Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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R 136a and its implications for understanding Wolf-Rayet stars and Wolf-Rayet galaxies

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Abstract. We argue that the WR phenomenon is simply a consequence of very high mass-loss rates (*i.e.*, it is independent of initial mass, composition, or evolutionary status) and that it occurs in very massive main-sequence stars. We explore this argument using new *HST* observations of R 136a, the compact cluster containing three high-mass WR stars on the main sequence. We suggest that the underlying cause of the WR phenomemon in these stars is mass-loss enhanced by rapid rotation. Finally, we explore the implications of luminous, main-sequence WR stars for interpreting unresolved WR star clusters and galaxies.

1. Introduction

I put to you a thesis: the Wolf-Rayet phenomenon in hot stars is simply a phenomenon of high mass-loss (more precisely, a high rate of mass-loss per unit area on the stellar surface). Other factors don't enter in. The WR phenomenon is independent of the original mass of the star: it is known to occur in stars starting out at 100 $M_\odot$ or at 1 $M_\odot$ (Heap 1982). It is also unrelated to the surface composition, since it appears in stars enriched in helium, nitrogen or carbon, and, I will argue, in stars of near normal composition. Most importantly, the WR phenomenon is independent of the evolutionary state of a star. Most stars going through the WR phase are evolved, some highly so. But there is a class of stars — stars with initial masses greater that 70 or 80 $M_\odot$ or so — that experience the WR phenomenon while still on the main sequence. It is entirely possible that such stars were born as WR stars.

In this talk, I will concentrate on this new class of WR stars — the very massive main-sequence WR stars. Actually, there have been hints for some time that the WR phenomenon sometimes occurs in young main-sequence stars. This time, we have proof: we can point to some very massive stars ($M \simeq 100\,M_\odot$) in the compact cluster, R 136a in the LMC; we can demonstrate that their spectra are *bona fide* WR spectra; and we can locate them on the main-sequence portion of their evolutionary tracks. The proof consists of more than just fixing the WR stars on the HR diagram. The real proof is that we can date the cluster from its isochrone defined by both the WR stars and the less massive (O-type) stars in the cluster. The age so determined is less than 2 Myr. For an age $t < 2$ Myr, the WR stars in R 136a must be main sequence stars rather than more evolved stars passing through this region of the HR diagram on a return trip.

I will use the rest of this paper to support these arguments and to examine the implications of this class of very massive WR stars. Section 2 gives an introduction to R 136a: why it is the ideal object for exploring the WR phenomenon in young, massive stars, and what are the physical properties of the WR-type members. Section 3 attempts to identify the underlying cause of the WR phenomenon in these stars. Finally, Section 4 explores the use of R 136a as a template for more distant systems. Much of the material for these sections is drawn from de Koter *et al.* (1997, 1998, hereafter KHH97, KHH98).

2. R 136a: discovery site of main-sequence Wolf-Rayet stars

R 136a is a compact star cluster less then a parsec across lying at the heart of R 136, which in turn is the main source of ionization of the 30 Doradus complex in the Large Magellanic Cloud. Like other clusters, R 136a is homogeneous in age and initial composition. It is unusual, however, in the large number of massive stars present. The large number is partly due to the density of stars in the cluster, but also related to the youth of the cluster. At a cluster age less than 2 Myr, even the most massive stars have not progressed beyond the main sequence, let alone finished their lifecyles, so very massive stars still exist in this cluster.

Although the cluster is extremely compact, with separations of only $0\farcs2$ not uncommon, it is resolved by *HST*. The three brightest stars in R 136a — R 136a1, R 136a2, and R 136a3 — are WR stars (Campbell *et al.* 1992; Parker *et al.* 1995; KHH97). The other stars in R 136a down to $M_V \approx -5$ are O3-types, the earliest (hottest) O spectral type. The fundamental properties of O-type stars can be derived quite precisely, thanks to the powers of modern spectral analysis and modeling (*cf.* KHH98). We therefore used the O-type stars along with the three WR stars to construct an empirical isochrone for the cluster, and from there, to derive a cluster age of 2 Myr or less.

3. R 136a: test site for stellar evolution theory

I now discuss the application of our analyses to understanding the WR phenomenon. One result of our analyses has to do with scatter in the wind properties of very massive stars. We find that spectral class (*i.e.*, spectral type and luminosity class) is not associated with a unique absolute magnitude; nor is it associated with a unique wind velocity. Hence, observed properties like M_V and v_∞ of stars in R 136a are not well correlated. The scatter is displayed in Figure 1, where the WR stars are shown as stars, Of/WR stars as large filled circles, Of stars as small filled circles, and O stars as open circles or arrows if only lower limits on $v_{\rm black}$ could be made. The star identifications are from Malumuth & Heap (1994). The more-or-less vertical line shows the expected wind velocity computed as $v_\infty = 3.5\, v_{\rm esc}$. There may be some argument whether 3.5 is exactly the right factor. The point is that these stars should have similar wind velocities. That there is such a wide range indicates that something is missing from the theory of radiation-driven winds.

Another result of our analyses has to do with mass-loss rates. There have been suggestions that the standard prescription for mass-loss (de Jager *et al.* 1998) is seriously in error when applied to young, very massive stars. In recognition of these deficiencies, Meynet *et al.* (1994) recalculated a grid of evolutionary tracks with the standard mass-loss rates raised by a factor of two. Even so, we find that the very massive stars in R 136a have mass-loss rates that are still 2-10 times higher than assumed in the new Meynet *et al.* models.

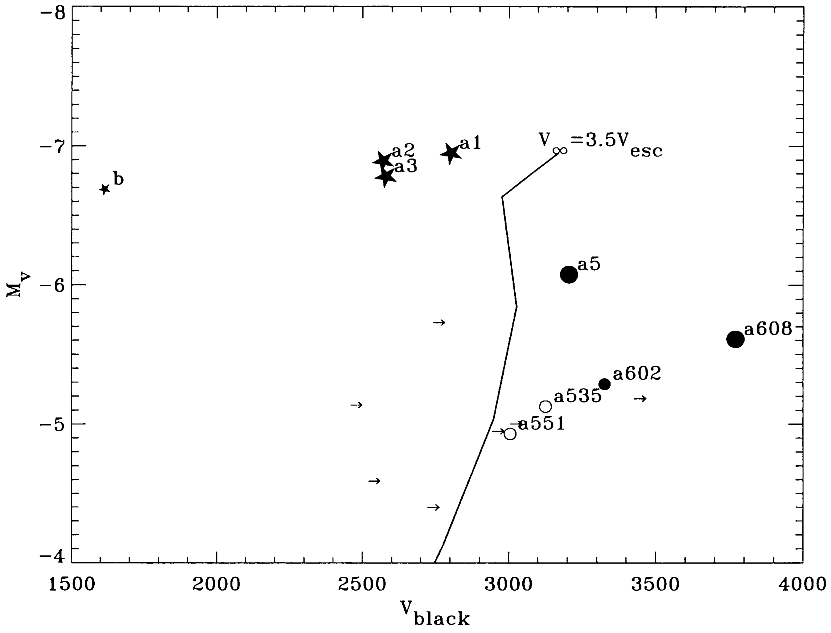

Figure 1. Absolute magnitudes and wind velocities ($v_{\rm black}$) in R 136a.

Both the wind-velocity problem and mass-loss problem may be related to the initial rotational velocity. According to Langer (1998) and Meynet (1998), the mass-loss rates of massive stars are highly dependent on rotational velocity at the time of formation, and rapidly rotating stars can have greatly enhanced mass-loss rates. Hence, stars having the same initial mass but different rotational velocities will evolve differently and take on different spectral appearances. Conversely, stars with the same spectral type may have different initial masses and ages. There is no one-to-one correspondence between spectral type and the fundamental properties of a star.

These theoretical findings are relevant to the WR phenomenon in massive, main-sequence stars. They raise the question: are the three WR stars in R 136a really such massive stars ($M_i \simeq 100\,{\rm M}_\odot$) as the KHH97 analysis suggests, or are they less massive ($M_i \leq 60\,{\rm M}_\odot$) but rapidly rotating stars in disguise? New evolutionary grids of rotating models will be a very welcome help in answering this question. If it should prove that main-sequence WR stars are rapid rotators and O stars are not, it will help explain why some stars, such as Mk 42 (Heap *et al.* 1991), that are as massive as the WR stars in R 136a can exist as O-type stars.

4. R 136a: template for distant, unresolved Wolf-Rayet systems

Having resolved R 136a and derived the properties of individual stars, we can put the cluster back together again with various Initial Mass Functions in order to explore the consequences of the IMF to the observed properties of the cluster

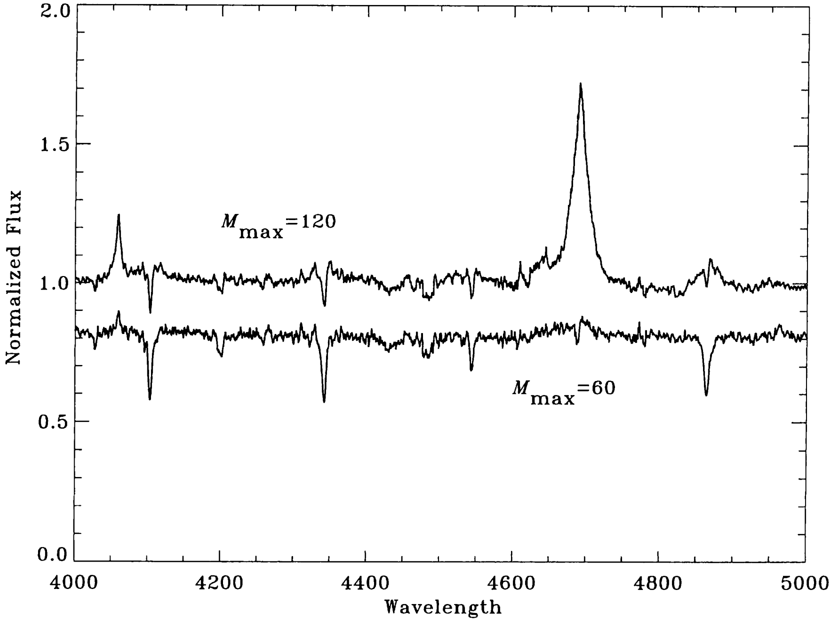

Figure 2. Effect of the IMF upper mass limit. For clarity, the spectrum with $M_{\rm max} = 60\,{\rm M}_\odot$ has been shifted downward by 0.2.

as a whole. In the synthesis, we co-add the observed spectra of all 15 stars in R 136a observed by the *HST*-GHRS and -FOS, weighted by their IMF fractions as determined from their initial masses. (Since we observed only stars more massive than 35 $M_\odot$, the synthesis is not complete. In fact, stars with $M_i \leq 35 M_\odot$ contribute nearly half the flux at He II λ4686.) Figure 2 shows the resulting integrated spectra for a Salpeter IMF.

A Salpeter IMF suffices to match the spectrum of R 136a, although its exact value is not well constrained by this exercise. What *does* have a profound effect is the upper mass limit of the IMF. If $M_{\rm max}$ is as high as $110\,{\rm M}_\odot$ as KHH97 estimated, then the calculated spectrum of R 136a looks just like the observed one (Melnick 1985; Walborn *et al.* 1992; Heap *et al.* 1992). But suppose the cluster were less dense. Statistically, its upper main sequence would not be populated because the cluster has fewer stars, and a more likely upper limit might be $M_{\rm max} = 60\,{\rm M}_\odot$. In that case, the cluster spectrum would look very different — more like a normal OB cluster. If such a cluster were unresolved, would we know that it had the same age and IMF slope as the WR cluster? Conversely, if R 136a were so distant as to be unresolved, would we realize that it is simply a very young cluster with no evolved stars?

These ambiguities must be kept in mind when considering unresolved WR star clusters or unresolved knots in WR galaxies. Since stars spend more than 75% of their lifetimes on the main sequence, could WR galaxies be composed of clusters containing very massive, main-sequence stars that are constantly replenished by continuing star formation? Probably not. It appears that most WR galaxies contain evolved WR stars. According to Schaerer *et al.* (1999), the spectra of most WR galaxies show C IV in emission, suggesting the presence of WC stars, which are highly evolved and very short-lived. In contrast, the main-sequence WR stars in R 136a show such weak C IV emission as to be undetectable in integrated spectra.

These results make sense in the context of the star-formation theory developed by Efremov & Elmegreen (1998). They demonstrate that the wider the separation of two stars, the greater their difference in ages is apt to be. With the wonderful resolution of *HST* images, we see that WR galaxies are composed of a collection of young star clusters, *i.e.*, a supercluster. Sometimes, these superclusters can spread out over tens of parsecs. According to Efremov & Elmegreen, a star-forming region 10 parsecs across should have a 3-Myr spread in ages; one 100 parsecs across, a 10-Myr age spread. The composite spectrum of a supercluster should reflect this spread in ages by showing spectra of both very young main-sequence WR stars as well as somewhat older, evolved WR stars.

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Discussion

Langer: You compared the mass-loss rates for luminous O-type stars to those of de Jager *et al.* What is the result if you compare them with the predictions of the radiation driven wind theory? Do we need an additional physical mechanism to enhance the mass loss rate, *e.g.*, pulsations or rotation? And if you argue for rotation as mass loss enhancing mechanism (as I did myself in recent papers) then you face the problem of anisotropic winds and the model atmospheres which you used to derive the mass loss rates might not apply.

Heap: The observed $\dot{M}$ is about seven times higher predicted from radiation-driven wind theory with single scattering, but it is less than a factor of 2 higher than predictions that take multiple scattering into account.

Schulte-Ladbeck: It seems to me your spectra show quite a few absorption lines. If any of these are good photospheric lines and if they are resolved, you should be able to determine $v \sin i$. This would give you an indication of whether or not $\dot{M}$ relates with rotation. Would you care to comment? From the 'atlas' which you showed, the absorption lines all seemed to be equally narrow.

Heap: Unfortunately, the absorption lines you see in the UV spectra of these stars are due to thousands of blended iron lines, mostly Fe V lines. There isn't a single isolated absorption line in the whole UV spectrum. Even if there were, the *HST*-GHRS spectra that I showed have a resolution of only $150\,\mathrm{km\,s^{-1}}$, which is by no means ideal for rotational-velocity determinations.

Maeder: You showed that the mass-loss rates should be higher. However, W.-R. Hamann showed that due to clumpiness in the WR and O star winds, the mass-loss rates should be reduced by a factor of two. Thus, it is difficult for us to know what exactly to do in future work.

Heap: Yes, this is a sticky problem. Alex de Koter, Ivan Hubeny, and I are now collaborating with John Hillier to come up with an improved mass-loss law.

Moffat: (1) Given that R 136a and NGC 3603 are stellar clones, as noted by Laurent, perhaps both of them should be considered as *Rosetta stones*. The inconvenience of the large IS extinction towards NGC 3603 is overwhelmingly compensated for by its 7 × shorter distance, making it apparently $\sim 50 \times$ less crowded! This makes NGC 3603 much easier to study without the worries of contamination. The real interest is to compare two similar objects at different metallicity. (2) As with NGC 3603, at least one of the three WR stars in R 136a must be a close binary, with a similar period of close to 4 days (Moffat & Seggewiss 1983; Moffat, Seggewiss & Shara 1985). In both cases, this may have important dynamical implications.

Massey: I need to point out that the results here depend a lot on what you conclude for the effective temperatures of the hottest and most luminous stars. For instance, your group and Rolf Kudritzki's group have gotten wildly different results for the same data on the same star – Mk 42. I think some real improvement can be made here by getting high S/N spectra on some of these O3 stars, which we're now doing with *HST*-STIS.

Heap: The München group gets O-star temperatures that are only about 10% higher than what we get, so I don't know that I'd call them wildly 'different'. But you're right: their higher temperatures lead to higher bolometric corrections, luminosities, and masses, so it's important to pin down the temperatures as closely as possible. We attempted to track down the source of the differences with results reported by KHH97. As to your second point, I will always agree with getting high S/N spectra of hot stars!

Vanbeveren: As shown by Petrenz & Puls (1996), if Hα is used to derive $\dot{M}$ with NLTE hydrodynamical models, the effect of rotation on the profile is essential; *i.e.*, given an Hα profile, the derived value of $\dot{M}$ is smaller the larger the rotation. So, my question is: the fact that you obtain high $\dot{M}$ values, could this be due to the fact that you did not account for the effect of rotation on the Hα profile and thus that your derived $\dot{M}$ values are too large?

Heap: Yes, that's possible, but to do the job properly, you have to go to 2-D models of the wind in order to take into account the concentration of material toward the equatorial plane. This is a big step — but it's something Ivan Hubeny and colleagues are working on right now.