Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Chemical enrichment from massive stars in starbursts

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Abstract. The warm ionized gas in low-mass, metal-poor star forming galaxies is chemically homogeneous despite the prevalence of large H II regions which contain hundreds of evolved massive stars, supernovae, and Wolf-Rayet stars with chemically-enriched winds. Galaxies with large WR star content are chemically indistinguishable from other vigorously star-forming galaxies. Furthermore, no significant localized chemical fluctuations are present in the vicinity of young star clusters, despite large expected chemical yields of massive stars. An *ad hoc* fine-tuning of the release, dispersal and mixing of the massive star ejecta could give rise to the observed homogeneity, but a more probable explanation is that fresh ejecta from massive stars reside in a hard-to-observe hot or cold phase. In any case, the observed chemical homogeneity indicates that heavy elements which have already *mixed* with the warm interstellar medium (thus accessible to optical spectroscopy) are homogeneously *dispersed* over scales exceeding 1 kpc. Mixing of fresh ejecta with the surrounding warm ISM apparently requires longer than the lifetimes of typical H II regions ($> 10^7$ yr). The lack of observed localized chemical enrichments is consistent with a scenario whereby freshly-synthesized metals from massive stars are expelled into the halos of galaxies in a hot, 10^6 K phase by supernova-driven winds before they cool and 'rain' back down upon the galaxy, creating gradual enrichments on spatial scales >1 kpc.

1. Introduction

Starburst galaxies contain hundreds to thousands of the most massive O-type stars and their Wolf-Rayet descendants (see other articles in these Proceedings). Massive stars are generally concentrated in clusters with typical diameters of ~10–20 pc. The duration of the starburst events in low-mass galaxies is thought to be 10 Myr or less, so that the duty cycle of massive star formation over the lifetime of the galaxy is small (Dohm-Palmer *et al.* 1998). In normal galaxies, these massive star clusters dominate the production of ionizing photons, the generation of mechanical energy input to the ISM, and the nucleosynthesis of α-process elements (*e.g.*, O, Ne, S, Si). Understanding the fate of these heavy elements after they are ejected by stellar winds and supernovae explosions is part of the larger objective to trace the life cycles of matter in the universe.

The impact of massive star evolution on a host galaxy is best studied in low-mass systems where the effect is most pronounced. Low-mass galaxies encompass a wide variety of objects with nomenclatures including blue compact dwarf galaxies (BCDG), H II galaxies, dwarf elliptical galaxies (dE), irregular (Irr), and low surface brightness (LSB) galaxies. Because low-mass galaxies are also relatively metal-deficient (Lequeux *et al.* 1979; Skillman 1989), the heavy element yield of a given number of massive stars has a relatively large impact on the chemical properties of the surrounding gas. The chemical composition of the stars and gas in low mass galaxies may be measured by optical spectroscopy of emission lines from prominent H II regions (warm ionized gas), absorption lines in stellar atmospheres (stars), or X-ray spectroscopy of emission lines from highly ionized atomic species (hot diffuse gas). Here I consider only abundance measurements of the warm photo-ionized gas in and around H II regions. Since oxygen is the most easily measured element in H II regions, the terms 'abundance' or 'metallicity' should be read here as the 'abundance of oxygen relative to hydrogen by number'.

Assessing the impact of massive stars on the chemical content of their host galaxies entails two distinct issues: (1) Do galaxies with large populations of evolved massive stars (*i.e.*, WR galaxies) show, as a group, signatures of chemical enrichment from the current generation of star formation? (2) Are there *localized* chemical fluctuations on spatial scales comparable to individual giant H II regions that might be due to heavy elements recently synthesized and released by massive stars (*e.g.*, 'self-enrichment', Kunth & Sargent 1986; 'local contamination', Pagel, Terlevich & Melnick 1986)? Since chemical abundances are like fossils that record the previous star formation activity, both types of elemental variations contain information about the star formation and gas dynamical history of the host galaxy.

2. Chemical abundances in Wolf-Rayet galaxies

Galaxies with large populations of evolved massive stars in the WR phase are sometimes termed WR Galaxies (see Conti, these Proceedings). There are presently no quantitative criteria by which objects are granted this distinction, and it has now become clear that the WR phase is a normal episode in the evolution of starburst galaxies. WR stars are observed in nearly all galaxies, including the Milky Way, the Magellanic Clouds, and even the extremely metal-deficient I Zw 18 (Izotov *et al.* 1997; Legrand *et al.* 1997). Nevertheless, some galaxies show prominent WR features in their integrated optical spectra, indicating a large fraction of stars in the WR phase. Some authors postulate that the interstellar gas in such galaxies may become 'contaminated' by nitrogen-rich and helium-rich winds of the evolved stars (Pagel, Terlevich & Melnick 1986). For this reason, such galaxies are often omitted from studies seeking to use the chemical properties of low-mass galaxies to measure the primordial helium abundance and other fundamental cosmological parameters (Pagel *et al.* 1992; Olive & Steigman 1995).

I have collected from the literature and self-consistently analyzed the oxygen, nitrogen, and helium abundances from nearly 100 low-mass galaxies, as compiled in Kobulnicky & Skillman (1996). Figure 1 and Figure 2 show the resulting chemical abundances. Filled circles distinguish galaxies with strong WR features from galaxies without strong WR features (open circles). A comparison of the two galaxy samples reveals no significant difference between their mean nitrogen abundances. Likewise, the mean helium abundances for the two samples are also consistent with one another. This result shows that, as a class, galaxies with strong WR features from evolved massive stellar populations do not exhibit

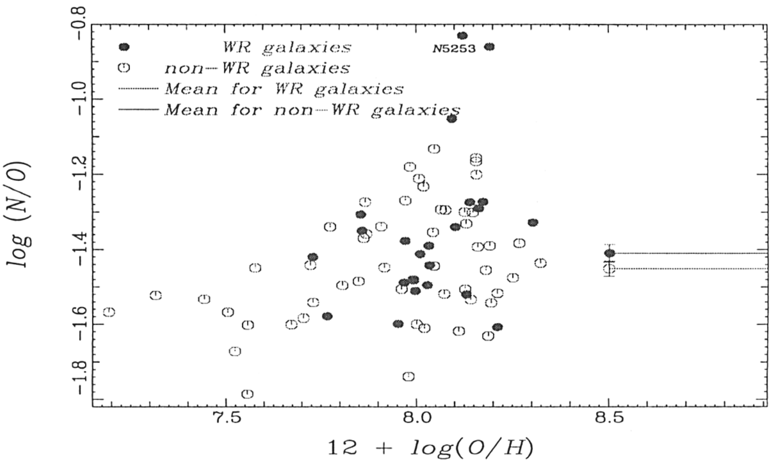

Figure 1. The oxygen abundance, as measured by 12+log(O/H), *versus* the nitrogen-to-oxygen ratio in low-mass, metal-poor galaxies from Kobulnicky & Skillman (1996). Filled circles distinguish galaxies with strong Wolf-Rayet features from those without (open circles). The mean N/O ratio for WR galaxies is consistent with that for non WR galaxies. There is no evidence that WR galaxies are chemically distinct in any way.

anomalous chemical properties compared to other star-forming galaxies. This result does not mean that evolved massive starbursts do not contribute heavy elements to the surrounding interstellar medium; we may only infer that the presence of strong WR features alone is not sufficient to distinguish galaxies which may have recently experienced an episode of chemical enrichment.

3. Localized chemical abundance fluctuations

3.1. Do chemical fluctuations exist?

Clusters of massive stars are, in theory, capable of creating large localized chemical enrichments (Esteban & Peimbert 1995). A typical $40\,M_\odot$ star may yield 2–6 $M_\odot$ of oxygen and several $\times 0.1\,M_\odot$ of nitrogen. Individual WR nebulae and supernova remnants exhibit pronounced concentrations of fresh nucleosynthesis products. Yet, on the scale of giant H II regions near massive star clusters in NGC 4214 (Kobulnicky & Skillman 1996) and NGC 1569 (Kobulnicky & Skillman 1997; Devost, Roy & Drissen 1997), NGC 2636 (Roy *et al.* 1996), and the SMC (Pagel *et al.* 1978; Russel & Dopita 1990) no measurable O, N, or He anomalies are seen in the surrounding warm photoionized medium. A quantitative comparison of expected chemical pollution *versus* observed abundance fluctuations is shown in Figure 3 for the case of the super star cluster A in NGC 1569. The measured N/O ratio along a 45″ strip adjoining the star cluster is plotted. The N/O ratio is a particularly robust measure of potential abundance fluctuations because it is relatively insensitive to errors in the adopted electron temperature. In Figure 3, no substantial variations beyond the mea-

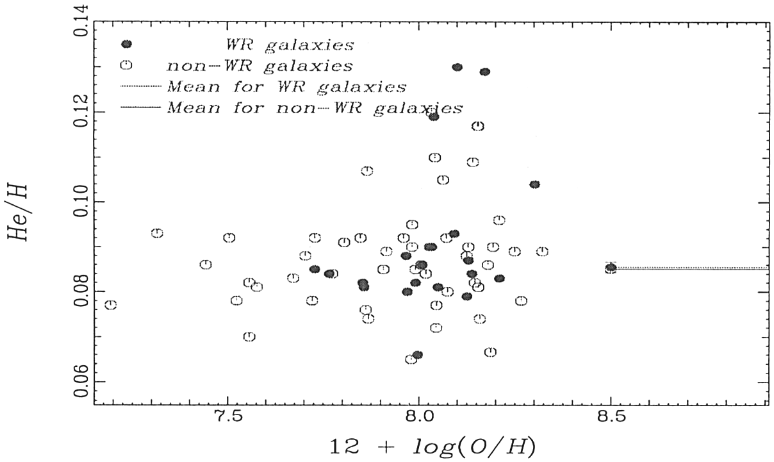

Figure 2. The oxygen abundance, as measured by 12+log(O/H), *versus* the helium-to hydrogen ratio in low-mass, metal-poor galaxies from Kobulnicky & Skillman (1996). Filled circles distinguish galaxies with strong Wolf-Rayet features. from those without (open circles). The mean He/H ratio for WR galaxies is consistent with that for non WR galaxies. There is no evidence that WR galaxies are chemically distinct in any way.

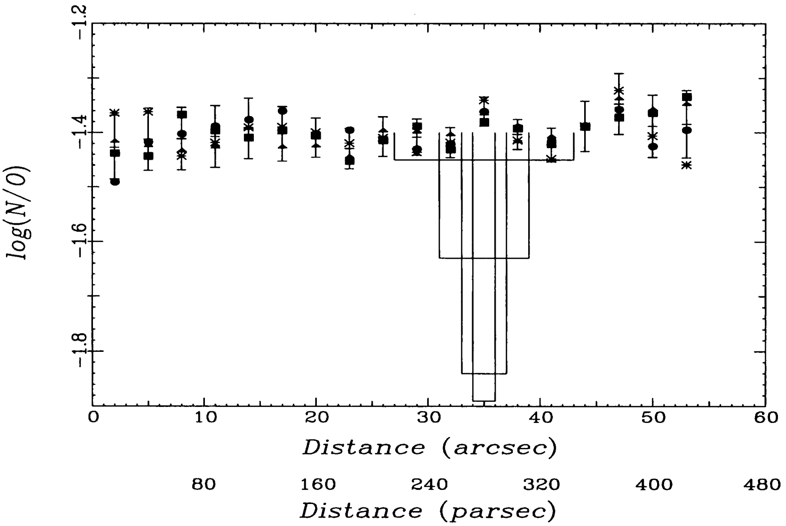

Figure 3. The N/O ratios along a 45″ strip of the ISM adjoining cluster A in NGC 1569. The expected magnitude of chemical enrichment (predominantly O enrichment) is shown by solid lines for four different spherical dispersal volumes. The observed variations are small in comparison to predicted enrichments, suggesting some of the freshly-released elements are hidden in a hard-to-observe phase.

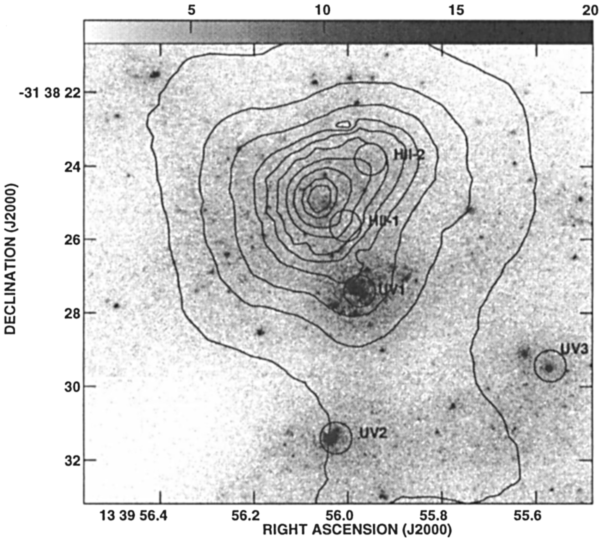

Figure 4. *HST* ultraviolet (greyscale) and Hα (contours) image of the central few arcsec of NGC 5253, showing the three UV-bright star clusters, and the location of *HST*-FOS apertures used to measure the region of nitrogen enhancement (Kobulnicky *et al.* 1997). The two apertures labeled H II -1 and H II -2 denote roughly the position and size of the region where nitrogen appears overabundant by a factor of 2–3 compared to the rest of the galaxy.

surement uncertainties are evident despite a sensitivity to N or O yields of just a few massive stars. For example, the slightly-elevated N/O ratio seen at the position number 12 at the 35″ mark could be caused by as few as two 40 $M_\odot$ stars.

NGC 5253 (Welch 1970; Walsh & Roy 1989; Kobulnicky *et al.* 1997) and possibly Markarian 996 (Thuan, Isotov & Lipovetsky 1996) remain the only galaxies where strong localized abundance anomalies are present. NGC 5253 contains a central starburst region (Figure 4) overabundant in nitrogen by a factor of 3 compared to the surrounding ISM. The nitrogen overabundant region appears to be ~60 pc in diameter and is centered on the heavily obscured star cluster to the NW of aperture H II -1. Schaerer *et al.* (1997) detect WR features near this location. One hypothesis is that 6–10 Wolf Rayet stars have 'polluted' this area with their nitrogen-rich winds. The N enrichment is equivalent to the nitrogen yield of ~8 WR stars, or ~120 Type I planetary nebulae. However, the lack of He enrichment at the same locations (Kobulnicky *et al.* 1997) is difficult to understand since localized enrichment by WR winds should produce elevations of both elements. Ground-based spectra (Walsh & Roy 1989) do show an He overabundance along with the N overabundance, lending credence to the WR star scenario.

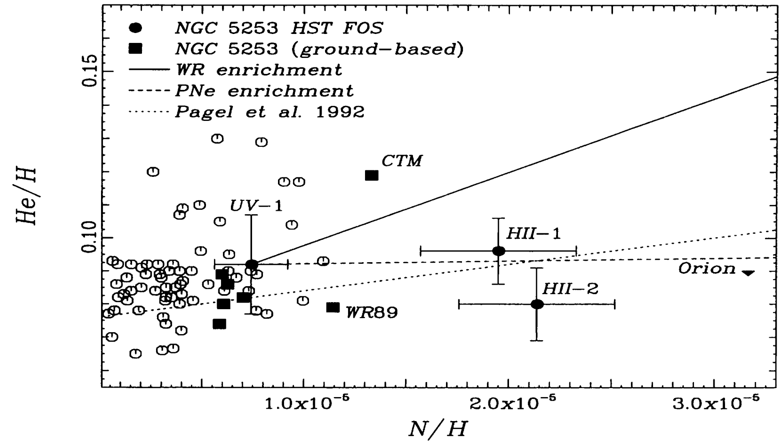

Figure 5. He/H *versus* N/H for 60 low-metallicity galaxies and NGC 5253. The ground-based observations of NGC 5253 are shown with filled squares, and *HST*-FOS data are plotted with filled circles. Positions H II -1 and H II -2 exhibit N abundances a factor of 3 above most metal-poor galaxies. Lines denoting the expected ratio of N and He enrichment from WR star winds and planetary nebulae are indicated. The lack of He enrichment accompanying the N enrichment is inconsistent with pollution by Wolf-Rayet star winds.

3.2. Is dilution the solution to pollution?

Can the lack of observed enrichment be due to rapid dispersal and dilution of the heavy elements? Not likely. Assuming an age of 10 Myr for cluster A, homogeneous dispersal within a sphere of a given radius, a filling factor for the ionized gas of 0.1, a gas density of 100 cm^{-1}, an IMF slope of –2.7 in the range 0.5–100 M$_\odot$ (see Kobulnicky & Skillman 1997 for details), the expected N/O deviations for a variety of dispersal scales are shown with solid lines in Figure 3. Adopting any combination of inhomogeneous dispersal, higher cluster age, lower filling factor or lower average gas density will enhance the expected chemical variations. Given typical expansion speeds of supernova ejecta, the heavy elements *could* be dispersed through a larger region than the largest simulated volume, and thereby become undetectable. However, such an extreme rapid-dilution scenario requires a finely-tuned, *ad hoc* dispersal mechanism to maintain the appearance of homogeneity of scales of several hundred pc. I Zw 18 provides an extreme test of the rapid dispersal hypothesis. In a small metal-poor galaxy like I Zw 18, even two O stars can produce significant chemical enrichment. Yet, both starburst knots in I Zw 18, separated by 300 pc, show identical chemical properties (Skillman & Kennicutt 1993). It seems that the heavy elements produced by the massive stars (down to 20 M$_\odot$) in cluster A in NGC 1569 are evidently not seen in the warm ionized medium.

4. Discussion

On scales of 10 pc to over 1 kpc, low-mass galaxies appear chemically homogeneous, indicating that the heavy elements are well dispersed throughout the warm ionized phase of the interstellar medium. The heavy elements are not necessarily well-mixed, however, as concentrations of massive star ejecta may exist on small, sub pc scales, or they may be incorporated into a phase of the ISM other than the warm, ~10,000 K photoionized medium. Given the lack of visible chemical enrichment around major starbursts, several explanations could be considered.

1) Perhaps the metals were never produced/released in the first place. If the number of massive stars originally present in the cluster has been overestimated based on the remaining stellar content, then the expected mass of heavy elements would be reduced. An abnormally low upper mass cutoff in the IMF, or an abnormally steep IMF could work to accomplish the observed effect. Yet, NGC 4214 and NGC 1569 do contain WR stars, so clearly the most massive stars have been, and are still present in the bursts.

2) An alternative suggestion requires black holes left by supernovae from massive stars to engulf the metals produced by the progenitor (e.g., Maeder 1992). This idea merits further theoretical investigation, but unless the lower mass limit for black hole formation, $M_{\rm BH}$ is considerably lower than $\sim 50\,M_\odot$, then the reduction of chemical yields would be too minor to resolve this problem. See discussion elsewhere in these Proceedings for current estimates of $M_{\rm BH}$.

3) The last, and most probable explanation for missing metals requires that the freshly-ejected metals reside in a hard-to-observe hot or cold phase (e.g., Tenorio-Tagle 1996). Since supernovae and the superbubbles formed by concerted supernovae contain copious X-ray emitting material, hot gas is the preferred explanation. The Cas A supernova remnant, for example, contains between $4\,M_\odot$ (Vink, Kaastra & Bleeker 1996) and $15\,M_\odot$ (Jansen, Smith & Bleeker 1989) of X-ray emitting material, consistent with the amount of ejecta expected from the progenitor. The pending generation of X-ray observatories should be able to measure the mass and metallicity of hot gas surrounding massive star clusters and make a direct comparison to expectations based on starburst models.

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Discussion

Legrand: I have a remark. When we are speaking about chemical enrichment in galaxies, we are always thinking in terms of bursts. However, there is no galaxy containing gas where the SFR is zero. All the LSBG or quiescent galaxies present a low residual star-formation rate. So between the bursts, there must be a continuous, but very low, star-formation rate. *E.g.*, in I Zw 18, I have shown that a continuous low SFR of 10^{-4} $M_{\odot} yr^{-1}$ reproduces perfectly the observed abundances of O and C after 14 Gyr. So I think that this low continuous SFR between bursts cannot be regulated, especially when dealing with low metallicity objects.

Kobulnicky: That's true, a low star-formation rate persists throughout most galaxies and would likely lead to homogeneous chemical properties. But strong bursts as we have observed in so many galaxies are a different story.

Meynet: The case of NGC 5253 is indeed quite puzzling, since one expects that if N is enriched, He should also be enriched. I was wondering if it would be possible to test the hypothesis of the hot gas-phase to look at nearby young associations both in X-rays and at 1.8 MeV in order to see if there is any correlation between the two. Such a correlation would favour indeed the hot-phase scenario.

Kobulnicky: X-ray data will certainly be important for telling the chemical make-up and homogeneity of the hot gas in galaxies. The 1.8 MeV line comes from the decay of ^{26}Al, is that right? So mapping the decay of this short-lived species may tell us where in galaxies the hot gas goes, and how far into galaxy halos it may go.

de Mello: Would you expect that star-formation rate occurs at the same rate everywhere in Low Surface Brightness galaxies as well? Or would it be patchy?

Kobulnicky: I believe LSBGs show much more uniform, low star-formation rates, and thus one would expect even more uniform chemical properties. But I really am not an expert on these types of galaxies, so I'll defer the question to someone more knowledgable.

Terlevich: Chip, would you care to comment on the difference between the *HST* and ground-based data (*i.e.*, Pagel *et al.*) on the He-abundance for the brightest cluster in NGC 5253?

Kobulnicky: That's a good point. Ground based data with 2–3$''$ spatial resolution seem to show an overabundance of He as well as N in NGC 5253. Our $0\farcs8$ *HST* apertures do not find elevated He where we do find elevated N. The theory that WR star winds created this enhancement would seem more viable, if both N and He enrichment are observed. It would be interesting to map this region at high spatial resolution ($0\farcs5$) with spectroscopy.

Kobulnicky: Reply to Roberto Terlevich who was surprised to see the high, nearly solar metallicity of He2-10. New optical spectra (Kobulnicky, Kennicutt & Pizagno 1999) show nearly solar metallicity. Previous data were of lower signal-to-noise, and produced O-abundance measurements with large uncertainties. The revised metallicity is consistent with its large CO and FIR luminosity.

Brinks: Comment: from what we know of the H I in dwarf galaxies, the H I disk is thick and blow-out is inhibited. So it seems more likely, as you propose, that the hot X-ray gas acts as the repository of the enriched material. Question: I have a conceptional problem. By the time you get your spectrum of an H II region, local enrichment has already occurred, so you are bound to find the same abundance ratios whereever you look?

Kobulnicky: I'm not so sure I understand. But starbursts span a range of ages of 3–20 Myr, (depending on the co-eval nature of the bursts), so the youngest should not be as heavily enriched as the older bursts, where most or all of the massive stars have completed their evolution and contributed much larger amounts of heavy elements to the ISM.

Maeder: I was wondering why we observe ^{26}Al in the galactic plane, if most of the ejecta go to the galactic halo. On account of the short life-time ($\sim 10^6$ yr) of ^{26}Al, this would seem difficult. However, in discussions with Roland Diehl and Georges Meynet during the coffee break, it appeared that the thickness of the ^{26}Al disk is pretty large and not necessarily in contradiction with your model, but maybe in support of it.

Kobulnicky: Indeed, ^{26}Al data of our Galaxy or others should be useful in tracing where massive star ejecta go.

Peña: I would like to comment that in planetary nebulae with [WR] nuclei we have not found nebular enrichment due to the highly processed material, mostly He and C, which is being ejected by the [WC] central stars. Mixing between the external H-rich nebulae and the internal He- and C-rich stellar wind seems to not take place easily.

Kobulnicky: Interesting point. Maybe the same type of explanation will apply here as well as in galaxies.