R136: A Cluster of O3 Stars!

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Abstract. We have used HST to obtain spectra of 65 of the bluest, most luminous stars in R136, and find that the majority of these stars are of type O3, the hottest, most luminous and massive stars known. The total number of O3 stars in this one cluster exceed the total number currently known elsewhere in the Milky Way or Magellanic Clouds. The highest-luminosity stars found are O3 If*, O4 If+, O3 If/WN6-A, and H-rich WN stars, with masses in excess of $120 M_{\odot}$, the highest masses for which appropriate evolutionary tracks are currently available. In accord with de Koter, Heap & Hubeny, we conclude that these WN stars must be core-hydrogen-burning stars whose spectra are WR-like due to high luminosity, and we find that their individual luminosities are a factor of 10 higher than normal WN stars of similar type, but like those found in the Galactic cluster NGC 3603, which they also resemble spectroscopically. Our spectroscopy does include stars as late as B0 V, and samples most stars in the core of the R136 cluster with masses $> 50 M_{\odot}$. The spectroscopy has been combined with HST photometry to study the star-formation history and initial mass function of the R136 cluster. The young age (< 1–2 Myr) for the highest-mass stars, combined with what was previously known for the intermediate-mass populations, suggests that the lower-mass stars began forming 4–5 Myr ago, and continued until the high-mass stars formed, consistent with the paradigm in which the formation of massive stars shuts down further star formation in the molecular cloud. Despite the unique preponderance of stars of the highest mass and luminosity ever seen, the IMF is found to be completely normal, with a slope $\Gamma = -1.3$ to -1.4. The number of high-mass stars is in good accord with that predicted by the IMF of the intermediate-mass stars, suggesting that a Salpeter-like IMF holds over the mass range $2.8 M_{\odot}$ to $120 M_{\odot}$ within the R136 cluster. The fact that the IMF slope in R136 is indistinguishable from those of Galactic and Magellanic Cloud OB associations suggests that star formation produces the same distribution of masses over a range of $\sim 200\times$ in stellar density, from that of sparse OB associations to that typical of globular clusters. The large number of O3 stars in R136 is then simply a consequence of its youth (< 1–2 Myr) and its richness, suggesting that the upper mass 'cutoff' to the IMF seen in OB associations may simply be the result of their sparsity.

The full text of our study of the R136 cluster will appear elsewhere (Massey & Hunter 1998); here we will summarize our results.

We undertook spectroscopy of 65 of the brightest, bluest stars in the R136 'supercluster' in order to determine the cluster's massive star content. Although HST WFPC2 photometry has allowed a comprehensive study of the intermediate-mass stars (2.8–15$M_\odot$), it is not sufficent for determining the initial mass function of the massive stars (Hunter et al. 1995, 1996). At the high effective temperatures characteristic of main-sequence stars with masses $> 20\mathcal{M}_\odot$, the colors are degenerate with effective temperature; even including the UV is not sufficient for effective temperatures above 30,000° (Hunter et al. 1997). However, such photometry was sufficent for picking out the brightest, bluest stars for spectroscopy. We used the FOS with a 0.26$''$ aperture, which allows stars even within the core of the R136 cluster to be isolated (Fig. 1).

To our initial astonishment, the vast majority of the spectra we obtained were of type O3! The total number of O3 stars in our sample exceeds the total number of O3 stars known in the Milky Way or elsewhere in the Magellanic Clouds.

Eight of the R136 stars are classified as O3-type supergiants (O3 If*), and we illustrate these spectra in Fig. 2. The O3 supergiants are distinguishable from lower-luminosity O3 stars by the strength of their He II λ4686 emission (the source of the 'f' in the spectral designation), the strength of N IV λ4058 emission (the source of the '*'), as well as the strength of the N V λ4603, 19 absorption feature. Like O3 stars of any luminosity class, the stars also show moderate He II λ4200 and λ4542 absorption with no indication of He I λ4471 or any other He I line. Walborn (1982) prefers the notation 'O3 If*/WN6-A' to designate those O3 If* stars with the strongest emission lines as an indication that their spectra are in some ways intermediate between an O3 and a Wolf-Rayet WN type. Conti (1988) further describes these objects, and argues that these are truly in 'transition' from O-type to WR-type. We note that there is really a continuum, however, of the strengths of the emission lines. As the He II λ4686 and N IV λ4058 emission lines become stronger, the N IV λ3480 line follows suit, going from complete absorption into emission. Similarly, Hγ develops a P-Cygni emission-line profile in both R136-015 (not shown) and R136-044. The spectra of these two stars resemble that of HD 93162, classified as a Wolf-Rayet star. Of our eight O3 supergiants, six have sufficiently strong emission to qualify as 'transition' O3 If*/WN6-A type; see, for comparison, the spectrum of Sk$-67°$22, illustrated by Walborn (1986).

These stars are all extremely luminous: M_V spans the range -5.5 to -6.9. Interestingly, the stars with the most extreme emission are not the most luminous, at least not as judged by their *visual* absolute magnitude. However, given that O3 stars can span a range in $T_{\rm eff}$, and hence in bolometric correction, it may be that these two stars are the most *bolometrically* luminous.

Among the other stars we found were three O4If+ types, numerous O3 Vs (including two possible double-lined O3 V+O3 V binaries), and a few dwarfs of later type, extending as late as B0 V. Perhaps of greatest interest, however, were our spectra of several early-type WN stars (Fig. 3).

The presence of Wolf-Rayet stars has often been used to set the age of the R136 cluster as 3–4 Myr, but such an age is glaringly at variance with the

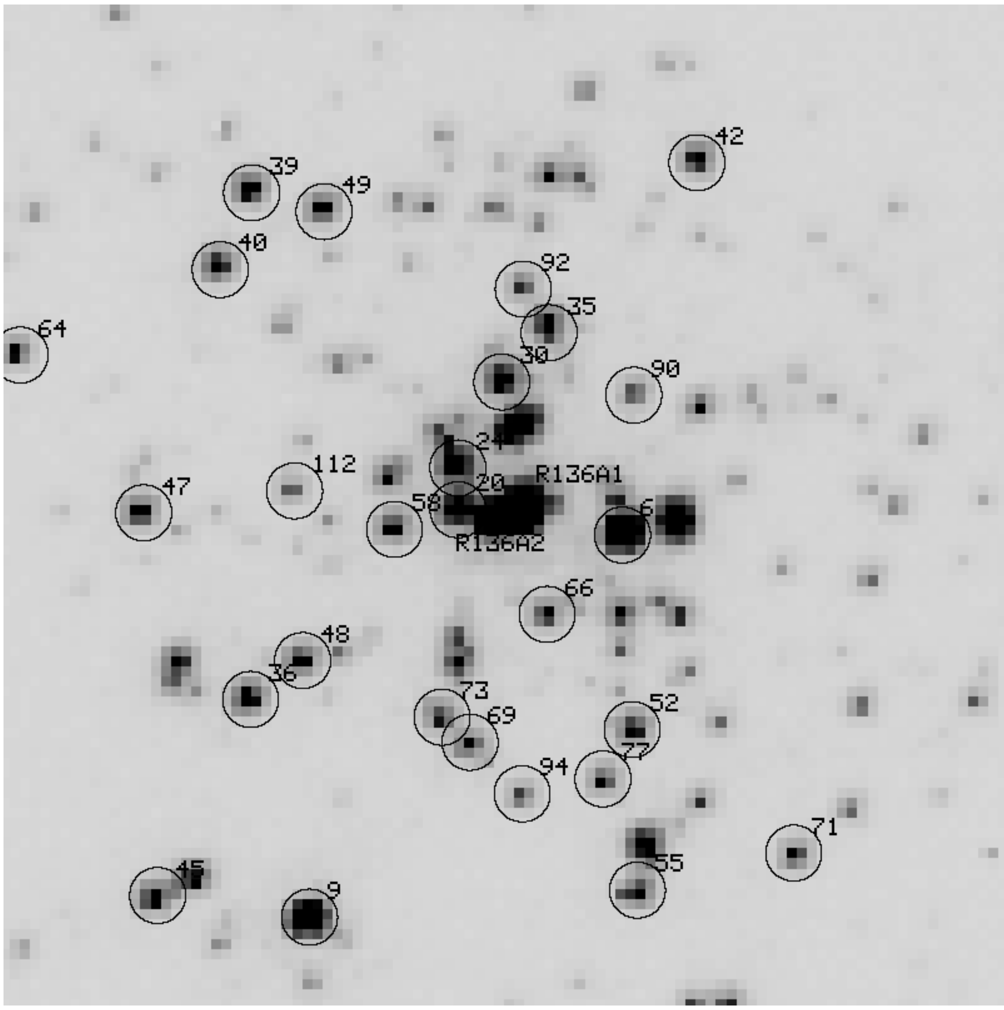

Figure 1. The central $4.55'' \times 4.55''$ portion of a PC frame containing the core of the R136 cluster. The identification of some of the stars observed spectroscopically is given; additional stars were observed outside this region. The size of the circles correspond to the $0.26''$ diameter entrance aperture of the FOS.

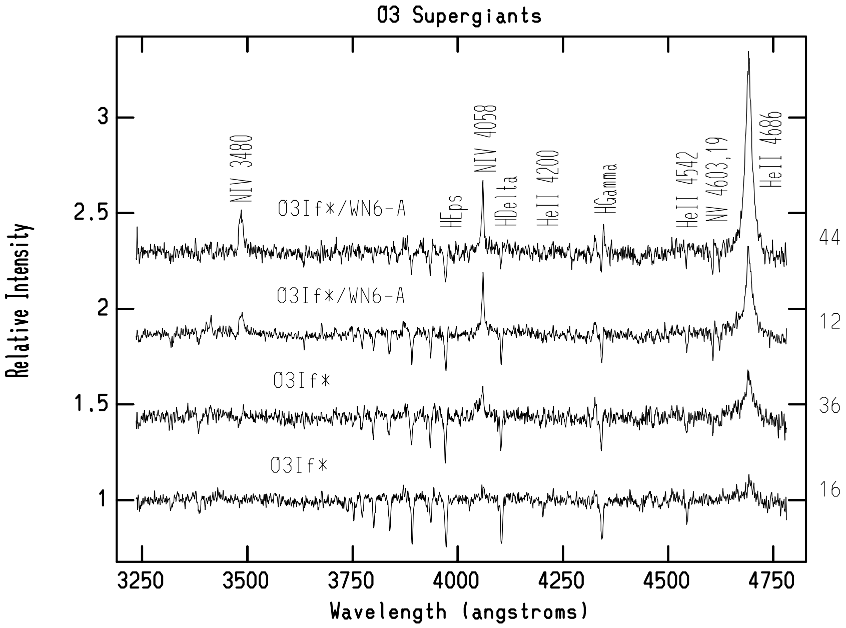

Figure 2. Representative examples of the O3 If* and O3 If*/WN6 supergiants. The emission feature on the blue side of Hγ is an artifact of the FOS, as is the extended blue wing to the N IV λ4058 line in R136-036.

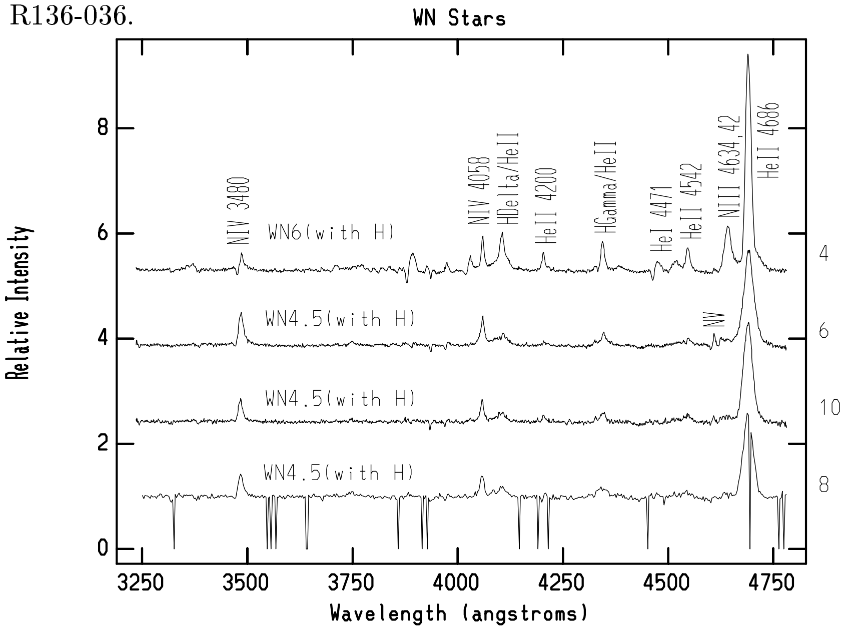

Figure 3. The WN Wolf-Rayet stars. All four of these WN stars show evidence of H in their emission line spectrum, as judged by the alternating strengths of Hδ/He II, He II λ4200, Hγ/He II, and He II λ4542. The drop-outs in R136-008 are due to dead diodes turned off in the FOS; this spectrum was not stepped, but was obtained as part of the acquisition process.

presence of O3 stars, which sets the age at a million years or less. While there are some bona fide Wolf-Rayet stars in the general R136 region, none of the four early-types (3 WN4.5 and 1 WN6) we observed is 'normal'. The early-type WN stars in the core of R136 are (i) H-rich, unlike other early-type WN stars, and (ii) a factor of ten more luminous at M_V than other early-type WN stars. We conclude that these are actually 'super-Of stars': H-burning objects which show WR-like features only because of their high luminosity, and hence strong stellar winds. This is in accord with the conclusion reached by de Koter, Heap & Hubeny (1997) based on their analysis of several R136 stars. Furthermore, these early-type WN stars are very similar to those illustrated by Drissen et al. (1995) in NGC 3603, another cluster that contains O3 stars but poses a condundrum due to the presence of WN stars.

We show our HR diagram in Fig. 4. We have constructed this diagram by assuming a temperature of 50 500 K for the O3 stars (Vacca, Garmany & Shull 1996), but also consider the effects of adopting the lower effective-temperature scale of Chlebowski & Garmany (1991). There is little difference in the masses for even the highest-mass stars.

Is the preponderance of very-high-mass stars indicative of a top-heavy IMF? No! Instead, the number of very-high-mass stars is exactly what we expect by extrapolating the IMF of the intermediate-mass stars found by Hunter et al. (1996). We show our IMF in Fig. 5. The IMF is completely normal: $\Gamma = -1.3 \pm 0.1$ or $\Gamma = -1.4 \pm 0.1$, depending upon whether the 'hot' or 'cool' temperature scale is used. A Salpeter (1955) slope has $\Gamma = -1.35$, and this is similar to what is found for OB associations in the Milky Way (Massey et al. 1995a) or Magellanic Clouds (Massey et al. 1995b).

We see stars in this cluster that are more luminous and massive than those seen anywhere else. This is also the richest, and youngest, cluster studied. This suggests that we really haven't seen evidence of a *physical* limit to the highest-mass star that can form – that instead what limits the mass of the highest-mass star in any region yet studied is simply the IMF becoming exhausted – that for a given number of stars, we hit a limit where only one star is produced. The reason, then, that we see stars of $\sim 150 M_\odot$ in R136 is simply its richness and age. *The upper mass 'cutoff' to the IMF is statistical, rather than physical, for regions so-far studied.*

For a brief time in the early 1980s it was believed by some that the semi-stellar core of the R136 cluster was itself a single, supermassive (2000–3000$M_\odot$) star, responsible for much of the ionization of the 30 Dor region (Cassinelli, Mathis & Savage 1981). This interpretation was shaken by the resolution of R136a into multiple components from ground-based speckle observations (Weigelt & Baier 1985), and put to rest when the first HST images revealed these (and multiple other) components were of comparable brightness and colour (Campbell et al. 1992). It is nevertheless interesting to note that Cassinelli et al. suggested that the alternative would require packing "on the order of 30 O3 or WN3 stars" within the R136 core. This was considered even less likely than the presence of a single object of several thousand solar masses (see discussion in Ebbets & Conti 1982). In retrospect this paper was in fact prophetical: we have confirmed the presence of 39 O3 stars.

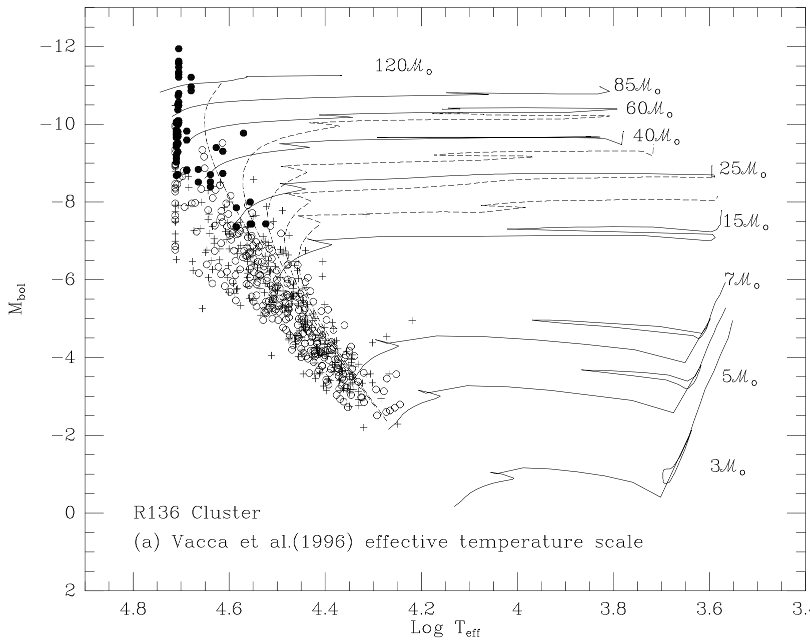

Figure 4. The HR diagram for the massive stars in R136. Filled circles are used for the stars with spectral types, and open circles for the stars with only photometry. The plus signs are used for stars whose reddening is uncertain. The evolutionary tracks of Schaerer et al. (1993) corresponding to the metallicity of the LMC are shown as solid lines, marked on the right by the zero-age-main-sequence masses. The dashed lines are isochrones at 2-Myr intervals.

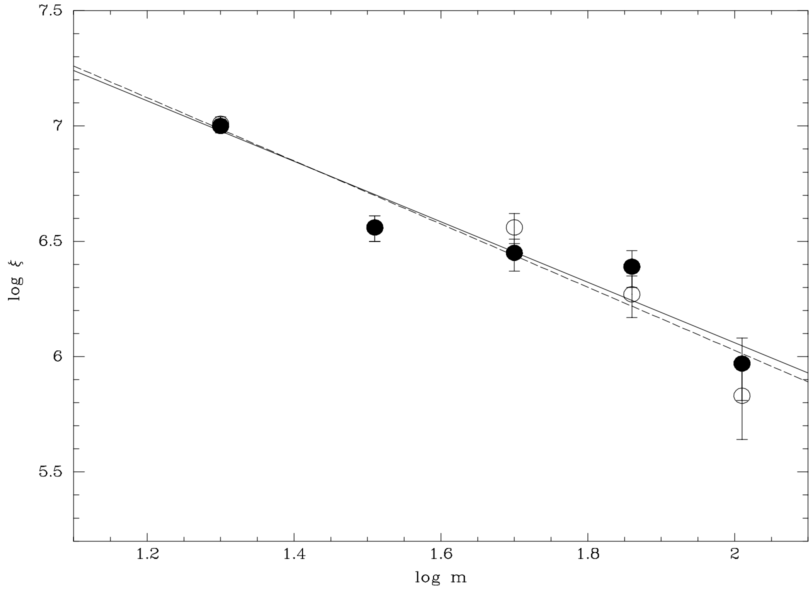

Figure 5. The initial mass function is shown for R136. The solid points and line use the Vacca et al. (1996) temperature scale, while the open points and dashed line are for the lower-temperature Chlebowski & Garmany (1991) scale.

Where Cassinelli et al. (1981) and others failed was in their assertion that the lower-mass stars were missing in the R136 cluster, that somehow the IMF was peculiar. Our spectroscopy, combined with the photometry of Hunter et al. (1997), yields an IMF slope that is characteristic of far sparser OB associations seen in the Milky Way and Magellanic Clouds. The preponderance of extremely massive stars is no more, and no less, than what we would predict using the intermediate-mass IMF from the work of Hunter et al. (1996). It is simply the young age and richness of the cluster that results in such an unprecedented massive-star population. Remarkably, the same IMF slope holds over the mass range from 2.8–5$M_\odot$ all the way to 120$M_\odot$, and over a stellar density range typical of OB associations to that which is typical of globular clusters.

Acknowledgments. We'd like to thank Peter Conti for presenting this work at the conference when we were unable to attend.

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Discussion

PSC: Although I've presented the talk, I reserve the right not to answer any questions!

Crowther: NGC 3603 is a Galactic counterpart to R136, and at last week's Herstmonceux Conference in Cambridge results were presented which also show a normal Salpeter IMF.

Hilditch: Could the problem you have of some stars being to the left of the ZAMS be solved by lowering the temperature scale? Later in the conference Tim Harries will be presenting evidence that such a reduction is indicated by binary-star studies, where the temperatures implied by Geneva models from the measured masses and radii are generally lower than those assigned spectroscopically.

Conti: Are you saying that some O3 stars have lower temperatures?

Hilditch: Well, we don't have any O3 stars, unfortunately; but the later O stars are cooler.

Maeder: Do you know if the O3 stars are concentrated to the centre of the cluster? Because in some very old clusters the most massive stars are found at the centre, and it cannot be a dynamical effect.

Bohannan: Peter, just put up the diagram showing the stars that were observed. Two-thirds – 40 out of 60 – are O3.

Conti: [Showing viewgraph; Fig. 1] Right, this is the inner part, but there isn't any obvious central concentration.

Nota: I just want to mention our poster [p. XXX], where we measure the IMF down to $0.8M_{\odot}$ (by summing everything that was available in the HST archive) and we find a turn-over at $1.5M_{\odot}$.

Conti: Hmm, for that mass the formation time is something like the cluster age, a few million years... interesting.