The Oxygen-Abundance Gradient in M33

M. I. Monteverde

Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain

Abstract. We report preliminary results on the stellar oxygen-abundance gradient in M33. Using B-type supergiants located at different galactocentric distances, we have analysed the O II-line spectra using non-LTE model atmospheres and line-formation calculations. We obtain an oxygen abundance gradient of -0.2 ± 0.1 dex kpc^{-1}, and compare this result to those derived using Galactic H II regions.

1. Introduction

Supergiants have been always considered of great interest in many fields of astrophysics, such as stellar evolution and abundance studies in different stellar environments. Detailed knowledge of the stellar parameters and chemical compositions of supergiants are needed to help guide these studies. Furthermore, with the Wind-momentum–Luminosity Relationship (WLR; see Kudritzki et al. 1992, 1995) it should be possible to determine the luminosity of supergiants, and therefore their distances, so they also have importance as distance indicators. However, the WLR is metallicity dependent, as pointed out by Puls et al. (1996), so it must be calibrated in terms of this parameter before using it for stars in other galaxies.

It is therefore important to extend this kind of study to other galaxies. Blue supergiants in the Local Group are ideal to do galactic astronomy in an extragalactic environment since they are the visually brightest stars in the galaxies, and in the Local Group one finds a wide range of metallicities and objects in all stages of evolution. So, after the Galaxy and the Magellanic Clouds, it is the turn of M31 and M33, which are, with the Milky Way, the large spiral galaxies in the Local Group; both also present strong abundance gradients. Between these two galaxies, M33 has several advantages over M31, namely its inclination (it is more face on), and its supergiants are visually brighter. So we have begun a programme to observe and analyse B-type supergiants in M33.

2. Observational Data

2.1. Photometry and Selection of Targets

In order to select the stars suitable for this work we used the M33 stellar-photometry studies by Humphreys & Sandage (1980) and Ivanov et al. (1993).

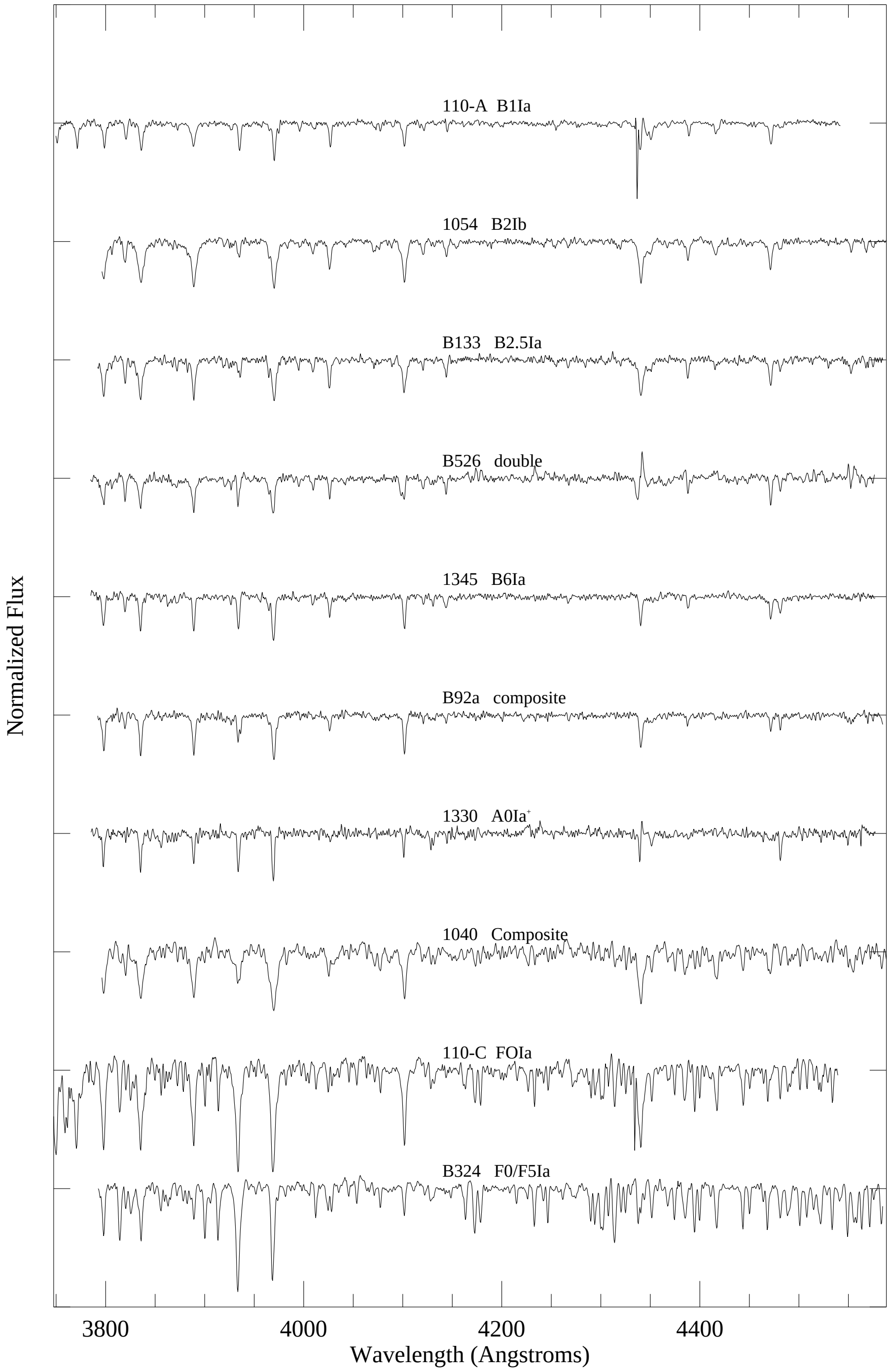

Figure 1. The blue spectra of the targets stars. Data are taken from Monteverde et al. (1996), where a discussion of the spectral types can be found.

We chose those blue stars with $m_V < 18$ and with colours corresponding to B-type stars.

2.2. Spectroscopic Observations

Spectra for ten stars were obtained in 1994 at La Palma by using the 4.2-m William Herschel Telescope and ISIS spectrograph. The spectral resolution is about 2Å. Each star was observed in two wavelength regions; the blue one (4000–4600Å) contains most of the features important to classify and analyse B-type supergiants. The other region is that of Hα, which is a luminosity-sensitive line and also a wind-diagnostic line. Details of the observations and Hα spectra can be found in Monteverde et al. (1996). Here, only the blue spectra are shown, in Fig. 1.

3. Spectral Classification

Once we obtained the spectra we proceeded to classify them, but spectral classification of stars in M33 it is not easy, because we need a spectral-classification system which is metallicity independent. The MK classification system is defined in terms of Galactic standards, so if we use it to classify stars of other galaxies (which might have a different metallicity) it may result in a wrong spectral type and a wrong luminosity class. This is because metal lines are important criteria to classify stars, and also metal lines are positively correlated with luminosity.

Lennon (1997) has devised a new classification system for supergiants in the Small Magellanic Cloud (SMC) which takes into account the low metallicity of this galaxy. The correspondence between these two systems is such that stars with similar physical parameters, metallicity aside, have the same spectral types.

Both classification systems were used to classify the M33 programme stars; that is, standards at Galactic metallicity and standards at SMC metallicity. We avoided using the strength of metal lines and paid attention to ratios of lines of the same elements but different ionization states, such as silicon, or to other metal lines, such as Mg II and O II. The hydrogen lines, Hα and Hγ, were used as luminosity-class indicators.

We have to say that not all the spectra are from isolated stars; there are some composite spectra, as can be seen in Fig. 1.

4. Stellar-Abundance Gradients

Radial abundance gradients in spiral galaxies are an important diagnostic in the study of galaxy evolution. As we know from studies in our Galaxy, spectroscopic analysis of B-type stars is an excellent way of determining abundances – see the very recent work on the abundance gradient in the Galaxy by Smartt & Rolleston (1997), and references therein.

Here, we are dealing with M33, for which there are several abundance studies based on H II surveys (see, e.g., Smith 1975; Kwitter & Aller 1981; McCall 1982; Vilchez et al. 1988). These studies have been summarized by Vila-Costas et al. (1992) and Henry & Howard (1995), and all of them establish relatively

Table 1. Programme stars. Identification numbers are taken from Ivanov et al. (1993; first column) and Humphreys & Sandage (1980; second column). The projected galactocentric distances, ρ, are in arcminutes.

Star Id.		Assoc	ρ	Sp. type
1054		OB142	$1'.0$	B2 Ib
0515	B133	OB31	$9'.4$	B2.5 Ia
1345		OB109	$16'.7$	B6 Ia
0785	110A	OB110	$17'.1$	B1 Ia^{+}

Table 2. Adopted atmospheric parameters for the programme stars.

Star Id.		Sp. Type	Adopted $T_{\rm eff}$	$\log g$
0785	110A	B1 Ia^{+}	22 500	2.50
1054		B2 Ib	20 000	2.50
0515	B133	B2.5 Ia	17 500	2.25
1345		B6 Ia	12 500	1.25

well an abundance gradient for oxygen in M33. It is therefore important to check if the gradient determined from H II regions is echoed by stellar spectroscopy.

The first results on stellar metal abundances in M33 were obtained by McCarthy et al. (1995), who reported Fe and Ti abundances for two A supergiants. We have undertaken a study of abundance gradients in M33, using B supergiants to compare with the results from emission-line spectra of H II regions. Thus, we have selected four targets classified as early B-type supergiants which are at different distances from the centre of M33. The spectral type, OB association, and galactocentric distance of each star under consideration are listed in Table 1.

5. Method of Analysis

Our studies are based on non-LTE, plane-parallel geometry in hydrostatic and radiative equilibrium. It is well known that the atmospheres of B supergiants are affected by stellar winds, so it would be more reliable to consider spherical geometry and hydrodynamic models. Then, however, we would be unable to obtain absolute metallicities, which need realistic physical models. Rather, we will concentrate on a non-LTE differential analysis relative to Galactic standards. Such a differential analysis relies on comparing each star to the appropriate Galactic standard, ensuring that both have similar parameters.

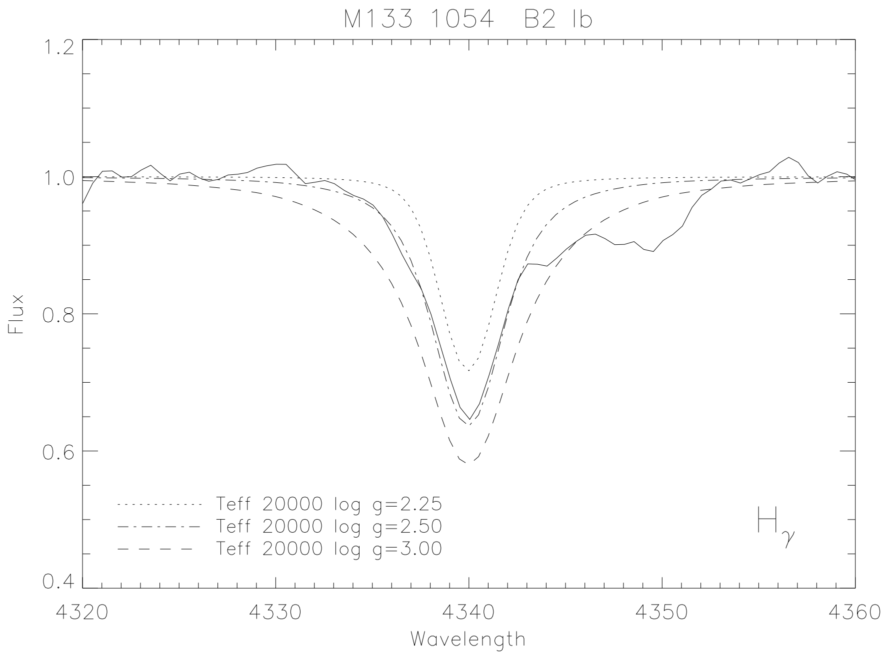

Figure 2. Example of surface-gravity determination.

5.1. Determination of Stellar Parameters

Effective temperatures for the observed B stars were deduced from their spectral types by using a temperature scale based on non-LTE calculations. For each adopted temperature we constructed a grid of gravities and chose that value which best fits Hγ; an example is shown in Fig. 2. We have assumed a normal helium abundance. The adopted atmospheric parameters are listed in Table 2.

5.2. Metal Abundances

We generated non-LTE model atmospheres for each star with the atmospheric parameters listed in Table 2. The subsequent non-LTE line-formation calculations were performed using the programs DETAIL and SURFACE. As regards the oxygen model atom, we used that set up by Becker & Butler (1988). Non-LTE curves of growth were constructed by using a range of oxygen abundances and microturbulent velocities, ξ. To estimate ξ we require a large number of lines of the same species available for measurement, which we do not have in our spectra, so to determine the microturbulence we assumed that the Galactic standard stars under consideration, all being in the solar vicinity, have solar oxygen abundances.

We chose the λ4366Å line for the first calculations because it is the strongest O II line in our spectra. We measured the equivalent widths of this line from the observed spectra of the M33 stars and their Galactic and SMC counterparts. Figure 3 is an example of the method of analysis, and shows curves of growth for different values of ξ. We adopted that microturbulence which gives solar abundance for the Galactic star. The first results can be found in more details in Monteverde et al. (1997).

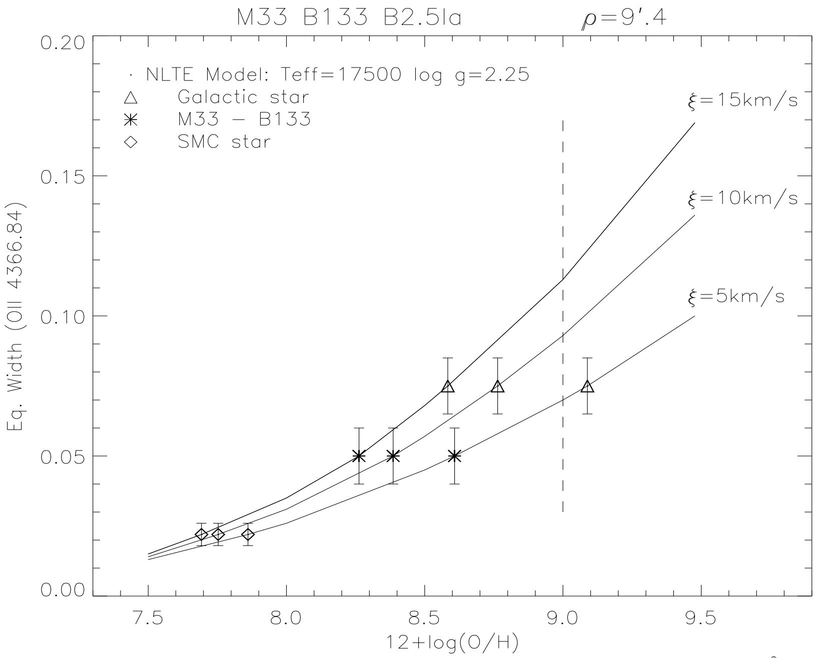

Figure 3. Non-LTE curves of growth for the oxygen $\lambda 4366$Å line, using three different microturbulence values. Vertical bars represent the error in the equivalent-width measurements. The dashed line indicates the solar oxygen abundance.

We continued the work by adding other O II lines to the calculations, such as $\lambda\lambda 4317$, 4319, and 4661Å. Figure 4 shows the results from the analysis with more than one line, and also those when only one line was taken into account.

6. Oxygen Abundance Gradient in M33

The differential abundance estimates are listed in Table 3, along with the adopted ξ values and the number of O II lines used for the analysis. Errors refer to the mean sample standard deviation. The exponential gradient functions in terms of the galactocentric distance, in kpc (R_g) and in arc-minutes (ρ), are:

$$\log(\mathrm{O/H}) - \log(\mathrm{O/H})_\odot = 0.2(\pm 0.1) - 0.2(\pm 0.1) R_g$$

$$\log(\mathrm{O/H}) - \log(\mathrm{O/H})_\odot = 0.2(\pm 0.1) - 0.04(\pm 0.02) \rho$$

A comparison of our results (asterisks) with those from H II studies (lines) is made in Fig. 5. We can conclude that a preliminary stellar oxygen abundance gradient has a slope of -0.2 ± 0.1 (dex/kpc), which is in good agreement with the H II-region results from Henry & Howard (1995; -0.22 ± 0.09 dex/kpc), and in reasonable accord with those from Vila-Costas (1992; -0.10 dex/kpc). The central regions of M33 seem to have metallicities above solar.

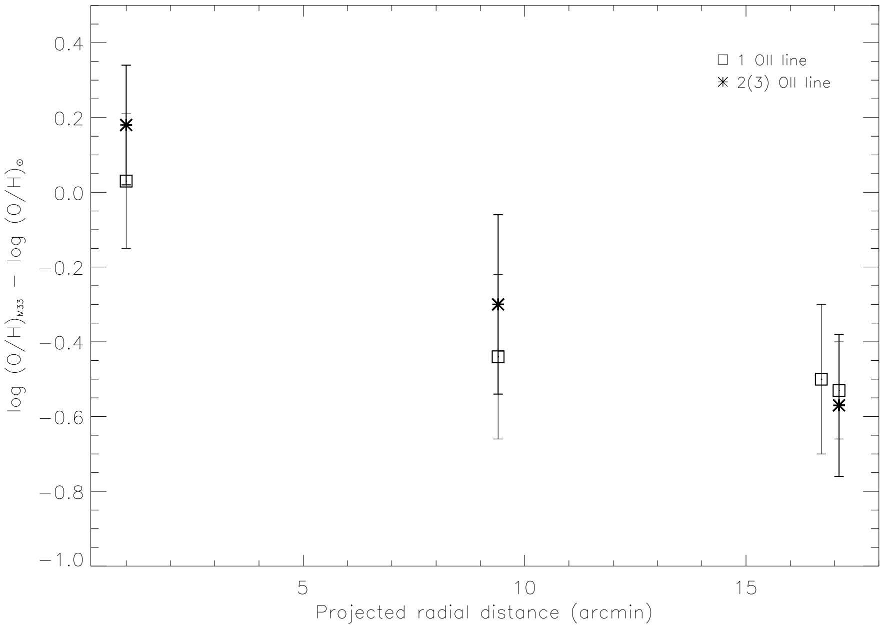

Figure 4. Differential oxygen abundance as a function of galactocentric distance for M33 stars. Symbols are: □, mean analyses done with only one O II line; $*$, more than one line considered.

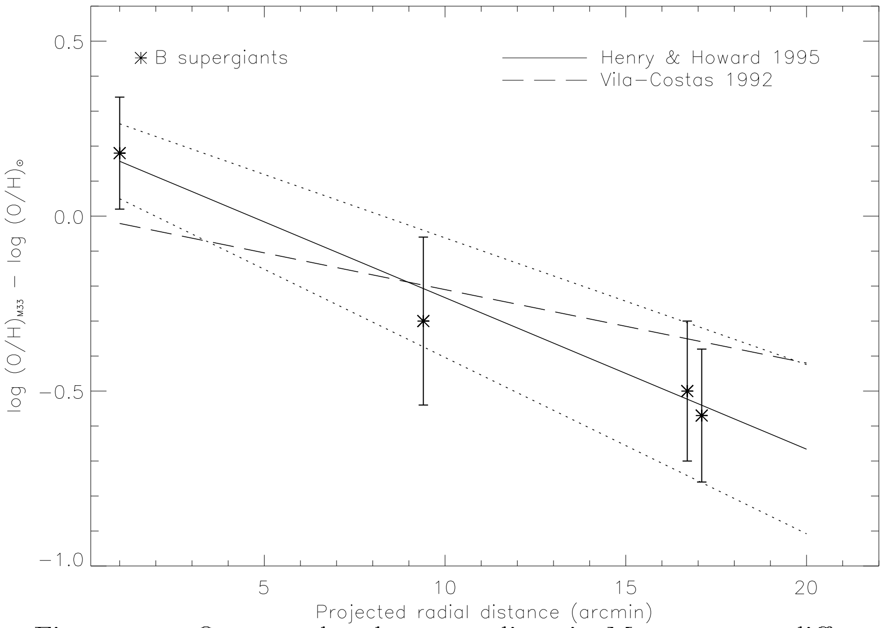

Figure 5. Oxygen abundance gradient in M33: oxygen differential abundance, $\log(\mathrm{O/H})_{\mathrm{M33}} - \log(\mathrm{O/H})_{\odot}$, as a function of galactocentric distance for M33 stars and H II regions. The gradients from H II-region analyses are represented by lines (dotted lines indicate errors).

Table 3. Non-LTE differential oxygen abundances for the programme stars compared to Galactic standards. R_g is the galactocentric distance and ρ the projected distance; n denotes the number of oxygen lines used.

Star	Id.	ρ (arc-min)	R_g (kpc)	n	ξ (km s^{-1})	log (O/H)− log (O/H)$_\odot$
1054		1.0	0.21	2	7	0.18± 0.16
0515	B133	9.4	1.98	2	5	−0.30± 0.24
1345		16.7	3.50	1	18	−0.50± 0.20
0785	110A	17.1	3.60	3	13	−0.57± 0.19

7. Future Work

We will continue this work by studying more stars at different radial distances; there are two more M33 B-type supergiants under analysis. Moreover, it will be necessary to obtain more reliable, though still differential, stellar parameters. The ionization balance of silicon will be considered to derive effective temperatures, instead of adopting them from the spectral classifications. Also, we will use silicon lines to improve the microturbulence determination. It will then be possible to determine silicon and magnesium abundances and compare them with oxygen gradient.

Acknowledgments. The work described above has been made possible by the invaluable help of Dr. A. Herrero. I am also grateful to Dr. D. J. Lennon and Prof. R.-P. Kudritzki for helpful discussions and information. The William Herschel Telescope is operated on the island of La Palma by the RGO in the Spanish Observatorio de El Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

References

Becker, S. R., Butler, K., 1988, A&AS, 201, 232

Henry, R. B. C., Howard, J. W., 1995, ApJ, 438, 170

Humphreys, R. H., Sandage, A., 1980, ApJS, 44, 319

Ivanov, G. R., Freedman, W. L., Madore, B. F., 1993, ApJS, 89, 85

Kudritzki, R. P., Hummer, D. G., Pauldrach, A. W. A., Puls, J., Najarro, F., Imhoff, J., 1992, A&A, 257, 655

Kudritzki, R. P., Lennon, D. J., Puls, J., 1995, in Science with the VLT, eds. J. R. Walsh & I. J. Danzinger (Springer), p. 246

Kwitter, K. B., Aller, L. H., 1981, MNRAS, 195, 939

Lennon, D. J., 1997, A&A, 317, 871

McCall, M. L., 1982, PhD Thesis, University of Texas

McCarthy, J.K., Lennon, D.J., Venn, K.A., Kudritzki, R.P., Puls, J., Najarro, F., 1995, ApJ, 455, L135

Monteverde, M.I., Herrero, A., Lennon, D.J., Kudritzki, R.P., 1996, A&A, 312, 24

Monteverde, M.I., Herrero, A., Lennon, D.J., Kudritzki, R.P., 1997, ApJ, 474, L107

Puls, J., Kudritzki, R.P., Herrero, A., Pauldrach, A.W.A., Haser, S.M., Lennon, D.J., Gabler, R., Voels, S.E., Vilchez, J.M., Watcher, S., Feldmeier, A., 1996, A&A, 305, 171

Smartt, S.J., Rolleston, W.R.J., 1997, ApJ, 481, L47

Smith, H.E., 1975, ApJ, 109, 591

Vila-Costas, M.B., Edmunds, M.G., 1992, MNRAS, 259, 121

Vilchez, J.M., Pagel, B.E.J., Díaz, A.I., Terlevich, E., Edmunds, M.G., 1988, MNRAS, 235, 633

Discussion

Barlow: How luminous are your targets? Could CNO-processed material be exposed at the surfaces, depressing the observed oxygen abundances?
Dufton: Changes in oxygen are relatively small.
Monteverde: The apparent magnitudes are around 16...
Kudritzki: ...so with a distance modulus of 24, the absolute magnitudes are around -8. These *are* very luminous stars, so there could be contamination, but oxygen is the last element to respond in CNO processing. My guess would be that you'd see effects in the carbon and nitrogen lines first.