Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Properties of nearby giant star-forming regions

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Abstract. I review the properties of two nearby giant H II regions — 30 Doradus and NGC 604, and of two nearby young star complexes now past the H II region phase — Constellation III and NGC 206. I discuss the stellar populations, mode of star formation, gas content, and kinematics as clues to what conditions may be like in more distant starburst environments.

1. Introduction

I have been asked to review the properties of some nearby giant H II regions with the view to what they tell us about starburst environments. These giant star-forming complexes are places to test assumptions and deductions from global properties of more distant regions of intense star formation, and in so far as conditions in distant galaxies are similiar, they can show us what is going on in more distant places. In this review I will focus on 30 Doradus in the LMC, as the quintessential giant H II region, and NGC 604 in M 33. I will also include two young regions that are not H II regions because they are old enough to have blown the gas away. These star complexes, Constellation III in the LMC and NGC 206 in M 31, are examples of what giant H II regions evolve to. This raises one cautionary note: properties of giant star-forming complexes change rapidly over timescales of 10 Myr as the region evolves. Therefore, for some properties we are only capturing the region at one particular instant of time: 30 Doradus and NGC 604 represent the properties of mature giant H II regions while NGC 206 and Constellation III are post-H II complexes.

2. Some global properties

A few basic global properties of the four regions are catalogued in Table 1. One can see that the star-forming complexes are of order 1 kpc in size. The nebulae themselves are of order 400 pc and have emission equal to that of nearly a thousand Orion nebulae. The original gas clouds that formed these complexes were of order 10^7 $M_\odot$. These regions are bright in the UV; NGC 206 stands out as one of the brightest regions in M 31 in UV images. They are also bright in X-rays, and have complex kinematics until they blow a hole in the gas. The holes that Constellation III and NGC 206 sit in are of order 1 kpc in diameter.

Efremov (1995) has suggested that large-scale complexes of OB associations are a common mode of star formation in disk galaxies, and that they are physical entities rather than chance collections. He argues that the star complex is the largest and initial scale of star formation that begins with gas superclouds of order 10^7 $\mathrm{M}_\odot$. A top-down scenario of star formation leads to individual giant molecular clouds within this region that form individual OB associations and clusters over an extended period of time. For the most part, the regions that we are focussing on here are the star complexes that Efremov has identified, with the possible exception of NGC 604 which is smaller.

Star formation within a star complex is not instantaneous. From 30 Doradus, Constellation III, and NGC 206 we see that the bulk of the star formation proceeds over a time scale of order 10 Myr. Furthermore, in 30 Doradus (Lortet & Testor 1991) and Constellation III (Reid *et al.* 1987; Olsen *et al.* 1997; Braun *et al.* 1997; Dolphin & Hunter 1998) there is no correlation of age with distance from the center of the region, indicating that star formation has not proceeded in any obvious sequential fashion; there may be some star induced star formation within the complexes but it is not so orderly as to be a function of radius.

Table 1. Some global properties

	30 Doradus[a]	NGC 604[b]	NGC 206[c]	Constellation III[d]
distance (pc)	0.055	0.84	0.77	0.05
age (Myr)[e]	$\leq$10 (20)	4	3–8 (40–50)	9–16
diameter (pc)	nebula$\sim$410 overall$\sim$1000	nebula$\sim$420	stars$\sim$950	stars$\sim$900
$L_{\mathrm{H}\alpha,0}$ (10^{39} erg s^{-1})[f]	18	5	0	0
$M_{\mathrm{H\,I}}$ (10^6 $\mathrm{M}_\odot$)[g]	14	2	2	15
M_{H_2} (10^6 $\mathrm{M}_\odot$)	4	4	0	0
M_{stars} (10^5 $\mathrm{M}_\odot$)[h]	$\geq$3 (110)	2	4	24
WR stars?	Y	Y	Y	N
X-ray (10^6 K)	2–10	1	...	2
L_{UV} (erg cm^{-2}s^{-1}Å^{-1})	...	...	$F(2000) \simeq 3\times10^{-13}$ $F(1550) \simeq 0.5\times10^{-13}$	...
gas kinematics	complex	complex	gas hole	gas hole

[a] Kennicutt (1984), Walborn (1991), McGee & Milton (1966), Cohen *et al.* (1988), Massey & Hunter (1998), McGregor & Hyland (1981), Hyland *et al.* (1992), Rubio *et al.* (1992), Wang & Helfand (1991a), Walborn & Blades (1997), Lortet & Testor (1991), Rubio *et al.* (1998).

[b] Kennicutt (1984), Hunter *et al.* (1996a), Rosa & D'Odorico (1982), Drissen *et al.* (1993), Wilson & Scoville (1992), Wright (1971).

[c] van den Bergh (1966), Brinks (1981), Chernin *et al.* (1995), Hunter *et al.* (1996b), Massey & Johnson 1998, Carruthers *et al.* (1978), Deharveng *et al.* (1980), Hill *et al.* (1992).

[d] Braun *et al.* (1997), Olsen *et al.* (1997), Dolphin & Hunter (1998), Dopita *et al.* (1985), Bomans *et al.* (1994).

[e] Values in parenthesis show older ages that there is some evidence for in the region.

[f] Units of about 100 Orion nebulae.

[g] Values for Constellation III and NGC 206 are estimates based on the H I content of the surrounding shell.

[h] Extrapolating the stellar IMF 0.1 to 120 $\mathrm{M}_\odot$. NGC 206: includes a factor of 1.5 to correct for cluster missed by the *HST*-WFPC2 census. 30 Doradus: Value is for the region surveyed by Parker (1993) plus R136; value in parenthesis extrapolates Parker region to entire 30 Doradus complex. Con III: extrapolates Dolphin & Hunter (1998) survey to entire complex.

Efremov has suggested that it is from these $10^7\,M_\odot$ 'superclouds' that the giant molecular clouds condense. 30 Doradus and NGC 604 are still young enough for us to get some sense of the molecular clouds out of which the stars have formed. Both regions indeed contain multiple clouds comparable to the giant molecular clouds in our Galaxy. In 30 Doradus, there are two clouds 420–500 pc in diameter with masses of $4.5–7\times10^6\,M_\odot$ (resolution of 140 pc and $1.3\,\mathrm{km\,s^{-1}}$, Cohen *et al.* 1988). In NGC 604, four clouds have been identified with diameters of 40–64 pc and masses of $0.3–0.5\times10^6\,M_\odot$ (resolutions of 30 pc and $2.6\,\mathrm{km\,s^{-1}}$, Viallefond *et al.* 1992, Wilson & Scoville 1992).

3. Stellar populations

Starbursts and regions of intense high mass star formation have been said to be deficient in lower mass stars or to have unusual stellar initial mass functions (IMFs). For example, in M 82 Rieke *et al.* (1993) have argued from global properties that the lower mass limit M_l is no less than a few $M_\odot$; similarly observational arguments have been made that Mrk 171 and Tol 65 have made only OB-type stars in their recent starburst (Augarder & Lequeux 1985); and theoretical arguments in the past have suggested that M_l could be as high as $10\,M_\odot$ in regions of intense massive star formation (Silk 1977, 1995; Elmegreen & Lada 1977; Larson 1985; Elmegreen 1997). However, observational arguments are necessarily based on global properties. In nearby star complexes, at least with *HST*, we can do a direct stellar census far enough down in mass to be able to place constraints on M_l. So, let us look at what we know about the stellar populations of these four complexes.

3.1. Massive stars

The massive star content is summarized for the four regions in Table 2. All four regions contain hundreds of massive stars. In 30 Doradus and NGC 206 most of the massive stars are found in OB associations scattered throughout the star complex; in NGC 604 they are found in two major groupings of stars; in Constellation III many of the more massive stars have died off by now.

However, 30 Doradus is unusual among these four complexes in containing the compact, luminous star cluster R 136. This star cluster is probably what a small globular cluster was like when it was young. R 136 has a half-light radius of 1.7 pc, a mass (extrapolated from 2.8 to $0.1\,M_\odot$) of $6\times10^4\,M_\odot$, and an $M_V = -11$ (Hunter *et al.* 1996c). Within the cluster there are 39 O3-type stars that have been observed and its most massive stars reach masses of $150\,M_\odot$ (Massey & Hunter 1998). And all this within a few parsecs! Therefore, R 136 epitomizes the intense star-forming environment. The stellar content of this very young cluster — the massive stars are only 1–2 Myr old — is normal (see next section); it contains so many very massive stars only because it is so young and so especially rich in stars altogether. Massey & Hunter (1998) have suggested, in fact, that the upper stellar mass limit that has been observed so far, $\sim150\,M_\odot$, is only statistical. Although there must be some physical limit, we have been limited in observing the mass ceiling by the small numbers of stars formed as well as the older age of regions.

Table 2. Massive star contents

	30 Doradus[a]		NGC 604[b]	NGC 206[c]
	R 136	Parker region		
$N(M_V \leq -4)$	120	450	186	280:
N(WC)	(1)	3	14 candidates	2
N(WN)	4	8		2
$N(WR)/N(M_V \leq -4)$	0.03	0.02	$\leq$0.08	0.01
N(WC)/N(WN)	(0.25)	0.38	...	1.0

[a] 'Parker region' includes only the region surveyed by Parker (1993) outside of R 136; R 136 is from Hunter *et al.* (1996c). The WC in the R 136 region is probably an interloper and not part of the cluster itself. The WN number does not include O3If*/WN6-A stars: 6 in R 136, 2 in 30 Doradus.

[b] Hunter *et al.* (1996a), Drissen *et al.* (1993).

[c] Hunter *et al.* (1996b), a factor of 1.5 has been included to account for the part of the cluster not surveyed with *HST*-WFPC2; Massey & Johnson (1998).

Wolf-Rayet stars are also present in all regions except Constellation III which is too old by now to contain any. I have entered some survey numbers in Table 2 that are of interest to people who study Wolf-Rayet galaxies. The WC/WN ratio is a function of metallicity (see Figure 8 of Massey & Johnson 1998) and the ratios in the table are what are expected for the metallicities of the galaxies. The $N(WR)/N(M_V \leq -4)$ ratios are also roughly what one expects from few Myr old populations (Leitherer & Heckman 1995).

However, R 136 offers a cautionary tale. Although R 136 contains four Wolf-Rayet stars, none of them are evolved objects as one usually expects Wolf-Rayet stars to be. They are over-luminous — by a factor of 10 — hydrogen-burning stars that are 1–2 Myr old rather than $\geq$3 Myr (de Koter *et al.* 1997; Massey & Hunter 1998). Furthermore, the equivalent widths of the λ4686 line is 70–100 Å, which is about normal for a WN star. Therefore, the flux in λ4686 is about 10 times higher than for a normal WN star, and these hydrogen-burning WN stars will each masquerade as 10 WN stars if you are counting stars from an integrated λ4686 flux. Thus, these stars could be partly responsible for the unusually high WN/O star ratio that is inferred in Wolf-Rayet galaxies.

3.2. Stellar Initial Mass Function

Slopes Γ of the stellar IMFs measured in these regions are listed in Table 3. The IMF, as a measure of the proportion of stars formed as a function of the mass of the star, tells us what the stellar populations of the star complexes are. Slopes comparable to that of Salpeter are also seen in most other clusters and associations in these and other galaxies. We see, therefore, that IMFs of stellar associations and clusters are 'normal' (that is, like Salpeter), to within the uncertainties, wherever one measures it, even in R 136! Abnormal IMFs have only been measured for field massive stars (Massey *et al.* 1995b). At this meeting, we have heard that global properties lead one to infer that interacting spirals have IMFs that are steeper than Salpeter and have unusually low upper mass limits (see Joseph, these Proceedings) and that Wolf-Rayet galaxies have

Table 3. Stellar Initial Mass Functions

region	Γ	mass range ($M_\odot$)	reference
R 136	−1.3±0.1	2.8–120	Hunter *et al.* 1996c, Massey & Hunter 1998
30 Doradus	−1.5±0.2	$\geq$12	Parker & Garmany 1993
NGC 604	−1.6±0.7	6.5–18	Hunter *et al.* 1996a
NGC 206	−1.4±0.5	6–15	Hunter *et al.* 1996b
Constellation III	−0.9 to −2.1±0.2	6.5–15	Dolphin & Hunter 1998

shallower than Salpeter IMFs (see Contini *et al.*, these Proceedings). We need to understand the discrepancy between these studies and those of individual star surveys of nearby star-forming regions.

3.3. Lower stellar mass limits

R 136 is the most extreme environment in which to test claims that the lower stellar mass limit should be high. It is also the place among our four complexes with the most stringent observed limit to M_l. In R 136 $M_l \leq 2.8$ $M_\odot$ (Hunter *et al.* 1996c). There are stars measured to ~1 $M_\odot$ in *HST*-WFPC2 images, but photometric and detection uncertainties are too large to say anything significant below ~2.8 $M_\odot$. *HST*-NICMOS observations in progress will, however, address the lower mass stars. For the time being, we can say that in an intense region of star formation like R 136, there are stars in normal proportions down at least to a few $M_\odot$, not just to 10–20 $M_\odot$.

4. Mode of star formation

In this section I want to examine the mode of star formation in these star complexes. By that I mean the richness, or number of stars formed, and the concentration, or number of stars per unit area that have formed in the region. In other words what are the star-forming regions like? Obviously, R 136 is the most extreme in terms of both of these parameters. It contains many stars and they are crammed into a small space. In fact, the concentration of stars in R 136 is about 300 times what is found in typical OB associations. Richness and concentration are shown for a variety of regions in Figure 1 (Parker & Garmany 1993; Massey *et al.* 1995a,b; Dolphin & Hunter 1998; Hunter *et al.* 1996a,b,c,1997; Hunter & Thronson 1995; Lynds *et al.* 1998). From this figure one can see that some, maybe even most, giant H II regions are just scaled OB associations; they have formed more stars but at the same spatial concentration as in typical OB associations. This includes 30 Doradus outside R 136, the bulk of the star formation in Constellation III, and NGC 604. NGC 206 has formed more stars than R 136 but is unusual in having a fairly *low* spatial concentration. Constellation III has formed some knots that are comparable in concentration, although not richness, to the populous cluster NGC 1818, but these knots still are less concentrated and rich than R 136 by factors of ten. Here we can also compare with three more distant galaxies. The giant northern H II region in the

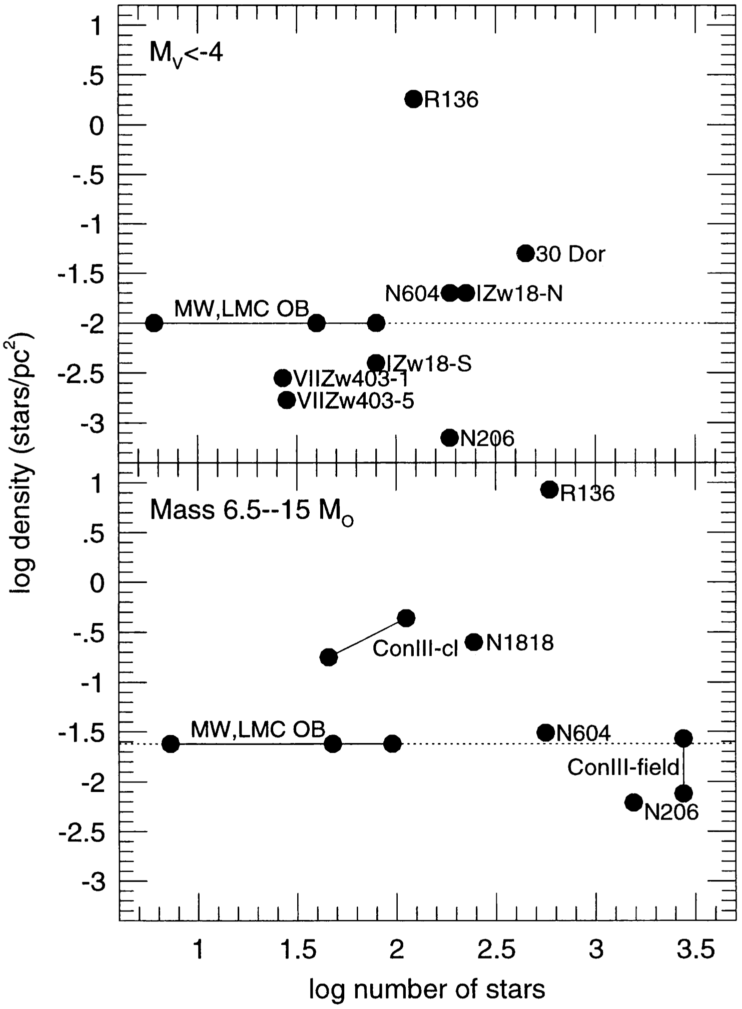

Figure 1. Richness and concentration of stars formed in various star-forming regions. The top panel is for stars brighter than −4, approximately all O-type stars, a parameter that varies as the region evolves. The bottom panel is for stars with masses 6.5–15 $M_\odot$, a quantity that does not vary for regions as young as these but that is harder to measure in more distant galaxies.

Blue Compact Dwarf galaxy I Zw 18, the southern H II region in that galaxy, the clusters in VII Zw 403, and the diffuse star formation in the Local Group starburst galaxy IC 10 (see poster by Hunter, these Proceedings) are all typical or scaled versions of OB associations. Therefore, not all BCDs/starbursts contain unusual star-forming regions even if they contain giant H II regions.

However, at least one, 30 Doradus, does contain a superstar cluster, R 136. In this regard, the 30 Doradus complex and Constellation III offer an interesting comparison. Both complexes contain or contained similar amounts of gas, are about the same size, formed stars over comparable time periods, and formed scattered OB associations. In many ways these two star complexes are very similar. Yet, 30 Doradus formed R 136 and Constellation III only formed little knots that are 30 times less concentrated and 10 times less rich in stars. Why? Is it that the distribution of the gas within the region was different? Is it the influence of the bar potential on 30 Doradus? This is an outstanding question in understanding star formation processes.

5. The H II regions

30 Doradus has been extensively studied as an H II region (Elliott *et al.* 1977, Scowen *et al.* 1998, Meaburn 1984, Kennicutt & Chu 1994, Chu & Kennicutt 1994, Cohen *et al.* 1988). We see that the H II region sits on one side of a tongue of H I. Many of the ionized gas filaments are ionization fronts eating into neutral gas (see schematic model by Elliot *et al.* 1977, Figure 28). The kinematics are complex with multiple velocity components resulting from 10–50 pc sheets, 3–15 pc shells with expansion velocities up to 200 km s^{-1}, and larger shells up to 100 pc with velocities of 35 km s^{-1}. The general turbulent velocity is $\sim$30–40 km s^{-1}. All of this is due to supernova remnants that have gone off throughout the region and the stellar winds, especially those from the stars in R 136. The kinetic energy in the ionized gas is estimated to be 10^{53} erg for the entire nebula over 10^7 years. In addition to all of this activity in the ionized gas, there is an expanding CO ring with a diameter of 500 pc, a mass of 3.8×10^6 $M_\odot$, an expansion velocity of 17 km s^{-1}, and kinetic energy of 3×10^{52} erg.

NGC 604 has been described as similar to the 30 Doradus nebula (Rosa & Solf 1984, Sabalisck *et al.* 1995, Yang *et al.* 1996, Rosa & D'Odorico 1982). It has supersonic motions of order 40 km s^{-1} due to thermal broadening, stellar winds, supernova remnants, and virial motion. There are shells and sheets with velocities up to 100 km s^{-1}. NGC 604 is also located on the edge of a huge H I cloud and is what is termed a 'blister' H II region. It too is churned up by supernovae, strong stellar winds, as well as the blister expansion. The kinetic energy in the H II is estimated to be 10^{52} erg.

In X-rays 30 Doradus and Constellation III have been well studied (Wang & Helfand 1991a,b; Bomans *et al.* 1994; review by Wang 1998). 30 Doradus exhibits X-ray bubbles surrounded by Hα shells plus diffuse X-ray emission. The gas shows a range in temperatures of 2–10 MK with the high energy gas mostly found around R 136. The hot gas contains $10^{52.5}$ erg and 10^4 $M_\odot$. This hot gas is the result of stellar winds and supernovae. The hot gas and H II gas are mixing in the core around R 136. The cavity has evaporative flows resulting from pressure gradient between the ionization fronts and interior of the cavity. Wang has a spectacular color image of 30 Doradus, combining X-rays, Hα, and UV, on his web page and I would urge you to look at it to appreciate the real complexity of this region.

Constellation III represents an older region, now a supershell (LMC-4). It exhibits diffuse X-ray emission with ridges of higher surface brightness, a temperature of several MK, and an X-ray luminosity for 0.1–2.4 keV of 10^{37} erg s^{-1}.

6. What happens next?

We know that the concentration of massive stars in Constellation III has blown a hole in the neutral gas, creating a supershell around it. An interesting question is whether this region, and regions like it, actually break out of the galactic disk. This has important consequences for the evolution of the galaxy. It is already fairly amazing that the LMC-4 supershell is 1.2 kpc in diameter. That seems extraordinarily large. Yet, Bomans *et al.* (1994) argue that the hot gas in LMC-4 has not yet even broken through to the halo and that, because of overpressure, it is still expanding into the ambient medium. However, the data are partial and noisy, and Dopita *et al.* (these Proceedings) argue that the X-rays in Constellation III are leaking in from the H II regions in the surrounding supershell. On the other hand, the LMC-2 supershell, adjacent to 30 Doradus, is argued by Wang & Helfand (1991b) from, admittedly noisy, Einstein data to have broken out with only a diameter of 500 pc, leading to a scale height estimate for the LMC that is smaller than that of the Milky Way. However, Points *et al.* (1996) argue that the structures in LMC-2 are more complicated than those of an expanding shell. Thus, in these two cases — supershells LMC-4 and LMC-2 — it is not entirely clear whether break-out has or will occur. We can expect that 30 Doradus and NGC 604, like Constellation III and NGC 206, will blow substantial holes in the gaseous disk, but what happens beyond that is still unclear. Again, we find contradictions in interpretation of observations: Dopita *et al.* (these Proceedings) argue that many of the shells in the LMC have already broken out while Brinks & Walter (these Proceedings) argue that the H I disks of irregulars are too thick to allow breakout. This is another area needing further study to iron out the contradictions.

Another issue is whether subsequent generations of stars beyond the complexes will form as a direct consequence of the energy input from these complexes. In the case of Constellation III we can see that a modest second generation has formed; they are the H II regions in the H I shell surrounding the Constellation (Dopita *et al.* 1985). On the other hand, theoretical considerations by Silk (1997) of the interstellar medium porosity suggest that numerous holes in the interstellar medium of galaxies make it even more difficult for galaxies to form stars overall. That this is a real issue is driven home by the stunning H I map of the LMC produced by Kim *et al.* (1998). These maps show the surroundings of Constellation III to contain many holes. Constellation III may well provide an example of the limitations of this process: There has been a a modest second generation, but will there be a significant third generation? The H I map of Kim *et al.* suggests that the interstellar medium may be too fragmentary to support a significant third generation beyond the complex.

7. Summary

These star complexes are found to be both simple and complicated. They are simple in that the stellar populations are, for the most part, assemblages of smaller building blocks that we are familiar with and contain stars in proportions that we have come to expect. They are complex in the interplay of massive stars with the leftover gas.

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Discussion

Selman: In your work for the high-mass range (Massey & Hunter 1998) you find an IMF slope, which is indistinguishable from Salpeter. For the intermediate-mass range

(Hunter *et al.* 1996) you find a slope only marginally flatter, and conclude that the two segments are consistent with Salpeter. But in Massey & Hunter (1998) you use the best fit IMF, which is flatter, to predict the number of stars with $M > 50\,\mathrm{M}_\odot$ and conclude that the prediction agrees with the numbers observed. Nevertheless, had you used the Salpeter slope, you would have been short by a factor of 2.5. Could you comment?

Hunter: When we take the intermediate-mass stars ($\Gamma = -1.0 \pm 0.1$, 2.8–15 $\mathrm{M}_\odot$) and predict the numbers of high mass stars (50–120 $\mathrm{M}_\odot$), we predict numbers that are close to what we observe. When we formally fit the high-mass stars only, we get a slope of $\Gamma = -1.3 \pm 0.1$. So what this says is that there is not much statistical difference between $\Gamma = -1.3$ and $\Gamma = -1.0$ for the high-mass stars only. Perhaps we should quote $\Gamma = -1.0$ for the whole range rather than $\Gamma = -1.3$, but in either case Γ is comparable to Salpeter within the uncertainties. The Γ is simply not precise enough to pin it down to more than a few 0.1. What we were particularly trying to show by extrapolating the intermediate-mass IMF up and predicting the number of high-mass stars was to show that the IMF was continuous and that there was nothing extraordinary in the large number of high-mass stars that we observed.

Marston: There appear to be no RSG or LBV stars in dense star clusters. Is there any evidence for the restriction of the slow outflows from such objects in regions of high pressure from stellar winds? And might this affect their evolution?

Hunter: I will have to difer that question to a stellar expert in the audience.

Elena Terlevich: We have detected one RSG and one star in the process of becoming an LBV in NGC 604 (spectroscopy): E. Terlevich *et al.* (1996 MNRAS 279, 1219), confirmed by poster of Maíz-Apellániz *et al.* (these Proceedings) with *HST* colours.

Polcaro: In the figures of the WR/O stars ratios you gave, did you include only the 'real' WR stars (*i.e.*, the chemically evolved high-mass stars), or also what was called in the previous talk the 'main sequence' WR?

Hunter: In Table 1 I include all WR stars. If one restricts oneself to only evolved WR stars, the only number that would change is that for R 136 which would go to zero. But, one of the points I tried to make was that in fact the presence of 'main sequence' WR stars will complicate the interpretation of $f(\lambda4686)$ in distant galaxies, partly because they are significantly younger than normal WR stars, and partly because they are so much more luminous in $\lambda4686$.

Polcaro: Comment on the reply: Actually, if the so-called MS-WR are included, these ratios do not give any information about the stellar evolution of the stellar association.