Constructing an Empirical Isochrone for the Massive Stars in the Core of the Starburst Cluster R136a

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Abstract. We present an empirical isochrone defined by fifteen very massive ($M_{\rm i} \gtrsim 35 M_{\odot}$) and luminous ($\log(L/L_{\odot}) \gtrsim 5.4$) stars in the core of the compact cluster R136a, near the centre of the 30 Doradus complex in the Large Magellanic Cloud. The programme stars are all of spectral type O3 and occupy only a relatively narrow range in effective temperature between 40 and 46 kK. We point out that the similarity in temperature is the result of almost vertical running isochrones at $M_{\rm i} \gtrsim 40 M_{\odot}$. Present day evolutionary tracks by Meynet et al. (1994) imply initial masses for the programme stars in the range $M_{\rm i} \simeq 37$ to $76 M_{\odot}$. Surprisingly, the observed mass-loss rates are up to three (two) times higher than is assumed in these tracks for $Z = 0.004$ (0.008). We derive a cluster age of slightly over 2 Myr.

1. Introduction

In 1983, Savage et al. studied the compact source Radcliffe 136a in the centre of the 30 Doradus H II region in the Large Magellanic Cloud (LMC). They concluded that *either* R136a is a compact cluster of normal stars of high mass (up to $\sim 100 M_{\odot}$), containing about 30 very early O and WN stars, *or* the light of the object is dominated by the presence of one or a few supermassive stars. Because the first option requires the presence of tens of the rarest stars found in galactic systems within a single stellar cluster, they opted for the supermassive-star scenario. Melnick (1985) questioned this conclusion, pointing out that with ever increasing instrumental resolution, more and more individual stars could be resolved near the 'edge' of R136a. After the first servicing of the HST in December 1993, it became for the first time possible to resolve individual stars in the very centre of the cluster (Heap et al. 1994).

It was expected that the three brightest members of the cluster would be highly evolved Wolf-Rayet stars as this was indicated by the strength of the He II $\lambda 4686$ emission line (Campbell et al. 1991). However, it was found by de Koter et al. (1997) that these stars are rich in hydrogen and that they are in fact young, main-sequence, hydrogen-burning stars, albeit stars featuring a mass loss so large that it is typical for real Wolf-Rayet stars. Such an unexpected mass-

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loss behavior has important implications for our understanding of the evolution of very massive stars, as it is predominantly mass loss that 'drives' the stars through subsequent phases of O-type, Of-type, Luminous Blue Variable, and Wolf-Rayet stars.

In this paper we present the results of a spectroscopic study of twelve of the brightest early O-type stars, all located in the cluster centre. The observing programme and spectral morphology are described in detail by Heap et al. (1998). The aim of the current study is to try to answer two questions, both of key-importance for our understanding of massive-star evolution. First, what are the mass-loss rates of these bright O-type stars? Do they match up with the rates currently used in evolutionary calculations, or do the rates differ – as in the case of the three brightest members? Secondly, what does the empirical isochrone defined by the programme stars look like? This isochrone may provide an important constraint to models of the evolution of very massive stars.

In Section 2, we discuss the diagnostic methods used in this investigation. The resulting basic parameters and mass-loss rates are given in Section 3. In this section, we compare the observed mass loss with rates used in contemporary evolution track calculations. In the last section, Section 4, we present and discuss the first empirical isochrone for very massive stars.

2. Diagnostic Methods

Unfortunately, the standard diagnostic method of constructing so-called '$T_{\rm eff}$–$\log g$' diagrams, based on non-LTE plane-parallel models, fails when applied to observations of the early O-type stars in R136a. The reasons are: *(i)* the resolution of the FOS is too coarse for profile analysis; *(ii)* the 'photospheric' profiles of H I, He I}, and He II lines may be partly filled in by nebular emission and by emission from the extended wind; and *(iii)* the temperature of all programme stars is higher than $\sim$40 kK, so that He I lines are absent or extremely weak, and therefore prohibits the use of the He I to He II ratio as a temperature indicator.

This implies that one needs to resort to the use of unified non-LTE models for both the determination of photospheric and wind parameters. The code that has been used to calculate all models presented in this paper is the most recent version of the non-LTE unified Improved Sobolev Approximation program ISA-WIND for stars with stellar winds (de Koter et al. 1993, 1997).

To identify which spectroscopic features are (most) sensitive to which stellar parameter(s), a grid of unified O-type star models was calculated. Essentially, the grid parameters are from Howarth & Prinja (1989), with mass-loss rates assigned using the fitting formula derived by Lamers & Leitherer (1993) and terminal flow velocities following Lamers et al. (1995). Clearly, the two most important diagnostics the grid should help identify are those for the determination of $T_{\rm eff}$ and $\dot{M}$. We will discuss these diagnostics in the remainder of the section.

2.1. Temperature

For the reasons stated above, we need to resort to the use of ultraviolet lines for the temperature determination. Figure 1 shows the equivalent width of absorption of the O IV $\lambda\lambda$1338, 1343, O V λ1371, Si IV $\lambda\lambda$1394, 1403, and N IV

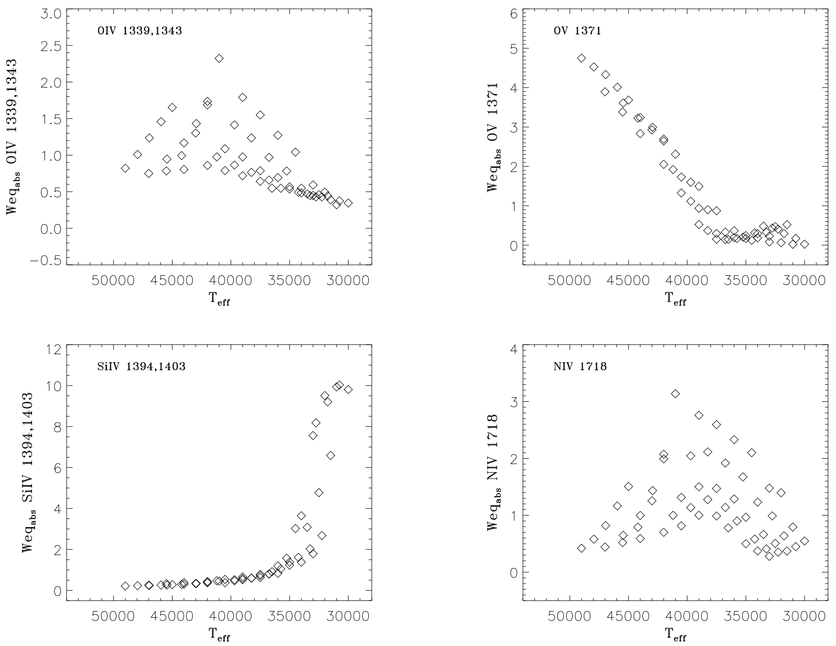

Figure 1. Predicted absorption equivalent widths for a grid of O-type star models. One clearly sees that the O IV, and N IV lines are sensitive to both mass loss and temperature. This also holds for Si IV, however, for our purposes this line is of only limited use as it is not observed as a wind line in the hot R136a stars. The O V line shows an almost linear increase in strength with temperature, which makes it a useful $T_{\rm eff}$ diagnostic.

λ1718 lines. The adopted metallicity is $Z = 1/4 Z_{\odot}$. The O IV and N IV lines clearly show a dependence on both $T_{\rm eff}$ and $\dot{M}$. The absorption in both lines is strongest for the O5 I model, which has the largest mass loss in the grid. At $\gtrsim$37 kK, the Si IV line is a photospheric absorption line. For temperatures down to $\sim$30 kK, the line is very sensitive to mass loss. Because of this, and because of the mass-loss versus luminosity relation for early-type stars, this line is a good luminosity diagnostic for mid-O-type stars. Clearly, the absence of any significant Si IV wind emission in our programme stars implies that all stars are hotter than $\sim$37 kK.

The O V line shows an altogether different behavior. This line is no longer present in significant strength at $T_{\rm eff} \lesssim 37$ kK. For higher temperatures, however, it shows an almost linear increase in strength with temperature. Moreover, the relation is fairly tight, indicating that the line is mostly sensitive to temperature and relatively insensitive to, *but not independent of,* mass loss. For these reasons, we select this line as our quantitative temperature diagnostic. We believe that this approach will at least result in a reliable *relative* temperature scale, providing all stars have the same surface oxygen abundance. De Koter et al. (1998) present evidence that all programme stars, except R136a5, still show

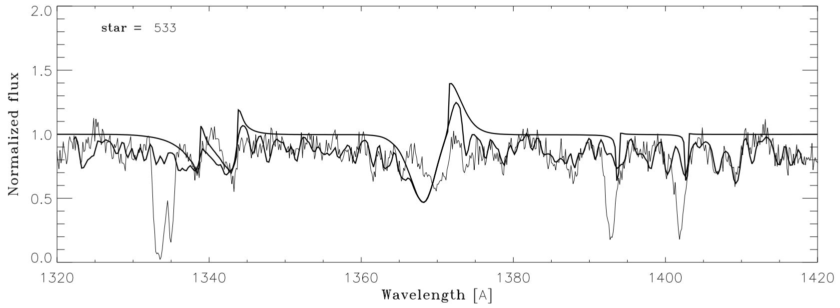

Figure 2. Comparison of the observed and predicted spectrum of star 533. The 'smooth' line represents a theoretical spectrum containing only the potential wind lines of O IV, O V and Si IV. The fit of the fully line-blocked synthetic spectrum is excellent, and even allows for an accurate determination of the system velocity. The line-blocked spectrum is used to properly account for the metal blends of the O V line.

their initial surface oxygen abundance; in R136a5 oxygen is depleted. Using an initial abundance for this star results in an overestimate of $T_{\rm eff}$ by $\sim$1 kK.

However, we cannot easily exclude that our temperature calibration may be subject to a systematic shift, for which several effects could be responsible: *(i)* contamination of the oxygen-line profile by the many metal lines present in the spectral range around 1371Å; *(ii)* the adopted LMC metallicity; *(iii)* errors in the O V ionization balance due to, most notably, the neglect of a consistent treatment of metal-line blanketing in our models.

In order to assess the importance of the first problem – and to correct for it – we have also modelled the blocking by metal lines using a generalized form of the modified nebular approximation (Schmutz 1991) to describe the ionization/excitation equilibrium of those metals not explicitly treated in ISA-WIND. This method is described in detail in de Koter et al. (1997). An example of a line-blocked spectrum is given in Fig. 2. If no attempt had been made to correct for the presence of metal lines, the measured equivalent width might have been overestimated, as it is difficult to determine which part of the observed absorption is due to O V and which part is due to metal blends. An overestimated equivalent width would result in an overestimate of the effective temperature (by up to $\sim$2500 K). When incorporating metal-line blocking one has to abandon the idea of measuring the equivalent width of individual lines, and has to replace it by the approach of measuring the total absorption equivalent width in a wavelength interval comprising the blueshifted O V absorption. We define our quantitative temperature diagnostic as follows: $T_{\rm eff}$ is determined by requiring that the total absorption equivalent width in the wavelength range from 1360 to 1372Å is matched by the model *that also has the correct mass loss and terminal velocity.*

Our temperature determination is obviously dependent on metallicity; a higher Z yields stronger lines, and consequently lower $T_{\rm eff}$ values. Comparing the basic grid for $Z = 1/4\,Z_\odot$ with one in which we adopt $Z = 1/2\,Z_\odot$ yields a shift of about 1500 to 1800 K towards lower temperature.

The last, but certainly not the least important point to be discussed is possible errors in the predicted O V ionization balance. Such errors may arise due to shortcomings in the physics treated in the model. We will comment on two such processes: *(i)* the neglect of the emission from shocks, yielding an extra source of ionization, and *(ii)* the neglect of the effect of metal-line blanketing, which is expected to lead to a lower ionization.

Soft X-ray emission from O-type stars is believed to be evidence for the presence of vigorous flow disruptions or shocks in the winds of these stars (Lucy & White 1980; Lucy 1982). The shocks themselves are thought to be caused by hydrodynamical instabilities, a mechanism first suggested by Lucy & Solomon (1970). Such instabilities are an intrinsic property of radiation-driven winds (Owocki et al. 1988). However, hydrodynamical simulations for self-excited wind instabilities show that in the lower part of the wind, below ∼1.5 stellar radii, radiative viscosity and line-drag effects may effectively eliminate the instability (Owocki 1994). Because the O V λ1371 line is formed mainly in this region, we do not expect shocks to be significant.

We neglect the effects of metal-line blanketing. A consistent treatment of these effects is anticipated to result in a lower ionization as such calculations probably produce a lower EUV flux. Although this is what one may expect intuitively, one should make some reservations until a truly self-consistent non-LTE treatment of metal line blanketing in a unified atmosphere is developed. For instance, one may argue that part of the added EUV opacity in line-blanketed calculations is offset by additional multiple scatterings in the diffuse radiation field, increasing the mean intensity in the photosphere and lower part of the wind and thus again increasing the ionization (Schaerer & Schmutz 1994). Still, a systematic underestimate of $T_{\rm eff}$, due to the neglect of metal-line blanketing, cannot be excluded at present (see, e.g., de Koter et al. 1994). A quantitative measure of such an underestimate is hard to give; however, it may be as high as a few kK for the early O-type stars analyzed in this paper.

2.2. Mass Loss

Mass-loss rates of early-type stars may be derived in several ways (for a recent review, see Lamers & Cassinelli 1996). The most *accurate* diagnostics are free-free emission of the ionized wind at radio wavelengths and the Hα line emission. The most *sensitive* method of determining $\dot{M}$, however, is that of fitting the P Cygni profiles of UV resonance lines. This last method allows for the detection of mass-loss rates as low as $\log \dot{M} \simeq -8$.

The free-free emission can only be used for stars with considerable mass loss (say $\log \dot{M} \gtrsim -6$) at relatively nearby distances (say within a few kpc), as otherwise the excess radio flux does not reach present-day detection limits. This eliminates this method for use with the R136a stars. The fitting of UV resonance lines, which in our case would mean C IV $\lambda\lambda$1548, 1550 and N V $\lambda\lambda$1238, 1242, drops from the list of possible mass-loss diagnostics because the observed lines of the R136a stars are either saturated (C IV in several cases) or are from a minor ionization stage for which the ionization fraction may depend critically on the

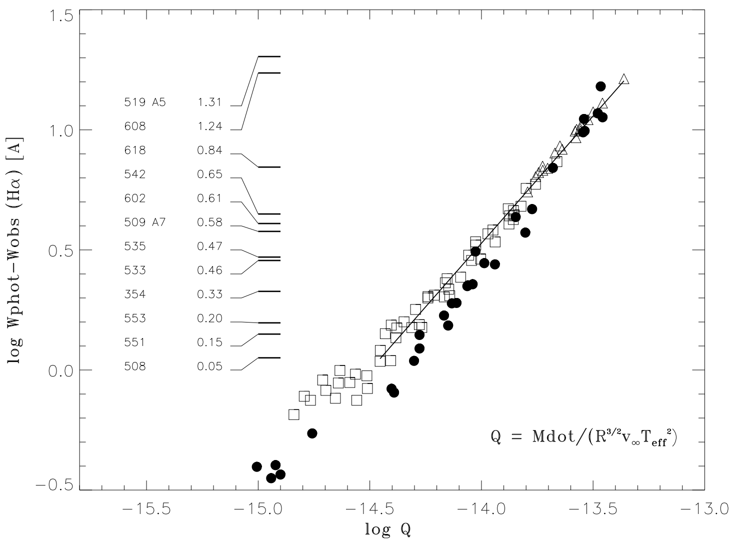

Figure 3. The Hα + He II λ6560 'curve of growth'. The models indicated by □-symbols are from the standard grid; those designated a $\triangle$ symbol are from a grid in which the mass loss has been multiplied by a factor of two. The hybrid Hα + He II line is essentially optically thin at $Q < -14.5$. The best fit for the (partly) optically thick case is represented by the solid line. Overplotted are the results for a set of unified atmospheres for O-type stars by the Munich group (•-symbols; Puls et al. 1996).

presence of shocks and X-rays in the wind (N V), processes for which our current models do not account. This leaves the Hα method.

The Hα + He II λ6560 'curve of growth' is shown in Fig. 3. It shows the net wind emission,

$$W_{\rm net} \equiv W_{\rm phot} - W_{\rm obs}, \tag{1}$$

versus

$$Q \equiv \frac{\dot{M}}{R^{3/2}\, T_{\rm eff}^2\, v_\infty} \tag{2}$$

with $\dot{M}$ in $10^{-6} M_\odot$ yr^{-1}, R in $R_\odot$, $T_{\rm eff}$ in Kelvin, and v_∞ in km s^{-1}. The net emission in Hα + He II λ6560 follows from the observed equivalent width, $W_{\rm obs}$, after correction for the (hypothetical) underlying photospheric absorption, $W_{\rm phot}(T_{\rm eff},\log g)$. The equivalent-width invariant, Q, has first been introduced by Schmutz et al. (1989) for fixed $T_{\rm eff}$. The dependence of $W_{\rm net}$ on basic parameters is extensively discussed by Puls et al. 1996, who derive a relation essentially similar to that of Eq. 2. The best fit is given by:

$$\log W_{\rm net} = 15.360\ (\pm 0.035)\ +\ 1.059\ (\pm 0.015) \log Q. \tag{3}$$

The $W_{\rm phot}$ values follow from a grid of hydrostatic models (more precisely, from unified models with a negligible low value for the mass loss). We find:

$$W_{\rm phot}/\log g = -5.573\ (\pm 0.036) + 1.406\ (\pm 0.084) \log T_{\rm eff}. \tag{4}$$

Table 1. Parameters of the programme stars. Star identification and visual magnitude from Malumuth & Heap (1994).

Name	$T_{\rm eff}$ (kK)	BC	V	$\log L$ ($L_\odot$)	R ($R_\odot$)	$M_{\rm i}$ ($M_\odot$)	M ($M_\odot$)	v_∞ (km s^{-1})	$\log \dot{M}$ ($M_\odot$ yr^{-1})
519 A5	43.2	−4.03	13.73	6.03	18.6	76	30	3000	−4.64
509 A7	40.7	−3.86	13.73	5.86	17.2	59	54	2900	−5.57
618	43.5	−4.05	14.25	5.82	14.3	58	44	3550	−5.17
608	43.5	−4.05	14.39	5.80	14.0	57	35	3750	−4.96
535	45.0	−4.15	14.49	5.62	10.6	49	46	3400	−5.86
354	41.0	−3.88	14.52	5.52	11.4	40	36	2850	−5.71
553	42.2	−3.96	14.56	5.58	11.5	44	41	3150	−5.80
508	40.6	−3.85	14.51	5.51	11.5	40	38	2900	−5.95
602	44.0	−4.08	14.63	5.72	12.5	53	46	3625	−5.44
551	45.4	−4.18	14.81	5.66	10.9	51	48	3150	−5.87
533	40.4	−3.83	14.81	5.44	10.7	37	34	3025	−5.78
542	42.3	−3.97	14.86	5.50	10.4	41	37	3050	−5.75

The relation is derived for the temperature range from 30 to 50 kK and reproduces $W_{\rm phot}$ to within 0.2Å.

The above relations were used to obtain a good first estimate of the mass loss. In the end, we tuned the models somewhat to get the best possible fit to Hα + He II. However, this required only adjustments of up to 0.2 dex.

3. Mass Loss and Evolution

The resulting photospheric and wind parameters are given in Table 1. In view of the importance of mass loss in the life of very massive stars, let us compare our results with the $\dot{M}$ values used in contemporary stellar-evolution tracks. The Geneva group have made extensive use of the mass-loss parameterization by de Jager, Nieuwenhuijzen & van der Hucht (1988; henceforth dJNH); see, for example, Schaller et al. (1992). They use the dJNH relation for all evolutionary phases of stars with non-negligible mass loss, up to the Wolf-Rayet stage. Recently, Meynet et al. (1994) have published tracks in which the dJNH mass-loss values, henceforth $\dot{M}_{\rm JNH}$, for stars on the main sequence have been multiplied by a factor of two. In Fig. 4, we compare our results with these multiplied $\dot{M}$ values for metallicity $Z = 0.004$. In a strict sense, the dotted box indicates the range of validity of our $\dot{M}(L,\, T_{\rm eff})$ formula; contours are given by the dot-dashed-dashed lines. We find:

$$\log \dot{M} = -1.25(\pm 0.21) + 1.99(\pm 0.20)\log(L/L_\odot) - 3.36(\pm 3.64)\ \log T_{\rm eff} \qquad (5)$$

The absolute mean deviation of the data points around this relation is 0.17 dex. The large error in $T_{\rm eff}$ dependence is due to the small temperature baseline. Looking at a representative $T_{\rm eff}$ value of 42.5 kK for the R136a stars, one sees that the dependence of mass loss on luminosity is only marginally weaker in the dJNH formula compared to the power-law index of 1.99 that we derive. A surprising difference, however, is that *the mass loss of the most massive R136a stars is ∼0.3 to 0.5 dex higher than the scaled Z=0.004 rates; and ∼0.15 to 0.35 dex higher than the scaled Z=0.008 rates.*

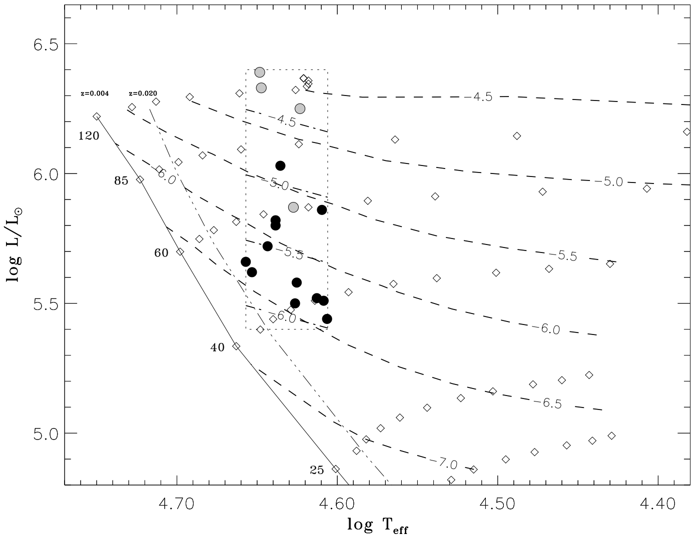

Figure 4. Comparison of our $\dot{M}(L,T_{\rm eff})$ representation with that of dJNH, for which contours of equal mass loss are given by the dashed lines (labels give $\log \dot{M}$). The dJNH mass-loss rates are for a metallicity $Z = 0.004$. Models along the evolutionary tracks of different initial masses are given by the shaded squares. The ZAMS for $Z = 0.004$ and for 0.020 are also given.

4. Empirical Isochrone

The twelve stars of our sample constitute an empirical isochrone of young, very massive stars in the HR diagram. There are three reasons why R136a is the ideal object to define such an isochrone: *(i)* Perhaps with the exception of the highly reddened Galactic cluster NGC 3603, it is the only resolved cluster rich enough in very massive stars. For instance, from Malumuth & Heap (1994) one may estimate that there are some 200 stars more massive than $10 M_\odot$, and there are at least a dozen stars with $M \gtrsim 40 M_\odot$. *(ii)* The observed stars, including those investigated by de Koter et al. (1997), cover a substantial range in initial masses, say from $M_{\rm i} \sim$35 to $130 M_\odot$, and luminosities, say from $\log(L/L_\odot) \sim$5.4 to 6.4. *(iii)* R136a has a very compact size; its radius is about $3''$, or 0.75 pc at the distance of the LMC. This implies a sound-crossing time of only ~100 000 yr; consequently, the twelve programme stars can be considered to have been formed simultaneously. *(iv)* The distance to the LMC is well known.

Figure 5 shows the upper part of the HR diagram in which we compare the location of the programme stars with the isochrones of the Meynet et al. (1994) tracks for 0, 1, 2, and 3 Myr at $Z = 0.004$. The temperatures of all stars are assigned a standard deviation $\Delta \log T_{\rm eff} = 0.025$. The slope of the plotted error bars show how the luminosity varies within $T_{\rm eff} \pm \Delta T_{\rm eff}$ due to the changing bolometric correction. The stars cluster around an age slightly above 2 Myr, although they do not strictly coincide with a single isochrone. This number is in agreement with the age derived by de Koter et al. (1997) for the Wolf-Rayet-

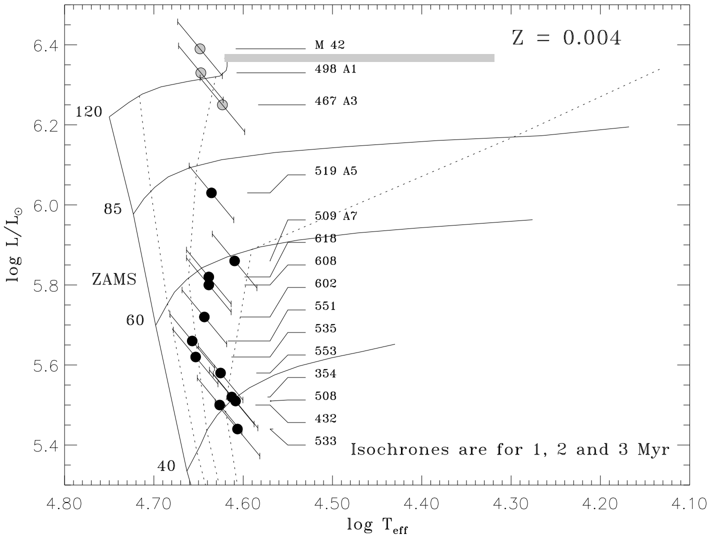

Figure 5. Comparison of the empirical isochrone defined by the programme stars with predicted isochrones by Meynet et al. (1994). The tracks used are for a metallicity $Z = 0.004$. The shaded bar for the track of initial mass $120 M_\odot$ indicates a main sequence WNL phase. The dotted lines give isochrones for 1, 2, and 3 Myr. On the basis of this comparison one finds a cluster age for R136a of slightly over 2 Myr.

like stars R136a1 & R136a3 and Melnick 42[2]. Close inspection of Fig. 5 reveals that the lower-mass stars seem somewhat older. However, one should not rush to conclude that this indicates non-coeval star formation. Simpler and more logical explanations may be able to explain the scatter of points around the best-fitting isochrone, e.g., differences in the HR-position due to different stellar rotational velocities.

Why is R136a so rich in stars of spectral type O3? Recall that Savage et al. (1983) considered it so unlikely that R136a could contain dozens of stars of such a very rare spectral type that they resorted to the hypothesis that R136a was dominated by the presence of a single or a few supermassive stars. The above question may be rephrased as: why do all the brightest cluster members fall in a small range in $T_{\rm eff}$, with values typical for O3 stars? This can be understood by looking at the behavior of the theoretical isochrones: *The derived* $T_{\rm eff}$ *values are so similar because the isochrone for ∼2 Myr runs almost vertically and because the distance in temperature between the isochrones of 1 and 3 Myr is very small.*

The effective temperatures of the programme stars have been derived assuming a metallicity $Z = 0.004$ for R136a. Suppose we had adopted $Z = 0.008$. How would this have affected the derived cluster age? There are two effects that need to be considered. (1) As pointed out in Section 2, an increase in metallicity

[2]Note, however, that Melnick 42 is positioned somewhat outside of the cluster and may not have been formed at the same time.

by a factor of two would lead to a decrease in derived temperatures by typically $\sim$1500 to 1800 K. (2) For $Z = 0.008$, the ZAMS, as well as the isochrones of the first few million years, shift towards lower temperatures compared to the $Z = 0.004$ tracks. The extent of this shift is $\sim$1000 to 1500 K (Meynet et al. 1994). As both effects work in the same direction, only a slightly lower age – by some 200 000 yr – is derived for R136a in case of a metallicity $Z = 0.008$.

A comparison of the stellar positions in the HR diagram with the Meynet et al. tracks for $Z = 0.004$ yields current masses that differ only marginally from their expected initial masses. The reasons are obviously the very low mass loss used in the tracks at locations near the main sequence – e.g., the stars at $\log(L/L_{\odot}) \lesssim 5.5$ start their lives with a $\dot{M} \sim 2\times10^{-7} M_{\odot}$ yr^{-1} – and the young age of $\sim$2 Myr. Even the most luminous star, R136a5, positioned on the track for $M_{\rm i} = 76 M_{\odot}\}$, has not lost more than $3 M_{\odot}$. All initial masses determined from a comparison with the $Z = 0.004$ Geneva tracks are given in column 7 of Table 1.

However, for the most luminous stars, say those corresponding to $M_{\rm i} \gtrsim 50 M_{\odot}$, the current stellar masses implied by the observed mass loss may be substantially lower. One does not expect incorporation of the observed mass loss in evolutionary calculations to lead to very different current masses compared to the Meynet et al. results for the stars with $M_{\rm i} \lesssim 50 M_{\odot}$. For instance, for star 533 a time integrated mass loss equal to the observed value will still only amount to a loss of some $3 M_{\odot}$. Using this very rough approach, estimated current masses for all programme stars are listed in column 8 of Table 1.

Returning to the most luminous stars, one should be cautious with the predicted initial and current masses listed in Table 1. Clearly, the given current masses are probably lower limits, as the observed $\dot{M}(L,T_{\rm eff})$ relation shows a lower mass loss for stars closer to the main sequence (see Section 4). However, the main-sequence masses may also be underestimated. The reason is the following: adopting a higher observed mass loss in new evolutionary-track calculations will result in a slower increase of luminosity in the main-sequence phase. This implies that it is a track with a *higher initial mass* which reaches the same point in the HR-diagram as an available lower-mass-loss track. Consequently, tracks using a customized mass loss will probably yield both higher initial and current evolutionary masses.

In any case, it is clear one may conclude that *for the brightest members ($M_{\rm i} \gtrsim 50 M_{\odot}$) one may anticipate that new evolutionary tracks, incorporating the observed $\dot{M}$ rates, will yield qualitatively different results compared to current calculations of very massive star evolution.* We intend to calculate such tracks in the near future. Such calculations, combined with population synthesis may yield new insight in the stellar composition and formation history of starburst clusters – for which R136a is a prototype – and starburst galaxies.

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Discussion

Crowther: I think we need to be very careful when we talk about 'Wolf-Rayet' and 'Wolf-Rayet-like' stars. If we observe something to have a Wolf-Rayet spectrum shouldn't we call it a Wolf-Rayet star, not relying on evolutionary definitions?

de Koter: Yes... just to clarify, these are not WR stars from the point of evolution.

Walborn: I think it might be useful to point out (since I know what's coming in the next talk; p. 355) that, in terms of ultraviolet wind morphology, if you see an O V line, then you have an O3 star. So what you've found, from the UV features alone, is that they're all O3 stars.

Maeder: Would it be possible to know where on your empirical isochrone you have an N/C ratio enhanced with respect to cosmic? This would be a very strong constraint on models... I know when people present data like yours there is always someone asking for more... [laughter].

de Koter: The method of using O V to determine the temperature clearly also depends on the abundance. With increasing initial mass, at some point you would expect to see oxygen depletion and nitrogen enrichment. I think you can see that by looking at the O IV and O V lines at the same time. I can always fit the O V line, obviously, just by changing the temperature, but I also have to fit O IV. It always works out for these stars, except for the most massive ones, where I predict too-strong O IV, which implies that in reality oxygen is being depleted. So for about 60 or $65 M_\odot$, at 2 million years, there may be some depletion.

Langer: The abundances are related to mixing, and there is an interesting point here, which is that if we consider stellar-evolution models which include rotational mixing we would not expect isochrones to be single lines any more, but rather we expect some scatter corresponding to scatter in the original rotation rates of the stars. When you showed you HR diagram you didn't show any error bars; can you say whether the scatter you see is 'serious', or is it just observational error?

de Koter: The uncertainty in temperature is around 2000 K; the scatter is therefore mostly just observational error.

Becker: When you get a fit to the oxygen lines, the silicon doesn't seem to fit at all...?

de Koter: It's interstellar.

Kudritzki: Just a comment concerning the results on mass-loss rates; these are not especially well suited to comparison with theory, as they depend on how well you have determined the stellar parameters. If you use wind *momentum,* that depends on luminosity only. Therefore it's better to compare the wind momentum, rather than mass-loss rate, with the predictions of theory; then you take out details of sensitivity to gravity determination, for instance.

de Koter: That's a good idea, I'll try that.