurements were acquired in different epochs. The synthetic SED has been reddened assuming a total-to-selective extinction ratio $R_v = 3.1$ and by adopting the extinction curve by Cardelli et al. (1989). We note that the selection of the extinction curve has little or no effect on the considered photometric bands, and the excellent agreement between observed and theoretical SEDs would not be affected. We have included a second model (dash-dotted line in Figure 10) computed for an enhanced mass-loss rate, set to the theoretical prediction discussed above. As previously indicated, the observed SED for wavelengths longward of the I band is clearly not consistent with this high mass-loss rate.

With respect to our final model, the good agreement in the infrared bands, and in particular the no detections at 8.0 and 24 $\mu$m (this last from inspection of archival Spitzer data), would indicate the lack of a significant amount of hot dust around the star, suggesting that UIT 005 is not surrounded by a nebula. While the presence of such a nebula is a common characteristic for many LBVs and would support the LBV nature of UIT 005, there are also cases of confirmed LBVs (for example, R110, Sk $\sim$ 69° 142a, and R85 in the LMC; Bonanos et al. 2009) where this nebula is absent.

The nature of this intriguing object is further complicated by its apparent isolation, as illustrated by Figure 1 where we see that it lies well beyond the periphery of its nearest cluster, NGC 588. Is it possible that this cluster was the original birth place of UIT 005? In Figure 11, we show the color–magnitude...
diagrams (CMDs) for all stars in the field (approximately covering 2.7 × 2.7 arcmin$^2$). It is known that NGC 588 contains two WN stars (Drissen et al. 2008) so it is potentially both young enough and massive enough to have produced a supergiant such as UIT 005. As Figure 11 demonstrates, UIT 005 fits nicely into the CMD of NGC 588 as one of the most evolved of its potential members. Furthermore, assuming a main-sequence lifetime of around 5 Myr (consistent with the age of 4.2 Myr estimated by Jamet et al. 2004 and Úbeda & Drissen 2009 for a somewhat lower metallicity), it would require a runaway velocity of around 40–50 km s$^{-1}$ to reach its current distance from the cluster, well within the range of velocities of known Galactic runaway O-type stars (McSwain et al. 2007). While not conclusive, for example, there are no radial velocity measurements for stars in NGC 588, the evidence above provides interesting circumstantial support for the idea that UIT 005 is a runaway star from NGC 588, with the ejection mechanism being either dynamical interaction in the cluster or an SN kick (from a yet more massive companion). This second scenario would require a much higher runaway velocity, since the SN progenitor would need some time to evolve. While this seems to favor the dynamical interaction as the ejection method, very little is known about the cluster itself, hence this scenario cannot be investigated further at this point.

5. CONCLUSIONS

Our detailed quantitative analysis of UIT 005 shows that this massive and luminous blue supergiant (B2-2.5la*, log $L/L_\odot \sim$ 5.9 dex, and $M \sim 50 M_\odot$) has a surface abundance pattern that presents peculiarities, in particular when considering its location in the disk of the M 33. From the point of view of the $\alpha$-elements for which we have information, Mg and Si abundances seem to follow the radial behavior (as traced by other B-type supergiants), while its O abundance appears to be depleted by a factor of $\sim$3.5 with respect to the expected local value. The $\alpha$/O ratios are hardly understandable as a product of previous stellar generations at this particular location in the galaxy, moreover, if we incorporate the derived high N/O ($\sim$8, by mass) and the He abundance. All together, and under the assumption that the star is evolving as a single object, the most likely explanation is that the observed chemical pattern is a consequence of the chemical evolution of the star that is showing an advanced stage of CNO processing on its surface. This picture is supported by the predictions of recent evolutionary models, although we must point out that some discrepancies are still present, such as the degree of chemical processing predicted by the models.

The derived parameters place the star in a region of the H–R where LBVs are usually found. The observations do not support its nature as an LBV, nor do they rule out the possibility of an LBV in a dormant state. UIT 005 could very well represent a transitory stage in the evolution of the most massive stars or even the precursor of an LBV. Subsequent monitoring of this object would help us to improve our knowledge of massive stars, bridging the gap between regular and more exotic blue supergiants.

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Figure 11. Color–magnitude and color–color diagrams constructed from the WFPC2/HST data, covering a field of $2.7 \times 2.7$ arcmin$^2$ approximately centered at the location of NGC 588. The reddening free color $Q$ is defined as $Q = (U - B) - 0.72 \times (B - V)$. The two known Wolf-Rayet stars in NGC 588 are identified by filled symbols, with the star marking UIT 005. For reference, we also show an isochrone for a population ∼5 Myr old.

(A color version of this figure is available in the online journal.)

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