WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS

LINDSEY F. SMITH
Mount Stromlo & Siding Spring Observatories
Australian National University
GPO Box 4, Canberra ACT 2601
Australia

ABSTRACT. The most striking feature of the Wolf-Rayet stars in the Magellanic Clouds is their subtype distribution. The range of WC subtypes found in the Large and Small Cloud agrees with evolutionary model predictions at the corresponding metallicities. It follows that the WR subtype distribution in any external galaxy is a clear indicator of the metallicity in that galaxy.

The fluxes in the emission lines of WC stars appear to be consistent within the LMC. This can be used (with some precautions) in the Milky Way and other galaxies to determine reddening, distance and the numbers of WR stars in compact regions.

1. Introduction.

Properties of the Magellanic Cloud WR stars which are immediately obvious are crucial clues to the intrinsic nature of the stars. Specifically:
* The LMC appears, on superficial examination, to be immensely rich in WR stars, with about 2/3 as many known there as in our own Galaxy. The proportional number to O stars is, in fact, lower; the richness is a result of our "ringside seat". The SMC, in sharp contrast, has only a few WR stars, despite a rich O star population.
* Our Galaxy contains WN2-9, WC4-9 and WO1-4 stars; numbers are fairly uniformly spread over the subtypes within each sequence. The WN population in the LMC and SMC are comparable. However, the WC and WO populations are very different: the LMC has 19 WC4 and only one each of WC5, WC6 and WO4; the SMC has only one WO4 star.
* In the SMC, all the WR appear to be binaries!

Since 1962, when I entered the field, the WR stars have evolved from a rare oddity to high vogue. The reason for the interest is that they are now understood to be the stripped cores of massive stars: 8 to $40M_\odot$ of helium and heavier elements. Their mere existence demonstrates that all stars above about 40 $M_\odot$ lose a large fraction of their mass by continuous mass loss during their main sequence lifetimes. The WR stars are responsible for about 30% of the heavy element enrichment and contribute substantially to mechanical heating of the interstellar medium (Cohen 1990). Perhaps most important of all: the striking variations in subtype population are successfully explained by the metallicity of the progenitor stars. One has only to establish the earliest subtype of WC stars which is common in a region to know the current metallicity of that region. Their imminent fate is to supernova, probably as type Ib (Nomoto 1990).

The "6th" Catalogue of Galactic WR stars (van der Hucht et al 1981) contains 159 stars and many more are

R. Haynes and D. Milne (eds.), The Magellanic Clouds, 267–272.

being discovered (Shara 1990). The last catalogue of the LMC has 100 stars (Breysacher 1981) and more have been found since (Moffat et al. 1987, Azzopardi and Breysacher 1985, Morgan and Good 1985, Testor and Schild 1990). The SMC has eight known WR stars (Azzopardi and Breysacher 1979). There are significant numbers identified in M31 and M33 and a few in local dwarf galaxies IC 1613, NGC 6822 (see Smith 1988 for references), and thousands in the star burst regions of Blue Compact Dwarf galaxies (Arnault et al. 1989).

2. What is a Wolf-Rayet Star?

Observationally, a Wolf-Rayet (WR) star is one with strong, broad emission lines of highly ionised He, C, N and O. They divide into three sequences: WN stars in which the emission lines are primarily He and N; WC stars with primarily He, C and O lines; and WO stars with primarily C and O lines. Within each sequence are subtypes of differing excitation, evidenced by differing dominant ions of each element. Hydrogen is extremely under abundant or absent (Smith 1973, Conti et al. 1983b).

Theoretically, there is an obvious correspondence between the dominant elements in each sequence and the products of hydrogen burning, helium burning, and carbon burning, respectively (Paczynski 1983). This suggested the now generally accepted explanation that the WR stars are stripped cores of much more massive progenitors (Smith 1973, Maeder 1982).

The method by which the stripping occurs is partially known. Paczynski (1967) first suggested that mass exchange in close binaries - which very neatly removes most of the hydrogen envelope - would produce a WR star. It seems clear that many of the observed WR binaries, in which the WR star is the more evolved but less massive of the pair, have undergone this process.

However, a high proportion of WR stars appear to be single stars. The mechanism whereby these stars achieve WR status appears to be mass loss through radiation pressure (Abbott 1982). This makes WR stars a possible or probable stage in the evolution of all massive stars, dependent only on whether the mass loss is able to remove all of the hydrogen envelope in the lifetime of the star. Since radiation driven mass loss depends on luminosity and hence on mass, there will always be a lower limit to the initial mass of a star that will achieve WR status, i.e. all stars down to some low limit of mass become WR stars. This is consistent with the relative numbers of WR and O stars (Smith 1973, Maeder 1982, 1990b).

Once the hydrogen envelope is removed, the star becomes a WN star and the mass loss rate increases dramatically - the rates for WR stars are up to two orders of magnitude greater than for O stars of similar luminosity. The continued mass loss eventually reveals material which has been processed in the helium burning core and is carbon rich; the star becomes a WC star. Finally, when most of the helium has been burned, the dominant elements are carbon and oxygen, and the star is classified WO (Barlow and Hummer 1982).

3. The Numbers of WR Stars.

The ratios of WR/O star numbers vary considerably from one place to another. Roberts (1962) first noted its low value (zero) in the anticenter direction. The ratio decreases dramatically from the inner to outer parts of the Galaxy and from the solar neighbourhood to the LMC to the SMC.

The cause of the variation has been attributed to metallicity (Smith 1968c, Maeder, Lequeux and Azzopardi 1980) and to variations of the IMF (Conti et al.1983a). The theoretical connection to metallicity is that higher mass loss rates for the progenitor O star are predicted when the metallicity is high (Abbott 1982).

This causes the star to reach the WR stars earlier in its evolution and thus increases the overall WR lifetime and the WC fraction of that lifetime (Maeder et al 1980; Maeder 1981). The lower mass limit for a star to attain WR status also decreases.

The theoretical connection to the IMF is that only massive stars become WR stars and so an increase in the relative numbers of massive stars will increase the WR/OB ratio. Both factors will have an effect. However, the evidence favouring metallicity as the ***dominant*** factor is now overwhelming.
* The correlation of both WR/OB and WC/WN with metallicity is excellent (Smith 1988; Arnault et al 1989; Maeder 1990b). The criticism of the correlation (eg. Massey and Conti 1983, Armandroff and Massey 1985, Massey 1986) is that regions with similar metallicity to the LMC and SMC have different ratios. The answer is (Smith and Maeder 1990) that, in the large spirals, metallicity at a given galactocentric radius covers a wide range (eg. Talent and Dufour 1979). Because higher Z regions have more WR stars as well as more WC stars, the average WR population will be weighted towards values characteristic of a higher Z value.
* The agreement between predicted and observed number ratios at different metallicity is excellent (Maeder 1990b).
* The detailed explanation of the WC subtype distribution (Smith and Maeder 1990), discussed below, clinches the argument.

4. The Subtype Distribution.

The unique feature of WR stars in the Magellanic Clouds is the selection of subtypes that predominate there. In the Galaxy, we find WC subtypes ranging from WC9 to WC4 and a few WO stars (the latter are rare); in the LMC, we find almost exclusively WC4 with one each of WC5, WC6 and WO4. In the SMC, we find no WC stars and only one WO4 star. The WC7-9 subtypes, which are absent from the Magellanic Clouds, are found in the Galaxy concentrated towards the centre (Smith 1968c, Hidayat et al. 1982, van der Hucht et al. 1988).

Smith (1968c) suggested, on circumstantial evidence, that the difference in WR population between the LMC, SMC and the Galaxy is due to different metallicity, the result of different histories of star formation in the various regions. A complete explanation of the subtype distribution was confounded by the fact that we did not know what basic parameters cause the different excitation in the atmospheres of the stars. There is a rough correlation of subtype and absolute magnitude (Smith 1968b, Lundstrom and Stenholm 1984); since the WR stars obey a strict mass:luminosity relation (Maeder and Meynet 1987, Langer 1989), mass is partially implicated, but is not a sufficient explanation since separation of the subclasses is poor.

A satisfactory explanation comes from the most recent evolutionary models of Maeder (1990a, Smith and Maeder 1990) which allow for variation of the mass loss rate with Z. The lower mass loss rate at low Z means that the processed core is exposed later in the evolution of the star, when the material is more "cooked" by thermonuclear reactions, resulting in a higher starting point for the C+O/He abundance.

Smith and Hummer (1988) found a strong correlation between WC subtype and C^{+4}/He^{++} ratio, in the sense that C/He increases from 0.03 for WC9 to 0.9 for WC4 stars. These abundances have been confirmed (Hiller 1989; Nugis 1990; Williams and Eenens, 1989). Since C^{+4} and He^{++} dominate over much the same region of the atmosphere (Hillier 1989 and private communication) the ion ratio is a good estimate of the total C/He ratio. Since C^{+4} and O^{+4} are blended in hydrogenic lines, the derived abundance ratios are, in fact, (C+O)/He. Identifying the WC subtypes with corresponding models via these surface abundances, produces the exact subtype distribution observed. Namely:
* At Z=0.002, as in the SMC, the WC core is exposed very late in the evolution, when most carbon is already converted to oxygen and only WO stars result:

* At Z = 0.005, as in the LMC, the WC core is exposed at C+O/He = 0.6, corresponding to WC4 stars;
* At solar metallicity, Z = 0.02, the core is exposed at C+O/He = 0.1, corresponding to WC8;
* To get C+O/He = 0.03, corresponding to WC9 stars, requires Z = 0.04, characteristic of the inner regions of the Galaxy only.
* A star, having attained WC status, evolves by continued mass loss to lower mass and higher carbon abundance (earlier subtype); hence, the correlation between subtype and luminosity (mass) is also explained. However, the relationship is Z dependent and, since a wide range of metallicities occurs in the Galaxy, the relationship will have a large scatter, as observed.

It should be mentioned that, in analogy with MS spectral types, low number subtypes are called "early" and high number subtypes called "late". For WR stars, this proves to be an unfortunate choice of words; since the high numbered subtypes occur *earlier* in the evolution of *more massive* stars, they are in every way both younger and earlier than their lower number relatives into which they evolve as they age.

The consequence of the WR subtype/metallicity connection is that identification of the highest number WC subtype which is present in any region immediately defines the local metallicity. The WC subtype is defined by three emission lines in the wavelength region 5500 - 5900 A, where interstellar absorption is low (Smith 1968a, van der Hucht et al.1981, Smith, Shara and Moffat 1990b). The strongest lines rise a factor 40 over the continuum of a single star, so the lines are conspicuous even in crowded regions where individual stars are not resolved.

5. Distance Determination: Calibration of Absolute Magnitudes and Emission Line Fluxes.

The LMC WR stars were used (Smith 1968b) to determine absolute magnitudes and colours of WR stars, the basis of distance determinations in the Galaxy by the usual method. The models discussed above (Maeder 1990a) predict that the masses, and hence the luminosities, of WC stars will be Z dependent (Smith and Maeder 1990); the small overlap of WC subtype between the Magellanic Clouds and the Galaxy precludes a definite test of the prediction. For WN stars, the identification of subtype and models is less clear; however a smaller Z dependence is likely. Most WN subtypes are present in both the LMC and the Galaxy; no significant differences in luminosity have been found (Breysacher 1986).

The standard photometric system for the WR stars (Westerlund 1966, Smith 1968b) uses interference filters which avoid, so far as possible, the emission lines. With the advent of linear detector arrays, spectrophotometry is routine and the colours may be derived from the spectra. Smith, Shara and Moffat (1990a,b) integrate over the half width of the filters without a weighing function. Massey (1984) and Torres-Dodgen and Massey (1988) integrate over a Gaussian profile to reproduce the filter colours. The latter have also introduced continuum, called "monochromatic" colours by drawing a continuum under the emission lines and taking the monochromatic value at the centre wavelength of the filters. Vacca and Torres-Dodgen (1990) have calibrated colours and absolute magnitudes of LMC and Galactic stars in this system. This method has the advantage in spectrophotometry that the continuum defined by the colours is exactly the one used to measure EW s. However, in distance determination by the conventional method (as done by Conti and Vacca 1990) it introduces a subjectivity into the continuum drawing which is a disadvantage.

WR stars can be detected to large distances because of their intrinsic luminosity and because the emission lines rise up to four magnitudes above the continuum. At large distance, crowding becomes a problem and the usual method of distance determination fails. A new method shows promise. Smith et al. (1990a) find that the flux in the CIV5808 and CIII/IV4650 lines of all (except one out of fifteen) LMC WC stars is the same within the observational errors. The single examples of WC5 and WC6 subtype have the same fluxes as the WC4 stars (however the line fluxes for the WO4 star are lower). If this were true of WC4-6 stars everywhere, then both distance and reddening could be easily determined from the line fluxes alone.

There is little doubt about the reliability of the line *ratios* which are the same in the LMC and the Galaxy and vary only slowly with subclass (-0.22 dex for WC4 to -0.56 dex for WC9; Smith, Shara and Moffat 1990b). However, there are several problems related to the calibration of the *fluxes*.

* Vacca and Torres-Dodgen (1990) derive extinction corrections for seven of the LMC WC stars using the 2200 A absorption feature. Their extinction corrections are much lower (about 0.5 mag) than applied by Smith et al.(1990a) and generate a much larger scatter in the continuum luminosities and colours. Schmutz (1990) assesses the disagreement and concludes that the colours are probably well defined but not so blue as derived by Smith, Shara and Moffat (1990b).

* More seriously, Smith, Shara and Moffat (1990b) find that the WC5-7 stars in the Galaxy have lower fluxes, by about 0.5 dex, than the WC4-6 stars in the LMC. The constancy in the LMC across subtype suggests that it is an intergalactic difference. Models (Maeder 1990a, Smith and Maeder 1990) predict that there will be a large difference in the sense observed, with low Z regions producing more massive (and hence more luminous) WC stars at the same surface abundance (subtype). This means that, for the fluxes to be useful as distance indicators, they must be calibrated as a function of Z.

Fluxes for HeII4686 and 1640 from WN stars in the LMC have been determined by Conti and Morris (1990). The *ratio* is 0.88+0.2 dex and can be used to determine reddening. The *fluxes* cover a substantial range and more information will be needed before they can be used for distance determination. (There are also systematic differences in EWs noted between LMC and Galactic stars of the same subtype suggesting that, as for the WC stars, differences may exist between galaxies.)

6. Binaries

Mass exchange in a close binary is a method of removing the hydrogen envelope and producing a WR star. It does not depend on metallicity and therefore continues to operate in low metallicity regions where the O stars are unable to remove the hydrogen envelope through radiation driven mass loss. The proportion of binary WR stars is expected to increase in low Z regions. This expectation corresponds well to the observed situation in the SMC where all WR spectra are composite and 5 of the 8 WR stars are proven binaries with spectroscopic velocity variation (Moffat 1988).

Binaries also provide masses; these range from 10 to $50M_\odot$ for Galactic stars. Data for Magellanic Cloud binaries is still scarce (Moffat, Niemela and Marraco 1990), but one oddity emerges already: two of the WC binaries in the LMC have periods of 2 and 3 days, much shorter than any WC binary in the Galaxy, for which the shortest is 8 days. The significance of this oddity is unclear.

References.

Abbott, D.C. (1982) ApJ. 259, 282.
Armandroff, T.E. and Massey, P. (1985) ApJ. 291, 685.
Arnault,Ph., Kunth,D. and Schild,H. (1989) A&A 224, 73.
Azzopardi, M. and Breysacher, J. (1979) A&A 75, 120.
Azzopardi, M. and Breysacher, J. (1985) A&A 149, 213.
Barlow, M. and Hummer, D. (1982) in C.W.H. de Loore and A.J.Willis (eds.) IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution, Dordrecht: Reidel, p 387.
Breysacher, J. (1981) A&A Suppl. 43, 203.
Breysacher, J. (1986) A&A 160, 185.

Cohen, M. (1990) in IAU Symposium 143, in press.
Conti, P.S. and Vacca, W.D. (1990) A.J. in press.
Conti,P.S. and Morris, P.W. (1990) Ap.J. in press.
Conti,P.S., Garmany,C.D., de Loore,C.W.H. and Vanbeveren,D. (1983a) Ap.J. 274, 302.
Conti, P.S., Leep, E.M. and Perry, D.N. (1983b) Ap.J. 268, 228.
Hidayat, B., Supelli, K. and van der Hucht, K. (1982) in C.W.H. de Loore and A.J.Willis (eds.) IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution, Dordrecht: Reidel, p 27.
Hillier, D.J. (1989) Ap.J. 347, 392.
Langer, N. (1989) A&A 210, 93.
Lundstrom, I. and Stenholm, B. (1984) A&A Suppl. 58, 163.
Maeder, A. (1981) A&A 102, 401.
Maeder, A. (1982) A&A 105, 149.
Maeder, A. (1990a) A&A Suppl. in press.
Maeder, A. (1990b) A&A in press.
Maeder, A., Lequeux, J. and Azzopardi, M. (1980) A&A 90, L17.
Maeder, A. and Meynet, G. (1987) A&A 182, 243.
Massey, P. (1984) Ap.J. 281, 789.
Massey,P. (1986) in C.W.H.de Loore, A.J.Willis, P.Laskarides (eds.), IAU Symposium No. 116, Luminous Stars and Associations in Galaxies, Dordrecht: Reidel, p 215.
Massey,P. and Conti,P.S. (1983) Ap.J. 273, 576.
Moffat, A.F.J. (1988) Ap.J. 330, 766.
Moffat, A.F.J., Niemela, V., Phillips,M.M., Chu, Y. and Seggewiss, W.M. (1987) Ap.J. 312, 612.
Moffat, A.F.J., Niemela, V. and Marraco,H.G. (1990) Ap.J. 348, 232.
Morgan, D.H. and Good, A.R. (1985) M.N.R.A.S. 216, 459.
Nomoto, K. (1990) in IAU Symposium 143, in press.
Nugis, T. (1990) in IAU Symposium 143, in press.
Paczynski, B. (1967) Acta Astron. 17, 355.
Paczynski, B. (1983) in M.K.V. Bappu and J. Sahade (eds.) IAU Symposium 49, Wolf-Rayet and High Temperature Stars, Dordrecht: Reidel, p 143.
Roberts, M.S. (1962) A.J. 67, 79.
Schmutz, W. (1990) in IAU Symposium 143, in press.
Shara, M.M. (1990) in IAU Symposium 143, in press.
Smith, L.F. (1968a) M.N.R.A.S. 138, 109.
Smith, L.F. (1968b) M.N.R.A.S. 140, 409.
Smith, L.F. (1968c) M.N.R.A.S. 141, 317.
Smith, L.F. (1973) in M.K.V. Bappu and J. Sahade (eds.) IAU Symposium 49, Wolf-Rayet and High Temperature Stars, Dordrecht: Reidel, p 15.
Smith, L.F. (1988) Ap.J. 327, 128.
Smith, L.F. and Hummer, D.G. (1988) M.N.R.A.S. 230, 511.
Smith, L.F. and Maeder, A. (1990) A&A, in press.
Smith, L.F., Shara, M.M. and Moffat, A.F.J. (1990a) Ap.J. 348, 471.
Smith, L.F., Shara, M.M. and Moffat, A.F.J. (1990b) Ap.J. in press.
Talent,D.L. and Dufour,R.J. (1979) Ap.J. 233, 888.
Testor, G. and Schild, H. (1990) A&A in press.
Torres-Dodgen,A.V. and Massey, P. 1988 A.J. 96, 1076.
Vacca, W.D. and Torres-Dodgen, A.V. (1990) Ap.J.Suppl. in press.
van der Hucht, K.A., Conti, P.S., Lundstrom, I. and Stenholm, B. (1981) Space Sci.Rev. 28, 227.
van der Hucht, K.A., Hidayat, B., Admiranto, A.G., Supelli, K.R. and Doom, C. (1988) A&A 199, 217.
Westerlund, B.E. (1966) Ap.J. 145, 724.
Williams, P.M. and Eenens, P.R.J. (1989) M.N.R.A.S. 240, 445.