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Spectroscopy of Massive Stars in NGC 6822 and M33

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ABSTRACT. We present blue spectra of massive stars in the Local Group galaxies NGC 6822 and M33. For all the targets, selected from our previous *Hubble Space Telescope* WFPC2 photometry, no previous spectroscopic studies exist, to our knowledge, except for a bright Wolf-Rayet star in NGC 6822. Photospheric parameters $T_{\rm eff}$ and gravity are derived by a model fit of the Balmer lines and multiband (UV to optical) photometry combined and are compared with evolutionary models. Inferred masses range from ≈7 to ≈40 $M_{\odot}$ in the sample. From the spectroscopy, we classify the Wolf-Rayet star in NGC 6822 as WN3(-4), with no hydrogen. We estimate its progenitor mass of ≈40 ± 10 $M_{\odot}$. For two stars in the NGC 6822 sample, our data are not sufficient to establish whether they are foreground stars toward NGC 6822 or they belong to the galaxy.

1. INTRODUCTION

Characterization of the massive star content in Local Group galaxies, which span over a dex in metallicity and a variety of morphology types, is important to relate star formation activity, and massive star evolution, to environmental parameters. Much progress has happened in recent years, thanks to the advent of ground-based telescopes with large collecting areas and of the *Hubble Space Telescope* (*HST*) imaging resolution (see, e.g., Massey 1998 for a review and Bianchi et al. 2001 for an example).

NGC 6822 is an irregular galaxy in the Local Group, with a metallicity intermediate between that of the Small Magellanic Cloud (SMC) and Large Magellanic Cloud (LMC) (Pagel, Edmunds, & Smith 1980; Muschielok et al. 1999). An indication of possibly lower metallicity was found in two stellar clusters (Chandar, Bianchi, & Ford 2000). Its massive star content has been characterized by ground-based CCD *UBV* photometry of a few regions (Wilson 1992; Massey et al. 1995a) and follow-up spectroscopy of some interesting objects, which revealed the presence of massive O-type stars in several of the OB associations (Massey et al. 1995a). The first global survey of NGC 6822 was the photographic study of Kayser (1967). Recently, Hodge et al. (1991) surveyed the whole galaxy with *B*, *V*, *J*, and *R* filters, and Bianchi et al. (2001) in *UBV* with Cerro Tololo Inter-American Observatory (CTIO) CCD images. More importantly to the focus of this work, Bianchi et al. (2001) studied two crowded fields containing young OB associations and two H II regions, with *HST* WFPC2 photometry in the F555W, F439W, F336W, and F255W filters. The four-band photometry has been used to derive photometrically extinction and temperature for the measured objects and to select massive star candidates for follow-up spectroscopy that will provide better measurements of stellar parameters. We present here results from the first spectroscopic data set of our follow-up program, obtained at the Canada-France-Hawaii Telescope (CFHT) in the blue range. The original goal was to obtain also red spectra to derive mass-loss parameters from the Hα line; however, the program could not be completed owing to weather conditions. Only one bright object has a useful spectrum in the range 4000–7000 Å. It is a Wolf-Rayet type star in NGC 6822 (§ 4). For the other stars, we restrict the analysis to the blue range and use Balmer lines in particular to refine $T_{\rm eff}$ and luminosity (§ 3).

Similarly, seven stars in M33 were also included in the program, selected from L. Bianchi et al. (2001, in preparation) *HST* photometry. This galaxy is similar to the LMC for metal content, and its star formation might be even more interesting as it is rather isolated, while the LMC history might reflect the influence of the Milky Way vicinity.

2. SPECTROSCOPIC DATA: TARGET SAMPLE

Multislit spectra were obtained in 1997 August 26–29 at the CFHT 3.6 m telescope equipped with the Optionally Stabilized Imager and Spectrometer (OSIS) spectrograph coupled with the V150 grism plus *B* filter. This provided a much lower resolution than originally planned in our program, since our other selected gratings could not be used.

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TABLE 1
List of Observed Stars in NGC 6822 and Derived Parameters

Object	R.A.(2000)	Decl.(2000)	Exposure (s)	m_{F255W}	U	B	V	$E(B-V)$	M_V	Hγ EW (Å)	T_{eff} (K)	$L/L_{\odot}$ (× 10^5)
LB-f1-739	19 44 48.83	−14 43 59.13	4200	18.10	18.43	19.15	19.08	0.26[a]	−5.19	4.0 ± 1	22000 ± 2000	0.55 ± 0.13
LB-f1-282	19 44 52.48	−14 44 29.87	4200	18.37	18.55	19.25	19.08	0.40[a]	−5.63	5.0 ± 1	25000 ± 2000	1.16 ± 0.26
LB-f1-68	19 44 51.66	−14 45 00.61	4200	18.94	19.28	19.80	19.67	0.28[a]	−4.53	4.5 ± 1	18000 ± 500	0.18 ± 0.01
LB-f1-156[b]	19 44 49.84	−14 45 39.32	4200	18.45	18.81	19.58	19.44	0.37[a]	−5.03	2.5 ± 1	28000 ± 2000	0.93 ± 0.20
LB-f2-75[c]	19 45 13.56	−14 45 12.66	7800	17.45	17.96	18.93	18.82	0.35[a]	−5.73	−9.8[d] ± 1	38800 ± 5000[a]	5.30 ± 2.49
LB-f2-131	19 45 08.58	−14 43 58.24	5700	19.85	19.94	20.58	20.33	0.44[a]	−4.50	5.6 ± 1	23000 ± 5000	0.33 ± 0.19
LB-f2-117	19 45 13.72	−14 43 43.64	5700	21.37	20.81	20.41	19.42	0.34[e]	−5.10	4.3 ± 1	6500 ± 500	0.08 ± 0.01
CTIO-931	19 45 12.29	−14 43 17.51	7800	…	18.47	17.84	16.86	0.42[e]	−7.91	9.9 ± 1	7000 ± 500	1.12 ± 0.04
CTIO-709	19 45 09.53	−14 45 21.07	7800	…	20.09	19.02	17.89	0.57[e]	−7.34	8.5 ± 1	7000 ± 500	0.66 ± 0.02
LB-f2-90	19 45 12.08	−14 45 25.64	5700	23.40	18.39	17.86	16.80	0.31[e]	−7.63	7.3 ± 1	6500 ± 500	0.84 ± 0.02
CTIO-897	19 45 16.61	−14 43 37.51	5700	…	20.02	19.71	18.89	(0.11)[f]	(−4.93)[f]	3.2 ± 1	6500 ± 500	(0.07 ± 0.02)[f]
CTIO-1761	19 45 08.42	−14 44 46.66	5700	…	18.33	17.95	17.05	(0.38)[f]	(−7.64)[f]	6.6 ± 1	7000 ± 500	(0.88 ± 0.04)[f]

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] From Bianchi et al. 2001.
[b] The position is 7″ from NGC 6822—star 5 of Armandroff & Massey 1985.
[c] NGC 6822—star 12 of Armandroff & Massey 1985.
[d] Mostly He II in this star.
[e] From this work.
[f] *Assuming* that the stars are supergiants at the distance of NGC 6822; however, they could also be foreground stars of low-luminosity class (see text).

The NGC 6822 stars were selected from the *HST* photometric sample of Bianchi et al. (2001), based on stellar parameters inferred from four-band WFPC2 photometry. The OSIS pointings were centered on two fields, covering approximately field 1 and field 2 of Bianchi et al. (2001) and shown in their Figure 1. Two masks were used for each field to sample more objects. The OSIS design limits the freedom of positioning the slits (to avoid superposition of the spectra), so the choice of objects was a compromise between the brightest massive star (photometric) candidates and positional convenience. Four additional stars were selected from CTIO *UBV* photometry (Bianchi et al. 2001) to use the remaining slits outside the WFPC2 fields. Targets in M33 were selected from the *HST* WFPC2 photometry of L. Bianchi et al. (2001, in preparation). The stars and their relevant parameters are listed in Table 1 (NGC 6822) and in Table 2 (M33).

The blue spectra cover the spectral region 4000–4800 Å; however, only a portion about 300 Å wide, centered at Hγ, has useful signal-to-noise ratio (S/N). Because of intermittent weather problems, the final total exposure times for the blue spectra varied from 3300 to 7800 s, achieved with repeated exposures of 900–1200 s each. The red spectra could not be completed owing to bad weather. The S/N is good over the whole range (4000–7000 Å) only for an extremely bright object in NGC 6822 (§ 4). The data were reduced using the IRAF package. The task CRREJ has been applied to remove cosmic rays. The final S/N for the co-added spectra is about 30 at Hγ for the best cases. The width of the lines in the wavelength calibration spectra shows that actual resolution was $R \approx 400$.

3. ANALYSIS

Because a much lower resolution than planned was achieved, full spectral modeling was not possible and only the strongest features could be used, in most cases only Hγ. In this section we derive the stellar T_{eff} and log g by comparison of the OSIS spectra with model spectra and photometric information combined (except for the W-R star, LB-f2-75, discussed separately

TABLE 2
List of Observed Stars in M33 and Derived Parameters

Object	R.A.(2000)	Decl.(2000)	Exposure (s)	m_{F170W}	U	B	V	M_V	Hγ EW (Å)	T_{eff} (K)	$L/L_{\odot}$ (× 10^5)
M33-2979	01 33 56.0	+30 31 26.6	3300	17.15	18.50	19.34	19.57	−5.54	5.0 ± 1.0	27000 ± 4000	1.34 ± 0.59
M33-3594	01 33 50.3	+30 32 26.0	3300	17.61	18.02	18.60	18.65	−5.83	5.6 ± 1.5	23000 ± 4000	1.11 ± 0.52
M33-4204	01 33 28.9	+30 33 22.6	4680	19.71	19.38	19.36	19.29	−5.83	6.0 ± 1.5	22000 ± 6000	0.99 ± 0.70
M33-2337	01 33 51.1	+30 39 00.6	3600	16.02	17.81	18.84	18.96	−6.16	2.0 ± 1.0	≥31000	≥3.64
M33-2417	01 33 51.8	+30 39 31.7	3600	16.56	17.76	18.67	18.78	−5.54	3.0 ± 1.0	28000 ± 1000	1.49 ± 0.16
M33-1407	01 33 52.2	+30 39 58.8	3600	18.50	18.68	19.30	19.38	−5.74	4.0 ± 1.0	≥30000	≥2.23
M33-485	01 33 31.9	+30 39 23.4	4200	…	21.67	22.06	22.16	−5.50	7.4 ± 1.0	18000 ± 4000	0.45 ± 0.22

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

in § 4). First, we used ATLAS9 (Kurucz 1993) to compute model atmospheres. This code takes into account the metal opacity using opacity distribution functions for multiples of the solar metallicity. For our spectra we used a metallicity $M = [-5.0]$, i.e., 10^{-5} solar values. Then, synthetic spectra of the photospheric lines were calculated with SYNTHE (Kurucz & Avrett 1981) and convolved to match the actual resolution of the data.

As initial guesses for the stellar temperature, we used the results from the four-band *HST* photometry of Bianchi et al. (2001) when available and/or from the Hγ equivalent width (EW) as described below. We computed a grid of models with $T_{\rm eff}$ in the range 5000–32,000 K using WIDTH9 (Kurucz & Avrett 1981) and used the grid to build a theoretical curve of growth of Hγ. From this curve (Fig. 1) an estimate of the effective temperature can be derived from the measured Hγ EW, as a function of gravity. EWs were measured by a Gaussian fit of the spectral line after removing possible continuum slope for the best-quality spectra; otherwise a measure of the area between the line profile and the continuum was obtained. The error in the measured EW was estimated (adapting the formula given by Leone, Lanzafame, & Pasquini 1995), with the relation

$$\Delta W = \frac{1}{2}\, b\, \frac{1}{\rm S/N}\,, \qquad (1)$$

where b is the total extension of the line.

The ambiguity between $T_{\rm eff} < 9000$ K and $T_{\rm eff} > 9000$ K (see Fig. 1) can easily be resolved from the photometric colors. For temperatures lower than 9000 K, the relation EW-$T_{\rm eff}$ is independent from the gravity value (see Fig. 1). Therefore, an unambiguous value of $T_{\rm eff}$ can be derived but no information on gravity. At hotter temperatures (>10,000 K) the derivation of $T_{\rm eff}$ is more uncertain when only the Hγ line EW is available. We can take advantage of the fact that all the hot stars in the sample are likely to be members of NGC 6822 and M33 and thus are at a well-known distance, and we restrain the value of gravity by imposing that the luminosity class be consistent with the measured magnitudes (Bianchi et al. 2001; L. Bianchi et al. 2001, in preparation), scaled by the distance and corrected for reddening. The observed magnitudes were scaled to absolute magnitudes as follows: for NGC 6822, we used DM = 23.47 (McGonegal et al. 1983) and reddening values from Bianchi et al. (2001), for M33 we used DM = 24.62 (Magrini et al. 2000) and an average $E(B-V)$ value of 0.16 (Massey et al. 1995a). The values of M_V are also listed in the tables. At $T_{\rm eff} = 30{,}000$ K, for instance, M_V varies—from luminosity class I to III to V—from -6.5 to -5.2 to -4.0. The difference is significant enough to remove the ambiguity among the various curves in Figure 1 using the photometry. The calibration of absolute magnitude with luminosity class (and gravity) for the range of stellar parameters of interest was taken from the compilation of Schmidt-Kaler (1982); the bolometric correction used to calculate the luminosity values were derived from the parametrization of Massey et al. (1995b). These calibrations are based on Galactic stars, which introduces an additional source of uncertainty given the different metallicity of the galaxies studied. However, although some indications exist that, e.g., the $T_{\rm eff}$–spectral type relation at low metallicity (Magellanic Clouds) differs slightly from the Galactic one, quantitative relations at different metallicities do not exist. Owing to all these factors, the indetermination of $T_{\rm eff}$ is larger for hotter stars (see Fig. 1), and this is reflected in the errors quoted in Tables 1 and 2.

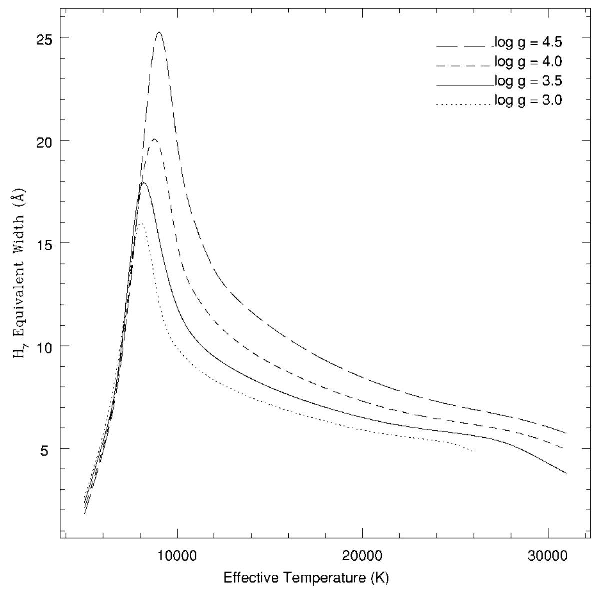

FIG. 1.—Equivalent width of Hγ as a function of $T_{\rm eff}$ and gravity from model calculations.

Values of $T_{\rm eff}$ were refined by visually choosing the best fit to the observed profiles. Because we could use only the Balmer lines (only Hγ in most cases), the metallicity of the model has no influence. Metallicity affects the emergent flux, at the ≤1% level in the Hγ wavelength region when going, e.g., from LMC to SMC values. However, when the line profile is normalized to its local continuum, the Hγ line itself does not change appreciably. Results of the line fits are displayed in Figures 2 and 3, and the derived parameters are listed in Tables 1 and 2. The dotted lines around the adopted models indicate a range of $T_{\rm eff}$ corresponding to the uncertainties in the Hγ EW, which appear to be a conservative but reasonable estimate, given the low resolution and the variable S/N of the spectra in the sample. Our LTE models are adequate for all the objects except for two M33 supergiants hotter than ≈30,000 K; above this temperature non-LTE effects might be significant at low gravity. For these two stars, only lower limits of $T_{\rm eff}$ could be given.

For all stars except the last two in Table 1, $T_{\rm eff}$ and photometry are consistent with supergiants at the distance to NGC 6822. In the case of the last two objects, the luminosity classification is

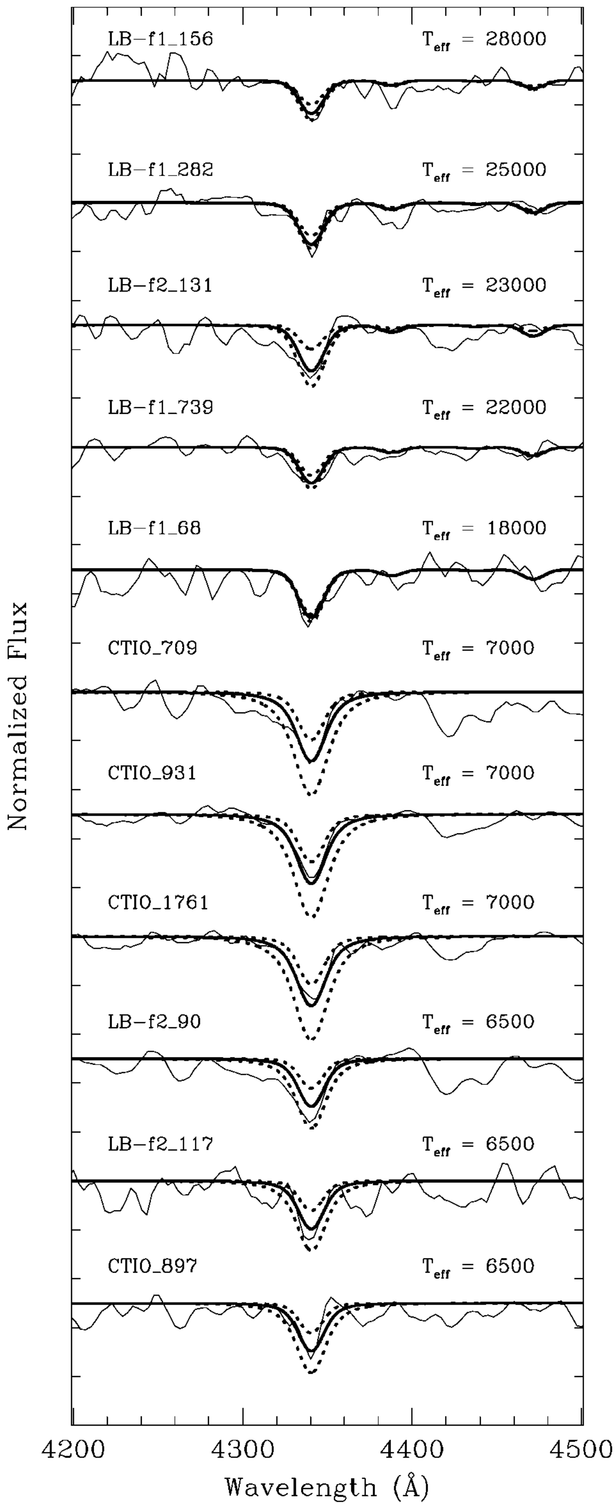

FIG. 2.—Normalized spectra of the NGC 6822 stars: the Hγ line. The solid thick lines are the model for the adopted temperature, and the dashed lines refer to models calculated for $T_{\rm eff} \pm \delta T_{\rm eff}$ (Table 1). The λ4430 interstellar diffuse absorption band is also visible.

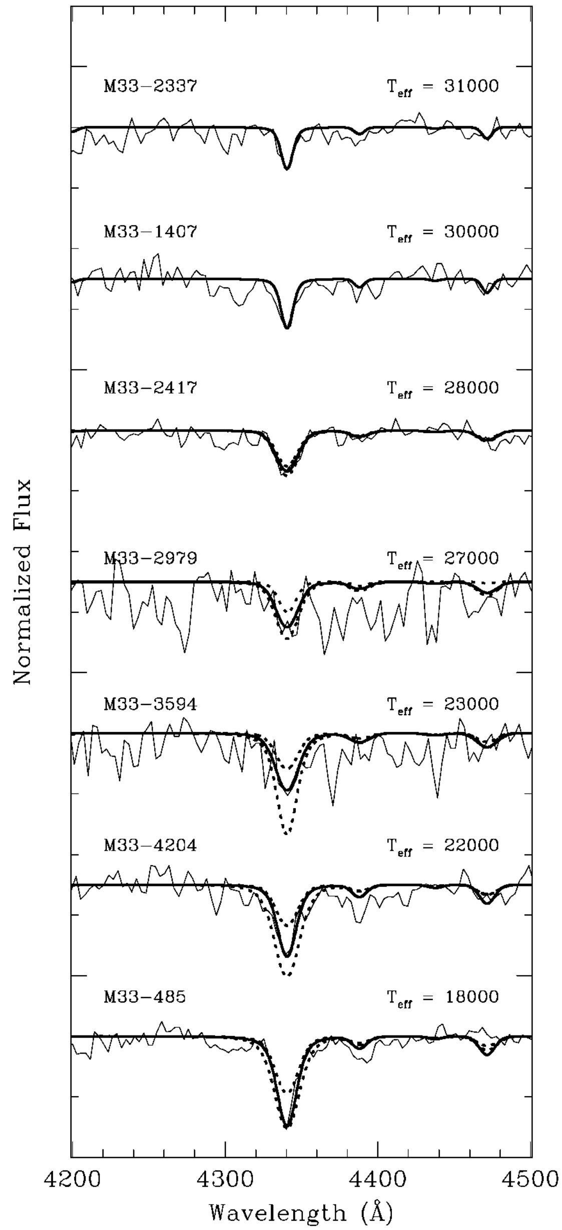

FIG. 3.—Normalized spectra (Hγ line) of the M33 stars. Symbols are as in Fig. 2.

ambiguous. For CTIO-897, photometric and spectroscopic data are compatible with a $T_{\rm eff} = 6500 \pm 500$ K. If it were a main-sequence star, its photometry would place it at 5.55 ± 0.89 kpc, and its measured color would indicate an $E(B-V)$ of 0.24, consistent with a foreground star. If it were at the distance of NGC 6822, photometry and temperature would be consistent with a late F supergiant; however, the photometric $E(B-V)$ would be only ≈0.11, inconsistent with the expected minimum value toward NGC 6822 [$E(B-V) = 0.25$; Massey et al. 1995a]. Therefore, it is most probably a foreground star. For

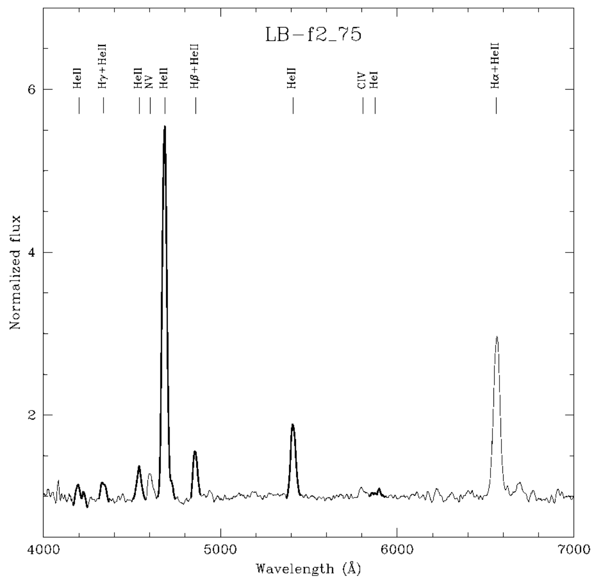

FIG. 4.—Spectrum of the W-R star in NGC 6822. Marked lines are those used for spectral classification.

CTIO-1761, we derive $T_{\rm eff} = 7000 \pm 500$ K. If it were a main-sequence star it would be at a distance of $d = 2.4 \pm 0.4$ kpc, but if it were a supergiant of luminosity class I–II its photometry would translate into a distance $d = 630$–290 kpc, consistent with the distance to NGC 6822 (≈500 kpc). The photometrically inferred extinction of $E(B-V) = 0.34$–0.38 (main-sequence to supergiant) is a plausible value for an NGC 6822 star. An unambiguous classification will require spectra with better spectral resolution (to derive gravity from the line profiles) and wider wavelength coverage.

4. THE WOLF-RAYET STAR IN NGC 6822

Among the stars in our NGC 6822 sample (see Table 1), LB-f2-75 shows a typical Wolf-Rayet emission-line spectrum. This is the only star for which we obtained a useful spectrum over a wide wavelength range, between 4000 and 7000 Å. The spectrum is shown in Figure 4. The position and magnitude are consistent with NGC 6822—star 12 of Armandroff & Massey's (1985) list of W-R candidates selected from narrowband imaging (spectroscopically confirmed as WNE by Armandroff & Massey 1991).

Classification of W-R stars was first defined by Beals (1938). Subsequent modifications by Hiltner & Schild (1966) and by Smith (1968) are still in use. Recently, in the attempt of clarifying the classification of the WN subtypes, Smith, Shara, & Moffat (1996) proposed a set of criteria based on (i) the ratio of He II λ5411 to He I λ5875 EWs as the primary discriminant of ionization subclass, (ii) the FWHM of He II λ4686 and/or EW of the He II λ5411 for the strength and width of the lines, and (iii) an oscillating Pickering decrement, defined by the two

TABLE 3
MAIN LINES IN THE SPECTRUM OF LB-f2-75

Ion	λ (Å)	EW (Å)
He II	4200	8 ± 3
He II (+Hγ)	4340	10 ± 1
He II	4541	13 ± 2
N V	4606	11 ± 1
He II	4686	151 ± 2
He II (+Hβ)	4861	17 ± 1
He II	5411	31 ± 2
C IV	5808	5 ± 2
He I	5875	≤ 2
He II (+Hα)	6563	98 ± 2

ratios of

$$\frac{4861}{\sqrt{(4541 \times 5411)}} - 1, \quad \frac{4340}{\sqrt{(4200 \times 4541)}} - 1 \qquad (2)$$

for a qualitative assessment of hydrogen presence. The spectral lines useful for the classification are listed in Table 3 together with their EWs. By applying the Smith et al. (1996) criteria, we classify LB-f2-75 as WN3(-4), with no hydrogen. The temperature, taken from the Bianchi et al. (2001) photometric estimate, is also consistent with a WN3 type.

5. CONCLUSIONS

The values of $T_{\rm eff}$ and luminosity derived from the spectral analysis and the photometry are used in Figure 5 to place the stars on the H-R diagram. Comparison with evolutionary tracks of Fagotto et al. (1994) (metallicity $Z = 0.004$) indicates that our program successfully identified a number of new massive stars in these galaxies, although no star more massive than $40 \pm 10\ M_\odot$ is found. Owing to the numerical limitations of the sample, no population statistics can be inferred. However, the fact that our UV photometric selection found independently a W-R star out of eight objects chosen from the *HST* UV-to-optical photometry is particularly significant. A census of number and distribution of W-R stars in Local Group galaxies, and in particular the relative WC/WN number ratio, gives important clues to the effects of metallicity on the evolution of massive stars. There is observational evidence that the WC-to-WN ratio increases from the solar vicinity (1:1) to the LMC (1:4.5) to the SMC (1:7) (Massey 1996), suggesting a progression with metallicity. If comparison among different galaxies raises the question of completeness (although recently Massey & Duffy 2001 demonstrated that the census of W-R stars in the SMC is quite complete), further, more unbiased, evidence is provided by a galactocentric gradient of the WC-to-WN ratio in M33, the WC types dominating in the central regions (Massey & Conti 1983; Massey & Johnson 1998). As metals drive the acceleration of winds by radiation pressure in hot stars, the mass-loss mechanism is more efficient at higher metallicity.

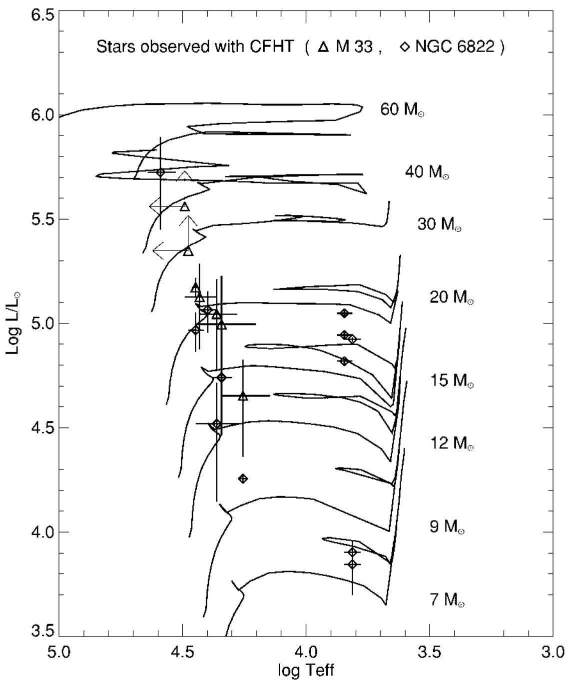

FIG. 5.—H-R diagram for the program stars. Evolutionary tracks are overplotted (mass values labeled).

Therefore, we can expect also the peeling of the outer layers to be more effective, thus exposing the products of the He-burning (WC stars). NGC 6822 has been surveyed for W-R stars with interference filters and follow-up spectroscopy by Armandroff & Massey (1985, 1991) and Massey et al. (1995c); four W-R stars were found, all of WN type. Our data refined the classification of one of them. The fact that no WC types have been detected yet is probably not significant given the small number statistics, but the abundance of WN-type stars is consistent with a very low metallicity.

Our analysis also confirmed that at least four of the cooler stars in the NGC 6822 sample are members of this galaxy. The two dubious cases were not selected from the *HST* photometry but only for positional convenience to exploit the additional slits outside the *HST* fields. The sample of NGC 6822 objects presented here covers a very limited fraction of the massive star candidates from Bianchi et al. (2001) *HST* photometry (see their Fig. 8). However, the results confirm that the fields studied in NGC 6822 are particularly rich in massive stars and the selection from the UV photometry very promising. A more extensive follow-up, with better resolution and wavelength coverage, is under way with the *HST* Space Telescope Imaging Spectrograph and ground-based telescopes (William Herschel Telescope and Very Large Telescope).

Except for LB-f2-75, none of the objects in our sample was included in previous ground-based surveys in these galaxies, to our knowledge.

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