STELLAR SPECTROSCOPY FAR BEYOND THE LOCAL GROUP

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ABSTRACT

Multiobject spectroscopic observations of blue supergiants in NGC 3621, a spiral galaxy at a distance of 6.7 Mpc, carried out with the ESO Very Large Telescope and focal reducer/spectrograph are presented. We demonstrate the feasibility of quantitative stellar spectroscopy at distances approaching a tenfold increase over previous investigations by determining the chemical composition, stellar parameters, reddening, extinction, and wind properties of one of our targets, a supergiant of spectral type A1 Ia located on the outskirts of NGC 3621. The metallicity (determined from iron group elements) is reduced by a factor of 2 relative to the Sun, in qualitative agreement with the results from previous abundance studies based on H II region oxygen emission lines. Reddening and extinction are \( E(B-V) = 0.12 \) and \( A_V = 0.37 \), respectively, mostly caused by the Galactic foreground. Comparing stellar wind momentum and absolute \( V \) magnitude with Galactic and M31 counterparts, we confirm the potential of the wind momentum–luminosity relationship as an alternative tool for estimating extragalactic distances.

Subject headings: galaxies: individual (NGC 3621) --- galaxies: stellar content --- stars: early-type --- stars: winds, outflows

1.INTRODUCTION

Detailed optical work with 4 m-class ground-based telescopes and the Hubble Space Telescope (HST) on individual blue supergiants has been carried out in recent years in the Galaxy, the Magellanic Clouds, and a handful of nearby galaxies, most notably M31 and M33 (McCarthy et al. 1995; Kudritzki 1998; Monteverde et al. 1997; Monteverde, Herrero, & Lennon 2000; Venn 1999; Venn et al. 2000, 2001; Dufton et al. 2000; Smartt et al. 2001). These stars are extremely luminous (up to \( M_V = -10 \)) and show signatures of strong mass outflows in their ultraviolet, optical, and infrared spectra, which are successfully interpreted in the framework of the radiation-driven wind theory (Kudritzki & Puls 2000; Kudritzki 2000). One of the main predictions of the theory, nicely confirmed by spectral diagnostics of supergiants in the Milky Way (Puls et al. 1996; Kudritzki et al. 1999), the Magellanic Clouds (Kudritzki 1998; Puls et al. 1996), NGC 6822 (Muschielok et al. 1999), M31 (Smartt et al. 2001; McCarthy et al. 1997), and M33 (McCarthy et al. 1995), is a tight relationship between the modified wind momentum (the product of the mass-loss rate, the terminal velocity of the winds, and the square root of the stellar radius) and the stellar luminosity:

\[
\dot{M}_w(R/R_\odot)^{0.5} = L^{1.5},
\]

with \( \alpha = 0.5 \) (Kudritzki 1998, 2000; Kudritzki & Puls 2000; Kudritzki et al. 1989). This wind momentum–luminosity relationship (WLR) has a great potential as a new, independent extragalactic distance indicator. Kudritzki et al. (1999) estimate that using the WLR technique with 10–20 A-type supergiants per galaxy and medium-resolution spectroscopy with 8 m telescopes from the ground distance moduli with an accuracy of about 0.1 mag can be obtained out to the Virgo and Fornax Clusters of galaxies. A detailed comparison with well-known primary distance indicators is now required in order to establish the reliability and applicability of the WLR. In this context, we are set to apply the methods of quantitative spectroscopy to A- and B-type supergiants in galaxies with known, mostly Cepheid-based, distances. Among the galaxies studied within the HST Extragalactic Distance Scale Key Project (Kennicutt, Freedman, & Mould 1995; Mould et al. 2000), NGC 3621 has been chosen for its moderate distance (40% that of the Virgo Cluster), maximizing our chances of detecting blue supergiants. In this Letter, we discuss the identification of suitable targets and the testing of our spectroscopic tools with the current observational capabilities of an 8 m telescope.

2.TARGET SELECTION AND OBSERVATIONS

For the spectroscopic target selection, we obtained broadband \( B, V \), and \( I \) CCD frames of NGC 3621 with Antu, the first unit of the Very Large Telescope (VLT) operated by the European Southern Observatory on Cerro Paranal, Chile, equipped with FORS (FOcal Reducer and low-dispersion Spectrograph) in imaging mode. The crowded-field photometry was carried out with the IRAF version of DAOPHOT (Davis 1994) and indicates that the brightest stellar objects in this galaxy appear at \( V = 20 \), corresponding approximately to an absolute magnitude \( M_V = -10 \), given the Cepheid distance modulus \((m-M) = 29.1 \ (\pm 0.2) \) and average reddening \( E(V-I) = 0.3 \) (Rawson et al. 1997). We selected isolated stars brighter than \( V = 22 \), with a color index of \(-0.1 < (V-I) < 0.6 \), corresponding to the expected location of reddened blue supergiants in the color-magnitude diagram. The target selection was finalized after inspection of archival HST WFPC2 images of a smaller field in NGC 3621 (to avoid, where possible, contamination by neighboring stars in our spectra) and rejection of objects showing nebular emission on top of stellar features, as revealed by the short-exposure spectra obtained during the commissioning phase of FORS2 at the second unit telescope of the VLT. Two H \( \alpha \) regions (one of which is located within a slit together with a stellar object) were included in the final sample, for future comparison of chemical abundances measured independently from stellar and nebular lines.

1 Based on observations obtained at the ESO Very Large Telescope.

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Optical spectra of our candidates were obtained on 2000 March 1–2 under 0.8 seeing conditions. The FORS instrument possesses excellent multiplexing capabilities, allowing spectra of 19 different faint objects to be taken simultaneously through separate slitlets, each approximately 20″ in length. Figure 1 shows the distribution of the targets, and Table 1 summarizes their position and photometric data. Several exposures, adding up to a total integration time of 10.7 hr, were obtained with a single multislit setup (600 groove mm\(^{-1}\) grism, 1″ slits), covering as a minimum the 3800–4900 Å wavelength range at 5 Å resolution. This range contains most of the spectral features useful for deriving the main stellar parameters (effective temperature, gravity, and chemical composition).

The photometric selection proved to be rather successful. We have identified in our spectra 10 supergiants, subdivided into spectral types as follows: B (one star), A (six stars), F (one star), and two luminous blue variable (LBV) candidates. Of the remaining targets, four have composite spectra, while another four show nebular emission superposed on stellar features, despite our efforts to avoid such occurrences. One early-A supergiant, one early-F supergiant, and one LBV candidate are displayed in Figures 2a, 2b, and 2c, respectively. The quality of the extracted spectra (with a signal-to-noise ratio [S/N] of order 50) is excellent, making the classification of spectral types using Galactic standard stars, together with a first estimate of effective temperatures, straightforward.

3. STELLAR PARAMETERS AND METALLICITY: A CASE STUDY

Using line-blanketed model atmospheres in hydrostatic equilibrium (Kurucz 1991, 1992) and detailed non-LTE/LTE line formation calculations (Przybilla et al. 2000a, 2000b), we can make a quantitative analysis of the spectra. We concentrate here on the object in Figure 2a (hereafter star a), for which we estimate an effective temperature \( T_{\text{eff}} = 9000 \pm 400 \) K from the spectral classification and subsequently derive a gravity of \( \log g = 1.05 \pm 0.15 \) (cgs) from fitting the higher Balmer series members (from H\(_7\) upward). A microturbulent velocity typical for luminous supergiants, \( \xi = 8 \) km s\(^{-1}\), is chosen for the spectrum synthesis calculations. A more detailed analysis.
comprising the remaining objects will be published elsewhere. The spectrum is well fitted with a chemical composition comparable to that of the Large Magellanic Cloud, assuming a reduction of metallicity by a factor of 2 with respect to solar composition \citep{Haser98}; however, their WFPC2 images of the region close to our stellar target has found a reduction of the oxygen abundance of the same order \citep{Ryder95}. Our analysis provides additional information concerning elements such as magnesium, iron, chromium, and titanium.

It is important to note that the spectral resolution of 5 Å allows a reasonable estimate of stellar metallicity by synthesizing the entire observed spectrum. We have tested this technique by reproducing the results obtained by detailed quantitative analyses of high-resolution, high S/N spectra of Local Group A-type supergiants \citep{Przybilla01}. However, we stress that it is difficult to determine precise effective temperatures from ionization equilibria of weak lines and microturbulence velocities and abundances from individual lines. Here we have to rely on the experience obtained from the analyses of Local Group objects using higher resolution spectra. In the next phase, we intend to work at a resolution of 2 Å as provided, for instance, by FORS2 at the VLT.

We determined the interstellar reddening by fitting the calculated energy distribution to the fluxes corresponding to the measured magnitudes. A total $E(B-V) = 0.12$ is found, consistent with most, if not all, of the effect being due to Galactic foreground reddening \citep{Burstein82}. This value is smaller than the one obtained by the HST Key Project [$E(B-V) = 0.23$; \cite{Rawson97}]; however, their WFPC2 field is closer to the central part of the galaxy, where dust lanes are prominent (Fig. 1). We therefore demonstrate that, in principle, stellar spectroscopy allows us to map interstellar extinction.
tion for accurate distance determinations. From the Cepheid distance modulus and an interstellar extinction $A_V = 0.37$, we derive an absolute magnitude $M_V = -9.0$ ($\pm 0.2$) for our object. The corresponding stellar radius, calculated from the model atmosphere flux in the V-filter, is $R = 250 \pm 25 R_\odot$, yielding a luminosity $L = 3.7 \times 10^5 L_\odot$.

4. WIND PARAMETERS AND THE WLR

Star $a$, with its very high luminosity, is the ideal target for testing whether or not it is possible to measure wind momenta of A-type supergiants in galaxies far beyond the Local Group. Mass-loss rates $M$ and terminal velocities $v_\infty$ are usually determined by the shape of the H$\alpha$ stellar wind line profile. However, because of the enormous strength of the wind driven by the luminosity, H$\beta$ is also affected by mass loss; and this allows us a first estimate of the stellar wind momentum. As in previous work done on the Milky Way (Kudritzki et al. 1999) and M31 (McCarthy et al. 1997) we adopt “unified model atmospheres,” which allow for departures from the local thermodynamic equilibrium, are spherically extended, and include the hydrodynamic effects of stellar winds in their stratification (Santolaya-Rey, Puls, & Herrero 1997). The calculated H$\beta$ profiles in Figure 4 show very clearly how mass loss affects the profile shape. The absorption profile is significantly filled by wind emission, enabling a reasonable determination of $M$. Since, contrary to H$\alpha$, the H$\beta$ fit does not allow us a direct determination of terminal velocities, we adopt a typical value of $v_\infty = 200$ km s$^{-1}$. Compared with other A-type supergiants (Kudritzki et al. 1999; McCarthy et al. 1997), the uncertainty introduced by this assumption is on the order of 20%. The mass loss of the A-type supergiant obtained in this way is $3 \times 10^{-6} M_\odot$ yr$^{-1}$, while the corresponding modified stellar wind momentum flow is $5.9 \times 10^{28}$ ergs cm$^{-1}$, with an accuracy of roughly 30%.

We compare in Figure 4 the WLR for Galactic and M31 supergiants of solar metallicity, for which we have adopted the stellar parameters given by Venn et al. (2000, 2001), Kudritzki et al. (1999), and McCarthy et al. (1997) together with a more recent distance determination to M31 equal to 783 kpc (Holland 1998) and a revised photometry for the M31 supergiants (Venn et al. 2000). Because of the small bolometric corrections of A-type supergiants, we use the absolute magnitude rather than the luminosity to display the relationship. Star $a$ is located slightly below the regression line. A natural explanation for this is the somewhat lower metallicity inferred from the analysis of the photospheric spectrum, which leads to lower wind momenta (Kudritzki 1998, 2000; Puls et al. 1996; McCarthy et al. 1995; Haser et al. 1998). An empirical calibration of the WLR metallicity dependence using A-type supergiants in the Magellanic Clouds is presently under way. The slight discrepancy might also be due to the uncertainty of the H$\beta$ fit. The forthcoming VLT observations of all of our targets at H$\alpha$ wavelengths will allow us to answer this question and to put additional data points onto the WLR plane. We are confident that this will also provide an independent constraint on the distance of NGC 3621.

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