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Wolf-Rayet stars and stellar winds

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Abstract. Wolf-Rayet (W-R) stars are evolved O stars showing unusual composition, and severe hydrogen depletion. Recent spectroscopic analyses that provide insights into the nature of W-R winds, and their similarity to O star winds are discussed. While it has been convincingly demonstrated that O star stellar winds are driven by radiation pressure, it is unclear whether the same mechanism can explain the much higher mass-loss rates of W-R stars.

Possible explanations for the high efficiency of radiation driven winds in W-R stars are reviewed. These solutions involve ionization effects, missing opacity sources, and the possibility that the required driving efficiencies have been strongly overestimated. Uncertainties in the present theory of radiation driven winds arising from the effects of rotation and inhomogeneities are also discussed.

Many of the uncertainties in our understanding of W-R stars could be clarified if reliable stellar models, which included the effects of non-LTE line blanketing, were available. Progress towards implementing non-LTE line blanketing is discussed. Preliminary model comparisons are made with recent HST observations of LMC WC stars.

1. Introduction

Wolf-Rayet (W-R) stars were first identified by Wolf and Rayet (1867) due to the presence of strong emission lines in their spectra. The unusual line ratios in W-R spectra indicate that the atmospheres of these stars have compositions far from solar. This conclusion has been reached using qualitative analyses (e.g., Smith 1973, Conti et al. 1983), and detailed modeling (e.g., Crowther et al. 1995abc, Koesterke and Hamann 1995, Hamann et al. 1995).

All W-R stars are deficient in H. Many have no detectable H emission; those that do have a H/He ratio a factor of 2 (or more) less than the solar value. The anomalous abundance in W-R stars is due to a combination of stellar evolution and extensive mass-loss via a strong stellar wind. This wind explains the presence of the emission line spectra and is capable of removing most of the outer envelope to reveal material that has been at least partially processed by nuclear burning cycles.

The W-R stars fall into three classes:

1. WN Stars: The spectra are dominated by emission lines of He and N. Carbon emission is also seen, while emission or absorption features due

to H are readily detected in some stars. In the galaxy approximately half of the W-R stars within 2.5 kpc of the Sun are of this type, but in the LMC they comprise approximately 80% of the W-R stars (Massey and Armandroff 1991). In these stars we are seeing the products of the CNO cycle at the surface. Thus the stars are deficient in H, C, and O, and rich in He and N. The N/He and C/N ratios deduced are consistent with those expected from CNO burning (e.g. Crowther et al. 1995b).

2. WC stars: The spectra are dominated by emission lines due to He, C and O. No H emission has been unambiguously detected. They constitute roughly 50% of the W-R stars in our galaxy. In these stars we are seeing the products of helium burning at the surface. The C/He mass fraction in the stars is typically greater than 0.1, and may approach unity (Hillier 1989, Koesterke and Hamann 1995).

3. WO stars: Only 5 of these stars are known (see Kingsburgh et al. 1995). The sequence is distinguished from WC stars by the presence of strong O VI λ3811, 3834 emission.

For a detailed discussion of W-R stars and their properties the reader is referred to the review by van der Hucht (1992), and IAU Symposium 163 (van der Hucht and Williams, 1995).

2. Spectroscopic Analyses of W-R Stars

Two atmospheric codes have been utilized in performing spectroscopic modeling of W-R stars. The first code was developed by Hamann and collaborators (Hamann 1985, 1987), the second by Hillier (1987, 1990). While no rigorous comparison of the two codes has been made, results obtained with both codes are in excellent agreement. While the agreement between the two codes is reassuring, this in itself does not validate the analyses since both codes are based on very similar assumptions. In particular, homogeneity is assumed and line blanketing has generally been neglected.

Since it is not the purpose of this review to summarize all the results obtained from W-R analyses, the reader is referred to the papers by Crowther et al. (1995abc), Koesterke and Hamann (1995) and Hamann et al. (1995) from which a useful overview can be gleaned. Results that may have a bearing on our understanding of the structure of W-R winds, and their relation to O star winds, are discussed below.

1. Properties of W-R stellar winds show a correlation with hydrogen abundance. This has been suspected for a long time, but has now been demonstrated qualitatively from an analysis of a large number of WN stars by Hamann et al. (1995). For O stars the mass-loss rates are known to scale with luminosity according to

$$\dot{M} = \alpha L^{\gamma} \tag{1}$$

with $\gamma = 1.62 \pm 0.19$ (Garmany and Conti, 1984). WN stars without H follow a similar relation, but with a constant (α) which is two orders of magnitude larger. In addition WN stars with H require α to have a value intermediate between O stars, and the H deficient WN stars. In fact, Hamann et al. (1995) show that α is directly correlated with the H mass fraction.

While the relationships mentioned above are very significant, it should be noted that there is a considerable scatter in the mass-loss rates at a given luminosity and H abundance. Other parameters, as yet unknown, are also influencing the mass-loss rates of W-R stars.

For Of and WN7(+abs) stars there is also a correlation of the wind terminal velocity with the H/He ratio, in the sense that the most H deficient stars have the lowest terminal velocities (Crowther et al. 1995c).

Whether these correlations are physical (i.e., indicate a real dependence of mass-loss and velocity on the H abundance of the envelope) or arise from some other property that is correlated with the H abundance is unclear.

2. Whilst WC stars have very different compositions from WN stars, their wind properties (mass-loss rates, and terminal velocities) are comparable to the strong-lined WNE stars.

3. There is a continuation of properties from O stars to luminous blue variables (LBVs) and WN stars which can be seen from a purely descriptive analysis of the spectra (e.g., Walborn 1971, 1973). It can also be seen through detailed analysis. Lamers and Leitherer (1993), for example, demonstrate that there is a smooth continuation between O and WN wind properties on the basis of a comparison of the ratio of predicted (using radiation driven wind theory) to observed mass-loss rates with wind density.

   This link between O and WN stars is further strengthened by proposed evolutionary scenarios. Crowther et al. (1995c) suggest the evolutionary links

   O → Of → WNLabs → WN7 → (WNE) → WC → SN

   for the most massive stars ($M_{\rm initial} > 60 M_\odot$). For stars of somewhat lower mass ($40 M_\odot < M_{\rm initial} < 60 M_\odot$) they propose the scenario

   O → LBV → WN8 → WNE → WC → SN

   These scenarios are based on the continuation of physical and morphological parameters, and are an extension of the evolutionary scenario proposed by Conti (1976). Crowther et al. confirm the Lamers and Leitherer suggestion of a smooth progression in mass-loss properties between the O supergiants and WNL stars.

3. Theory of O and W-R Stellar Winds

It is now generally accepted that the winds of O stars are radiatively driven, although there are still discrepancies between theory and observation. The work of Castor et al. (1975) showed that winds could be driven from stars by radiation pressure acting on thousands of lines in the UV and extreme UV spectral regions.

Radiation pressure both initiates the flow, and sustains it. The work of Castor et al. has been extended and improved, most noticeably by the group in Munich (Pauldrach 1987, Pauldrach et al. 1987, 1994). The accuracy of the best models is still subject to debate. From an analysis of 28 OB stars Lamers and Leitherer (1993) deduced that theoretical mass-loss rates were a factor of 2 lower than observed, and theoretical terminal velocities 40% higher. The discrepancies in the mass-loss rates were dominated by the supergiants — i.e., stars evolving towards the WN class.

For W-R stars the situation is unclear — present radiation driven wind models are incapable of generating the large observed mass-loss rates.

3.1. The W-R Momentum Problem

While the theory of radiative driven winds successfully explains the observed mass-loss rates for O stars it fails for W-R stars. In discussing radiation driven winds it is useful to define the ratio η by

$$\eta = \frac{\text{Wind momentum}}{\text{Radiation momentum}} = \frac{\dot{M}V_\infty}{L/c}$$

This number, termed the wind performance number by Springmann (1994), gives an indication of the efficiency at which radiation momentum is imparted to the gas. If momentum was imparted to the wind only by "single scattering" (i.e., by scattering of a photon in a single line) the limit on η is unity. If "multiple scattering" is important η can greatly exceed unity — the upper limit (which is well over 100) being set by energy considerations.

For O stars, $\eta < 1$, and the observed mass-loss rates can be explained by single scattering. Multiple scattering is a second order effect — it must be considered but it does not dramatically alter the O star mass-loss scale (Puls 1987).

For W-R stars, the observed performance numbers generally exceed unity, ranging to above 100 for some WC stars. Values as high as 50 for WNE stars are not uncommon. These values are, in principal, achievable by radiation driving **providing** there is sufficient wind opacity. In fact, Gayley et al. (1995) prefer to think of the problem as an opacity problem, rather than a momentum problem.

The momentum problem has been extensively discussed by Gayley et al. (1995) and Springmann (1994). From their analytical and Monte-Carlo simulations they deduce that the performance number is approximately the number of thick lines in a frequency interval $\nu V_\infty/c$ where V_∞ is the terminal velocity of the wind. Thus in a W-R star with $\eta = 50$ and $V_\infty = 2000\,\mathrm{km\,s^{-1}}$ there needs to be of order 17,000 optically thick lines per decade of frequency (in practice this density is only required in the spectral region where most of the flux is emitted). At present, existing line lists do not achieve this line density.

Several solutions to the high performance numbers in W-R stars have been proposed. None are entirely satisfactory.

Ionization effects: Observations of WN and WC stars, together with the assumption of an accelerating flow, suggest that the ionization of W-R winds decreases with increasing radius (Kuhi 1973, Schulte-Ladbeck et al. 1995). This has been confirmed by detailed modeling (Hillier 1987a, 1988, 1989). On this basis Lucy and Abbott (1993) investigated W-R winds, and found that performance numbers of 10 could be achieved when the ionization structure of the wind was allowed for. These models, while providing insights into radiation driving, do not alone solve the W-R momentum problem since the models are global (and hence not locally consistent), and do not achieve performance numbers of 100 exhibited by some W-R stars.

Missing opacity Eichler et al. (1995) note that it is possible that the Rosseland mean opacities used for stellar structure calculations are still too low. This applies even to the revised OPAL opacities (Iglesias et al. 1992). They note that even an increase of 20 to 30% can be important for the dynamical structure of W-R stars. Mechanisms suggested to increase the Rosseland mean opacities are additional line broadening, and inclusion of lines due to the less abundant iron group elements.

Missing wind opacity: In order to model W-R winds it is clear that the line list used to determine the radiative acceleration must be complete. The line lists have always been worse for W-R stars than O stars because of the higher effective temperatures. While the situation has improved, there is strong evidence that additional lines still need to be included. In particular, Schmutz (1995) noted in his WNE model that the OPAL opacities exceeded the model opacities by a factor of 2 in the inner regions of the wind, clearly indicating the absence of important driving lines. In the outer regions the opacities, as expected, exceed the OPAL opacities because of the presence of the velocity field.

Reducing the momentum problem: One way of solving the momentum problem is to reduce the mass loss rates of W-R stars, or to increase their luminosity. In either case the performance numbers would be reduced and radiation pressure would be more able to drive the flows. A reduction in the required performance numbers may be allowed given the present uncertainties with models of strong lined W-R stars.

1. The observed mass-loss rates could have been overestimated if, for example, clumping in the wind is important. Calculations by both Hillier (1991a), and Schmutz (1995) suggest that this could reduce the mass-loss rates, and hence the required performance numbers, by a factor of 2.

2. At present the luminosities are derived from modeling the theoretical spectra, and are basically determined by ionization ratios (e.g. He I to He II line strengths). Since most of the flux is emitted in the extreme UV, and hence cannot be directly measured, there is some concern about the validity of the models.

   The present generation of models ignore line blanketing in the extreme UV. The consequence of this assumption, particularly for the strong lined WNE and WC stars, is unknown. For LBVs, and the WN7-WN8 stars, the available evidence suggests that the neglect of blanketing is not significantly influencing the derived parameters (Schmutz 1991, Crowther et al. 1995a).

For the WNE and WC stars the models show inconsistencies in ionization ratios as compared with observation. These inconsistencies probably reflect the neglect of line blanketing (and possibly clumping). Given the large performance numbers exhibited by WNE and WC stars it is expected that line blanketing must be crucial to understanding the line formation.

Schmutz (1995) has also suggested that the luminosities are being incorrectly determined because of photon loss in the He II Lyα line. This photon loss is supposedly due to overlapping lines, possibly Fe. While this idea is very speculative, the sensitivity of the ionization structure to the continuous radiation field near the He II Lyα line is well documented (e.g., Hillier 1987a), and indicates the importance of performing accurate radiative transfer calculations between 350Å and the He II limit at 228Å.

Clumping also provides a means of increasing the derived luminosity. This occurs because the strengths of the He I lines show a stronger sensitivity to clumping than the He II lines. In the presence of clumping a higher luminosity is required to obtain the same He II/He I line ratios as in a nonclumped model. This effect is seen in the models of both Hillier (1991a), and Schmutz (1995).

If both of these effects — reduced mass-loss rates and higher luminosities — apply the required performance numbers may be reduced down to values less than 10. Since this is similar to the performance number achieved by the Lucy and Abbott (1993) model, radiation pressure would then be able to drive the winds.

Other mechanisms, such as pulsational instabilities (Glatzel et al. 1993), have also been proposed to explain the high mass-loss rates in W-R stars. For example, pulsations could help initiate the flow whilst radiation pressure would drive the flow to infinity (e.g., Langer et al 1994).

4. Uncertainties in Radiation Driven Wind Theory

Although radiation driven wind theory has been remarkably successful in explaining the observed wind properties of O stars, the current implementation of the theory, by necessity, makes many assumptions. These assumptions must limit the applicability of the present generation of models, and will necessitate future revisions. At what level these revisions will be important is unclear, and is undoubtedly dependent on the nature of the individual star, and its evolutionary state. They may hold the key to understanding W-R mass-loss rates.

Below we discuss several of the major uncertainties in the present generation of models. We do not consider uncertainties arising from the atomic models, and will not discuss the possible influence of magnetic fields.

4.1. Rotation

Rotation is generally ignored in O star studies, but at some level it must begin to influence our understanding of mass-loss rates and terminal velocities of O stars. It can affect the observed spectra, possibly invalidating parameters derived from standard analysis (i.e., those which include rotation only as a broadening agent). More importantly it will influence the dynamics of the wind.

Very recently a significant breakthrough in our understanding of radiation driven winds in the presence of rotation was achieved. Bjorkmann and Cassinelli (1993) showed that rotation leads naturally to an enhanced flow in the equatorial plane. This important result arose directly from the realization that once material leaves the surface of the star the only forces acting on the gas are radial (the inward gravitational force and the outward radiative force). Consequently the trajectory of the particle is confined to an orbital plane passing through the center of the star, and which is perpendicular to the momentum vector (which is conserved).

When the radial velocity is larger than the rotational velocity the particle will tend to move radially. In the reverse case, however, the particle trajectory will naturally loop toward the equatorial plane. The particle is prevented from passing through the plane, however, by interactions with the rest of the wind. Ram pressure confinement then leads to equatorial enhancement in density. The amount of enhancement is dependent on the speed of the velocity law, the ratio of the rotational velocity to the critical velocity (= escape velocity/$\sqrt{2}$), and the ratio of the winds terminal velocity to the escape velocity (Bjorkmann and Cassinelli 1993).

In B stars the radiation driving is inefficient, and the terminal velocity of the wind is close to both the rotation velocity and the critical velocity. In this case a large equatorial enhancement ($\sim<$ 100, Bjorkmann and Cassinelli 1993) is expected, and this provides a simple explanation for Be stars. Detailed numerical simulations by Owocki et al. (1994) show that the mechanism does lead to a significant enhanced flow along the equatorial plane. In reality the situation is complicated by the difficulty of solving for the correct radiative force, the presence of shocks resulting from material moving to the equatorial plane from either side, and the possible existence of material which falls back onto the star.

For O stars, on the other hand, the terminal velocity of the wind greatly exceeds the rotational velocity, and very little enhancement of the density in the equatorial plane is expected to occur. This explains why the standard theory works for O winds, even in the presence of rotation.

The situation for W-R stars is uncertain. First, rotation rates are unknown — there is no simple diagnostic that can be used to measure the rotation rates. Second, it is unclear what the shape of the velocity law is in W-R stars. The observed emission lines in W-R stars are primarily dependent on the velocity in the outer regions of the wind where $v > V_\infty/2$. If the velocity law is slow[1], which has been suggested by Koenigsberger (1990), rotation can have a significant influence on the wind structure even when the rotation velocity is significantly less than both the critical velocity, and the terminal velocity of the wind (Cassinelli et al. 1995). If rotation is important, then we would expect to see evidence for non-sphericity in either the line profile shapes, or by the presence of continuum and line polarization.

[1]The velocity law for an O star wind can generally be characterized by a law of the from $v(r) = V_\infty(1 - R_*/r)^\beta$. O stars have $\beta \approx 0.7$ (Groenewegen and Lamers 1989). Slow velocity laws have $\beta > 2$.

Observational evidence for/against a non-spherical atmosphere is ambiguous. First, the existence of flat-topped He I and C III line profiles in both WN and WC stars suggest that the winds are spherically symmetric (Castor 1970). At present, however, the degree of non-sphericity allowed by the observed profiles has not been determined. We also note that W-R stars, unlike Be stars, do not generally show double peaked profiles.

Recently some evidence has come forward that suggests that some of the He I profiles show hints of double peaked profiles (Underhill et al. 1990, Eenens and Williams 1994). These important observations need confirmation, with careful allowance made for blending and telluric features. In particular we note, based on fairly simple theoretical considerations, that the He I λ10830 and He I λ5876 profiles should show similar emission asymmetries, and thus simultaneous observations of both lines would help alleviate problems with blending and telluric absorption.

Polarization, at least in principal, provides an unambiguous test for sphericity; if a star shows intrinsic (i.e. not interstellar) polarization it can't be spherically symmetric. Unfortunately the asymmetry could arise from the presence of a companion star. In several, supposedly single, W-R stars intrinsic polarization has been detected (St.-Louis et al. 1987, Drissen et al. 1987) providing unambiguous evidence for asymmetric winds.

In general the polarization is highly variable, and often indicates that the system has no axis of symmetry. One way to interpret the available data is to assume that the winds, while globally spherically symmetric, contain inhomogeneities whose size and location in the wind vary almost randomly (Robert et al. 1989). For WR6 (HD 50896) and WR134 (HD191765) the available data does allow flattened winds (Schulte-Ladbeck et al. 1990, 1991, 1992) but even in these cases the intrinsic polarization variability, particularly for WR6, confuses the analyses.

For several single WC stars intrinsic polarization is not detected (St.-Louis et al. 1987), and together with the line profiles this can be used to constrain the geometry of the outflow (Hillier and Schulte-Ladbeck, in preparation).

4.2. Variability and Clumping

Radiation driven winds are inherently unstable (e.g., Owocki and Rybicki 1984). Detailed 1-D numerical simulation of time dependent radiation driven winds have been performed by Owocki (Owocki et al. 1988, Owocki 1994), and most recently by Feldmeier (1995). These simulations suggest that most of the mass loss in O star winds occurs in dense shells (e.g., Owocki et al. 1988, Feldmeier 1995). Presumably in more realistic 3-D studies these shells would be fractured on a scale yet to be determined. It should be noted that radiation driven wind theory, in the absence of rotation, predicts radial clumping only.

The simulations also reveal an incredibly complex wind structure containing dense clumps, strongly rarified regions, and hot shocked gas. This shocked material will give rise to X-ray emission and extreme UV emission which can influence the ionization structure of the winds (Cassinelli and Olson 1979), and consequently the dynamics.

Both O and W-R stars are known to be X-ray sources (e.g., Chelebowski et al. 1989, Pollock 1987). The radiation-driven wind instabilities provide a natural explanation for the source of X-rays in single stars, and at least qualitatively, can explain the observed X-ray spectrum of the best studied O star, ζ Pup (Hillier et al. 1993).

Observationally, variability in O and W-R stars is well documented. In O stars, for example, narrow absorption components (called discrete absorption components or DACs) are seen in the unsaturated absorption components of UV P Cygni profiles (e.g. Lamers 1994, Kaper and Henrichs 1994). These shift in velocity (towards the blue), and alter in strength. While many ideas have been postulated, a convincing explanation for the behavior of these narrow components has not yet been provided (but see Owocki and Fullerton 1994).

In addition to the DACs, the maximum velocity of the wind, as determined from the variability of the absorption profile, varies erratically in both O and W-R stars (e.g., Kaper and Henrichs 1994). This, at least qualitatively, can be explained by the inherent instability of the wind.

In W-R stars low level variability (amplitude $< 10\%$) in the emission profiles is seen (e.g., Robert 1994). In many stars this variability reveals itself as small amplitude fluctuations, which move away from line center over time, on the top of emission profiles. They are generally interpreted as inhomogeneities (clumps) in the wind. Like O stars, W-R stars also show variation of the absorption components of P Cygni profiles.

In addition to profile variability, evidence for clumping in W-R winds comes from an analysis of electron scattering wings in W-R stars. W-R profiles (e.g. He II 5411Å) show a red wing which is due to electron scattering (Hillier 1984, 1991a). Models, however, predict a wing a factor of 2 stronger than observed. This can be explained if the wind is clumped since most diagnostics of W-R mass-loss rates are sensitive to the mean square density, whereas the strength of the electron scattering wing is sensitive to the mean density. Thus a clumped wind can explain the observed W-R spectrum but with a reduced mass-loss relative to a smooth homogeneous wind. A reduction in observed mass-loss rates would dramatically alter models of the evolution of massive stars.

5. Non-LTE Line Blanketing

It is clear from the above discussion that many problems remain with our understanding of both O and W-R winds. Many of these problems could be clarified if we had sophisticated codes capable of handling the non-LTE line blanketing.

Recent advances in computing power and computational techniques have led to several groups investing a large effort into including non-LTE line blanketing into both plane-parallel static atmospheres (e.g., Anderson 1991, Dreizler and Werner 1993, Hubeny and Lanz 1995) and spherical atmospheres with velocity fields (e.g., Hauschildt 1993). We have also begun a program to incorporate non-LTE line blanketing into our code. As a first step we have included blanketing due to H, He, the CNO elements, and Fe.

The non-LTE code is extensively discussed by Hillier (1987a, 1990, 1991b). The code solves the radiative transfer equation for stars with spherically extended flows using either the Sobolev approximation, or the full solution of the comoving-frame radiative transfer equation. To facilitate the simultaneous solution of the radiative transfer equations and the statistical equilibrium equations a partial linearization method is used. Although the formulation is different the method is closely related to procedures which use approximate lambda operators, and has similar convergence properties.

In order to include non-LTE line blanketing several assumptions need to be made. Our approach has been driven primarily by our desire to include as many lines as possible, in order to fully recover the effects of line blanketing, but with the need to minimize the number of levels whose populations must be explicitly solved for. The key ingredients of our approach are listed below, and will be discussed more fully by Hillier and Miller (in preparation).

1. Radiative transfer in the lines is treated "exactly". Exactly in this context means that no opacity redistribution or sampling techniques are used. We still make the usual assumption, for example, of complete redistribution in the line. At present we also use a Doppler profile, but this can be easily modified.

2. The model atoms are simplified using the idea of "super levels" first pioneered by Anderson (1989, 1991). This technique has also been used with great success by Hubeny and Lanz (1995), and Dreizler and Werner (1993).

   In this approach, levels with similar energies and properties are treated as a single level. Only the populations of the super levels are solved for in the rate equations. The population of an atomic level in the real model atom can be found assuming that it has the same departure coefficient as the corresponding super level.

3. Level dissolution using a technique similar to that of Hubeny et al. (1994) is utilized.

The beauty of treating the lines exactly, and using super levels, is that it recovers LTE radiative transfer at depth. Another advantage is flexibility. In our approach the number of super levels, and their links to the real atomic levels, is easily modified. This allows flexibility in testing the accuracy associated with different super-level assignments.

In order to illustrate progress in our blanketing calculations we will make some comparison with recent HST observations of WC stars in the LMC.

5.1. HST Observations of WC stars in the LMC

In collaboration with Hamann, Koesterke, Krudritzki, Lennon, and Butler we have undertaken a project to obtain HST spectra of 1 WO and 6 WC stars in the LMC. The WC stars are all of spectral type WC4, and were chosen on the basis that they were not known to be binaries.

Spectra for the six WC stars have been obtained, and an analysis is in progress. A comparison of a model calculation with the UV spectrum of HD 37026 is shown in Fig.1. The gross characteristics of the spectra are in agreement, although individual line strength differ between theory and observation, typically by a factor of 2. This is not surprising since the model is *not* a fit, and the models themselves are still under extensive development.

While our models are very preliminary they do indicate several important points regarding the analyses of LMC WC4 stars:

1. The continuum in both the UV and optical is probably not seen anywhere. This is best illustrated by Fig. 2 where we show the synthetic spectrum, and the continuum (computed using the same model but ignoring all line transitions). Even in these models, which still lack many lines, do not show dielectronic transitions, and are neglecting all multiplet structures, the continuum is almost completely masked by lines.

2. The WC spectra are insensitive to the O abundance. The best region for deducing the O abundance appears to be in the spectral region 3000 to 3500Å.

The new blanketed models also allow the influence of level dissolution and line blending in high series members (particularly He II) to be examined. These effects create a pseudo continuum in the neighborhood of important jumps (e.g. Balmer jump at 3650Å), as illustrated in Fig. 3 by a model appropriate to a WNE star.

Several improvements, outlined below, are still being made to our blanketed models:

1. Inclusion of multiplet structure for the CNO elements. This will double the number of C lines included in the code and will allow better computation of synthetic spectra.

2. Inclusion of lines due to Ni, and higher lines in Fe. This will increase the blanketing in the UV and will allow us to better determine fundamental stellar parameters. As noted, for example, by Kurucz (1991) and Schmutz et al. (1990) individual lines in line blanketing calculations are generally unimportant — rather it is the number of lines that will determine the overall influence of the lines on the spectrum and on the wind structure. The importance of including as many lines as possible has been beautifully illustrated by Hauschildt (1994) for nova models.

It is clear that the inclusion of non-LTE line blanketing, and the ability to compute full synthetic spectra, should allow greatly improved analysis of WR and O stars, and hence the derivation of reliable stellar parameters. More importantly, it will allow a sound framework to investigate the importance of clumping, rotation, and variability, and hence further our knowledge of O and W-R stellar winds.

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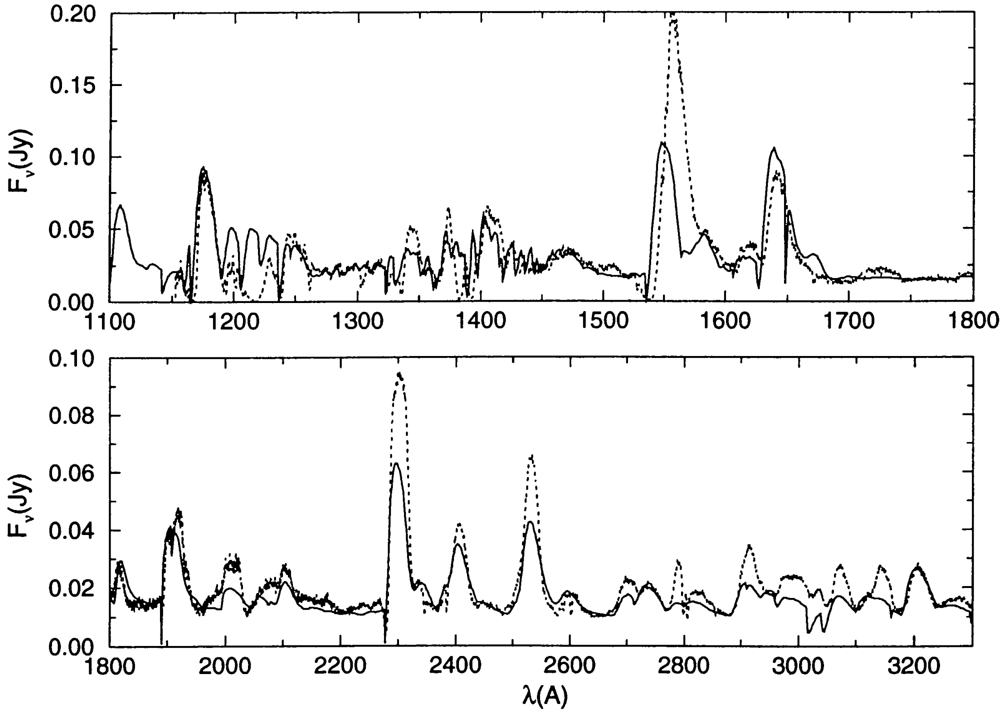

Figure 1. Comparison of a model spectrum (solid line) with HST observations of the WC4 star HD 37026.

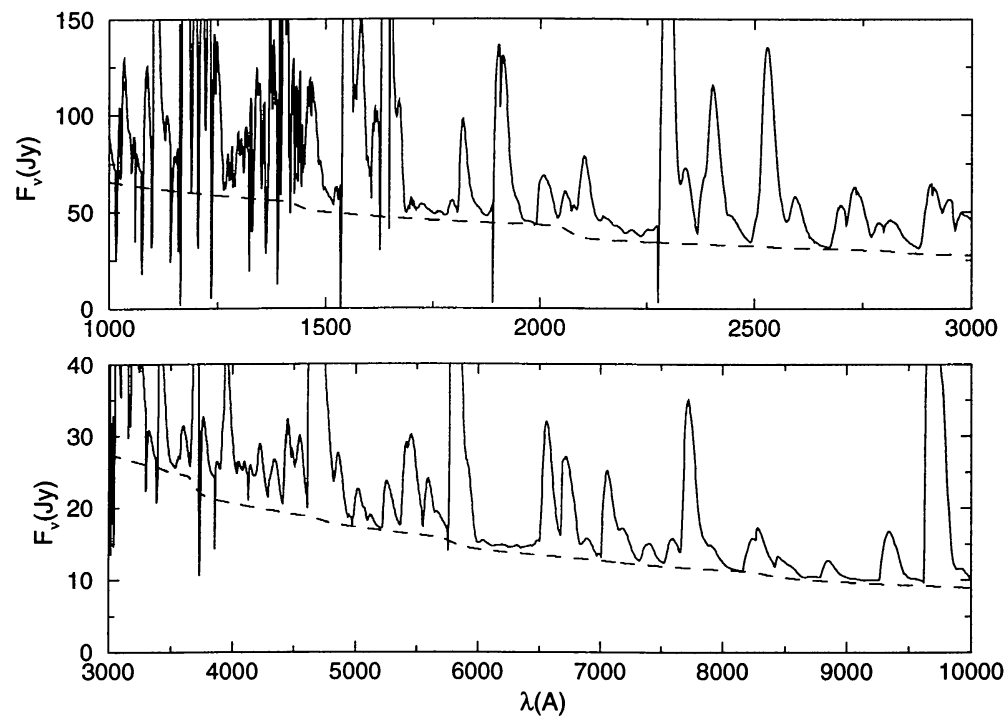

Figure 2. Illustration of the masking of the continuum by emission lines in a WC4-type spectrum.

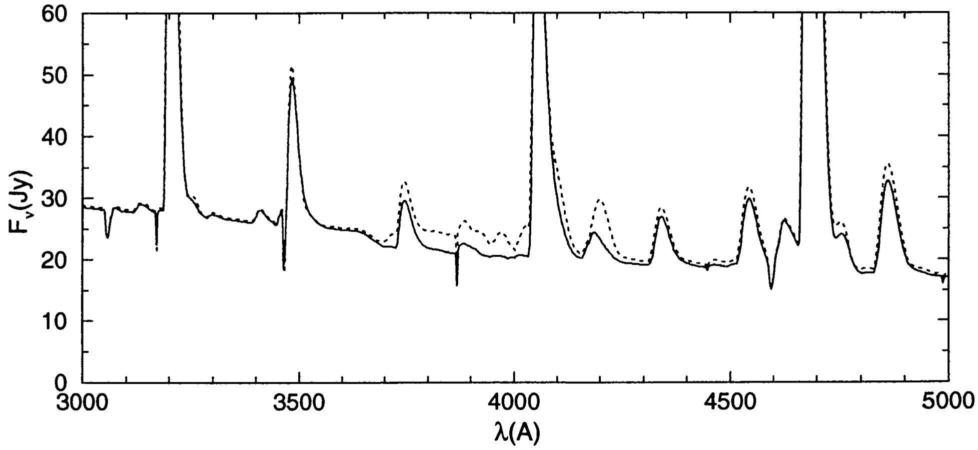

Figure 3. Illustration of the blending of high series members in a WNE-type spectrum. The solid line is for a model with 10 He II levels; the dashed line for a model with 30 He II levels.

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