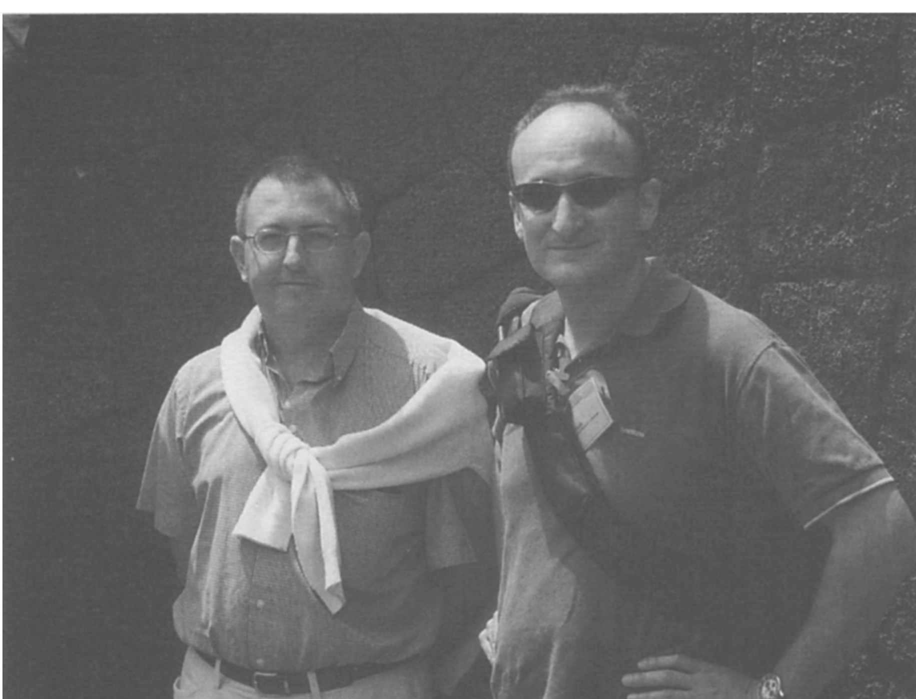
Part 1

Atmospheres of Massive Stars



Artemio Herrero (SOC), and César Esteban (LOC), ready to start

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A Massive Star Odyssey, from Main Sequence to Supernova
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Parameters of massive OB stars

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Abstract. I review our knowledge about effective temperatures and masses of massive OB stars paying special attention to results recently obtained using new atmospheric models including sphericity, mass-loss and line-blanketing. The new temperature scales for O dwarfs and supergiants are lower than previously accepted. No systematic mass discrepancy is found among O supergiants, although individual problematic cases still remain. It is shown that model atmospheres give answers consistent with binary systems. Good agreement is found between theoretical predictions and observations of the Wind Momentum-Luminosity relationship for Galactic O-type supergiants. Finally, I review the status of the WLR in M 33.

1. Introduction

There is a large number of parameters of OB stars that might be discussed. All of them are linked and changes in anyone affect necessarily the results obtained for the others. In this review, I will concentrate on the effective temperatures and the stellar masses. As a natural consequence, radii, luminosities, ionizing fluxes and gravities will also be mentioned. Finally, I will say a few words about the Wind Momentum–Luminosity Relationship (WLR) and its present status in M 33. For other important parameters like abundances the reader is referred to other articles in these Proceedings (see the contributions by Smartt, Venn and Lennon) or to published works (see Penny (1996) or Howarth *et al.* (1997) for rotational velocities; Kudritzki & Puls (2000), for winds, mass-losses and terminal velocities; Walborn (2002) for absolute magnitudes).

2. Stellar parameter determination

For massive OB stars, where the high temperatures preclude the efficient use of photometric methods, the classical way to determine stellar parameters is to use optical spectral lines to construct some fit diagram using the He ionization equilibrium (see *e.g.*, Herrero *et al.* 1992 for details). A classical fit diagram is the $T_{\rm eff}$ - $\log g$ diagram in which we place the points representing best fits for each individual spectral line considered in the analysis. Figure 1 in Herrero, Puls & Najarro (2002) is an example using the O9V star 10 Lac. The Balmer lines are very good indicators of the stellar gravity, while the lines of both He ionization stages are strongly temperature dependent. The point in the diagram where all lines cross determines the adopted parameters and the dispersion around this point gives and indication of their error.

Unfortunately, the fit diagrams that we obtain are not always as clean as the one obtained for 10 Lac. When we go to higher temperatures and wind densities, like those found for example in the O5.5I(f) star Cyg OB2#8A, the He II lines loss sensitivity to temperature and behave more like the H lines, which are now not so good indicators of the gravity because of wind effects. At the same time, the He I lines, although still very sensitive to temperature and gravity, become very weak. The parameter determination is now more complicated and the size of the error box increases. It is thus advisory to use other ionization equilibria and wavelength regions. Works by Crowther & Bohannan (1997), Taresch *et al.* (1997), Crowther *et al.* (2002), Herrero *et al.* (2002) and Bianchi & García (2002) are examples of the combined use of optical and UV data from different satellites, while for the IR I refer to the contribution by Margaret Hanson (these Proceedings). Of course, new criteria have to be carefully tested and calibrated or they will increase the dispersion in the results.

Not all fit criteria can be used under all circumstances. The codes and physics employed will determine the lines that can be used for our fit and the reliability of our parameters. Initially, non-LTE codes had to assume plane-parallel geometry and hydrostatic equilibrium, either using pure H-He models (see Herrero *et al.* 1992), line-blocking (Herrero, Puls & Villamariz 2000) or line-blanketing (Hubeny & Lanz 1995). These codes are limited when used for O-type supergiants and cannot be applied to stars with strong winds. With the development of computers and numerical techniques, there are now several codes that compute model atmospheres with sphericity, mass-loss and wind blanketing, like for example CMFGEN (Hillier & Miller 1998), WM-basic (Pauldrach, Hoffmann & Lennon 2001) and FASTWIND (Santolaya-Rey, Puls & Herrero 1997; Puls, 2002). Other works that contributed to the development effort are those by Gabler *et al.* (1989), that introduced the concept of Unified Model Atmospheres, Schaerer & Schmutz (1994), that pointed out the strong influence of mass-loss in the H/He diagnostic lines or de Koter *et al.* (1996).

3. Effective temperatures

The diagnostic criteria and model atmospheres employed have a large impact on the determined effective temperature. As an example, the derived effective temperature of λ Cep has strongly varied during the last fifteen years. These changes are not related to stellar variability, but to the evolution of our codes.

In this work I will concentrate in the temperature scale of O-type supergiants, although I note that Martins, Schaerer & Hillier (2002) have recently presented a new temperature scale for O-type dwarfs based on EW measurements and CMFGEN calculations. Their temperatures are lower than previous ones by up to 4 000 K, in agreement with the results discussed below for supergiants.

The most recent temperature scale for O-type supergiants is that of Vacca, Garmany & Shull (1996), based on plane-parallel, hydrostatic, pure H/He model atmosphere analyses, mainly published since 1992, while the previous scale by Chlebowski & Garmany (1991), although based on models of similar characteristics, was cooler. The reason has to be found in the improved model atoms (specially He) that were implemented in the late eighties thanks to the introduction of new numerical techniques allowing more atomic levels to be explicitly

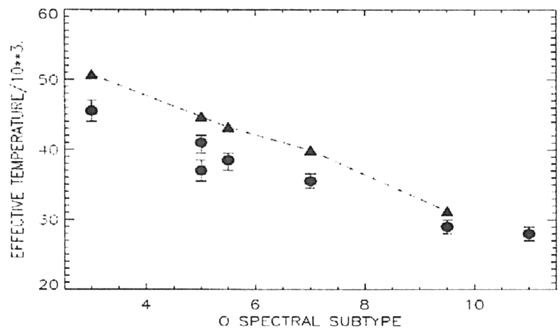

Figure 1. The $T_{\rm eff}$ scale as determined from Cyg OB2 supergiants using non-LTE spherical, line-blanketed models with mass-loss (from Herrero *et al.* 2002, circles) compared to the Vacca *et al.* 1996 scale (triangles).

treated. Usually, the new (upper) levels provided new channels for the electrons to decay to the lower levels, whose populations increased relative to the upper levels of the studied transitions. As a consequence, the corresponding spectral lines (like for example the He I 4387 line) became deeper, and temperatures had to be raised to account for the observations.

3.1. A new effetive temperature scale for O-type supergiants

Very recently, three papers dealing with the temperature scale of O-type supergiants have been submitted: those by Crowther *et al.* (2002), Herrero *et al.* (2002) and Bianchi & García (2002). The first authors analyze Magellanic Cloud supergiants using CMFGEN calculations; the second analyze galactic stars in Cyg OB2 using FASTWIND; finally, Bianchi & García use WM-basic calculations for Galactic O6 stars. Therefore, all authors use different implementations of the same physics: spherical, line-blanketed model atmospheres with mass loss.

I illustrate the results by Herrero *et al.* (2002) in Figure 1, because they cover the spectral range from O3 to B1. We can see that the new determined temperatures are lower than those given by the Vacca *et al.* (1996) scale by up to 8 000 K. We also see that, at a given spectral type, the temperatures of two stars may differ even when accounting for errors.

Other authors have also used spherical codes with mass-loss to determine effective temperatures of Galactic O-type supergiants that can be used for a new temperature scale. We can see in Figure 2 that their results are consistent with those of Herrero *et al.* (2002). Figure 2 also contains the results of Crowther *et al.* on MC O-type supergiants. We see that their temperatures fit well the lower envelope formed by the Galactic stars. Although we would expect the MC stars to be hotter because of the lower metallicity (and consequentely lower opacity) this is again an effect of the larger wind density.

Why are the new temperatures lower? The explanation lies again in the reaction of the diagnostic lines to the new conditions. The new opacities produce a strong blocking of the UV flux and a higher ionization degree of He at the formation depth of photospheric lines. As a consequence, He I lines are now shallower and temperatures have to be lowered in order to fit the observations.

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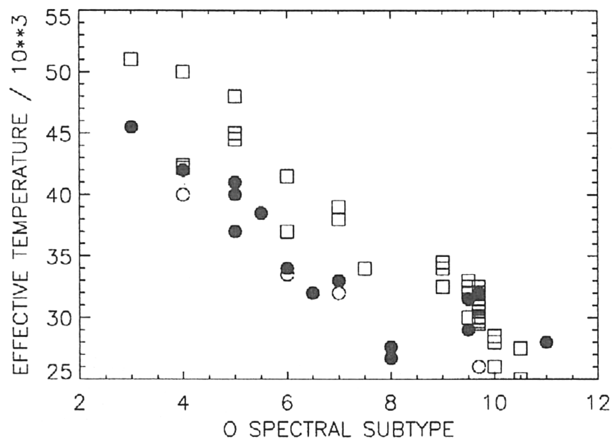

Figure 2. The $T_{\rm eff}$ scale for supergiants using values from different authors. Open squares correspond to Galactic supergiants with plane-parallel, hydrostatic determinations; solid circles correspond to Galactic stars with spherical models with mass-loss and open circles to the Magellanic Clouds stars analyzed by Crowther *et al.* (2002). Spectral subtypes larger than O9.7 correspond to B-type stars.

What's the reason for the dispersion in effective temperature at a given spectral type? A part is due to the fact that the results come from different authors analyzing different samples with different codes and adopting different fit criteria. However, we have seen in Figure 1 that even when this is not the case stars of the same spectral type can have large differences in effective temperature. Metallicity differences may also introduce small changes, but the comparison between Galactic and Magellanic Clouds stars indicates that the actual reason is found in the different wind densities of the stars (see for example Crowther & Bohannan 1997, for a related discussion).

3.2. Emergent fluxes

The strong blocking in the UV, produced when we include metal-line opacities in the new models, increases the emergent optical flux with respect to the models without metals. As a consequence, the observed stellar magnitudes can be fitted with lower temperature models. Equivalently, similar radii are obtained when fitting the observed visual magnitude with the new models at lower temperatures and with the older models at higher ones. Therefore, the luminosities of the O-type stars are reduced by about 0.2 dex in average. A comparison between the emergent fluxes of CMFGEN and FASTWIND shows that both codes agree very well both when metals are included and when they are not. Therefore the above result about the lower luminosities can be considered as well established.

This, of course, affects the ionizing fluxes emerging from the star. A plot of the number of H-ionizing photons per unit surface *vs.* effective temperature for the Cyg OB2 supergiants analyzed by Herrero *et al.* (2002) shows a very good agreement with the prediction of Vacca *et al.* (1996). At first sight, this may be surprising, as the Vacca *et al.* numbers are based on LTE plane-parallel,

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hydrostatic, full-blanketed Kurucz models. The explanation is that to compare per unit surface we have to take away the radius influence. Temperature is then the main parameter and if the opacities are comparable (which is the case when we consider them in a statistical sense) also the spectral flux distributions are similar. Therefore, emergent H-ionizing fluxes compare very well when using line-blanketed models at the same effective temperature, either non-LTE spherical with mass-loss or LTE plane-parallel and hydrostatic.

The situation however changes completely if we consider the total number of H-ionizing photons *vs.* the spectral type. This last property is the one commonly used when dealing with ionizing stars, and as we have seen, the effective temperature *vs.* spectral type scale has to be changed. Therefore, for a given spectral type we have now a lower luminosity, and thus the number of ionizing photons is much reduced as compared to the corresponding Vacca *et al.* calibration. The dispersion at a given spectral type is large, because in addition to the influence of wind density on the derived effective temperature there are also differences in the radii. Although the new total number of H-ionizing photons may be reduced by nearly an order of magnitude in some cases, in others it can be even larger than the value given by the Vacca *et al.* calibration depending on the individual stellar parameters. We conclude that it is very dangerous to adopt statistical values for individual stars.

4. Masses of massive OB stars

Our knowledge of the masses of massive OB stars has been burdened during the last decade by the so-called *mass-discrepancy*. With this term we express a *systematic* difference between the spectroscopic masses (those derived from the analyses of stellar spectra using model atmospheres) and the evolutionary ones (those derived by placing the star in the H-R diagram and reading out the mass from evolutionary tracks). The mass discrepancy was found by Herrero *et al.* (1992) by comparing spectroscopic masses derived from non-LTE plane-parallel, hydrostatic, pure H-He model atmospheres and evolutionary masses derived from evolutionary tracks without rotation.

A review of the data given in Herrero *et al.* (1992) and other values in the literature shows that the problem is found for supergiants, while for dwarfs only a few individual cases are found, not a systematic discrepancy. This may well be related to stellar winds. Herrero *et al.* (1992) found a correlation between the mass discrepancy and the distance of the star to the Eddington limit.

This suggested that the inclusion of sphericity and stellar winds might solve the mass discrepancy, but this was not the case (Herrero *et al.* 1995, 2000), although it helped to reduce the discrepancy. However, with the addition of metal-line opacities in the new models the case for supergiants is similar to the one for dwarfs: a few individual cases still show important discrepancies that need an explanation, but we cannot speak of a *systematic* discrepancy. The reason is that we have increased the gravities (an effect due primarily to the wind) and have reduced the temperature without changing the gravity (an effect due primarily to line-blanketing). These effects increase the spectroscopic mass and at the same time reduce the evolutionary mass (because luminosities are now lower). The final result is an agreement between spectroscopic and evolutionary masses, except for a few cases that have to be individually studied.

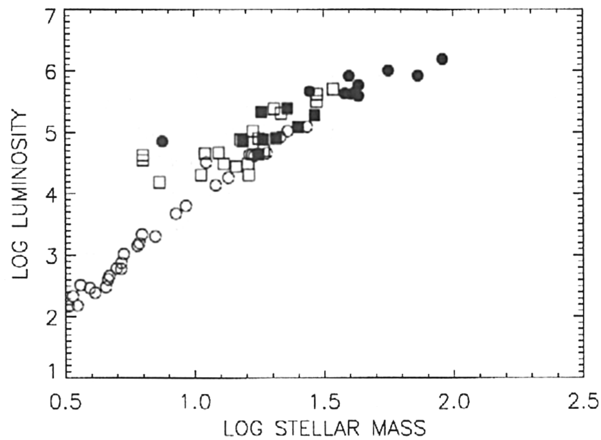

Figure 3. The observed M - L relation from detached binary systems compiled by Ribas *et al.* (2000, open circles), early type systems from different authors (open squares), spectroscopic determinations for O-type dwarfs from Herrero *et al.* (1992, solid squares) and new determinations for O-type supergiants using spherical model atmospheres with mass-loss and line-blanketing (several authors, solid circles). Luminosities are given in solar units.

4.1. Binaries

The best way to test stellar masses is to use binaries. In Figure 3 I have plotted the M - L relation for a number of stellar ensembles. Open circles are values compiled by Ribas *et al.* (2000) from detached binary systems. These are very reliable, and its lower envelope defines the observed M - L relation for stars in the ZAMS. The main drawback of these data is that they only reach a mass of around 30 $M_{\odot}$. I have thus added data for binary systems with early type stars (open squares) collected from the literature (Burkholder, Massey & Morrell 1997; Harries, Hilditch & Hill 1998; Penny *et al.* 2001; Gies & Penny 2002). These data are in general not for detached binary systems, and this is reflected in the fact that the stars are generally found to be overluminous, and fall above the lower envelope defined by the Ribas *et al.* data.

We can now add the stars for which we have derived spectroscopic values. First we can add dwarf data (solid squares). We see that, except for a few cases, dwarfs fit well into the sequence of the Ribas *et al.* data, however without extending much the upper mass. When we add the values determined with the new models for supergiants (solid circles), we see that they nicely extend the Ribas *et al.* lower envelope until masses of about 90 $M_{\odot}$. Of course, the spectroscopic data show a larger scatter around an imaginary line representing the lower envelope to the M - L relation, but this only reflects the larger uncertainties in the spectroscopic values as compared to the much more accurate binary data. We also see that some of the supergiants are possibly overluminous for their masses. In general, this is an expected result due to evolution.

Binary systems containing early stars are very difficult to use for evolutionary tests, because any discrepancy (specially those indicating overluminous stars) can be attributed to interaction between the components. However they can be very well used to test model atmospheres. The most interesting cases

Table 1. Stellar parameters of the components of HD 115071 (O7-8V+O9IV) from orbital (Penny *et al.* 2002) and FASTWIND spectroscopic analysis. The range in the orbital parameters depends on whether the stars fill their Roche lobe or not, while the range in the spectroscopic masses comes from the possible range in stellar radii, that were adopted from the orbital analysis.

stellar parameter	primary orbital	primary spectroscopic	secondary orbital	secondary spectroscopic
$T_{\rm eff}$ (K)	32 000	32 500	29 000	30 000
$\log g$ (cm s^2)	3.9 - 3.8	3.8	3.7 - 3.5	3.5
M ($M_\odot$)	6.8 - 11.0	4.8 - 10.3	3.9 - 6.3	2.8 - 5.8

will be those in which the stars are found to be overluminous from the orbital analysis of the system. This will be the case for close binary systems, for which the Doppler tomography offers us the possibility of dissentangle the spectra of the components and analyze them. We have made a first application of this combined technique to HD 115071 (O7-8V+O9IV), whose orbital parameters have recently been derived by Penny *et al.* (2002). Table 1 gives the stellar parameters derived by Penny *et al.* and those derived from the analysis of the individual spectra using FASTWIND after adopting the stellar radii obtained from the orbital analysis (we latter checked that the models consistently reproduce the observed combined magnitude of the system). We see that both results compare very well in this preliminary analysis.

5. The Wind Momentum–Luminosity Relationship

In a review by Kudritzki & Puls (2000, their equations 10 and 18) about winds from hot stars, they discuss the Wind Momentum–Luminosity Relationship. Briefly, if the stellar wind is radiatively driven we expect a relation of the form

$$\log D_{\rm mom} \equiv \log(\dot{M} v_\infty R^{0.5}) \;=\; x\,\log(L/L_\odot) + \log D_0 \;\propto\; \frac{1}{\alpha'}\log L + {\rm C} \quad (1)$$

The coeeficients of the WLR, $\log D_0$ and x, are expected to vary as a function of spectral type and luminosity class. Equation 1 shows that it is possible to derive the luminosity of a star (and therefore its distance) by analyzing its spectrum, provided that we have calibrated the constants appearing in Equation 1 for the appropriate metallicity.

The discrepancy in the stellar masses that we have seen in the precedent section becomes a momentum problem (Lamers & Leitherer 1993; Puls *et al.* 1996; Vink *et al.* 2000). However, with the newly determined parameters we obtain values that agree very well with the theoretical expectations. Thus Herrero *et al.* (2002) obtain $x = 1.92 \pm 0.22$, $\log D_0 = 18.31 \pm 1.30$ for Cyg OB2 supergiants using spherical models with mass-loss and line-blanketing, while the theoretical predictions by Vink *et al.* (2000) are $x = 1.826 \pm 0.044$, $\log D_0 = 18.68 \pm 0.26$ when accounting for multi-scattering. Compared to the values given by Kudritzki & Puls (2000) $x = 1.51 \pm 0.18$, $\log D_0 = 20.69 \pm 1.04$ (from spherical models with mass-loss but without metal opacities), the new determinations agree

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better with the theoretical predictions from which cannot be distinguished within the observational uncertainties.

We have, however, to point out that the new determinations also show that stars with larger wind densities seem to have wind momenta larger than predicted. This could be related to ionization changes in the winds or, more probably, to wind clumping (see Puls, these Proceedings).

The purpose of accurately calibrating the WLR is to use it for extragalactic distance determinations. The stars in M 31 and M 33 constitute a very important test. For a review about the M 31 results, see Kudritzki & Puls (2000). According to our analyses of M 33 supergiants, these give results that agree very well with the Galactic ones, when we account for the fact that they have in some cases lower metallicities. Two stars depart from this behaviour: M33-B133 and 110-A. These stars are metal poor, but have larger wind momenta than their Galactic counterparts. In the case of M33-B133 this is due to the star having a close companion, only detected in the *HST*-STIS acquisition camera, while in the case of 110-A this is due to the star having spectral features that resemble those of a LBV. It is thus not surprising that the star behaves similarly to P Cygni, that also has a very large wind momentum for its spectral type. In general, however, the results give support to the idea of using extragalactic blue supergiants as distance indicators (see Kudritzki *et al.* 1999 for more details).

6. Conclusions

We have seen that the temperature scale of O-type stars is cooler than hitherto assumed. This has also an important impact in the number of ionizing photons that emerge from the star.

The *systematic* mass discrepancy found by Herrero *et al.* (1992) for supergiants seems to have been solved, although there still remain too many individual cases that deserve a proper explanation. Model atmospheres seem to give right answers when compared to orbital analyses in binaries.

The observed and predicted WLR agree for O-type supergiants. However, there are indications that the scatter in the observed relation may be due to physical reasons, probably wind clumping that is still unaccounted for in present-day model atmospheres of OB stars.

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Discussion

MASSEY: Concerning the dispersion in the spectral type to $T_{\rm eff}$ scale, I was surprised you didn't mention any observational issues, particularly sky subtraction. Rolf Kudritzki and I have gotten long-slit *HST*-STIS observations of stars in the R 136 cluster to determine their physical parameters. Some of these had previously been observed by Heap and de Koter with GHRS and the FOS, which lacked the ability to subtract sky. Our Hα profiles are much weaker, and it's clear that the other data were contaminated by nebula emission. This can also be a significant problem at He I λ 4471, particularly in the Magellanic Clouds if care isn't exercised. A second but related issue are the cases where M_V isn't well determined due to reliance on older, large aperture photometry.

HERRERO: Yes, you are right. There are a lot of problems related with the observations and their reduction, including for example the rectification of the continuum, which is sometimes really difficult! We tried to be as careful as possible and consider those uncertainties in the $T_{\rm eff}$ error bars. We obtain different temperatures at a given spectral type, and this is actually expected from physics, so I think that at least part of the dispersion has a physical cause. But you are right, the effects you mention may introduce additional scatter in the relation.

WALBORN: I recommend that anyone working in M 33 compare the HD charts in some Milky Way fields with the Digitized Sky Survey. The former have a resolution of $1'$; the latter has $\sim 1''$ and shows order(s) of magnitude more stars. Current spatial resolution in M 33 is comparable to the HD charts. Many 'stars' in M 33 must be composites of multiple objects.

HERRERO: Yes, in this case (M33-B133) we had to wait for *HST* observations to realize that it has a close companion. By that time we had already done a lot of previous observations and checks. This is always a risk in extragalactic work.

SCHAERER: Your plots and statements on the WLR seem to imply a different (steeper) slope of the WLR for the SMC than for the Galaxy. Is this correct or just a misunderstanding? We (Martins *et al.*, these Proceedings) find indications for a much steeper WLR in the SMC from an analysis of SMC N81 O-type stars.

HERRERO: I didn't state it, there are too few points on the diagram to claim it, but this is expected from theory if α is smaller in the SMC.

MOFFAT: The reduction in $T_{\rm eff}$ for O-type stars reminds me of the situation for WR stars, which have more extreme winds and there is a huge difference in $T_{\rm eff}$ at $\tau \simeq 2/3$ and at the hydrostatic core. Are O-type stars behaving in the same way, *i.e.*, $T_{\rm eff}$ at $\tau = 2/3$ is lower than at $R = R$(hydrostatic)?

HERRERO: No, there is not significant effect, except at very high wind densities (high for O supergiants). The radius at $\tau = 2/3$ remains close to the hydrostatic radius. This can be seen in dwarfs, where winds are nearly negligible and $T_{\rm eff}$ goes also down where sphericity and line-blanketing are included. It is more an effect of the higher ionization degree in the inner layers affecting the diagnostic lines.

KOENIGSBERGER: Is the reduction in the $T_{\rm eff}$ scale you find in optical lines consistent with results from UV line spectra?

HERRERO: Yes, this has been shown by Crowther *et al.* (2002) for their Magellanic Cloud stars and has been confirmed be Paco Najarro in our group for some of our Cyg OB2 stars.

CONTI: You have discussed the $T_{\rm eff}$ scale for Cyg OB2 supergiants and found a lower $T_{\rm eff}$ scale for the hottest stars. Is this also true to main sequence stars?

HERRERO: Yes, Martins *et al.* have calculated a new $T_{\rm eff}$ scale for O-type dwarfs and got similar results, although temperatures do not decrease as much as for O-type supergiants.

KUDRITZKI: Artemio, your mass-luminosity relationship shows beautiful agreement with binaries, However, as you pointed out, the two most massive objects are now revealed to be multiple, but still the fit the curve. Does that mean that the diagnostic value of your diagram is zero?

HERRERO: No, for that conclusion we have to claim that all points in the diagram are binaries. The correct interpretation of the diagram is that the isolated stars are at the right position on the diagram. To delete some points because of undetected binarity does not change the fact that the rest of the points extend the sequence given by the detached binary systems.