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SPECTROSCOPIC ANALYSES OF MASSIVE BLUE STARS (GALACTIC OR EXTRAGALACTIC)

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RESUMEN

Repasamos los recientes avances en nuestro conocimiento de las estrellas masivas a través del análisis de sus espectros. Discutimos brevemente las mejoras en los modelos de atmósfera y en los métodos de análisis.Se comparan los resultados obtenidos en estrellas del Grupo Local y se describe el estado actual de diferentes cuestiones que permanecen abiertas, como la escala de temperaturas de las estrellas OB, la Relación entre el Momento del Viento y la Luminosidad o la rotación estelar.

ABSTRACT

We review recent advances in our understanding of massive stars through the analysis of their spectra. Improvements in model atmospheres and analysis methods are briefly discussed. Results obtained for stars in the Local Group are compared and the present status of different open questions, like the temperature scale of OB stars, the Wind Momentum-Luminosity Relation or the stellar rotation, is outlined.

Key Words: local group — stars: atmospheres — stars: early-type — stars: mass loss

1. INTRODUCTION

Massive stars play a central role in our understanding of the Universe. During their evolution, they inject huge quantities of radiative and mechanical energy that modify their surroundings to finally explode as supernovae, sometimes generating Gamma Ray Bursts, and leaving behind neutron stars or black holes. The consequences of such destiny reach far-lying regions, triggering new star formation epidodes. And the elemental abundances of very important ions are altered, from He and O to Si and Fe through C, N, Na, Mg and Ca, to mention only some of them. They represent for us the gateway to the early Universe, as they dominate the spectra of nearby starbursts and high z galaxies.

To take adavantage of the presence of massive stars in relation to so many astrophysical problems we have to be able to explain their structure and evolution, predict their fluxes at all wavelengths, understand their physics under different conditions. The way we follow is to try to reproduce their observed properties, particularly their spectra, using our model atmospheres. But we have to do it not only for a limited sample of stars, but for massive stars under all possible conditions, specially for different metallicities. Fortunately, the Local Group displays a large range in metallicity, rendering it an excellent laboratory to study the physics of massive stars.

I'm particulaly happy in this occasion that the first paper in which I could collaborate (a very small contribution) analyzing stars in the Local Group beyond our Galaxy had Virpi Niemela as one of the co-authors.

2. MODEL ATMOPSHERE STATUS

Model atmospheres for massive stars have experienced a boost in the last few years, as a consequence of the work continously developped since the early eighties. Thanks to this work, we have today different codes available that can be used for different applications in the field of massive blue stars. Table 1 gives an overview of these codes and their characteristics. Note that these data are only for a rough overview. Codes may offer several possibilities for a given characteristic, be coupled together, or the point (for example, the execution time) may depend on details of the calculation. Detailed information can be found in Santolaya-Rey, Puls, & Herrero (1997) and Puls et al. (2005) for FASTWIND; Hillier & Miller (1998) for CMFGEN; Pauldrach, Hoffmann, & Lennon (2001) for WM-basic and Lanz & Hubeny (2003) for TLUSTY.

Of course, these codes are different and therefore some careful cross-check is always needed. Results from such comparisons may be found in Puls et al. (2005) (for a FASTWIND, CMFGEN, WM-

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TABLE 1

A SIMPLE COMPARISON OF PROPERTIES OF CODES SUITABLE FOR THE ANALYSES OF MASSIVE BLUE STARS.

	FASTWIND	CMFGEN	WM-basic	TLUSTY
Geometry	Spherical	Spherical	Spherical	Plane-parallel
Wind	Yes	Yes	Yes	No
Blanketting	Approx.	Yes	Yes	Yes
Rad. Transfer	CMF-Sobolev	CMF	Sob+Cont.	Observers frame
T Structure	e^- balance	Rad. Eq.	e^- balance	Rad. Eq.
Photosphere	Yes	Approx.	Approx.	Yes
Phot. Broadening	Yes	Yes	No	Yes
Hydrod.	No	No	Yes (Sobolev)	No
Exec. time (h)	0.3	12	4	4

basic comparison) with some update in Najarro et al. (2006) and in Martins, Schaerer, & Hillier (2005a) (for a CMFGEN, TLUSTY comparison).

The new models have produced important changes in the O stars calibrations of spectral type vs. different physical parameters. Particularly important is the change in the effective temperature scale of O stars. Figure 1 shows a comparison of several temperature scales. We see that the new temperature scales are cooler than previous ones. The main reason is the introduction of line blanketing, that acts as an additional opacity source in the UV, as compared to pure H-He model atmopsheres. Figure 2 (taken from Repolust, Puls, & Herrero, 2004) explains the effect.

2.1. *The FLAMES Survey of Massive Stars*

Present model atmospheres rely on a number of assumptions, particularly that the stellar wind is driven by radiation. As shown by Kudritzki et al. (1995) this implies the so-called Wind Momentum-Luminosity Relation, expressed as

$$\log D_{mom} = x \log(L/L_{\odot}) + D_0$$

where D_{mom} is the product $(\dot{M} v_{\infty} R^{1/2})$ and x and D_0 are related to metallicity. To check this relation and the predictions of the radiatively driven wind theory is one of the most important tasks presently open in massive stars fields.

To test the WLR at LMC and SMC metallicities is one of the main objectives of the FLAMES Survey of Massive Stars (P.I., S.J. Smartt). This is an ESO Large-Programme with 120 hours VLT-FLAMES observing time, plus some extra time to complement the observations (mainly with FEROS).

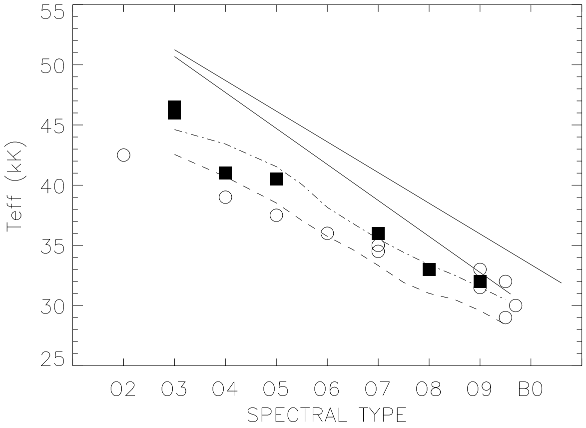

Fig. 1. A comparison of temperature scales for O dwarfs and supergiants. Solid lines correspond to the Vacca et al. (1996) scales for dwarfs (upper line) and supergiants (lower line), while the dash-dotted and dashed lines are the Martins et al. (2005a) scales for dwarfs and supergiants, respectively. Solid squares stand for dwarfs from Repolust, Puls, & Herrero (2004) and open circles stand for supergiants from the same authors. We see that the Repolust et al. and Martins et al. scales compare well, while the Vacca et al. scale is much hotter.

Three galactic clusters for comparison and two clusters in each of the Magellanic Clouds were observed. Table 2 quotes some numbers that give an idea of the observational effort.

To analyse such a large number of stars requires a lot of time and to lower it, Mokiem et al. (2005) have presented an automatic fit method for O stars based on the use of a genetic algorithm that takes advantage of the fast computational properties of FASTWIND. The algorithm has been applied to the analysis of LMC and SMC O stars observed in the

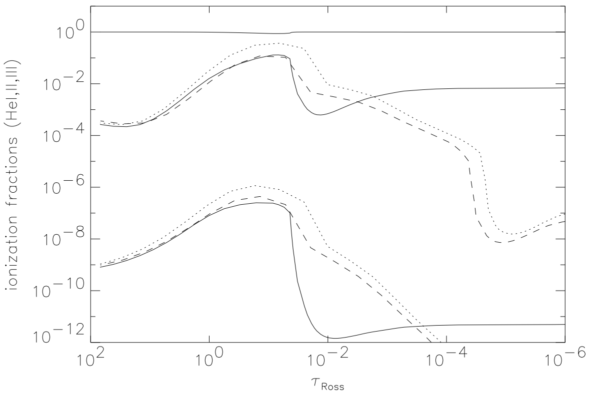

Fig. 2. The effect of line blanketing on the He ionization fraction. The calculation is for a model corresponding to HD 15629, an O5.5 V star. The He ionization fractions increase from HeI to HeIII. Solid lines correspond to the blanketed final model and the dashed lines to the hotter, unblanketed models. Note that both models have very similar ionization fractions, and thus predict the same spectrum. On the contrary, those of the unblanketed model with the same temperature as the blanketed one (dotted line) are different. The reason is that the radiation blocked and sent back by the increased opacity raises the temperature of the blanketed model in the corresponding layers (from Repolust, Puls, & Herrero 2004).

TABLE 2

OBSERVATIONS IN THE FLAMES SURVEY OF MASSIVE STARS

	Galaxy	WR Stars	O Stars	B Stars
NGC 3293	MW	-	-	99
NGC 4755	MW	-	-	98
NGC 6611	MW	-	13	40
NGC 2004	LMC	1	4	107
LH9/10	LMC	-	44	76
NGC 330	SMC	-	6	109
NGC 346	SMC	-	19	86
Total		1	86	615

FLAMES Survey, resulting in the largest number of O stars homogenously analyzed. As the distance to the stars is known, it is possible to derive the stellar radius and obtain the luminosities and wind momenta for this large number of stars.

The results for the WLR have been presented in Mokiem et al. (2007b) and indicate a partial agreement with the theoretical predictions by Vink et al. (2001). Mokiem et al. confirm that the WLR decreases with metallicity in the expected way: it is highest for the Milky Way, intermediate for the LMC and lowest for the SMC, in amounts that also agree with the predictions. Moreover, Mokiem et al. confirm that the metallicity dependence of the mass-loss rate also agrees with theoretical values. Thus, for α in the relation $\dot{M} \propto Z^{\alpha}$ Mokiem et al. obtain $\alpha = 0.83 \pm 0.16$, compared with the value by Vink et al. $\alpha = 0.69 \pm 0.10$.

2.2. *Model Atmosphere Status: A word of caution*

However Mokiem et al. (2007b) could not confirm all the predictions of theory. While the standard radiatively driven wind theory is well stablished for luminous stars, some aspects are still controversial. We emphasize here two of them: the possible presence of wind clumping and the possible breakdown of the theory at relatively low luminosities, of the order of $\log(L/L_{\odot}) \approx 5.2$.

Mokiem et al. found a systematic displacement in the ordinate between the observed and predicted WLR for the Milky Way, the LMC and the SMC (a difference in D_0, see above). The difference corresponds to an overstimation of the observed mass-loss rates by a factor of about 2. Other authors have also found differences between the observed and predicted WLR, like Herrero, Puls, & Najarro (2002), Repolust, Puls, & Herrero (2004) or Massey et al. (2005). The easiest way to explain this would be through wind clumping. As the emission in H_{α} (the main mass-loss diagnostic line used by Mokiem et al.) is due to e^{-}–H^{+} encounters, it will be roughly proportional to ρ^2, and because $<\rho^2> \neq <\rho>^2$ assuming a smooth wind in the presence of clumping will end in too large values for the wind density and therefore the mass-loss rate through the equation of continuity. A recent analysis by Puls et al. (2006a), including a coarse radial dependence, has shown that clumping is present at least in the denser winds. Because the results from Puls et al. are based on diagnostics that depend on ρ^2 (H_{α}, IR and radio) it is not possible to derive the absolute value of the clumping, but only the relative clumpiness between regions where the different diagnostics form. For the thinner winds, no significant difference could be found. For the denser winds, the average correction in the mass-loss rates was a factor of 2 (toward values lower than for smooth winds).

The wind diagnostic lines in the UV are usually not affected by wind clumping, because the mass-loss rates are derived from absorption resonance lines, being therefore proportional to ρ and not to ρ^2. However, these lines are usually saturated in O stars, and can therefore not be used for mass-loss determination. Using the P V doublet at $\lambda\lambda$1118, 1128 Fullerton et al. (2006) find very large factors (of the order of 10 and more) between the H_α and UV mass-loss rates. The same factors are found by other authors (see references in Fullerton et al.) and in B supergiants (Prinja et al. 2005). However, while clumping may also play a role here, and even offer an explanation if we adopt extreme clumping factors (see also Puls et al. 2006b), such huge differences probably need an extra effect to explain the low ionization fraction found for P IV and P V, like the inclusion of X-rays ionization or problems with model atoms.

The second problem to which we refer, the possible breakdown of the radiatively driven wind theory, has been noticed by Bouret et al. (2003) in NGC 346 stars and Martins et al. (2004) in N81, who showed that for SMC stars with relatively low luminosity the derived mass-loss rates were much lower than predicted. Later, Martins et al. (2005b) have shown that the effect is present also in Galactic stars, and therefore metallicity cannot be claimed to be reason for the breakdown. Martins et al. attribute it to a decreased line force parameter α (not to be confused with the α exponent in the $\dot{M}$-Z relation above), but the reason for it is unknown.

3. MASSIVE BLUE STARS IN THE SMC AND LMC

The study of stars in the Magellanic Clouds provide us with very important relations, namely those of the stellar parameters with metallicity. Of course, the FLAMES Survey of § 2.1 represents also an important contribution here. The first relation we may check for variation with metallicity is the $T_{\rm eff}$ vs spectral type relation. Two major works have been published recently, that of Massey et al. (2004, 2005) and that of Mokiem et al. (2006, 2007a). Both works show a qualitative agreement: stars in the SMC are hotter than their counterparts in the Milky Way, and stars in the LMC tend to lie in between (although not in a very clear way), results being similar for dwarfs and supergiants. However, we should note that the intrinsic scatter is very large at any spectral subtype. For example, at O7, the SMC stars by Mokiem et al. (2006) enclose in temperature their LMC and Galactic counterparts.

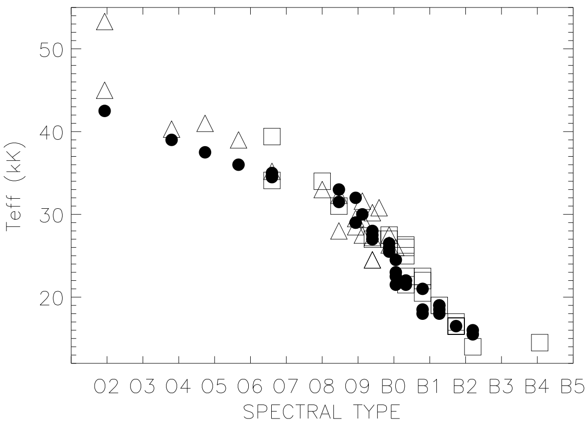

Fig. 3. The temperature scale for O and B supergiants in the Milky Way (solid circles, Repolust et al. 2004), the LMC (triangles, Evans et al. 2004; Mokiem et al. 2007b) and the SMC (squares, Trundle & Lennon 2005; Mokiem et al. 2006). The O supergiants are hotter at lower metallicities, and the trend seems to be present until spectral type B1. For later stars, there is no clear trend anymore. Compare with Figure 1.

Note that the agreement between Massey et al. and Mokiem et al. is to be expected: they use the same techniques and the same code (FASTWIND) for their analyses. On the contrary, while for Massey et al. (2005) the SMC O4-O5 dwarfs are hotter than their Galactic analoges, for Bouret et al. (2003) the opposite is true. This is interesting, as Bouret et al. use CMFGEN to analyse the stars. However, they only analyzed six stars in NGC 346, and thus we shouldn't give this difference a strong statistical value. But it is clear that further work is needed before we consider the temperature scale of O stars well stablished at different metallicities.

For the B supergiants, the situation is slightly different. The scales derived by Crowther et al. (2006) for Galactic stars, Evans et al. (2004) for LMC, and Trundle & Lennon (2005) for SMC ones agree, and there is no clear systematic difference between stars from different metallicities at a given spectral type, although the trend towards hotter types for lower metallicities seems to be present until spectral type B1. Figure 3 gives an overview of the temperature scales of Galactic and Magellanic clouds O and B supergiants, with data from Repolust, Puls, & Herrero (2004) and Mokiem et al. (2006, 2007b) for O supergiants, and from Crowther et al. (2006), Evans et al. (2004), and Trundle & Lennon (2005) for B supergiants.

Another important parameter of massive stars that has to be studied with metallicity is rotation. Rotation may strongly influence the evolution of massive stars (Maeder & Meynet 2000) and a metallicity dependence is predicted for their rotational velocity: because stellar winds are larger for higher metallicities, therefore producing a larger loss of angular momentum at the surface as compared to stars of lower metallicity, the fraction of fast rotating stars should decrease with increasing metallicity.

This is supported by the finding by Maeder et al. (1999) who studied stellar clusters in the Galaxy, the LMC and the SMC and found a clear trend towards a larger fraction of Be stars for clusters of lower metallicity. Recent studies by Heap et al. (2006) and Mokiem et al. (2006) confirm a large N and He enhancement in the stars of the SMC, in agreement with theroetical expectations of CNO contamination induced by rotational mixing. However, the same study by Mokiem et al. does not find clear evidence of a larger initial rotational velocity in the stars of the SMC, as compared to the Galactic stars.

An additional point that has to be considered is the possible existence of extra line broadening that is attributed to rotation while being due to other effects, like large or meso-scale turbulent motions. Ryans et al. (2002) have shown that a large fraction of the line broadening in B supergiants is due to turbulent-like motions, while Simón-Díaz & Herrero (2007) have recently shown, using the Fourier transform method that line broadening in O stars has also a turbulent-like contribution. While this extra broadening is comparable in dwarfs and supergiants, it is more important in the latter due to the comparatively smaller rotational and collisional broadening mechanisms.

Finally we will refer here to advances in the mass discrepancy problem. In the Galaxy, the recent works by Herrero et al. (2002), Repolust et al. (2004), and Mokiem et al. (2005) show that there is no evidence for a systematic mass discrepancy as that originally described by Herrero et al. (1992), although some small problems may still be present for stars with $M_{spec} \approx 20\ M_{\odot}$ or lower, or for some stars that seem to occupy a line parallel to the 1:1 relation in the M_{spec} vs M_{evol} diagram, but a slightly too large M_{evol} values. However, the evidence for these two aspects is limited and they should not be considered as firmly stablished.

The situation is different and more complicated when the analyses of stars in the Magellanic Clouds are considered. In the LMC, the results from Massey et al. (2004) and Mokiem et al. (2007a) seem to indicate the same difficulties that we have just pointed out for the Galactic stars. In addition Massey et al. find a strong mass discrepancy for very hot stars, as do Mokiem et al. for 2 of their 4 O2 objects, with the other two reaching the 1:1 line only because of very large error bars. Therefore, Massey et al. (2004) and Mokiem et al. (2007a) show some reminiscences of the mass discrepancy in the LMC, but at least their results are consistent. However, while Mokiem et al. (2006) do not find evidence of mass discrepancy in the SMC (even the limited problems that we have refereed above are not present or appear in milder form), Heap et al. (2006) find a large mass discrepancy in their SMC stars. More work will be needed for a final word, but we note here again that Mokiem et al. and Massey et al. use the same code (FASTWIND), while Heap et al. have used TLUSTY.

Herrero & Lennon (2004) suggested that the abundance and mass patterns found in massive blue stars could be explained by a combination of rotation and mass-loss. According to these authors, the evolution of very massive stars (initial masses of the order of 50-60 $M_{\odot}$ or more) is dominated by mass-loss, while for the lower end of the massive stars (masses in the ZAMS of 20-25 $M_{\odot}$ or less) peculiarities in the evolution (like particular abundance patterns) would be due to rotation. For stars of masses in between, the particular characteristics of each star would determine the subsequent evolution. If this scenario is correct, rotation could play an increasingly important role compared to mass-loss as metallicity decreases.

4. MASSIVE BLUE STARS IN NEARBY SPIRAL GALAXIES

The analysis of massive blue stars in spiral galaxies offers the opportunity to study the evolution of these stars under different conditions, as in the Magllanic Clouds, but in addition we can also study the structure and abundance patterns of these galaxies similar to our own.

The two major works in this context are those by Urbaneja et al. (2005a,b) in NGC 300 and M33. In M33 Urbaneja et al. (2005b) use observations of massive blue stars obtained with the WHT and the Keck-II telecopes, at R≈2500–5000 and SNR ≥ 100. Analyzing a total of 11 stars, Urbaneja et al. could determine the radial O/H abundance gradient, that agrees well with that found in HII regions by Vilchez et al. (1988), although it cannot solve the question whether the gradient decreases linearly with constant slope or has two zones, with a strong fall of the O abundance in the innermost part and a small, nearly horizontal slope in the outer regions. The stellar Mg and Si abundances follow the trend of the O abundances but with shallower gradients, a difference that, if confirmed, cannot be easily explained by present models. Taken together, the α-elements abundances indicate solar metallicities for the central regions of M33. Finally, an interesting comparison with type I Planetary Nebulae indicates that there has been no significant O contamination over the past 3 Gyr.

In NGC 300 Urbaneja et al. (2005a) analyzed observations taken with the VLT-FORS2 (Bresolin et al. 2002a,b). These observations are of lower SNR and resolution than those in M33 because of the larger distance to NGC 300 (about 2.2 Mpc), and forced changes in the analysis technique. An important lesson is that we can derive the stellar parameters and abundances of the brightest B superginats in other galaxies even with resolutions of $R\approx1000$, thanks to the relatively few lines present in the spectra of these stars (although the good SNR is still needed, even more than at higher resolution or metallicity). The large distance of NGC 300 has also made impossible to obtain directly *Te* for the HII regions in NGC 300, so that the O abundances in these regions were derived using different calibrations. The comparison with the stellar data favours the calibration by Denicoló, Terlevich, & Terlevich (2002), that gives a similar value for the radial O/H gradient and the central O/H abundance to those of Urbaneja et al. (-0.033 ± 0.026 dex kpc^{-1} and 8.57 ± 0.13 dex). In this case the Si and Mg gradients agree with the O one.

Taken together we see that both works give consistent results: the O abundances derived from B-supergiants trace a gradient that is consistent in both galaxies with studies from HII regions and give central abundances lower than previously accepted.

However, the study of stars in external galaxies is subject to numerous problems. One of the most important is stellar crowding, and is illustrated in Figure 4, where we show a HRD for the B supergiants analyzed by Urbaneja et al. (2005b). Two of the stars (110A and B133) are very close to the Humphreys-Davidson limit, with one of them (110A) clearly above it. In images taken with the HST-STIS accquisition camera we can see that B133 has a close companion star. Two similar stars are within the circle of 1 arcsec diameter that represents the seeing disk under which the stars were observed from the ground. Therefore, the luminosity derived for B133 is too large, and the star, still very luminous, has a luminosity that does not challenge the theory of stellar structure. Moreover, an indication of this companion could be seen in the UV spectrum of B133, that was peculiar (Urbaneja et al. 2002) But this is not the case for 110A, for which no peculiarity was found in the UV spectrum, nor in the optical (except for emission in the Balmer lines), nor in the HST accquisition image. Therefore, 110A may be one of the most luminous known stars, and even an example of a higly structured atmosphere leading to *porosity* as suggested by Owocki (2004), although the possibility of an even closer companion (or companions) than in the case of B133 has always to be considered.

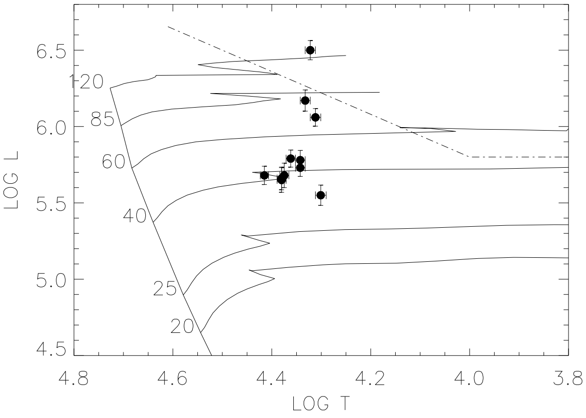

Fig. 4. The HRD of the M33 stars observed by Urbaneja et al. (2005b). Tracks are non-rotating tracks by Schaller et al. (1992) for Galactic metallicity. The dashed-dotted line represents the Humphreys-Davidson limit. Star 110A is the point above that limit, and B133 is the point immediately below it. While the luminosity of B133 should be corrected by the presence of a close companion (and its UV spectrum shows a peculiar SiIV profile), 110A seems to be an isolated, very luminous star.

To find some particularly interesting objects is one of the appealing possibilities of the extragalactic stellar spectroscopy. For example, we have found that UIT 005, a B2.5 supergiant in M33 is a very evolved object, with a very low O/H content indicating a very evolved evolutionary status. The spectroscopic analysis gives an actual mass of 41 ± 10 $M_\odot$, while the evolutionary mass is in the range 33–44 $M_\odot$. Figure 5 gives an idea of the comparison of UIT 005 with evolutionary tracks and with other stars in M33. Clearly, the position is consistent with a spectrum showing weak O lines as a consequence of advanced evolution.

The full power of the extragalactic stellar spectroscopy will only be reached when we are able to perform extense analyses of stars all over the surface of the host galaxies. To this end, we have started a program to observe stars over M33, to trace a 2D map of stellar abundances in this galaxy. This way, we expect to be able to asses the detailed abundance pattern in M33, indicating possible differences between arms and interarms regions, or between the center and the outskirts of the galaxy. This project

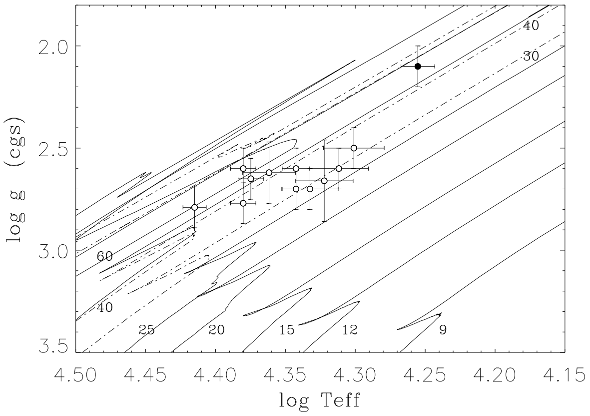

Fig. 5. $T_{\rm eff}$–log g diagram of the stars in M33 analyzed by Urbaneja et al. (2005b), together with the position of UIT 005 (the solid symbol). Temperatures and gravities have been derived from the analysis of the spectra. Labels correspond to the initial stellar masses. Solid lines are for Meynet & Maeder (2003) tracks for solar metallicity, and dash-dotted lines are for Meynet & Maeder (2004) tracks for Z=0.008. The advanced position of UIT 005 is clear in the figure.

is presently being prepared to be accomplished with the multiobject spectrograph OSIRIS to be attached at the GTC. We hope to start this program early 2008, as soon as the GTC begins regular operations.

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DISCUSSION

Y.-H. Chu - Some stars in N11B have IR excess indicating circumstellar envelopes or disk from the star formation process. These need to be taken into account in the FLAMES ... analysis.

A. Herrero - Yes, a circumstellar envelope may have influence on the analysis if it emits in the continuum and dilutes the spectral lines, or if it absorbs some light and modifies the measurement of the magnitude. We do not expect large effects at this resolution but will check these stars.

P. Massey - If clumping changes the mass-loss rates by only factors 1–3, this does not bring the mass loss rates calculated from the models into agreement with other measures. What do you think is the remaining problem?

A. Herrero - You are referring to the figure comparing mass loss rate derived from Hα and radio with those derived from the UV (using PV) in which discrepancies are very large. This can be additionally due to the extreme ionization of (photospheres?) through X-rays in the wind.

L. Penny - What was the average amount of "other" broadening present in the Simón-Díaz et al. (2007) study? And was there any metallicity dependence in this amount?

A. Herrero -Allow me a small correction: It is a Simon-Diaz & Herrero paper, and it is still going through the referee process. The amount of extra broadening depends on luminosity class. Dwarfs close to the ZAMS have a broadening dominated by rotation, while the influence of the extra broadening decreases when you move towards earlier types and higher luminosity classes. For evolved stars in the O3-B1 domain the extra broadening can dominate over rotation. Estimations ?? term of an equivalent "turbulent" velocity may run from 20 to 80 $\mathrm{km\,s^{-1}}$, approximately.

N. Walborn - Do you have a nitrogen abundance for UIT005?

A. Herrero - Yes, the star is N overabundant. Unfortunately, we do not have a reliable C abundance. But it is clear that the star has a high [N/O] ratio, indicative of an advanced phase of evolution. Moreover, the derived [N/O] ratio is consistent with that expected from the evolutionary models.

A. Maeder - The "mass discrepancy" problem is likely more the fact that stars are overluminous for their masses, which may be due to various effects.

A. Herrero -Yes, you are right. Presently is more exact to speak about "mass comparison". Most of the stars have evolutionary and spectroscopic masses that agree, and for therest there are effect that we have to explore, but that could explain the difference between both methods.

Virpi learns that a new asteroid has been named after her.