SPECTRA OF MASSIVE BLUE STARS

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Abstract. In this paper I shall talk primarily about the SIGNATURES of hot, luminous, and massive stars, not only direct spectroscopy but also indirect means for discovering and studying them. I will consider the observations of radiation from various wavelengths and what may be inferred from stars in our Galaxy, in nearby systems where individual stars have been or potentially may still be identified, and in even more distant galaxies where only integrated properties of such objects may be observed. I will point out the opportunities that await us at wavelengths other than optical and the openings of new windows on understanding massive-star evolution in galaxies by the Hubble Space Telescope. It is important to keep in mind that these stars are very luminous, particularly in the UV regions, and have total lifetimes of only a few million years. Their presence serves to notify us of star formation in the very recent past.

1. CLASSICAL SPECTROSCOPY

Here I refer to the utilization of the stellar absorption lines in the “blue” part of the optical spectrum. This wavelength region was initially chosen as it was nominally the most sensitive for photographic emulsions; fortunately, it also included some of the Balmer lines which are prevalent in so many stars. With the advent of new electronic detectors, we are no longer limited to this narrow window of stellar spectroscopy, but it still affords us a well-calibrated region to begin our observations. The stellar absorption-line spectrum arises from the photosphere, which for most stars can be taken to be plane parallel; furthermore, there is a close and generally well-understood relationship between the properties of this photosphere and that of the underlying star. In other words, one can derive effective temperature, $T_{\text{eff}}$, and luminosity, $L$, from observations of the stellar spectrum once the “calibration” problem has been addressed.

Massive blue stars are those of spectral type O, with the addition of the somewhat more evolved B and A supergiants. The lowest mass of stars called “massive” could be that for which the final episode is a SN explosion, say 10 solar masses. A more readily accessible lower limit might be that of the boundary between O and B main-sequence
stars, or about 15 solar masses. The latest evolutionary phases are represented by the W-R objects for the most massive stars, more than, say, 35 solar masses. K and M supergiants, which are the subject of the following talk, generally correspond to the core He-burning phases of somewhat less massive objects. I shall concentrate my remarks on only the most massive stars, which produce most of the Lyman-continuum radiation in galaxies and whose winds are important contributors to the dynamics of the surrounding interstellar medium.

O stars can be readily identified by the presence of He II absorption lines in their spectra; the feature at 4541 Å and its comparison to a He I line at 4471 Å give the numerical subtypes. A subset of O stars, called Of, have the He II λ4686 line in emission, a point to which I shall return later. B supergiants are distinguished from O types by the absence of He II; the prominent lines are those of He I and the Balmer series. The line widths are narrow and several line ratios (e.g., He I λ4471 vs. Mg II λ4481) lead to the numerical subtypes. In A supergiants, the He I lines are absent, the Balmer series lines are narrow but at maximum strength, and the numerical subtypes are distinguished by the strength of the K line of Ca II compared to the nearby hydrogen features.

A recent paper by Walborn and Fitzpatrick (1990) shows in great detail the spectral sequences of Galactic O and B stars in the blue region of the spectrum. These “linearized” (normalized) data were derived from electronic detectors which will be the standard scheme by which future classifications of individual stars will be done. Spectroscopy is under way by these authors for analogous objects in the Large and Small Magellanic Clouds. The stars in these galaxies, being somewhat metal deficient with respect to the solar vicinity, show differences in spectral appearance and in their classification parameters which are rather subtle for the LMC but pronounced for the SMC.

Wolf-Rayet (W-R) stars, by contrast, evidence a predominant emission-line spectrum in the optical, and in other wavelength regions. This is caused by their strong stellar winds, due, in turn, to their high luminosities and advanced evolutionary state (Abbott and Conti 1987). The relationship between the spectroscopic properties of the wind and the underlying star is not yet all that well understood, but in the last few years there has been great progress in modeling such objects (e.g., Hillier 1989; Schmutz et al. 1989). While the presence of emission features has delayed our understanding of the physics of the spectra, such lines appear well above the continuum of the star, thus enabling us to detect and classify them to much fainter magnitudes than stars with only absorption lines.

The W-R classification types are primarily two, the WN and WC. Strong helium and nitrogen lines are found in the former, and helium, carbon, and oxygen ions in the latter (e.g., Smith 1968). A sparsely populated subset of W-R stars with strong oxygen lines in the optical is called type WO (Barlow and Hummer 1982). These types represent objects in which the products of core H-burning (WN) and core He-burning (WC, WO) have been revealed at the stellar surfaces due to previous and continuing mass loss by stellar winds, along with internal mixing of material.

The strongest line in WN stars in the optical is the (4-3) transition of He II at 4686 Å; those of WC stars include C III λ4650, along with C III λ5696 and C IV λ5808. In WO stars, the O VI feature at 3820 Å is prominent. Various numerical subtypes, with corresponding terms WNE (early), WNL (late), WCE, and WCL can be found from the line ratios of various ions in W-R winds.
2. SPECTROPHOTOMETRY

With the advent of electronic detectors has come the ability to acquire observations over wavelengths not readily accessible to photographic emulsions. One also finds an opportunity to obtain the monochromatic energy distribution, and line fluxes. In other wavelength bands, for example the far-UV regions, OB stars show evidence of their own stellar winds from the presence of P-Cygni profiles in several of the resonance lines, even while photospheric absorption features are still found. In W-R stars, the resonance transitions also typically show P-Cygni profiles, while the subordinate UV lines are in emission due to the strong stellar wind.

In several figures to follow, I will show some examples of newly reduced data from the International Ultraviolet Explorer satellite, combined with optical spectrophotometry adapted from Conti and Massey (1989) and from the near-infrared (NIR) regions (Conti et al. 1990). These enable one to get a feeling for the spectral signatures of O and W-R stars over nearly a decade of wavelength. The data have been fluxed and corrected for interstellar extinction using the normal prescriptions for OB stars by Savage and Mathis (1979) and for W-R stars by Vacca and Torres-Dodgen (1990). For hot stars such as these, the continuum fluxes between 1200 Å (the short-wavelength IUE cutoff) and about 1 micron (the long-wavelength CCD limit) change by a factor of about 1000. This is only the “tail” of the total energy emitted by these stars; the maximum of the emergent energy distribution is below the IUE limit for many of the O and W-R stars. As I will discuss later, the radiation from below the Lyman limit manifests itself in other ways.

Figure 1 gives the ultraviolet and optical spectra of a typical early-type O star (the NIR data are not yet available). The strong absorption plus emission features at 1400 Å and 1550 Å are the P-Cygni profiles of the Si IV and C IV resonance transitions, respectively; N IV at 1718 Å is also seen. Since this is an O star, emission features due to He II at 1640 Å, 4686 Å, and 6560 Å are found, along with a N III blend at 4640 Å. Careful inspection will reveal the presence of absorption along higher members of the Balmer series and in some other He II transitions. The flux scale used enables one to plot the entire spectrum, but most spectral absorption features are very difficult to see. A typical O star would appear much like this star, with the exception that the He II λ1640, 4686, and 6560 lines would be in absorption, the N III lines absent, and the UV resonance lines less prominent.

Figure 2 shows the UV, optical, and NIR spectra of a typical WN7 (WNL) star. Here the overall spectral features are in emission, with the exception of the P-Cygni profile for the C IV resonance line. The leading emission features are at 4686 Å due to He II, and the N III blend at 4640 Å (also found in O stars). Nearly all the other lines are due to helium and nitrogen ions. Hydrogen is present in this WN7 star as may be seen by comparing the strength of the purely Pickering series at 5411 Å, 4541 Å with the stronger Balmer/Pickering lines at 6560 Å, 4860 Å, 4340 Å. A Paschen line is also found near the He II feature at 10124 Å.

Figure 3 shows the spectrum of a typical WN5 (WNE) star (one without hydrogen). The lines are stronger, and broader, than in the WN7 star of Fig. 2. One may also notice that the line widths appear to increase with wavelength, but this is an artifact of plotting in these units rather than in velocity width. The strongest line in the spectrum is the (4-3) transition of He II, and several transitions of N IV appear quite prominent. It must be obvious that the classification of a W-R star such as this, with its emission-line spectrum, is much easier than for an absorption-line star such as illustrated in
Fig. 1. Spectrophotometry of HD 14947, type O4f. The P-Cygni lines in the UV, and the emission lines of N III and He II in the optical, indicate the presence of a moderately strong stellar wind. The absorption features come from the stellar photosphere.

Before turning to the WC class, I would like to show some spectra of a WN star from the infrared (IR) regions at a few microns. Spectroscopy at these wavelengths for massive blue stars is in its infancy. In fact, I am not aware of any systematic studies of O or Of stars beyond 10830 Å, where a prominent He I line is found. Figure 4, adapted from Hillier et al. (1983), shows the spectrum of another typical WN5 star. Here the data have not been fluxed. The prominent lines are nearly all due to high-level transitions of He II. The strongest feature is the (7-6) transition at 3.09 microns; it has a larger equivalent width than 4686 Å but, of course, its line flux is much smaller. This line, or other He II transitions which do not blend with hydrogen, would be good indicators of the presence of WN stars in IR spectral regions.
Figure 2. Spectrophotometry of WR12, a typical WN7 (WNL) star. Nearly all lines are in emission, indicating a very strong stellar wind. The spectral subtype is given by the appearance of the $N\,III$ and $N\,IV$ features in the optical.
Figure 3. Spectrophotometry of HD 89858, a typical WN5 (WNE) star. Nearly all lines are in emission, indicating a very strong stellar wind. The spectral subtype is given by the appearance of the N IV and N V features in the optical. Some of the He II transitions are labeled.
Figure 4. IR spectroscopy of HD 50896, a typical WN5 (WNE) star. Most of the emission features are due to recombination transitions in He II. The (7-6) line at 3.09 microns is the strongest in the spectrum, rivaling 4686 Å in equivalent width.
Figure 5 shows the spectrum of a typical WC8 (WCL) star. The most prominent lines are the classification pair at C III λ5696 and C IV λ5808, along with the C III λ4650 feature and 9711 Å also due to C III. At the log flux wavelength scale shown here, the UV features at C IV λ1550 and C III λ1909 are relatively weak in equivalent width compared to the lines in the optical or NIR but their fluxes are, of course, larger.

Shown in Figure 6 is the spectrum of a typical WC6 (WCE) star. There are some overall differences from the WC8 star of Fig. 5, but the most important change is the ratio of the classification lines: C III λ5696/C IV λ5808. Here the ratio is less than unity; in WCL stars it is greater than 1. In WC stars, the line width also becomes larger with earlier spectral subtype; in Figs. 5 and 6 the increase in line width with increasing wavelength, in wavelength units, is obvious but is an artifact of plotting with this unit rather than velocity width. It is quite easy to distinguish between WN and WC stars in any of the spectral regions: UV, optical, or NIR. There is little difference in the continua of these objects as we are observing out on the “tail” of the emergent energy distribution.

Infrared spectra of several WC stars have been presented by Smith and Hummer (1988), but their figures do not easily lend themselves to reproduction for this talk. Instead, I show in Figure 7 a spectrum of a WC5 star, HD 193793, which while not typical, nevertheless shows a very strong C IV emission-line feature at 2.09 microns (adapted from Lambert and Hinkle 1984). This line is present only in WC types; conversely, the (10–7) He II transition at 2.19 microns that is very strong in WN types is not present to any great extent in WC stars. By detecting either of these emission features one would be able to ascertain the presence of WN or WC stars in the 2-micron window.

Why would IR spectroscopy of W-R stars be useful? There are splendid opportunities to detect WN and WC stars in heavily obscured regions. This may have application to the study of galactic structure, or to the investigation of the massive-star population of heavily reddened IRAS bright galaxies. For example, I have recently been curious about the location of spiral arms in our own Galaxy. We (Conti and Vacca 1990) have plotted the locations of the known W-R star population (which is a highly non-uniform and incomplete sample) in galacto-centric coordinates. We find a vertical scale height of 45 pc as befits an extreme Population I sample. However, the segregation of stars in longitude, while suggestive of “arms” or regions with concentrations of these massive stars, does not show any “spiral” structure. Probably this is due to incompleteness, and this problem is dominated by the extinction in the galactic plane.

A typical O or W-R star has an $M_V$ of $-5$. At a distance of 10 kpc (a little beyond the galactic center) the distance modulus is 15. Without extinction, such a star would have an apparent magnitude of +10, well within the reach of very modest telescopes. As an illustration of the opportunities afforded by the study of blue stars in the infrared, Table 1 is instructive. I have illustrated the expected apparent magnitudes at several bands for an O star at 10 kpc with an assumed 25 magnitudes of extinction in $V$.

<table>
<thead>
<tr>
<th>Band ($\lambda$):</th>
<th>$V$</th>
<th>$R$</th>
<th>$I$</th>
<th>$J$</th>
<th>$H$</th>
<th>$K$</th>
<th>$L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_V$:</td>
<td>25</td>
<td>18.8</td>
<td>12.0</td>
<td>7.0</td>
<td>4.7</td>
<td>2.8</td>
<td>1.4</td>
</tr>
<tr>
<td>$V - \lambda$:</td>
<td>0</td>
<td>-0.1</td>
<td>-0.4</td>
<td>-0.7</td>
<td>-0.8</td>
<td>-0.9</td>
<td>-0.9</td>
</tr>
<tr>
<td>$m_{\lambda}$:</td>
<td>35</td>
<td>28.9</td>
<td>22.4</td>
<td>17.7</td>
<td>15.5</td>
<td>13.7</td>
<td>12.3</td>
</tr>
</tbody>
</table>
Figure 5. Spectrophotometry of HD 117297, a typical WC8 (WCL) star. Nearly all lines are in emission, indicating a very strong stellar wind. The spectral subtype is given by the appearance of C III and C IV features in the yellow part of the spectrum.
Figure 6. Spectrophotometry of HD 92809, a typical WC6 (WCE) star. Nearly all lines are in emission, indicating a very strong stellar wind. The spectral subtype is given by the appearance of C III, C IV, and O V features in the yellow part of the spectrum.
Figure 7. IR spectroscopy of HD 193793, a WC5 star. Although this object is not typical of the class, the presence of a strong C IV feature at 2.09 microns is found throughout most of the WC sequence.

The point of this table is two-fold: (1) to remind all of us that as one goes into the infrared wavelength regions (JHKL), the extinction drops dramatically; and (2) there is not all that much difference in the intrinsic magnitudes in these wavelength bands, as related to $V$, for blue stars (in comparison to type A).

With the advent of IR area detectors, it is now possible to image at apparent magnitudes which are similar to those in the last row of Table 1. An intriguing project would be to devise narrow-band filters which isolate, say, the He II 2.19$\mu$ and C IV 2.09$\mu$ emission-line features in WN and WC stars and attempt to detect W-R stars at much deeper locations in our Galaxy than has heretofore been possible. Unfortunately, the spatial coverage of the current generation of IR detectors is too small to just blindly point along the Galactic equator. A pilot program to investigate the W-R population of obscured giant H II regions is under way by myself, Taft Armandroff, and Phil Massey. We are working at 1 micron, where large-scale CCD detectors are still sensitive, and using line filters which isolate the He II 10124 Å line (Figs. 2 and 3) and C III 9711 Å (Figs. 5 and 6), along with an intermediate continuum point. This may not be at a long-enough wavelength to sufficiently penetrate the dust in and near these massive star-forming regions, but it is a start in a new wavelength regime.

3. INDIRECT SIGNATURES

Massive blue stars are typically associated with surrounding gas and dust. In some cases, the very youngest O and B stars may be completely obscured by their initial birth clouds and not visible at all at optical wavelengths. However, the radiation from such stars, and W-R objects, may be detected indirectly, from their Lyman Continuum...
radiation which both excites the gas and heats the dust.

Individual hot stars, or associations of them, give rise to ionized “Strömgren spheres”, or H II regions, in the surrounding ISM. The excited gas may be detected by the presence of nebular emission lines of various ionic species and from radio recombination lines of hydrogen (and certain molecules). Radio observations also lend themselves to the detection of the CO molecule, which is typically associated with molecular hydrogen and is often found concentrated in Giant Molecular Clouds (GMCs). These are the sites of massive-star formation (e.g., Myers et al. 1986).

In some cases, particularly the “youngest” H II regions, the parent dust cloud may completely shroud the exciting stars. The emergent stellar radiation will heat the dust, which will then radiate in the IR where it can be readily detected through the intervening IS medium as a “point” or slightly extended source. Wood and Churchwell (1989 and references therein) have studied such so-called ultra-compact H II (UCHII) regions. It is possible to make estimates of the number of exciting stars from the integrated luminosity in the infrared. It will be interesting to compare the expected numbers in these regions with actual counts of O stars once IR spatial photometry begins to be applied (e.g., Littler et al. 1989).

The radio fluxes and the nebular recombination lines may be used to estimate, among other things, the quantity and quality of the Lyman-continuum radiation emitted by the star or stars within an H II region. This step requires a calibration of the emergent Lyman-continuum predictions from stellar models with properties of real stars. Nearly all investigators have used Panagia (1973) to derive from the observed total of Lyman-continuum photons emitted an appraisal of the number of “equivalent” main-sequence O stars present.

The most energetic H II regions have come to be called giant H II (GHII) regions; the word supergiant H II region has also appeared in the literature. I have been unable to find precise definitions of the boundaries between these designations but there seems to be general agreement among investigators as to which regions are which. See also Kennicutt’s review in this volume. In Table 2 I have adapted from Shields (1990) and Kennicutt (1984) some observed and inferred properties of selected H II and GHII regions in our own and other galaxies, along with two so-called W-R galaxies (from Osterbrock and Cohen 1982). W-R galaxies are a subset of “starburst” galaxies in which the presence of W-R stars is inferred from the appearance of a He II λ6686 stellar emission line above the integrated continuum. Bill Vacca, a student at Boulder, and I have been involved in some detailed analysis of about ten of these objects (see our poster paper).

I have labeled Table 2 as “Massive Star-Forming Regions” to emphasize the continuum of properties of the blue stellar population within them.

Readily observed properties are the number of Lyman-continuum photons, N(Lyc) (photons/sec), and the line luminosity at Hα (ergs/sec). A value of log N(Lyc) of 51.0 appears to be a useful dividing line between H II and GHII regions: those less energetic have typically been given the former label and those more energetic the latter. This is as good a place as any to suggest such a value as a defining property.

An important derived property is the equivalent number of main-sequence O5 V stars producing the observed Lyman-continuum radiation. The calibration of Panagia (1973) was based on the Auer-Mihalas (1972) non-LTE, unblanketed hot-star models and the Conti (1973) empirical calibration of spectral types. More recent observations and improved models, which incorporate the effects of wind line blanketing upon the emergent continuum, suggest the calibration of Panagia is reasonably accurate for later
O and B main-sequence-type stars, but for the earliest O classes it is about one subtype too hot (Bohannan et al. 1990). In other words, the column headed O5 V really refers to O4 V stars under the modern spectral-type—temperature calibration. I need to note here that the Panagia calibration was derived for stars of solar composition and may not apply as well for those with substantially different abundances. This latter issue is currently being addressed by Kudritzki and associates.

The number of O5 V stars (I will continue this usage for ease of comparison with the literature) is a single-point estimate of the number of O stars present; if an IMF is specified one could then infer the numbers of O stars at other spectral types. This has sometimes been done using a “standard” IMF. Note that such an analysis from H II regions is insufficient to derive an IMF. This would require an analysis of the quality of the Lyman-continuum radiation, that is, the piecewise contributions over wavelengths below 912 Å. Such a step is usually not taken but could in principle be accomplished by detailed modeling of line strengths of ions other than hydrogen; this is hard to disentangle from potential composition differences and the physically non-uniform spatial distribution of density among various excited regions. For a thorough discussion of the prospects and difficulties in deriving an IMF for massive stars in “starburst” galaxies, see Scalo (1989).

In (so far) a few cases, actual counts of O stars and O5 V “equivalents” have been made for some H II regions and compared to those expected from the Lyman-continuum estimates (Massey et al. 1989a,b). The agreement is within a factor 2 and thus gives us confidence in the overall appropriateness of such indirect measurements.

The penultimate column of Table 2 gives either the counted number of W-R stars, or in the W-R galaxies an estimate based upon the measured integrated flux of He II λ4686. The O5 V/W-R number ratio in H II and GHII regions is of the order of 10 which is about what would be expected if the former and latter numbers represent the core-H-burning and He-burning lifetimes, respectively, and all (equivalent) O5 V stars become W-R types. In the W-R galaxies, the O5 V/W-R number is smaller; while this might be interpreted as indicating anomalous IMFs, I would rather wait until our analysis of such systems is complete before asserting such a strong conclusion.

The main point of Table 2 is to show some well-known examples of H II and GHII
regions in terms of their hot-star content and to illustrate the connection to "starburst" galaxies, of which the W-R galaxies are not yet a well-studied subset. As Kennicutt (1984) has stressed, H II and GHII regions should not be considered to form a single-parameter family of increasing energy. There are substantial morphological distinctions among them, for example, the surface brightness and the stellar densities (not illustrated here). On the other hand, as far as the numbers of hot stars are concerned, it is of interest to compare such massive star-forming regions. There are nearly five orders of magnitude in Lyman-continuum luminosity in passing from Orion to the brighter W-R galaxies (at least one "IRAS galaxy", discovered by Armus et al. (1988), is a W-R type and may be somewhat more luminous than Mrk 309). It seems to me that we may be able to understand the massive-star content of "starbursts" by analogy with the better-known GHII regions. NCG 5471 in M101 is similar in its integrated hot-star properties to the W-R galaxy NGC 6764, for example.

There are some intriguing questions raised by Table 2. For example, the GHII region W49 is highly obscured by surrounding dust and cannot be observed in the optical. Some 27 O5 V-star "equivalents" are present from the Lyman-continuum analysis; are several W-R stars also there? It may be possible to address such questions by IR narrow-band photometry utilizing the W-R emission features at 2.09 and 2.19 microns, as I have indicated previously. Are there really more W-R stars in NGC 6764 and Mrk 309 than O5 V equivalents? This would imply a very flat IMF or a very short "starburst" interval. NGC 5471 has 750 O5 V-star equivalents. Does it have any W-R star population?

Let me discuss the spectral signatures and hot-star content of several of the GHII regions given in Table 2. Here we are dealing with objects for which at least some of the individual stars have been identified and studied spectroscopically. If we were to compare complete stellar data with integrated spectra of these nearby regions, then we could better understand more distant GHII clouds where the individual stars cannot be resolved and we can only observe their integrated properties. This intercomparison has not yet been addressed quantitatively in the literature, due both to the incompleteness in the stellar spectroscopy and the lack of integrated spectrophotometry for the regions in question.

NGC 3603 (the core is catalogued as HD 97950) is a relatively unobscured GHII region in our own Galaxy. The core, about 1 pc in size, contains several unresolved hot stars, at least one of which is a WN star from the optical spectrum (e.g., Moffat et al. 1985). Some 20 O5 V-star equivalents should be present from the nebular-line analysis, but presumably would be found within a more extended 5-pc region centered on HD 97950; Figure 8 illustrates its integrated UV and optical spectrum. The line widths of the emission features indicate the presence of a WN star; O stars are also present as indicated by the Balmer, He I, and He II absorption lines. Such a spectrum is typical of what is seen in some much more distant GHII regions and W-R galaxies (see below).

Moffat et al. (1985, 1987), Melnick (1985), and Walborn (1986) have discussed the hot-star content of the core (R136) and vicinity of 30 Dor in the LMC. R136 is of a few pc in size and the brightest component R136a has been resolved by speckle techniques into four brighter and four fainter components (Weigelt and Baier 1985), one of the former of which is a WN type. An integrated optical spectrum of R136 is given, for example, by Moffat et al. (1985) and an ultraviolet one by Cassinelli et al. (1981). One finds the presence of broadened He II λ4686 and 1640 emission features in these spectra. Over 200 O5 V-star equivalents are predicted to be present in the
extended 30 Dor GHII region from the nebular-line analyses. Ongoing identification and classification of the stars in the 30 Dor vicinity is being carried out by Garmany, Massey, Parker, and Walborn (private communication), who have identified at least 100 O types (see the review by Walborn in this volume). At least 15 W-R stars have been identified in this region according to Moffat et al. (1987). While as yet there exists no integrated spectrum of the nebulosity of 30 Dor which extends over several arc minutes (about 50 pc), it will be important to compare the final O-star statistics with the predictions from such recombination spectra.

Optical and UV spectra of the GHII region NGC 604 have been given by Rosa (1980), Conti and Massey (1981), and Benvenuti (1983). W-R emission features at 4686 Å and 1640 Å due to He II are found in the integrated spectrum. At least three W-R stars have been identified within NGC 604, which is about 100 pc in size,
comparable to the 30 Dor Nebula; more may be present. It will be difficult to attempt spectroscopy of the O-star population of NGC 604 given the distance modulus of 24.3 for M33, but 65 O5 V-star equivalents are predicted. I would like to stress that the integrated spectrum of NGC 604 looks very much like R136 and HD 97950 in having O-type and W-R features.

Finally, integrated ultraviolet and optical spectra of the GHII region NGC 5471 have been given by D’Odorico et al. (1983) and Rosa (1980). Here there is certain evidence for O stars but that for W-R types is ambiguous. A narrow and possibly nebular He II λ4686 emission line is found in the optical; the IUE data have too low a signal/noise to be useful for the detection of He II λ1640. Given the results for the previous three GHII regions, I would be surprised not to have W-R stars present in NGC 5471. Spectral observations of this distant GHII region need better S/N and higher spectral resolution than currently exist. Over 750 O5 V-star equivalents are expected; optical spectroscopy is probably not possible with the sensitivity of current ground-based instruments, but might be feasible with the new generation of 8-m telescopes.

It would be important to obtain UV spectra of the individual exciting stars of GHII regions such as those listed above. The crowding problem, and UV brightness, could be overcome by the Hubble Space Telescope observational performance. Guaranteed-Time-Observer approved programs will consider the nearest of the two GHII regions discussed above.

4. WOLF-RAYET GALAXIES

I would now like to take a large step outward in distance (and interpretation) to those galaxies (or condensations within) in which only integrated spectra can be obtained and which show evidence of W-R stars from the presence of He II λ4686 emission in their integrated optical spectra. These W-R galaxies overlap but extend another decade in luminosity from GHII regions as indicated in Table 2 (and another decade brighter still as inferred from the luminous IRAS galaxy found by Armus et al. 1988). Kunth and Schild (1986) have discussed some properties of 11 of these objects and note that the flux of the He II λ4686 feature scales very roughly with the integrated magnitude of the galaxy. It seems to me that these objects form a continuum in their hot-star properties with the GHII regions in nearby galaxies. Some 30 W-R galaxies are known; they have been found serendipitously by those studying emission-line galaxies. While it is possible to initially confuse W-R galaxies with Seyferts having a He II λ4686 emission feature, the nebular lines in the former are narrow and their excitation is stellar.

As I have already noted, Vacca and I are involved in a detailed analysis of a subset of W-R galaxies for which we have been able to obtain 4-m time at CTIO. I would like to show, in Figures 9 and 10, examples of spectra of the W-R galaxy He2-10, the “first” known W-R galaxy (Allen et al. 1976). Figure 9, adapted from our 2D-Fruti observations, shows the strong nebular emission-line spectrum excited by O-type stars; the continuum is very “blue” and a weak Balmer series is found in absorption. On the scale shown here, a broad He II λ4686 emission feature is not very obvious but is present. Aside from the nebular lines, the overall spectrum is similar to that shown in Fig. 1 and Fig. 8. Among questions we would like to answer from spectra such as these are: numbers (and types?) of exciting stars inferred from the recombination lines; composition of excited gas; numbers and types of stars contributing to the continuum and to the absorption-line spectra; age and duration of the starburst; etc.

Figure 10 is an expanded version of Fig. 9 near the vicinity of the He II λ4686
Figure 9. Spectroscopy of He2-10, a W-R galaxy. The nebular lines are excited by O-type stars; the continuum is relatively "blue"; weak upper Balmer series lines and a Balmer jump due to A-type stars can be seen. A broadened emission feature at He II $\lambda$4686 in the integrated spectrum arises from the presence of WN stars in this "starburst" galaxy. Aside from the nebular recombination lines, this object has a spectrum much like that of HD 97950, the core of NGC 3603 (Fig. 8).

feature, its broadened nature is apparent. The nebular lines are unresolved at the resolution of 4 Å used with the 2D-Fruttai detector at the 4-m. Several "artifacts" of this instrument remain in the data. The narrow emission line just shortward of 4686 Å is the [Fe III] line at 4658 Å. It is also present in many (all?) of the W-R galaxies known to me, and also in a few blue compact galaxies with only O stars identified. The overall emission-line spectra of W-R galaxies look very much like those of GHII regions. I would like to stress that for studies of galaxies such as these, the highest feasible S/N and spectral-resolution data are required.

In our (Vacca and Conti) preliminary analysis we also have identified the N III $\lambda$4640 emission-line blend in several W-R galaxies. We are thus reasonably certain that these broadened features are due to WN-type stars. We have no certain evidence for C III $\lambda$4650, nor for lines at C III $\lambda$4596 and C IV $\lambda$5808, which in WC stars are as strong as or stronger than He II $\lambda$4686 in WN-type stars. Such lines are found in some GHII regions containing individual WC stars. It appears that W-R galaxies may have relatively more WN than WC subtypes, as contrasted to the solar vicinity where the ratio is near unity. The Magellanic Clouds contain more WN than WC stars, which has been attributed to their lower "metal" abundance (e.g., Maeder 1990). W-R galaxies might be like the MCs in their composition and W-R content but this potential connec-
tion must await our detailed analysis of the properties of the galaxies themselves. I need to point out that the stellar emission-line features so far identified in W-R galaxies also look very much like those of "transition" Of/WN stars (Bohannan and Walborn 1989). It is possible that such spectra arise in the most massive and luminous main-sequence stars whose very strong winds could give rise to emission features in the optical. W-R galaxies would be excellent candidates for Hubble Space Telescope observations in order to disentangle the recent star-formation phase—a few million years given the presence of W-R and O-type stars—from the underlying (previous generation?) of stars of type A that one infers are present from the relatively weak Balmer absorption lines and Balmer jump.

5. PRESENT AND FUTURE DIRECTIONS

Hot, luminous, blue stars are a snapshot of the massive-star SFR a few million years ago. They may be used to probe conditions in "starburst" galaxies and other locations where star formation is occurring.

A census of individual stars in various environments may be used to better understand the processes under which massive stars form. For example, O stars may be sampled in the solar vicinity and the Large and Small Magellanic Clouds, each having a different initial composition and a varied past history of star formation. It is likely that a complete census of the SMC can be completed and compared to the solar vicinity
(2.5–3 kpc); such work is now under study by Garmany and Massey and associates. A complete count of the O-star population of the LMC is not completely outside the reach of current telescopes, but will require a long-term, dedicated observational program and cooperation from TACs. Counts of W-R stars within the solar vicinity, and in the Magellanic Clouds, appear nearly complete. W-R stars are also being identified and studied in other galaxies of the Local Group (Armandroff and Massey 1985; Massey et al. 1987; Moffat and Shara 1987) and in more distant sites such as the Sculptor Group (Armandroff and Massey, private communication). Such stars may be used to sample environments differing from the MCs and the solar vicinity.

W-R stars may be used to investigate the spiral structure of our Galaxy in connection with other such extreme Population I indicators as GHI and UCHII regions and GMCs. NIR and IR observations may be able to probe the interstellar extinction which otherwise limits our knowledge of such star-forming regions.

Extragalactic GHI regions may be a paradigm for starburst galaxies, at least as far as their massive-star population is concerned. Analysis of these regions, which are considerably nearer than typical starburst galaxies, may further our understanding of star formation. In particular, W-R galaxies may be the "youngest" examples of the starburst phenomenon and may indicate the presence of anomalous IMFs in such regions. H II and GHI regions and W-R galaxies appear to form a continuum of their massive-star properties and detailed analysis of each will help our understanding of all.

I would like to thank Phil Massey and Jean-Marie Vreux for use of their optical and NIR spectrophotometry of O6 and W-R stars in our ongoing collaborations. The figures have been made with kind assistance from Ken Brownber, Pat Morris, and Bill Vacca and come from various stages in their Ph.D. dissertations. I appreciate continuing support from the NSF under Grant AST88-06594 and from NASA under contract NAG5-1016.

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DISCUSSION

N. Devereux: Are the W-R galaxies luminous in the IRAS data?

Conti: Several are strong IRAS sources. Tim Heckman has done some work on them.
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T. Heckman: The two galaxies having the most luminous W-R \( \lambda 4686 \) features (IRAS 01003-2238 and Mrk 309) are both very luminous IRAS sources (few \( \times 10^{12} \) and few \( \times 10^{11} \) \( L_\odot \), respectively). Lee Armus and I have found tentative evidence for W-R stars in a fair number of IRAS-selected galaxies. However, there is as yet no clear statistical link between the "IRAS galaxy" and "W-R galaxy" phenomena.

S. Lamb: I have been looking at interacting starburst galaxies in the UV with IUE. We find that Arp 248b has W-R spectral characteristics in this part of the spectrum. We plan to look at more interacting starburst galaxies in the coming year to see if others of this class also show evidence for large populations of massive stars.

A. Moffat: In the past decade there has been an overzealous trend to overestimate the number of W-R stars (e.g., \( \sim 50 \) W-R in NGC 604 by D’Odorico and Rosa in 1981 based on slit spectroscopy, versus \( \sim 10 \) W-R now based on narrow-band imagery by Drissen, Moffat, and Shara 1990) in giant H II regions and W-R galaxies. I hope that, in future, slit work will be backed up by direct, high-resolution, narrow-band imagery to get a complementary, unbiased estimate of the number of W-R stars.

Conti: I agree. Some of the W-R numbers in my table are estimates based upon the integrated fluxes at \( \lambda 4686 \). These have not all been calculated in a self-consistent manner.

R. Pogge: On W-R galaxies, I point out that Mrk 309 and NGC 6764 are nuclear sources whereas the other Kunth and Schild W-R galaxies are blue compact dwarfs or isolated H II regions in small irregulars. I feel uncomfortable lumping the former two in as the environments are quite different: the nuclei of spiral galaxies vs. isolated giant H II complexes in irregulars.

Conti: The current list of W-R galaxies is quite a mixed bag of objects. I was only drawing attention to the similarities in the massive-star (O-type and W-R) content.

F. Bruhweiler: I would like to point out that in galaxies with AGNs as well as starburst activity, you may have extended emission-line regions which can mimic properties of W-R-type features. This can be a problem, especially in the UV. For example, in NGC 1068, there is a very highly ionized, extended emission-line region with N V, C IV, He II, and C III] as revealed in the UV spectra seen with the IUE (see Bruhweiler and Truong—a poster paper in this meeting). To the uninitiated observer this emission superimposed on the bright starbursts may be mistaken for W-R features. Indeed, this has been erroneously suggested in the case of the bright UV knots in NGC 1068.

Conti: In the cases of W-R galaxies I am considering, the line widths of He II \( \lambda 4686 \) are larger than those of the nebular features, which are unresolved (unlike in typical Seyferts). I agree one needs to be careful.

M. Shara: You mentioned the 3.09 \( \mu \) line as a good place to look for heavily reddened Galactic and extragalactic W-R stars. Why is this line so strongly preferred to the other IR lines you showed, which appear to be as strong, or stronger?

Conti: It is further into the IR and thus has less extinction. Others might also be suitable, but one must avoid the Brackett lines which may have nebular contributions.
I. Gatley: As a practical matter it gets rapidly more difficult to work beyond about 2.5 μ because of thermal background emission. You have plenty of lines to use in the 2 μ region, and I expect they will prove the most useful.

I enjoyed your appreciation of the usefulness of infrared, and think that an important function of this meeting will be to convince the rest of the participants that it’s true!

N. Walborn: (1) Another useful IR indicator of W-R stars is the large ratio of He I to Brackett γ in the 2 μ region, as shown by McGregor et al. for the WN9 class in the LMC and by Allen et al. in the Galactic Center. (2) Even finer distinctions among Of stars can be made from wind features in low-resolution UV spectra, e.g., Si IV < C IV and He II present indicate an early-Of spectrum, while in a mid- or late-Of Si IV = C IV.

R. Joseph: How useful is detection of W-R features in galaxies for doing quantitative astrophysics? From fluxes in such features, for example, can one infer numbers of W-R stars contributing to the emission?

Conti: In principle one can do that and we are planning to come up with the numbers in some 10 W-R galaxies soon (see Vacca and Conti poster at this workshop).

J. Bland Hawthorn: To underscore Bob Joseph’s point, a comparison of the number of W-R stars with the number of, say, O stars may shed light on whether the high-mass star-formation rate is impulsive, continuous, or whatever.

Conti: I concur. Work on this problem is underway (see Vacca and Conti poster). The number of O stars can be estimated from analysis of the nebular lines.

N. Langer: What could be the explanation for the fact that you find only evidence for WN stars in W-R galaxies, and none for WC stars? Could it be that late WNs come from more massive stars than WCs, and the effect is an indication of the starburst being very young? Or is it something completely different?

Conti: I suspect it is the initial composition: in the SMC the WN/WC ratio is large. This has been attributed (e.g., Maeder, this workshop) to its lower abundances relative to the solar vicinity where the WN/WC ratio is near unity. While we do not have the numbers yet I think the W-R galaxies are SMC-like in composition.

N. Walborn: Indeed, the W-R population of giant H II regions is dominated by WN types. My own feeling from the observational morphology is that the most massive (100–200 M☉) stars may not make it to a WC stage.

L. Drissen: A comment on Langer’s question: not only in W-R galaxies is the WC/WN ratio very low; in Local-Group giant H II regions (30 Dor, NGC 604, NGC 595) the WC/WR ratio is below 0.2. Most of these WN stars are of WNL subtype.

Conti: This may have to do with the relatively low abundance of the elements.

A. Campbell: Following the points that there are almost no WC stars in the SMC,
and therefore that the presence of W-R stars in star-forming regions may be an abundance effect: we have a sample of 45 H II galaxies, but only the highest-abundance objects show WR features. None with O/H $\lesssim 0.2(O/H)_{\odot}$ seems to contain W-R stars. Perhaps in metal-poor objects the stars contain too few metals to drive the strong wind necessary to strip an O star down to a W-R star. Also, in H II galaxies, those W-R stars that are seen are of subtype WN—more evidence of insufficient stripping.

A. Moffat: Another important parameter in the W-R/O ratio in starbursts is the age (cf. Drissen 1990, Ph.D. thesis): if the region is too young ($\lesssim 2 \times 10^6$ yr) or too old ($\gtrsim 7 \times 10^6$ yr) there will be no W-R stars (these values apply to solar abundances). For lower metallicity, this "window" gets narrower and the W-R/O ratio falls off, reaching essentially zero at $Z \lesssim Z_{\odot}/10$ or so. The reason is simple: if the region is too young, W-R stars have not had time to form; if too old, they have evolved away already.

G. Hensler: Are there X-ray fluxes measured from your W-R galaxies? Do the energetics show already the explosions of Type II SN? How does this fit into the evolutionary scenario of starburst galaxies?

Conti: I think several are X-ray sources but I don’t recall if they are anomalous. I would expect that W-R galaxies would not be environments in which SN have yet played much of a role in the energetics; that will come later when the W-R stars are gone and the SN rate becomes appreciable as the burst ages and stars further down the main sequence evolve.

S. Heap: In a QSO observed by John Hutchings a couple of years ago it was found that in the host galaxy, not in the nucleus, there is He II $\lambda$4686 in emission. After we deconvolved the images of the galaxy it turned out that it is a barred spiral and that one is simply seeing a young spiral-arm population. It is 5 or 10 arc seconds away from the nucleus and so this brings up a question in my mind of what is the going definition of a starburst. What is the difference between a W-R galaxy and a W-R starburst galaxy? What is your working definition of a starburst?

Conti: My working definition, but I’m not insisting on it, is that you know you have a starburst when you see the intense nebular lines. Because then you know you have O stars there and the argument is you could not have had that going on for the last $10^{10}$ years because you would have used up all of your gas. Sargent and Searle, I think, made this argument back in 1970 when they first discussed blue compact galaxies. If you see a lot of O stars, you have to have something which is turned on and off. Maybe it is turned on only once, maybe it’s turned on several times. But it could not have been going along for the age of the Universe with the number of O stars implied by those nebular lines. It may even be true that if you are making only O stars it still cannot go on for $10^{10}$ years. So it has to be a burst. That is a minimum definition but I’m not insisting that’s the only definition. At a later stage you may just see a lot of stars and the O stars have long since gone.