

Parameters of massive stars in the Milky Way and nearby galaxies

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Abstract: We present in this contribution a review of recent results of parameters of massive OB stars in the Milky Way, the Magellanic Clouds and nearby spirals. The review is timely because of the strong lowering of the temperature scale of Galactic OB stars produced by the new model atmospheres, including sphericity, blanketing and mass-loss, that are also discussed, and because of the boost suffered by extragalactic stellar physics in the last years. The effects on the determination of mass-loss and the Modified Wind Momentum-Luminosity Relationship are discussed, and a comparison with evolutionary models is provided. We finally present a comparison of abundances from OB stars and H II regions in Orion and M33.

1 Introduction

Massive stars play a key role in many astrophysical fields, from the interaction with their surrounding medium to the origin of GRBs and the possible reionization of the Universe. Therefore, the interpretation of a large number of data and observations relies on our knowledge of the stellar parameters and evolution of these stars. This, on the other hand, is very model dependent. A simple example may be given by the energy emitted by a starburst region. Assuming that this is the energy emitted by the recently formed stars, the derived IMF will depend on the prediction of the stellar emergent fluxes for stars of a given mass. This relation, on the other hand, will rely not only upon our calibration of effective temperature against spectral type, but also on the wind density of the star.

2 The new temperature scale for Galactic massive OB stars

Since NLTE models are available, the temperature scale of massive OB stars has been determined using model atmospheres to fit a given ionization equilibrium. Helium, being the atom used to spectroscopically classify the earliest stars, has become the traditional temperature indicator for these objects. Of course, the resulting temperature scale is model dependent.

Very recently a number of calculations from different authors have strongly changed the temperature scale of massive OB stars. These calculations have been based on new families of model

atmospheres that include sphericity, mass-loss and line-blanketing, in addition to NLTE. The combination of all these factors results in temperatures that are much cooler than those hitherto assumed.

Vacca et al. (1996) presented a compilation of the spectroscopic determinations of effective temperatures of massive OB stars. They gave preference to the most recent calculations, that at that time were mostly based on plane parallel, hydrostatic, unblanketed model atmospheres. Their temperature scale for supergiants can be seen in Fig. 1-left.

The first calculations pointing to a cooler temperature scale were those from Martins et al. (2002), who used CMFGEN (Hillier & Miller 1998), a code with all the improvements indicated above. These authors limited their calculations to OB dwarfs, so that the influence of mass-loss effects were negligible. Therefore, the main differences with Vacca et al. were clearly due to line-blanketing. These differences could reach up to 4000 K for early types, and decreased towards O9 and B0 types.

The work from Martins et al. was followed by a series of papers with similar results. Herrero et al. (2002) gave a temperature scale for supergiants in Cyg OB 2 using FASTWIND (Santolaya-Rey et al. 1997; Puls et al. 2005), another code with NLTE, sphericity, mass-loss and (in this case approximated) line-blanketing. They found differences up to 8000 K. In this case both mass-loss and line-blanketing, played a role. These authors also showed that two stars with the same spectral type and luminosity class may have different effective temperatures if their wind densities are different. Repolust et al. (2004) presented an analysis of 24 stars, based on a slightly improved version of FASTWIND that confirmed these trends. These same trends have also been confirmed by Martins et al. (2005) who have calculated models with CMFGEN and have given a new temperature scale for massive OB stars of different luminosity classes. These temperature scales agree quite well with those from Repolust et al., and confirm that new models result in effective temperatures that are several thousands Kelvin cooler for early and intermediate spectral types, decreasing towards late spectral types. The different temperature scales can be seen in Fig. 1-left.

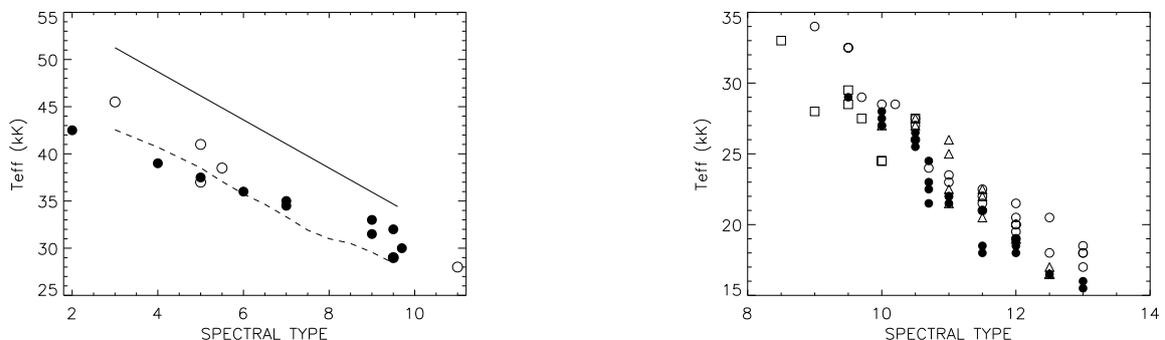


Figure 1: **(Left)** The temperature scale for Galactic O supergiants. The solid lines are for the Vacca et al. (1996) scale, the dashed line for the scale defined by Martins et al. (2005) (the one the authors define as the theoretical scale), filled symbols are data from Repolust et al. (2004) and open symbols are data from Herrero et al. (2002). **(Right)** Temperature scale for B supergiants in the Galaxy and the Magellanic Clouds. Circles are for the Galaxy: open, for McErlean et al. (1999) and solid for Crowther et al. (2005). Triangles are for the SMC (Trundle et al. 2004, 2005) and squares for the LMC (Evans et al. 2004)

OB stars in the Magellanic Clouds have been analysed by Massey et al. (2004, 2005) using FASTWIND. Their results confirm that supergiants are 3000–4000 K cooler than dwarfs of the same spectral type at any metallicity. However, a clear trend of temperature with metallicity at a given spectral type and luminosity class is not seen: authors obtain that SMC dwarfs and supergiants are hotter than Milky Way counterparts, but while LMC dwarfs seem to extend the SMC scale, LMC supergiants seem to extend the Milky Way scale.

For types O9–B0 there is no clear difference between temperature scales from different authors

or metallicities. It is then not strange that a comparison of temperatures scales for B supergiants results in no apparent difference between Galactic (from McErlean et al. 1999, Crowther et al. 2005), LMC (Evans et al. 2004) and SMC analyses (Trundle et al. 2004, 2005), although the new results for Galactic B supergiants by Crowther et al. (2005) indicate for them lower temperatures than the older (plane-parallel and hydrostatic) scale from McErlean et al. We can see all these scales in Fig. 1-right. The very large scatter at a given spectral type and the low number of data points, which can be attributed to the different wind densities, mask any effect due to metallicity.

The change in the temperature scale has been due to the spectacular progress on the development of the model atmospheres, which has been essentially driven by allowing the treatment of metal line blanketing. The effects of line blanketing were anticipated several decades ago (e.g., Mihalas, 1978) and have been incorporated in a number of modern codes. Results presented in this review are mainly based on FASTWIND (Puls et al. 2005) and CMFGEN (Hillier & Miller 1998). The reader is referred to Herrero & Najarro (2005) for more details about this ensemble of codes, and to Puls et al. (2005) for a thorough discussion concerning the description of the above codes and a detailed comparison of FASTWIND and WM-Basic (Pauldrach et al. 2001) and CMFGEN.

Figure 2 displays the effects of line blanketing on the He and H ionization structure of a O3If star. For the case presented in Fig. 2 we have selected three different models. The first one (solid) corresponds to a blanketed model with $T_{\text{eff}}=45.5\text{kK}$, $\log g=3.7$ and $R=15.6R_{\odot}$. The second model (dashed) has same parameters but no blanketing, while the third one (dash-dot) is hotter $T_{\text{eff}}=50\text{kK}$, $\log g=3.8$ and $R=14.6R_{\odot}$ and reproduces equally good the observed spectra of the O supergiant as well as the observed V magnitude. All models have the same wind-strength parameter $Q = \dot{M}/(R_*v_{\infty})^{1.5}$.

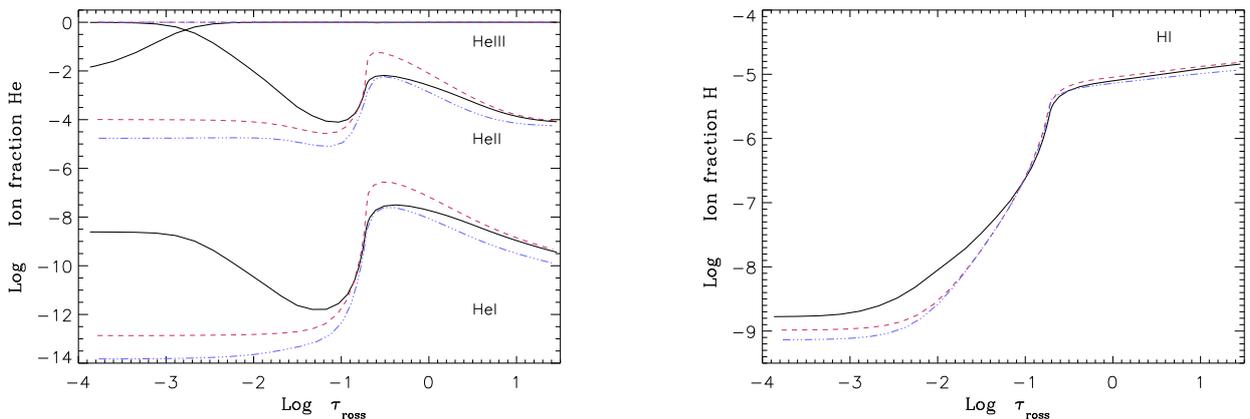


Figure 2: Effects of line blanketing on the helium (**left**) and hydrogen (**right**) ionization structure of a O3If supergiant.

From Fig. 2 we see that blanketing (solid) severely enhances the He ionization in the line formation region with respect to the cool unblanketed model (dash), so that a degree of He ionization similar to the hot unblanketed model (dash-dot) is obtained by decreasing T_{eff} by almost 5000 K. As the flux is blocked and a certain amount of photons are backscattered, flux (luminosity) conservation demands a more efficient diffusion in the inner photosphere. Since this effect is controlled by the temperature gradient (diffusion approximation) the temperature is increased in this region (back-warming). In other words, the basic diagnostic for temperature determinations in O stars, namely the He ionization balance reacts strongly to blanketing and causes the observed reduction on the effective temperature scale. Inspection of the impact of blanketing on the H ionization structure of O stars (Fig. 2-right) tells us that only minor changes are produced in the ionization degree of H and, therefore, only small variations should be expected in the inferred mass loss rates (assuming they are derived from $H\alpha$, as He II 4684Å would be severely altered). Finally, it should be noted that the relatively strong wind of the star blocks the He II ionizing radiation and forces recombination of He III to He II, with important implications on the number of He II ionizing photons.

Given the importance of blanketing and the strong revision to stellar parameters that the inclusion of this effect has led to, it is crucial to compare thoroughly different atmospheric codes and check for consistency among them. Important cross-tests have been carried out for each code (see Puls et al. 2005). Encouragingly, excellent agreement is found throughout most of the parameter domain among these codes.

3 Mass loss in massive stars

3.1 The Wind Momentum Luminosity Relation (WLR)

Since the winds of hot stars are driven by radiation, one should expect a tight relationship between the mechanical momentum of the stellar wind and the photon momentum. Actually, the theory of radiative driven winds (Castor et al. 1975; Abbott & Klein 1975; Pauldrach et al. 1986; Kudritzki et al. 1989) predicts that the “modified stellar wind momentum” depends directly on luminosity through the Wind Momentum Luminosity Relation (**WLR**)

$$\log D_{mom} = \log D_0 + x \log(L/L_\odot), \quad D_{mom} = \dot{M}v_\infty (R_*/R_\odot)^{0.5} \quad (1)$$

where the coefficients D_0 and x are a function of spectral type and luminosity class. Further, the coefficient controlling the dependence on luminosity, x , is determined by the statistics of the thousands of metal lines driving the wind, so a different WLR has to be established for each metallicity environment (see Kudritzki & Puls 2000, for a thorough discussion). During the last decade an enormous effort has been made to calibrate the WLR as function both of spectral type and metallicity and compare the results with the predictions by theory (Puls et al. 2000; Vink et al. 2000, 2001).

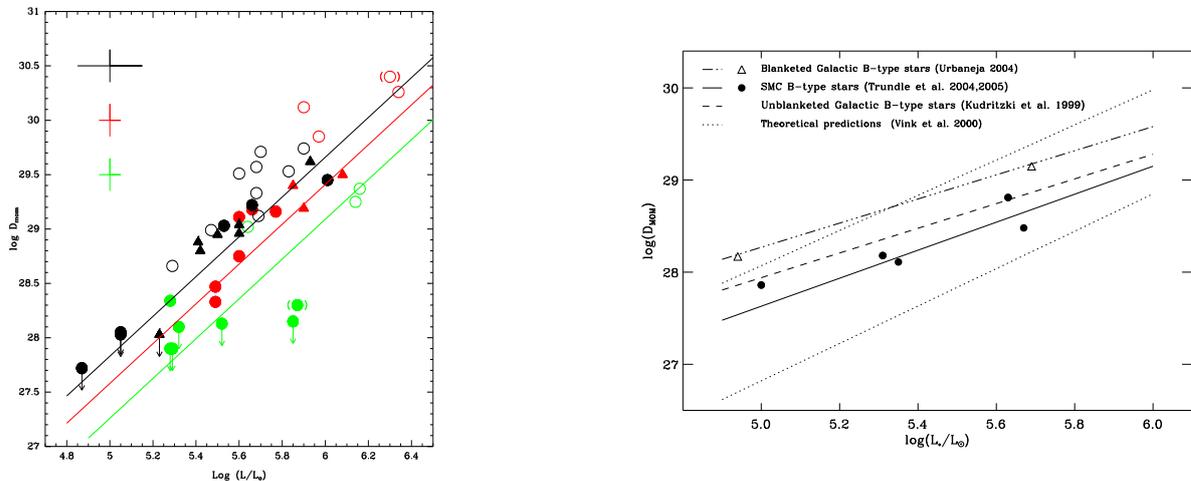


Figure 3: Metallicity scaling of the WLR for O and B supergiants. **(Left)** Z scaling for O supergiants (adapted from Massey et al. 2005). **(Right)** Z scaling for B supergiants (Kudritzki et al. 1999; Urbaneja 2004; Trundle et al. 2005). (dash-dot): linear regression to galactic stars with blanketed models (Urbaneja 2004); (dashed): unblanketed galactic (Kudritzki 1999); (solid): blanketed SMC (Trundle et al. 2005); (upper dotted) theoretical galactic predictions (Vink et al. 2000); (lower dotted) theoretical SMC predictions (Vink et al. 2001). Note the considerable correction to the modified wind momenta for B-supergiants due to line blanketing

Results on the metallicity dependence of the WLR for O stars and B supergiants and their comparison with theoretical predictions are displayed in Fig. 3. From Fig. 3-right we see how the modified momenta of galactic B-supergiants obtained with blanketed models (Urbaneja 2004) agree much better with theoretical predictions than those obtained with unblanketed models (Kudritzki et al. 1999),

although a significantly different slope is obtained. The whole worsens in the case of the SMC, where the WLR obtained from blanketed models (Trundle et al. 2005) differs severely from theoretical predictions (Vink et al. 2001). In the case of O stars, the situation is significantly improved. From Fig. 3-left (see Massey et al. 2005, and references therein) we see how the theoretically predicted WLRs for O stars in the Galaxy, LMC and SMC are reasonably well reproduced by spectroscopic studies.

3.2 Clumping

From Fig. 3-left, we also note, however, that some of the supergiants present “too large” modified momenta (higher mass loss rates). This effect was realized by Herrero et al. (2002). Repolust et al. (2004) confirmed this effect and suggested that clumping could account for excess of modified momenta on those supergiants showing $H\alpha$ in emission (see Fig. 4). Hence the presence of clumping in the wind, i.e. the region where $H\alpha$ emission was arising would lead to an overestimate of the true mass loss rate of the star. The existence of clumping was postulated on theoretical grounds by Owocki et al. (1988), who showed that radiation driven winds are inherently unstable and that would lead to the formation of a highly structured wind (clumping). Observationally, evidence of clumping in O stars has been found on the far ultraviolet P v line (Crowther et al. 2002; Hillier et al. 2003; Massa et al. 2003) and in the infrared continua (Blomme et al. 2002, 2003). Thus, assuming that wind inhomogeneities were responsible for the observed discrepancies in O supergiants, Repolust et al. (2004) estimated that a clumping factor of $f=0.2$ (leading to a correction of -0.36 dex in the modified wind momenta of these stars) was enough to account for these “outliers”. These results of these clumping corrected momenta are shown in Fig. 4 and provide much better agreement with the theoretical predictions.

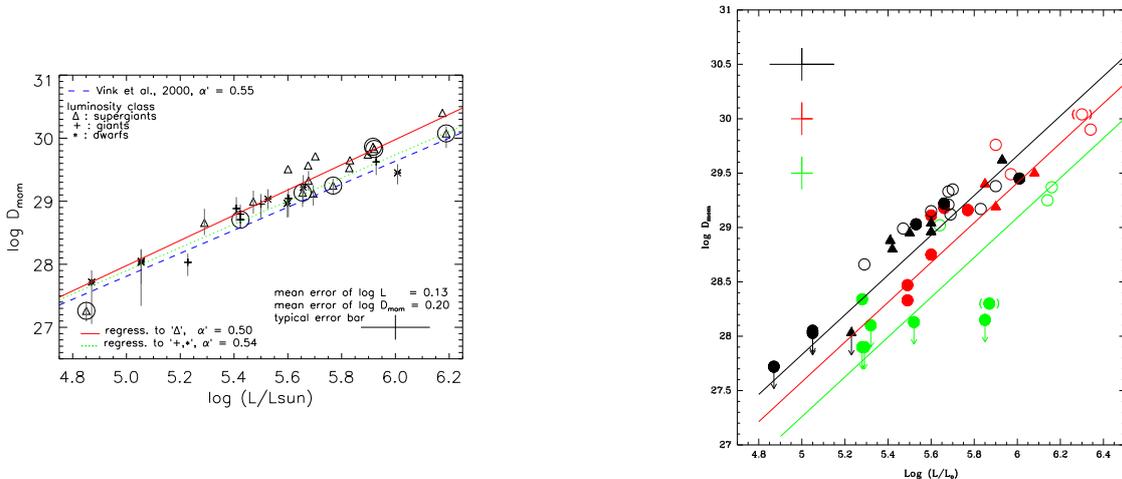


Figure 4: Hints of Clumping WLR. **(Left)** Galactic WLR for O stars (from Repolust et al. 2004). The enhanced modified momenta obtained for the supergiants showing emission in $H\alpha$ suggest the presence of clumping in the winds of these stars. **(Right)** Z dependent clumping corrected WLR for the Galaxy, LMC and SMC (from Massey et al. 2005). The mass loss rates of the stars showing $H\alpha$ in emission have been corrected assuming a clumping value of $f=0.2$

3.3 Thin winds

Puls et al. (1996) showed that the observed WLR for O-type dwarfs exhibited a severe curvature toward very low wind momenta for luminosities lower than $\log L/L_{\odot} = 5.3$. Herrero et al. (2002) obtained a very low value for the mass-loss rate of the O9.5V star 10 Lac (more than one order of magnitude below the theoretically predicted), and recently Bouret et al. (2003) and Martins et al. (2004, 2005b) have obtained similar results on analysis of O dwarfs in the SMC and the Galaxy.

Therefore, there is a breakdown of the WLR for low luminosity O dwarfs. One important conclusion from the above studies is that the discrepancy in the mass loss rates obtained seems not to be related to metallicity, as it is present on both the Galactic and SMC stars.

However, present results based on UV studies may suffer from effects such as X-rays, advection or adiabatic cooling, whereas most mass-loss rates for dwarfs derived so far are only upper limits, due to the insensitivity of the usual mass-loss estimator $H\alpha$ on low mass-loss rates. Consequently, a detailed investigation by means of *sensitive mass-loss diagnostics* in dwarfs over a larger sample is crucial to confirm their very weak-wind nature. $B\alpha$ may well be this diagnostic, in view of its strong sensitivity to \dot{M} , particularly for very weak winds (see Najarro et al. 1998, Herrero & Najarro 2005).

4 Comparison with evolutionary models: the mass discrepancy

One of the best ways to advance in our knowledge is the comparison of results from different theories and models. The comparison of evolutionary and atmosphere models is a permanent source of inspiration for new findings and improvements in these models.

Herrero et al. (1992) found in the first extensive NLTE analysis of massive O stars that the masses derived from the spectroscopic analysis were systematically lower than those derived from the evolutionary tracks after placing the stars on the Hertzsprung-Russell Diagram. The difference between the evolutionary and spectroscopic masses, that they called *mass discrepancy* was too large to be attributed to uncertainties in the determined parameters, and therefore a systematic effect due to some failure in the models, either atmospheric or evolutionary, was suspected.

The new model atmospheres have considerably improved the situation, as can be seen in Figs. 19 and 20 of Repolust et al. (2004) (see also the discussion in Repolust et al. 2004, or Herrero & Najarro 2005). Although the agreement is not perfect, the situation is much better than in the paper by Herrero et al. (1992), where most of the stars were far from the 1:1 relation, particularly the supergiants.

What's the situation in the Magellanic Clouds? One would expect that it should be better, because the major contribution to the error in the Galactic stellar masses (the distance uncertainty) is reduced. Further, the main reason for the failure of the model atmospheres (the presence of strong winds) should have a considerably lower impact in the low metallicity environment of the Magellanic Clouds. However, results from Massey et al. (2004, 2005) do not support this view. These authors find that a large number of stars both in the LMC and the SMC show the mass discrepancy. Even more, the mass discrepancy is found both for dwarfs and supergiants (this is however consistent with winds having a small effect in the discrepancy). This different behaviour of Galactic and Magellanic Clouds comparisons is a new challenge for our knowledge of the stellar structure at different metallicities.

5 Massive stars and H II regions

5.1 Trapezium stars

M42 in Orion is the reference H II region. Very recently, Esteban et al. (2004) have reanalysed the nebular abundances in Orion and found oxygen values only slightly higher than those of the Sun, the F-G dwarfs or the B dwarfs (see their Table 15). In fact the small difference they find is due to the assumption that a small fraction of oxygen is trapped into dust. Thus, Esteban et al. obtain an oxygen abundance in M42 of 8.65 dex for the gas phase, increasing to 8.73 dex when a correction for dust depletion is taken into account.

In view of their interest, Simon-Díaz et al. (2005) have recently newly analysed the Trapezium stars. These objects provide the most direct comparison to M42 abundances. Dwarfs with spectral types close to O9-B0 are ideal for the determination of the oxygen abundance, because they contain

a lot of O II lines. The dominant star in the Trapezium, 1θ Ori C, being an earlier type, has been excluded from this study.

To get an oxygen abundance as accurate as possible Simon-Díaz et al. (2005) set up a very detailed model atom and did a very careful study of the behaviour of each individual multiplet, by following the procedure described in Simon-Díaz et al. for each one of them. This procedure is designed such that it is easy to detect the anomalous behaviour of individual lines within multiplets, whatever the reason (uncertainties in the atomic parameters, unknown blends, etc.). These lines can then be removed from the analysis.

While this is a long way, it is rewarding. Simon-Díaz et al. (2005) have thus obtained the oxygen abundance of Trapezium stars. Their result - an average oxygen abundance of 8.63 ± 0.06 dex - is much lower than other determinations (see Cunha & Lambert 1994) but compares very well with the abundance obtained by Esteban et al. (2004) for the gas phase of M42: 8.65 ± 0.03 dex. This excellent agreement between the results from the spectroscopic analysis of stars and photoionized regions gives us confidence in both kinds of analyses.

5.2 Massive stars in M 33 and NGC 300

Now we can proceed to more difficult tasks, as for example the determination of the stellar radial oxygen gradient in M 33 to compare it with the one obtained from H II regions. The first steps in this direction were given by Monteverde et al. (1997, 2000). However, these authors only analysed four B-supergiants in M 33, while very recently, Urbaneja et al. (2005a) have presented an analysis with 12 M 33 stars. All these authors followed procedures similar to those of Simón-Díaz et al. (2005) (actually Simón-Díaz et al. followed and improved the procedures of these authors). The result, seen in Fig. 5, shows an excellent agreement between the radial oxygen gradient derived from stars and from H II regions (taken from Vilchez et al. 1988). Very recent results from Crockett et al. (2005) confirm these trends. Of course, error bars are now larger in both kind of objects than they were for Orion, and this is affecting the conclusion that we can derive from the data. For the stars this is not a matter of resolution, but more of SNR. An idea of the impressive state-of-the art of extragalactic stellar spectroscopy can be seen in Urbaneja et al. (2005a).

However, these results still have to be improved to place really serious constraints on the chemical evolutionary models of M 33. Firstly, the central steep rise of the oxygen abundance, although present in both sets of data (the recent data by Crockett et al. do not include this region), has to be confirmed, as it relies on only two objects; secondly, data still do not allow to distinguish between a linear gradient throughout M 33, and a different slope in the inner and outer regions (or some other possibility of this kind); and thirdly, actually a radial gradient is not what is needed, as two objects at the same radial distance from the center may actually be kiloparsecs away: a map of isoabundances on M 33 is really needed.

Urbaneja et al. (2005a) not only determined oxygen abundances for the B-supergiants, but also Si and Mg abundances. The abundances of these elements follow the trend displayed by the oxygen abundances, although with shallower gradients. This difference in the gradients cannot be explained at this point using the present theories of stellar and galactic structure and evolution.

The situation in M 31 is less clear. Results from Trundle et al. (2002) and Venn et al. (2000) do not show evidence of a radial O gradient (the former authors obtain a similar result for Si and Mg). This is in apparent contradiction to results from H II regions (see the above authors), but we have to take into account the much more limited range in galactocentric distance of these works and the much less favourable inclination of M 31 as compared to M 33.

M 33 and M 31 do not constitute the limit. The recent work by Urbaneja et al. (2005b) about B supergiants in NGC 300 (at 2.2 Mpc) shows how it is possible to extend this kind of work beyond the Local Group, still obtaining individual abundances of chemical elements in spite of a reduced resolution, although with larger error bars. These authors obtain stellar results that are consistent with H II regions. However, only for a particular calibration of the R_{23} index. In this way, stellar

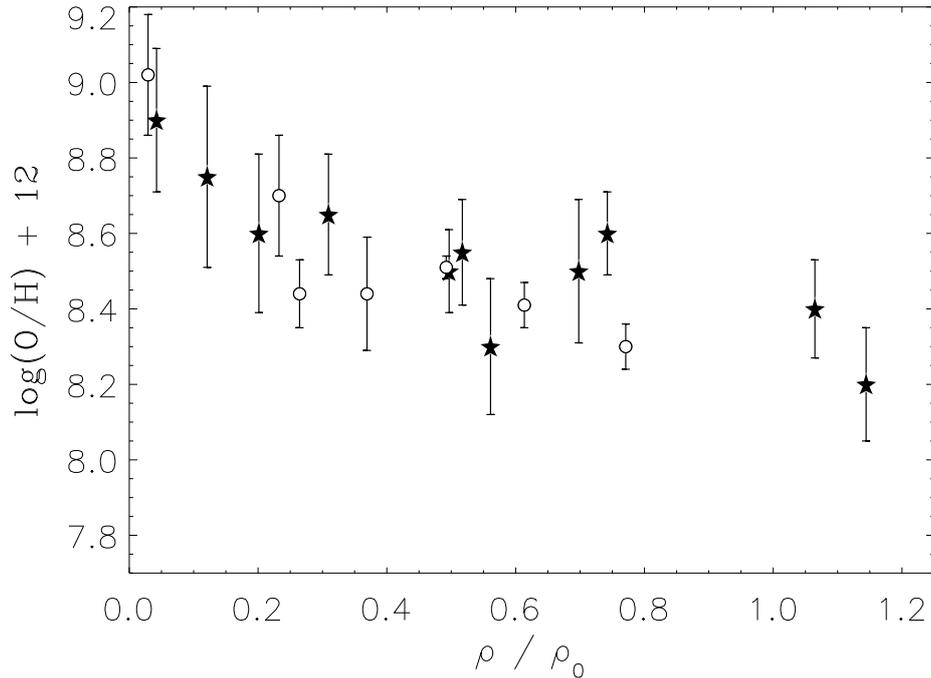


Figure 5: Comparison of the stellar and H II regions radial O gradient in M33. The abscissa gives the deprojected distance to the center of M33 in units of the Holmberg radius ρ_0 (28.77 arcmin). Stars are represented by asterisks, while H II regions are represented by circles (from Urbaneja et al. 2005a)

results not only support the H II regions data (or they don't!), but may also help to distinguish between different calibrations in H II regions.

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