Wolf-Rayet Stars*

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1 Introduction

Wolf-Rayet (W-R) stars are a class of peculiar stars first identified in 1867 by C. J. E. Wolf and G. Rayet. Unlike the spectra of most stars, which are dominated by narrow absorption lines, the spectra of W-R stars show broad emission lines. The rich emission line spectrum makes them easy to identify, by spectroscopic observations, even at large distances.

W-R stars are divided into three broad spectroscopic classes (WN, WC and WO) based on the emission lines present in their spectrum. WN stars show emission lines predominantly of helium and nitrogen, although emission due to carbon, silicon, and hydrogen can readily be seen in some of these objects. In contrast, the spectra of WC stars are dominated by carbon and helium emission lines with hydrogen and nitrogen emission absent (Fig. 1). WO stars, which are much rarer than either WN or WC stars, are similar to WC stars except that oxygen lines are more prevalent, and there is a tendency to exhibit lines arising from atomic species of higher ionization.

These spectra classes are further divided into subclasses on the basis of line ratios, yielding a classification by ionization. The WN stars which exhibit spectra showing emission from high ionization species (e.g., He II, N V, O VI) [1] are designated WN2. Those showing emission from low ionization species (e.g., He I, N III) are classified as WN9, although recently the W-R spectral classification has been extended to WN11. Similarly, WC stars showing emission from high ionization species (e.g., He II, C IV, O VI), are designated WC4 while those exhibiting the lowest ionization (e.g., He I, C II) are designated WC9. In the literature there is also a tendency to refer to WN stars of classes 2 to 5 as early type (WNE) and classes 6 to 9 as late type (WNL). Similarly WC4-6 stars are designated as WCE, while WC7-9 stars are designated as WCL. Although there are important exceptions, WNE stars generally show no evidence for H emission while H emission is present in WNL stars.

The distribution of Population I W-R stars, which are discussed in this article, is similar to that of O stars; they are primarily located in the spiral arms of our galaxy and near H II regions. W-R masses range from an uncertain lower limit of about $5\,M_\odot$ to in excess of $60\,M_\odot$, while surface temperatures range from a lower limit of 25,000 K to greater than 100,000 K. Because of their spatial association with O stars, and their peculiar surface abundances, W-R stars are generally believed to be descended from O stars.

Approximately 220 W-R stars are known in our galaxy but this number is certainly incomplete. Most are hidden from our view by dust, which absorbs and scatters light (a process termed interstellar extinction), within our galaxy. Estimates of the total number of W-R stars in our galaxy range from 1,000 to 2,000. The rarity of W-R stars is due to the initial mass function which favors the production of low mass stars, and the short evolutionary lifetime of W-R stars, which is only a few $\times 10^5$ years. Their rarity belies their importance. All stars more massive than approximately $25\,M_\odot$ (for solar metalicity) pass through a W-R phase. Further, over the lifetime of a galaxy, W-R stars (and their progenitors) have an important influence on the energetics, dynamics, and chemical evolution of the interstellar medium (ISM).

In addition to the Population I W-R stars, some central stars of planetary nebula also show W-R emission features. Their spectral types are inserted between [] to distinguish them from Population I W-R stars. They are of type [WC], and have lower masses (less than $1\,M_\odot$) and lower lumi-

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[1] He II is a spectroscopic designation used to indicate the ion for a transition between bound levels in singly ionized helium (i.e., He^+).

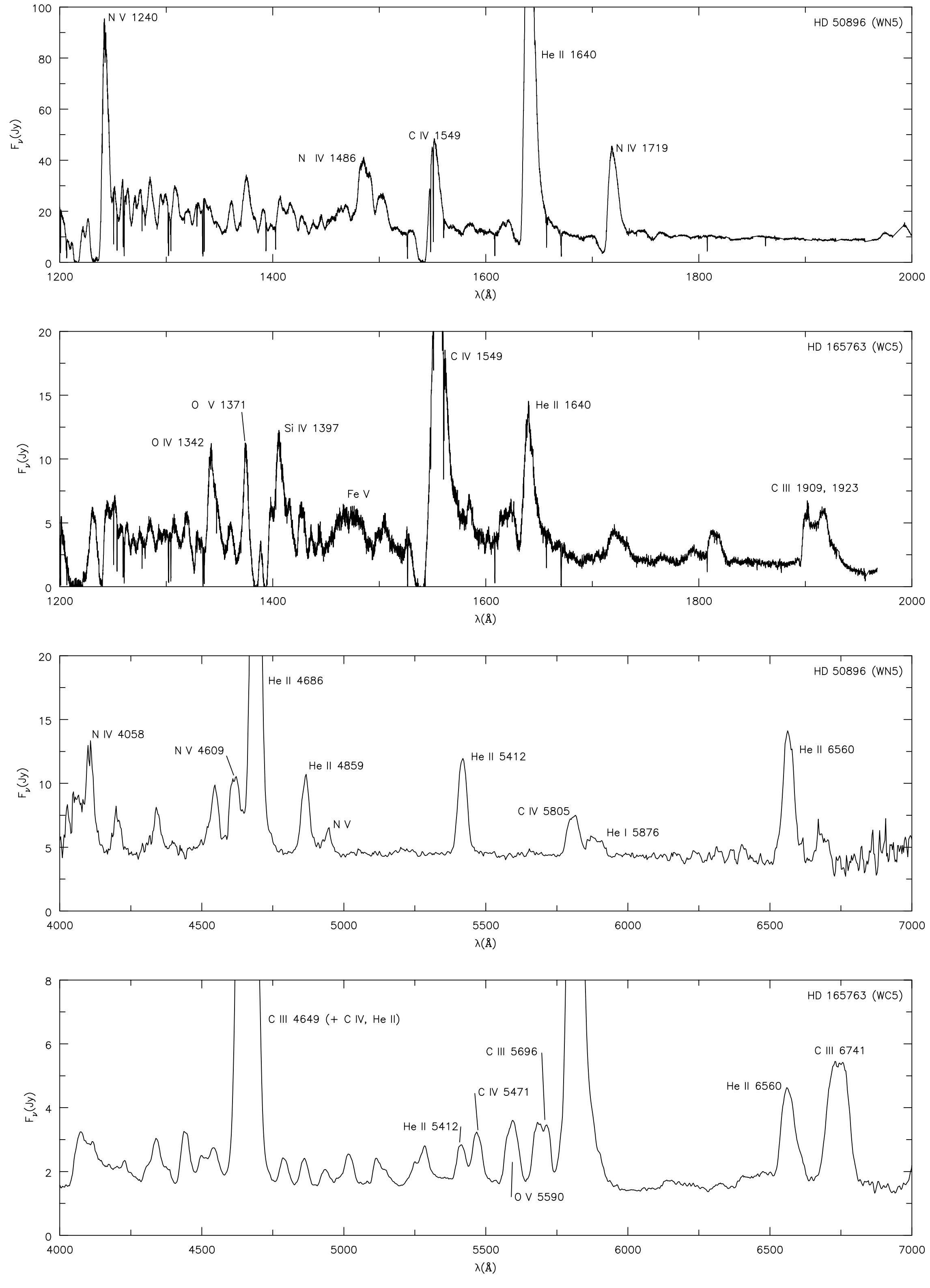

Figure 1: UV and Optical spectra of the WN5 star HD 50896 and the WC5 star HD 165763. The major emission line features are identified, although it should be noted that many lines, particularly in the WC star, are blends. Notice the very distinct differences between the WN5 and WC5 spectra. The optical spectral region, which can be observed from the ground, has typically been used to classify W-R stars. Since the advent of space astronomy, the UV spectral region has provided additional invaluable diagnostics on the properties of W-R stars.

nosities (generally $< 3 \times 10^4\,L_\odot$). The spectra of planetary nebula W-R stars are often dominated by strong narrow nebula emission lines. In some cases they can be difficult to distinguish spectroscopically from normal Population I W-R stars although in some [WC] stars N and H emission is seen. Because of their distinct evolutionary histories, they will not be further discussed in this article.

2 Basic Model

The basic model for W-R stars is that of a hot star which is suffering extreme mass-loss. The mass-loss occurs via a continuous stellar wind which is accelerated from low velocities near the surface of the star to velocities that exceed the surface escape speed. The observed spectrum originates over a range of radii with the optical continuum forming close to the stellar core, while the emission lines originate from a volume that can extend beyond 10 stellar radii.

The observed mass-loss rates (i.e., the amount of material lost per year) are extreme, typically in excess of $10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$. These mass-loss rates are sufficient to affect the evolution of the star, and must be incorporated into stellar evolutionary calculations. The (average) maximum velocity of material in W-R winds (called the terminal velocity, V_∞) ranges from $800\,\mathrm{km\,s^{-1}}$ to in excess of $3000\,\mathrm{km\,s^{-1}}$, and typically exceeds the escape velocity from the surface of the star. It is generally believed, although it has yet to be rigorously demonstrated, that the mass-loss is driven by radiation pressure acting through numerous bound-bound atomic transitions of Fe, and other atomic species in the extreme UV ($\lambda < 900\,\mathrm{Å}$).

The bulk of the material in the wind is believed to be cool — that is, it has a temperature substantially lower than the effective temperature of the star. Energy input into the wind primarily occurs through photoionization by the intense UV radiation field emanating from the central source. Thus photoionization is the ultimate source of the line emission that originates in the wind, although individual emission lines form through a variety of different processes — recombination, collisional excitation, and continuum fluorescence.

3 Determination of Stellar Parameters

The spectra of most stars are determined by 3 basic parameters: the effective temperature (T_{eff}), the effective surface gravity (g_{eff}), and the chemical abundances. For an assumed metallicity, large grids of models can be constructed simply by varying T_{eff} and g_{eff}.

The effective temperature is defined by the relation

$$L = 4\pi R_*^2 \sigma T_{eff}^4$$

where L is the luminosity and σ is the Steffan-Boltzmann constant. The effective temperature is the surface temperature that a star of radius R_* would have if it radiated as a blackbody (a perfect thermal emitter and absorber).

The effective surface gravity is defined by

$$g_{eff} = (1-\Gamma)\,\frac{GM}{{R_*}^2}$$

where M is the star's mass, G is Newton's gravitational constant, and Γ is a correction for the influence of radiation pressure. In conjunction with the equation of hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho g_{eff} \left(\frac{R_*}{r}\right)^2$$

where P is the pressure and ρ is the density, this sets the scale height of the atmosphere, h_*. For an isothermal atmosphere, h_* is given by

$$h_* = \frac{kT}{\mu \mathrm{m}_H g_{eff}}$$

where μ is the mean particle mass in atomic mass units (amu), and m_H is the atomic mass of hydrogen. For most normal stars $h_* << R_*$, curvature effects can be ignored, and the atmosphere can be treated as a plane-parallel slab. As a consequence of the small-scale height, the Sun has a definite radius at optical wavelengths.

For W-R stars the situation is quite different. First, the atmosphere is extended, and consequently radiation escapes from the star over a range of radii. Further, the radius of the star at an optical depth (τ) of 2/3 depends on the adopted mass-loss rate, and is a function of wavelength (Fig. 2). The difficulty of uniquely defining R_*

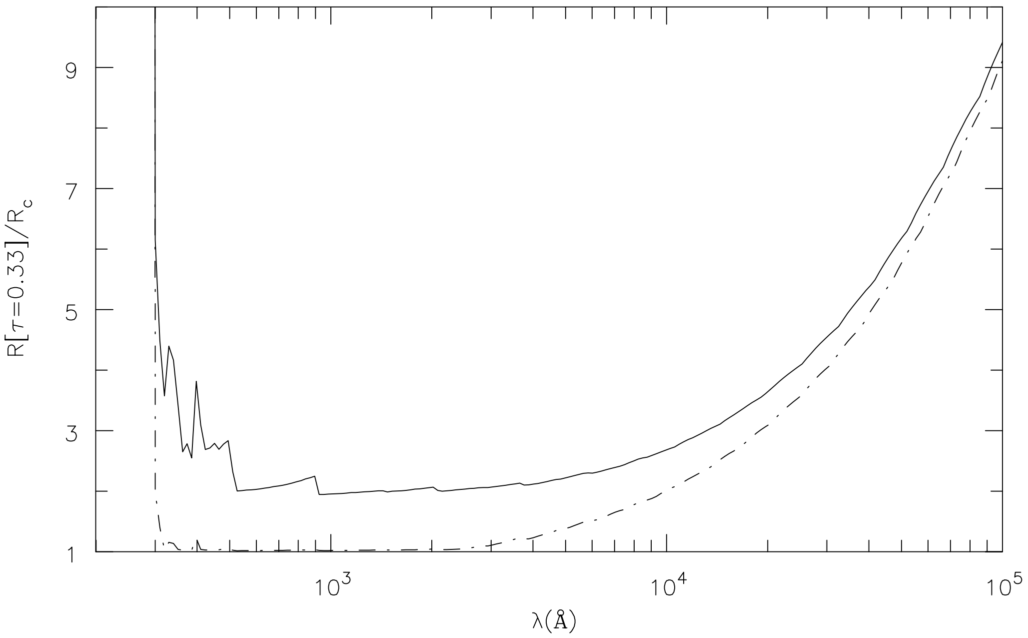

Figure 2: Illustration of how the 'radius' of the star varies with wavelength for the WC5 star HD 165763. The solid line shows the 'radius' at which the 'continuum' optical depth, τ, is 1/3, which occurs in the wind at all wavelengths. The broken line is identical except the electron scattering opacity was not included in the computation of τ. The bulk of the observed flux in this model is emitted between 300 and 2000 Å. R_c is the radius of the hydrostatic core — that is, the approximate radius the star would have in the absence of a stellar wind. For the illustrated model it was $1.8\,R_\odot$

has led to difficulties in comparing T_{eff} derived from evolutionary models with that obtained from spectroscopic analyses. Second, g_{eff} does not have a direct influence on the stellar spectrum, simply because emission from the stellar wind dominates the spectral appearance of the star. Third, the abundances are non-solar and must be determined observationally. Indeed it is the abundances that determine to which class (WN, WC or WO) a W-R star belongs.

In addition to the abundances (primarily of H, He, N, C, and O) it has been found from numerical experiments that the spectra of W-R stars are determined primarily by 2 parameters: T_{eff} and a wind density parameter, W_ρ. The latter, which plays a similar role to g_{eff}, can be defined by

$$W_\rho = (\dot{M}/V_\infty) R_c^{-3/2}$$

where R_c is the radius of the hydrostatic core. Two stars will have very similar spectra if they have similar abundances, and if T_{eff} and W_ρ are similar. The dependence of the spectra on W_ρ arises because most of the radiative processes in an extended atmosphere depend on the square of the density. As a consequence of the scaling, it is impossible to deduce the distance of a W-R star from the Sun using its spectrum.[2] In principle, $\dot{M}$ and V_∞ should depend on the other stellar parameters – composition, M, L, and R_*, but as yet our theoretical understanding of mass-loss from W-R stars is not sufficiently advanced to deduce the relationship.

Because of the low wind densities (10^8 to 10^{14} electrons cm^{-3})[3] the simplifying assumption of lo-

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[2] Stellar evolution introduces a correlation between spectral-type and luminosity which may statistically allow distances to be derived for stars of a given spectral type. However for an individual star the derived distance may be grossly in error, particularly if the spectral type can originate via different evolutionary sequences. This is exemplified in the difficulty of determining whether some W-R stars belong to Population I, or are the central stars of planetary nebula.

[3] For comparison, the density of water on Earth is of order

cal thermodynamic equilibrium (or LTE) cannot be made when modeling W-R spectra. When LTE holds, it can be assumed that the ionization state of the gas and the populations of the atomic levels can be found via application of the principles of statistical mechanics, and thus are (simple) functions of the local temperature and density only. For LTE to prevail, collisional processes, which couple the atomic populations with the electrons (and hence to the local electron temperature), need to occur faster than radiative processes.

In contrast, in W-R atmospheres radiative processes tend to dominate over collisional processes, and hence it is necessary to solve the equations of statistical equilibrium at each depth. For each atomic level of each species we assume that all the processes (radiative and collisional) populating the level are in equilibrium with all processes depopulating the same level. The major difficulty arises because the rates are a function of the radiation field, which in turn is a function of the unknown populations. Thus the radiation field and atomic populations must be solved for simultaneously, and in general an iterative procedure is necessary to obtain consistency.

Initial modeling of W-R spectra concentrated on the H and He spectra only. The second generation included CNO elements, while the most recent generation of models include iron and other species. The inclusion of iron (and similar species) in non-LTE calculations has been a major stumbling block for atmospheric calculations for O and W-R stars for many years. The iron-group ions have both a wealth of atomic levels, and an enormous number of bound-bound transitions. The advent of faster computers with large memories, new numerical techniques, and the availability of atomic data have now made it feasible to include iron and other species in non-LTE.

3.1 Determination of T_{eff}

The effective temperatures of W-R stars are determined primarily using ionization arguments. Consider a sequence of models with prescribed mass-loss and velocity law, but with different effective temperatures. Such a sequence of models will exhibit a smooth variation in line ratios for lines from two successive stages of ionization. In early WN modeling it was customary to compare He II 5411 with He I 5876 since both lines are easily observed, and are relatively blend free. In more recent modeling N lines can also be used to constrain the effective temperature, while in WC stars C and O lines can be used. The analyses generally give consistent results. Discrepant results do occur, and probably result from a poor treatment of line blanketing (the generic name given to the influence of thousands of bound-bound atomic transitions on an atmosphere) and/or density inhomogeneities in the stellar wind.

Analyses of the spectra of ring nebula around W-R stars offers a method of checking on the energy distributions predicted by atmospheric modeling, since the nebula are ionized by the star's radiation field. For ring nebula around WNE stars these analyses have usually shown reasonable consistency. However, for some WNL and WC stars the observed nebular spectrum was of lower excitation than would be predicted using the stellar UV radiation field derived from the modeling. The recent inclusion of line blanketing in the stellar atmospheric models has removed this discrepancy for at least one ring nebula around a WN8 star.

3.2 Abundances

The severe non-LTE conditions in W-R stars initially made it difficult to understand their peculiar emission line spectra. Do W-R stars possess peculiar (i.e., non-solar) abundances? Is the difference between the WN and WC stars due to an abundance difference, or is it an excitation effect? Detailed recombination and spectroscopic analyses have now firmly established that W-R stars are characterized by non-solar abundances.

In WN stars H, C and O are depleted, while N and He are enhanced. For WN stars, N(H)/N(He) ratios (by number) range from approximately 4 to < 0.1 (the solar value is 10). The observed abundances are consistent with the idea that material processed by the CNO nuclear burning bi-cycle has been revealed (or mixed) at the surface (see Sect. 6).

In WC stars, He, C, O, and Ne are all enhanced. N(C)/N(He)=0.1 to 0.5 while the less certain N(O)/N(He) ratios are typically 0.1. H

$10^{22} molecules\, cm^{-3}$

and N are not expected in WC stars, and are not detected. The variation of N(C)/N(He) and N(O)/N(He) with WC subtype is still the subject of much debate.

3.3 Determination of Mass-Loss Rates

Mass-loss rates can be determined in several ways: First, free-free radiation in the dense stellar wind gives rise to a detectable flux at radio wavelengths. From measurements of the radio flux, S_ν, the mass-loss rate, $\dot{M}$, can be determined from the simple formula

$$S_\nu = 23.2 \left(\frac{\dot{M} z}{V_\infty \mu} \right)^{4/3} \left(\frac{\gamma g \nu}{d^3} \right)^{2/3}$$

where d is the distance to the W-R star in kpc, $\dot{M}$ is the mass-loss rate in $M_\odot\,\mathrm{yr}^{-1}$, V_∞ is the terminal velocity of the wind in $\mathrm{km\,s^{-1}}$, z is the mean ionic charge, μ is the mean ionic mass (in amu), γ is the number of electrons per ion, ν is the frequency in Hz, and g is the free-free gaunt factor (which is the quantum correction factor to the semi-classical formula for free-free radiation) at frequency ν. S_ν is measured in Janskys (1 Jansky = $10^{-23}\,\mathrm{ergs\,cm^{-2}\,s^{-1}\,Hz^{-1}}$). The greatest uncertainties in the derived $\dot{M}$ arise from uncertainties in stellar distance, and in the ionization state of the gas in the radio emitting region.

Second, the IR flux can be used in a similar manner, although in this case it cannot be assumed that the wind has reached its terminal speed. Third, optical and UV emission lines can be used. Typically, recombination lines are used since they are less sensitive to the precise details of their formation. Mass-loss estimates obtained from different methods generally agree to within a factor of 2.

It has generally been assumed that the winds of W-R stars are spherical and homogeneous. Thus at any location in the wind the density can simply be found from the principle of mass-conservation, giving

$$\rho = \frac{\dot{M}}{4\pi r^2 v(r)}$$

where $v(r)$ is the velocity as a function of distance, and is assumed to monotonically increase with r. However, emission line variability studies and analyses of emission line profiles suggest that the wind is clumped (i.e., non-homogeneous) on small scales. If this is true, mass-loss estimates are too large — possibly by factors of 3 or more. This has very important implications for stellar evolution calculations. A change in $\dot{M}$ by only a factor of 2 (over a star's life) has a profound influence on the evolution of massive stars. This is seen in theoretical evolutionary calculations, and can also be indirectly inferred from the different WN/WC ratios in the galaxy and our nearest extragalactic neighbor, the Large Magellanic Cloud (LMC). In the LMC the mass-loss rates are expected to be lower because of the lower metallicity.

The extreme mass-loss properties of W-R stars can be characterized by the "wind performance parameter", η, defined by

$$\eta = \frac{\dot{M} V_\infty}{L/c}.$$

$\dot{M} V_\infty$ is the (scalar) momentum of the wind, while L/c is the momentum that could be transferred if all the photons, and hence all the momentum in the radiation field, were absorbed. For O stars, η is typically less than unity. For W-R stars values as high as 100 have been obtained, although by allowing for inhomogeneities and line blanketing it has been possible to reduce the values to less than 10. Values of η in excess of unity do not rule out a radiation driven wind — they simply indicate that each photon has to scatter many times within the wind so that it delivers η times its momentum to the wind. It has been difficult to produce radiation driven winds for W-R stars since current models do not have the necessary number of bound-bound atomic transitions to perform the required number of scatterings.

4 Binaries

Approximately 50% of W-R stars occur in binaries — a number comparable with O stars. In the past there has been considerable discussion on the importance of binarity for the W-R phenomena. For example, it was once thought that W-R stars could only originate in a binary system. Mass-loss from the W-R progenitor would then occur by Roche-lobe overflow. The major uncertainty in evolutionary calculations of binary systems is how much material is lost from the system during

Roche-lobe overflow (rather than being accreted by the companion). More recently the binary channel for the production of W-R stars has virtually been ignored. There is little doubt, however, that the binary channel is important, and it must be considered when linking W-R types with evolutionary calculations (although many researchers would disagree with this statement).

At least 3 (broad) distinct classes of W-R binary systems can be envisioned: W-R + OB star, W-R + W-R, W-R + compact companion (neutron star or black hole). All (confirmed) W-R binaries belong to the first class, W-R + W-R systems are expected to be rare, although WR98 (where WR98 denotes the 98th Wolf-Rayet star in the sixth catalogue of W-R stars) may be an example of such a system. The third class is expected on evolutionary grounds. Although the existence of such systems has been difficult to verify, several good candidate systems are known. Cyg X-3 can be considered a possible example.

W-R binary systems are extremely useful. First, and foremost, they allow a direct determination of stellar masses, independent of evolutionary models. The use of these masses in constraining single-star evolutionary models presupposes that W-R stars in binaries have properties similar to single W-R stars — a proposition that cannot be reliably tested because of poor statistics and uncertainties in the properties of W-R stars.

Second, the O star can be used to probe the structure of the W-R stellar wind. Indeed it was this technique, applied to the W-R+O binary V444 Cygni which gave the first direct evidence that W-R stars are hot (i.e., surface temperature in excess of 60,000 K). More recently it has become evident that polarization studies of binary systems may allow determinations of mass-loss rates which are insensitive to the presence of inhomogeneities within the stellar wind.

4.1 X-ray emission

Most W-R stars are thermal X-ray sources. They can be classified into two categories — single W-R stars and binary W-R stars. In single W-R stars the observed ratio of X-ray to bolometric luminosity is approximately 10^{-7}, although there is a scatter of at least a factor of 3 about this value. The X-rays are believed to originate within the stellar wind through radiation driven wind instabilities which lead to high velocity shocks ($V_{\rm shock} = 100$ to $600\,{\rm km\,s^{-1}}$) and clumping of the wind. These shocks generate X-ray emitting gas characterized by temperatures between 10^6 and 10^7 K . The shocks probably permeate most of the wind, however because of the high wind densities most of the X-rays are absorbed in the wind.

A few W-R stars are stronger and/or variable X-ray emitters. In these binary systems the X-rays can be generated from the high temperature gas (of order 10^7 K) created via shocks generated in a wind-wind collision. The two best examples are the WN+O system V444 Cygni, and the WC+O system HD193793 (WR140). Both exhibit a periodic X-ray variability broadly consistent with that expected from a wind-wind collision in a binary system. Alternatively the X-rays could be generated via accretion of wind material onto a compact companion.

4.2 Dust formation

This topic, by all rights, should not belong in a discussion on W-R stars since dust is destroyed by intense UV radiation, and requires low temperatures ($<$ 3000 K) for its formation. Yet dust is seen around some WC stars, and moreover dust is seen to be created in the vicinity of some WC stars. Two distinct dusty WC classes may exist: Binary systems and single stars.

In many WC9 stars, presumed to be single, conditions within the C rich stellar wind appear to allow dust formation. The dust nucleation routes, and how the dust (and the necessary prerequisite molecules) forms despite the presence of an intense UV radiation field is unclear. If the stars are single, inhomogeneities generated by radiation instabilities probably play an important role in allowing dust to form.

The second class are the binary systems, with eccentric orbits, with HD193793 (WR140) being an excellent example. In these systems dust does not normally form, however binary interaction near periastron (i.e., minimal orbital separation) can facilitate dust formation. Apparently the high densities generated in the wind-wind interaction have the right conditions for dust formation. As in the

Figure 3: A grey scale image at 2.27 μm showing the distribution of dust in WR104, as found by interferometric observations with the KECK telescope. The dust moves away from the system radially — the apparent spiral motion is an illusion. It results from the rotation of the dust formation zone as a consequence of the orbital motion of the binary system. The ring of dust, as illustrated, has an angular diameter of approximately 160AU (or 0.1 arcseconds). (Picture courtesy of W Danchi, J. Monnier, and P. Tuthill, Berkeley.)

single WC stars, the dust formation is not understood.

Recent interferometric observations of WR104 with the KECK telescope have revealed directly the dust outflowing from the interaction region of the binary (Fig. 3).

5 Related stars

In the upper part of the Hertzsprung-Russell (H-R) diagram, many different classes of massive luminous stars exist: Of stars, blue supergiants (BSGs), red supergiants (RSGs), luminous blue variables (LBVs) and WN/Of stars. One of the goals of massive star evolution is to understand the links between the various classes of objects, and the distribution of massive stars between the different classes. Below we briefly discuss some of the salient features of each class.

Of stars are O supergiants exhibiting emission lines in the optical. They are O stars that have evolved off the main sequence. WN/Of stars exhibit spectral characteristics of both Of and WNL stars. It was this intermediate characteristic that suggested an evolutionary link between the Of stars, and bona-fide WN stars.

LBVs, as their name suggests, are luminous blue stars which show irregular variability on a time scale of hours to centuries. Some LBVs have exhibited giant outbursts in which their visual brightness and bolometric magnitude increased by several magnitudes. During such outbursts several solar masses of material may be ejected. Other LBVs, such as AG Car, show moderate outbursts on a timescale of a decade. During these outbursts the effective temperature changes but the bolometric luminosity and mass-loss rate is almost constant. The most famous LBVs are P Cygni, which suffered a giant outburst in the 1600s, and η Car which underwent a major outburst in the 1840s. The outburst suffered by η Car ejected a bipolar nebula, referred to as the Homunculus, which has a major axis diameter of 17" (approximately 4000 AU). Images of the Homunculus are amongst the most spectacular obtained by the Hubble Space Telescope.

A major breakthrough in our understanding of massive stars was achieved when one LMC Of/WN star (now classified as WN11), R 127, was observed to undergo an LBV-like outburst, suggesting an evolutionary link between LBVs and Of/WN stars.

LBVs are now regarded as a key phase of massive star evolution. It is believed that during the LBV phase a massive star ejects most of its hydrogen-rich outer envelope, allowing it to become a W-R star. A key observation that has led to this scenario is the absence of red-supergiants with luminosities comparable to the most luminous O stars. Evolutionary calculations show that during the LBV phase, extensive mass-loss can prevent the star from evolving into a red supergiant. The mechanism of mass-loss during the LBV phase is not yet understood, although it may be related to the star evolving towards the modified Eddington limit. The classical Eddington limit provides a lower limit on the mass of a star, of a given luminosity, based on the assumption that the radiative force arising from the electron scattering opacity cannot exceed gravity. The modified Eddington limit takes into account that other radiative processes also contribute to the opacity, and further that stellar rotation can effectively lower the surface gravity. The maximum luminosity exhibited by supergiants in the H-R diagram is termed the Humphreys-Davidson limit.

6 Evolution

W-R stars are believed to be descended from O stars. The basic evolutionary sequence, first proposed by Conti in 1976, is

O → Of → W-R

Since that time observational and theoretical work has led to refinements in this basic sequence. From the theoretical work of Maeder and collaborators, one such sequence for stars with initial masses greater than $50\,M_\odot$ is

O → OIf → BSG → LBV → WN → WC → supernova

while stars between 35 and $50\,M_\odot$ have the alternative sequence

O → BSG → YSG → RSG → YSG → WN → WC → supernova

Other sequences have also been proposed. Suffice to say that the precise evolutionary path that an individual massive star follows (which depends on the star's initial mass and composition, and possibly its rotation rate and whether it has a companion), is still uncertain. No firm link has been established between the different ionization classes within the WN and WC sequences, although there has been some success in linking spectral types with initial stellar mass. The unknown roles of binary interactions and rotation only add to the confusion.

Both WN stars and WC stars are generally believed to be on the helium burning main sequence, although some of the luminous hydrogen-rich WN stars may still be core hydrogen burning. If the latter is true, it means that the spectroscopic and theoretical definitions of W-R stars are inconsistent. This creates difficulties in comparing observed W-R/O number ratios with theoretical predictions. The W-R/O ratio is an important observational constraint since it provides a method (at least in principle) of determining the minimum stellar mass which will evolve into a W-R star. For a solar metallicity this is generally believed to be approximately $25\,M_\odot$, but higher values cannot be ruled out.

In massive stars, H burning occurs via the CNO bi-cycle through a sequence of reactions, with the CNO species acting as catalysts. In the CN cycle the following reactions occur:

$$\begin{aligned} {}^{12}\mathrm{C} + {}^{1}\mathrm{H} &\rightarrow {}^{13}\mathrm{N} + \gamma \\ {}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + e^{+} + \nu \\ {}^{13}\mathrm{C} + {}^{1}\mathrm{H} &\rightarrow {}^{14}\mathrm{N} + \gamma \\ {}^{14}\mathrm{N} + {}^{1}\mathrm{H} &\rightarrow {}^{15}\mathrm{O} + \gamma \\ {}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + e^{+} + \nu \\ {}^{15}\mathrm{N} + {}^{1}\mathrm{H} &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He} \end{aligned}$$

The 4th reaction is the slowest, and as a consequence much of the original C (and O from the other reactions in the CNO bi-cycle) is converted to N. The total number of CNO nuclei remains unchanged. When equilibrium is obtained, the ratio of ^{14}N to ^{13}C nuclei is approximately 50, very different from the solar ratio of 0.27.

In normal stars the nuclear processed material remains within the stellar core, and cannot be observed. However, in O stars and their descendents, extensive mass-loss peels off the outer hydrogen-rich layers. Nuclear processed material, once inside the convective core of the star, is eventually revealed at the surface. In addition to mass-loss, it is now believed that mixing, possibly induced by stellar rotation, can help reveal nuclear processed material at the stellar surface.

In WC stars the mass-loss has been so extensive that the products of He burning are revealed at the stellar surface. The predominant reactions for helium burning are

$$^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{8}_{4}\mathrm{Be}$$

$$^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + \gamma$$

$$^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$$

The variation in surface abundances as a function of current mass for a star with an initial mass of $40\,M_\odot$ is shown in Fig. 4.

7 W-R stars in external galaxies

W-R stars are moderately easy to detect in external galaxies owing to their strong emission lines.

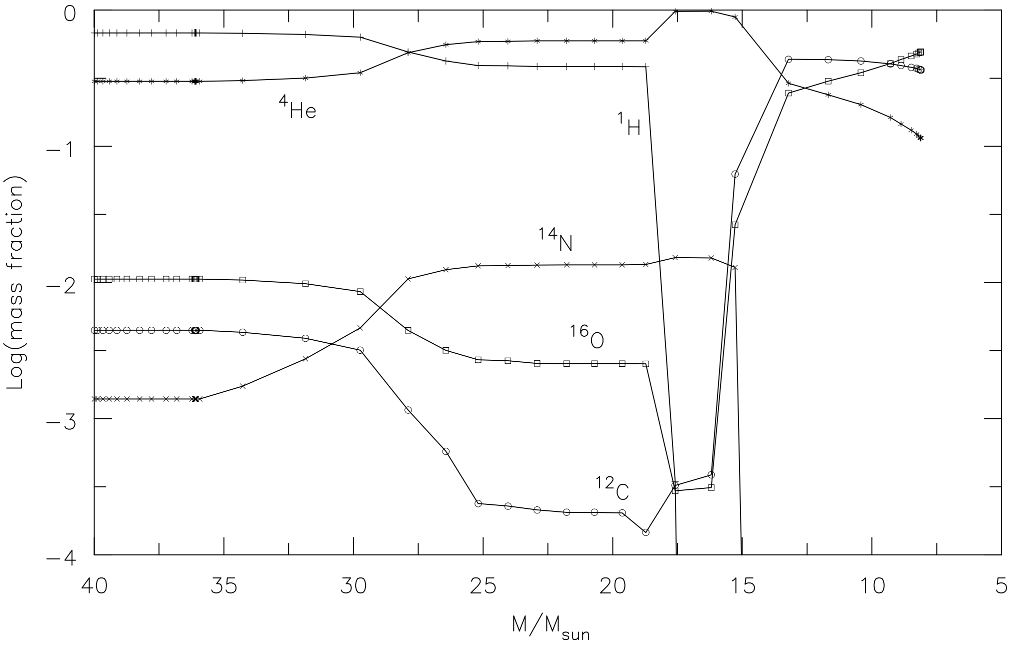

Figure 4: A diagram showing the evolution in surface abundances as a function of mass for a star with an initial mass of $40 M_{\odot}$. The WN phase occurs when the star's mass is between (approximately) 15 and $30\,M_{\odot}$, while the WC phase occurs when M$< 15\,M_{\odot}$. For most of its 4.8×10^6 yr life the star has a mass close to its initial value (e.g., after 4.2×10^6 yrs, its mass is still $\approx 36\,M_{\odot}$). The lifetimes of various stages are very dependent on the adopted assumptions (e.g., overshooting and mixing) and the adopted mass-loss rates. Overshooting refers to the phenomena of convective motions extending into a convectively stable region because the convective velocities are non zero at the interface between the convectively stable and unstable regions. Mixing refers to the process of mixing two chemically distinct regions of the star — for example rotation might induce nuclear processed material to be transported to the surface layers. The calculations were undertaken by the Geneva group (Maeder, Meynet, Schaller, and Schaerer) for solar metallicity, with overshooting and 'normal' mass-loss rates.

Typically they are found by performing a photometric survey in 2 filters. The passband of one filter is centered on a strong emission feature (generally the He II - C III/C IV complex at 4640-4690 Å) while the second passband is centered on the continuum only. W-R stars will be relatively bright in the emission line passband. Alternatively, they can be found using low dispersion prism spectroscopic surveys.

Both the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) have been extensively surveyed for W-R stars. In the LMC 134 W-R stars are known, while in the SMC only 9 are known. The difference in the number of W-R stars is believed to be due to a combination of the star formation rates, and the lower metallicity of the SMC (which inhibits W-R production). Interestingly, the ratio of WN to WC stars in the LMC is 4.5, substantially larger than the observed ratio of 1 in the solar neighborhood. This is generally interpreted as a metallicity effect.

W-R stars have also been found in many Local Group galaxies: e.g., M31, M33, IC1613, and NGC6822. The study of individual W-R stars in these galaxies is in its infancy. To date, efforts have been directed primarily into determinations of the WN/WC, O/W-R, and RSG/W-R number ratios which allow global issues, such as the effect of metallicity and the star formation rate on W-R production, to be addressed.

W-R stars have also been found in many galaxies exhibiting extensive star formation (often called starbursts). Indeed some galaxies are termed W-R galaxies if they exhibit strong Wolf-Rayet features in their integrated spectra. The presence of W-R stars in these galaxies immediately provides an age determinant. The starburst has to be older than approximately 2 million years so that the most massive O stars that formed in the burst have had sufficient time to evolve into W-R stars. They also provide an upper limit of about 7 million years since after this time all massive stars that pass through a W-R stage will have done so. Both age limits are metallicity dependent.

8 Outstanding Problems

There are many outstanding problems related to W-R research. Several of the most important problems related specifically to W-R stars are discussed below:

1. What initiates and drives mass-loss from W-R stars? Is radiation pressure, as currently believed, responsible for mass-loss from W-R stars? Why are mass-loss rates for W-R stars an order of magnitude higher than that of their O star progenitors?

2. What is the role of rotation in W-R stars (and their progenitors) in modifying the spectral appearance of the star? What is the role of rotation in massive stars in enhancing mixing processes and in enhancing mass-loss rates, and hence in modifying stellar evolution?

   It is essential for evolutionary calculations, whatever the mass-loss mechanism, that we are able to derive mass-loss rates from first principles. Ideally

   $$\dot{M} = \dot{M}(M_{init}, t, x, y, z, \Omega(t))$$

   where M_{init} is the initial stellar mass, t is the current age of the star, and x, y, and z are the chemical abundances (hydrogen mass fraction, helium mass fraction and metal mass fraction), and where the rotation rate $\Omega(t)$ is itself determined via the intial rotation rate and the subsequent mass-loss.

   A related question is the role of magnetic fields in massive star evolution. While the magnetic fields may be too weak to affect mass-loss rates they could be important in determining angular momentum losses, and hence play an indirect role on mass-loss through the dependence of $\Omega(t)$ on magnetic field strengths.

3. What is the detailed structure of W-R winds (shape and homogeneity)? How does the presence of inhomogeneities affect the determination of the fundamental stellar parameters? How coupled is the mass-loss to the details of the wind structure?

4. What is the role of binaries in massive star evolution? Are there classes of W-R stars (and LBVs) that only come from a binary evolutionary scenario? How much is our understanding of single star evolution being confused by the evolution of OB stars in interacting binary systems?

5. Because of uncertainties in the treatment of convection, mass-loss processes, and rotation, there are still many issues in single star evolution which must be addressed. Also of concern is whether W-R stars give rise to black holes (as presumed), and to what class a W-R supernova belongs.

Acknowledgements: This contribution is a brief synopsis of our current understanding of W-R stars. This understanding is the cumulative result of 130 years of W-R research by many astrophysicists whose individual contributions cannot be acknowledged.

Associated articles: W-R galaxies; W-R nebula; Stellar winds; Luminous Blue Variables; Planetary Nebula central stars, mass loss, winds; Stellar atmospheres: early-type stars; Stellar evolution; High-Luminosity stars

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While some of the articles are somewhat dated, the discussion between the symposium participants is rewarding, and is sadly missing in most recent symposia.