Near-IR Diagnostics and Tests of Blanketing in Early-Type Stars

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Abstract. We evaluate near-IR diagnostics for the determination of stellar properties of late-Of supergiants and WNL stars. Parameters derived from CTIO and UKIRT infrared observations show good agreement with previous optical analyses, providing data are of sufficient spectral resolution and signal-to-noise. He I 1.083μm provides an excellent wind-velocity indicator, He II 1.012μm and 3.091μm temperature diagnostics, and He I 2.058μm is very sensitive to the extreme-ultraviolet energy distribution. We also discuss the role played by H II regions in probing the Lyman continuum of hot stars, where line blanketing by heavy elements plays an important part. We illustrate this for 209 BAC (WN8), for which a line-blanketed flux distribution provides improved agreement with nebular observations relative to previous unblanketed models.

1. Introduction

Although hot, luminous stars emit the majority of their energy in the ultraviolet, the interstellar medium (ISM) conspires to prevent this energy from reaching the Earth's atmosphere. Interstellar dust severely degrades transmitted fluxes at ultraviolet and optical wavelengths, while the Lyman continuum of hot stars is completely absorbed by intervening hydrogen atoms for all but a few nearby B stars.

Here we will discuss the suitability of observations in the near IR (1–5μm) for quantitative spectroscopic analysis of early-type stars. To date, Crowther & Smith (1996) have found that analyses based exclusively on near-IR diagnostics

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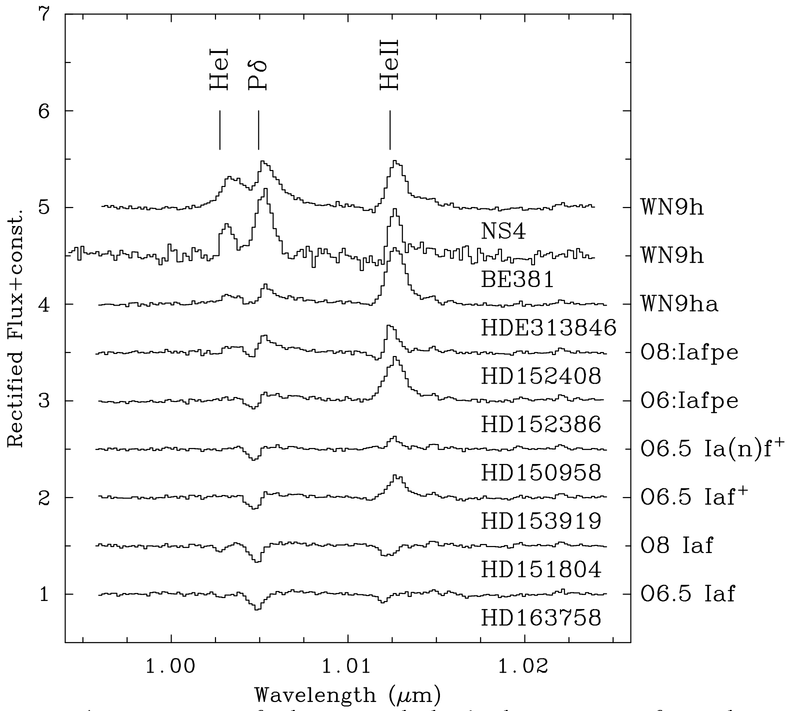

Figure 1. A montage of the morphological sequence from late-O supergiants to WNL stars around 1μm (CTIO–IRS observations).

provide good agreement with UV/optical studies for hot, early WN-type stars. Najarro et al. (1998) investigate constraints on early-type stars from mid-IR (Infrared Space Observatory) observations. Bohannan & Crowther (1998) discuss our present results in greater depth. Detailed IR studies are timely since progress in instrumentation (e.g., adaptive optics) will soon allow improved IR spatial resolution relative to optical wavelengths, of application to crowded fields in external galaxies.

We also investigate tests of theoretical Lyman-continuum flux distributions using H II regions associated with early-type stars. Substantial progress has recently been made in incorporating heavy-element line blanketing in hot stars, with importance in extreme-ultraviolet (EUV) energy distributions. Recent results for O stars incorporating non-LTE effects result in improved agreement with observations of associated H II regions (e.g., Stasińska & Schaerer 1997). For WR stars, Esteban et al. (1993) identified significant discrepancies between non-LTE model fluxes and WNL ring nebulae, attributing discrepancies to the neglect of line blanketing. Here we investigate whether new blanketed models for WR stars (Hillier & Miller 1997) allow us to resolve these inconsistencies (for a detailed discussion see Crowther et al. 1998).

2. Observations

Near-IR spectroscopic observations of several late-O supergiants and WNL stars were obtained during 1996 at the 4-m Blanco Telescope at Cerro Tololo Inter-

American Observatory (CTIO) using the Infrared Spectrometer (IRS), and at the 3.8-m UK Infrared Telescope (UKIRT) using the Cooled Grating Spectrograph (CGS4). These new datasets provide spectral resolutions of approximately $100\,\mathrm{km\,s^{-1}}$ – significantly greater than previous near-IR observations of early-type supergiants – allowing us to discern critical spectral features and to enable accurate determination of stellar parameters. In Fig. 1 we illustrate the morphological sequence from normal Of stars to WNL stars around He II 1.0124μm, with (photospheric) absorption features switching to (wind) emission.

We have identified near-IR counterparts to the usual optical spectral diagnostics for Of and WNL stars. Emission strengths of hydrogen (Hα, Brγ), He I ($\lambda\lambda$5876Å, 1.0830μm), and He II ($\lambda\lambda$4686Å, 1.0124μm) are closely correlated. In addition, He II 2.1885μm (10–7) shows an identical morphology to He II 5412Å (7–4), indicating that for late Of stars these lines are formed in identical regions in the stellar atmosphere (contrast with early Of stars; Conti et al. 1995).

The spectral resolution and signal-to-noise of our observations allow line blends to be distinguished, particularly those involving important metal transitions of carbon and nitrogen. For example, the 2.11-μm emission feature observed in Of and WNL stars has been assumed to be formed principally by He I $4s$–$3p$, with N III 8–7 providing a minor contribution (Hillier 1985). This prediction is confirmed in our high-signal-to-noise UKIRT observations of HDE 313846 (WN9ha) which reveal a double-peaked profile, with components at 2.113μm (He I 2.113μm) and 2.115μm (N III 2.1149μm). Further, HDE 313846 also shows weak C IV $3p\,^2\mathrm{P}^\circ$–$3d\,^2\mathrm{D}$ emission at 2.069μm and 2.078μm, while these features are absent in NS4 (WN9h). An identical behaviour is observed for the optical C IV doublet at $\lambda\lambda$5801–5812Å.

The terminal wind velocity of O-type stars is most accurately determined from the blueward edge of the absorption trough in the UV P-Cygni resonance profiles of C IV or Si IV (Prinja et al. 1990). Since no accurate wind-velocity diagnostic is available in the optical, the near IR is the obvious spectral region to use for heavily reddened O stars. In particular, He I 1.0830μm provides an accurate wind-velocity diagnostic for stars with extreme mass-loss rates since the lower level of this transition is metastable and is consequently formed in the outermost region of the wind. The superiority of this transition to He I 5876Å is well illustrated by HD 151804 (O8 If). For this star P-Cygni absorption for λ5876Å reaches $\sim$95% of the local continuum at only $\sim$400 $\mathrm{km\,s^{-1}}$, in contrast to $\sim$1300 $\mathrm{km\,s^{-1}}$ at 1.0830μm, in good agreement with 1445 $\mathrm{km\,s^{-1}}$ derived from UV resonance-line measurements (Prinja et al. 1990).

3. Analysis

The theoretical model atmosphere used in our spectroscopic analysis is that of Hillier (1987, 1990), an iterative technique which solves the transfer equation in the comoving frame subject to statistical and radiative equilibrium in an expanding, spherically-symmetric, homogeneous, and steady-state atmosphere. We perform two sets of calculations, one based on the usual UV/optical diagnostics (e.g., Crowther & Bohannan 1997), hereinafter Model V, the other based exclusively on near-IR lines (Model K). We shall focus here on model results for HD 152408 (O8: Iafpe) and NS4 (WN9h).

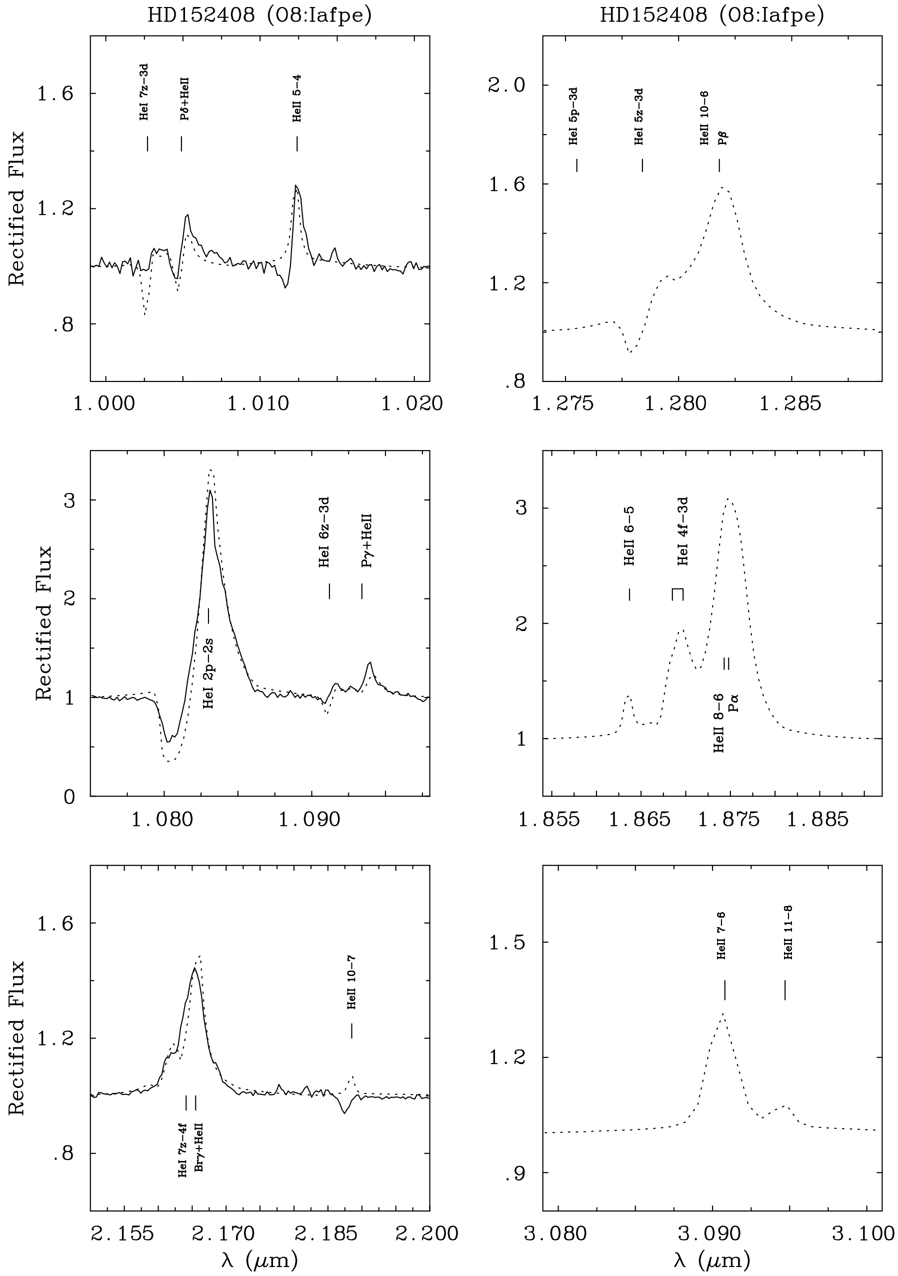

Figure 2. Synthetic fits (dotted lines, Model K) to near-IR CTIO–IRS spectra for HD 152408 (O8: Iafpe, solid lines). He II 3.09μm provides an important temperature diagnostic for WNL stars in heavily reddened environments since it is unblended and is much stronger than He II 2.1885μm. The Pβ synthetic profile is in excellent agreement with ESO–IRSPEC observations of HD 152408 by Najarro (1996, personal communication).

Table 1. Derived stellar parameters using near-IR (Model K) and optical (Model V) analyses for HD 152408 (O8: Iafpe) and NS4 (WN9h).

Star	Model	T_* (kK)	R_* ($R_\odot$)	log L ($L_\odot$)	log $\dot{M}$ ($M_\odot$ yr^{-1})	v_∞ km s^{-1}	H/He #	M_V
HD 152408	K	27.2	35.4	5.79	−4.60	915	1.6	−7.0
	V	28.5	32.4	5.80	−4.62	955	1.5	−7.0
NS4	K	29.5	22.8	5.55	−4.33	700	0.8	−6.3
	V	30.2	22.6	5.58	−4.35	700	1.0	−6.3

We summarize stellar parameters derived from our analyses in Table 1. Overall, Model K results are in good accord with those from Model V, except that slight revisions are necessary due to improved constraints on (assumed) velocity laws. In Fig. 2 selected near-IR synthetic profiles are compared with CTIO–IRS observations of HD 152408. Observed profiles are fairly well reproduced except for the precise He II 1.0124μm and He I 1.0830μm shapes, which result from the compromise velocity law. In addition, the observed He II 2.1885μm (10–7) *pure* absorption profile contrasts with the predicted *pure* emission feature.

Stellar temperatures are systematically lower when based on He II 10124Å instead of He II 4686Å, i.e., we are presently unable to fit all optical and IR spectroscopic features with a single model at one temperature. The discrepancy between observed optical and near-IR He II line strengths for WR stars was first remarked upon by Schmutz (1991). Atomic data cannot be at fault since good agreement was obtained by Crowther & Smith (1996) for WNE stars using identical techniques. Although this remains unresolved at present, a more realistic consideration of the ionization balance via line blanketing may improve the situation by modifying the relative population of the relevant He II levels.

Since ultraviolet and optical observations may be unavailable in some cases due to heavy reddening, we have compared interstellar-reddening estimates based exclusively on IR photometry with those derived from fitting theoretical continua to dereddened energy distributions over the entire UV to IR spectral range. Overall, we find that IR reddening estimates match true extinctions fairly well, with the exception of NS4 (WN9h) for which we obtained $E(B-V) = 2.14$ from $(J-K)$ photometry, which is somewhat lower than $E(B-V) = 2.40$ obtained from fits to the entire energy distribution. Consequently, its luminosity would be underestimated by ~0.1 dex relying exclusively on IR observations.

He I 2.0581μm provides a sensitive diagnostic of the EUV energy distribution of early-type stars (Najarro et al. 1994; Crowther et al. 1995a). The emission strength of this line depends crucially on the coupling of its upper level with the ground state via an alternative decay route at λ584Å. Although the branching ratio is $\sim 10^3$ in favour of the λ584Å transition, emission at 2.0581μm occurs if the optical thickness of λ584Å is sufficiently high. For HD 152408 we find that the temperature obtained from our Model V analysis reproduces the observed 2.0581-μm emission-line strength, while the slightly lower temperature required

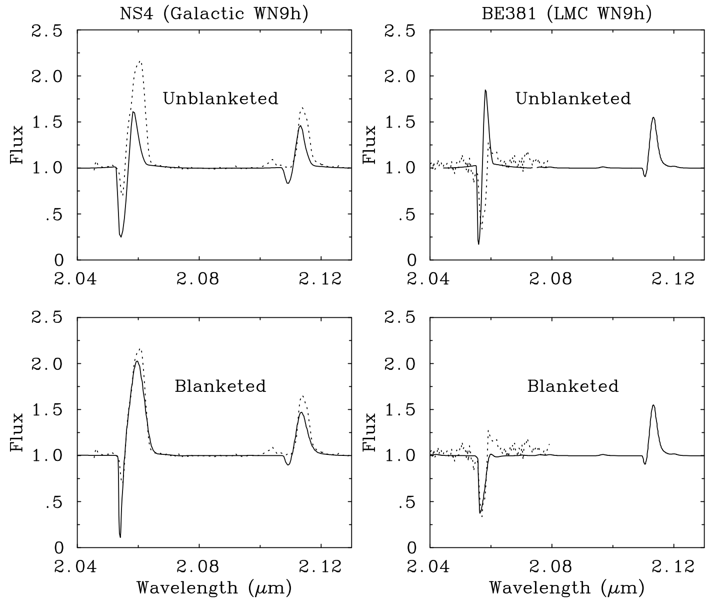

Figure 3. Line profiles (solid lines) calculated from blanketed model atmospheres reproduce He I 2.0581μm observations (dotted lines) for WN9h stars – NS4 in our Galaxy and BE381 in the LMC – where profiles from unblanketed models, assuming identical stellar parameters, were discrepant (Crowther et al. 1995a, Bohannan & Crowther 1998).

in Model K causes a sharp increase in the predicted emission strength. Initial calculations including metal blanketing lead to a significantly modified EUV energy distribution and so solve this discrepancy in our Model K results. This is further illustrated for the two WN9h stars NS4 (WR105) and BE381 (Brey 64). As their spectral classification suggests, these stars are almost identical in the optical and near IR. However, He I 2.0581μm is strongly in emission in NS4, with only weak emission observed in BE381. Line-blanketed calculations suggest that differences in the heavy-metal abundances between the two galaxies is sufficient to explain their observed appearances via differing EUV blanketing (see Fig. 3).

Several diagnostics employed here are located in the I and J bands, regions unavailable in extremely obscured environments. We can, however, suggest alternative diagnostics at longer wavelengths, such as He I 1.7002μm and He I 2.0581μm (if a strong P-Cygni profile is present) for wind-velocity measurements or Brα for H-abundance determinations. Of particular interest are suitable He II lines, since they provide reliable temperature indicators. For studies of He I sources at the Galactic centre (e.g., Najarro et al. 1997), He II 2.1885μm is generally weak or absent. Alternative, stronger He II features are located at 1.864μm (6–5) and He II 3.09μm (7–6) as illustrated in Fig. 2 for HD 152408. Unfortunately, the former lies very close to Pα and in a spectral region poorly accessible from ground-based telescopes. He II 3.09μm, despite its location in the thermal IR, does not suffer from significant blending and so may provide a crucial temperature diagnostic for late WN or Of stars within very heavily

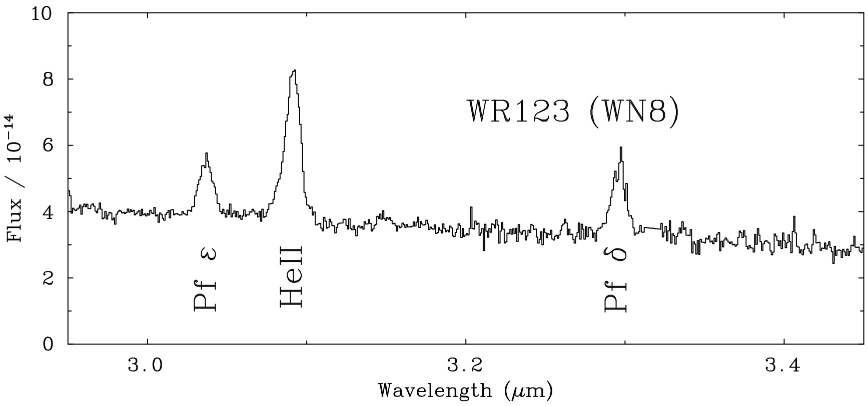

Figure 4. Ground-based UKIRT/CGS4 observations of HD 177230 (WR123, WN8) showing the prominent He II 3.09-μm emission feature.

reddened environments. This is illustrated in Fig. 4 showing (previously unpublished) UKIRT/CGS4 observations of HD 177230 (WR123, WN8).

Table 2. A comparison between observed nebular-flux ratios (Hβ=100) in M1–67 (Esteban et al. 1993) and those predicted by photoionization models of the central star 209 BAC (WN8), using both unblanketed and blanketed flux distributions with parameters (T_*=33kK, log $L/L_\odot$=5.4) obtained by Crowther et al. (1995b). Observed nebular abundances and densities (n_e=1050 cm^{-3}) are fed into calculations.

Line	Observed	Unblanketed	Blanketed
3727 [O II]	15	72	19
5007 [O III]	<1	123	0
5755 [N II]	1.0	5	1.3
5876 He I	2.0	30	0.1
6584 [N II]	313	384	335
6731 [S II]	16	6	8
9069 [S III]	12	59	20
S^{2+}/S^+	1.1	25	5
O^{2+}/O^+	<0.03	1.2	0.0
T_e(K)	6200	9400	6200

4. H II Regions as Probes of EUV Fluxes in Early-Type Stars

A major test for the current generation of model atmospheres for early-type stars is whether they are able to reproduce observed properties of associated H II regions. While recent results for O stars are encouraging (Stasińska & Schaerer 1997), Esteban et al. (1993) found inconsistencies between unblanketed non-LTE model fluxes for WNL stars and observations of their ring nebulae. In

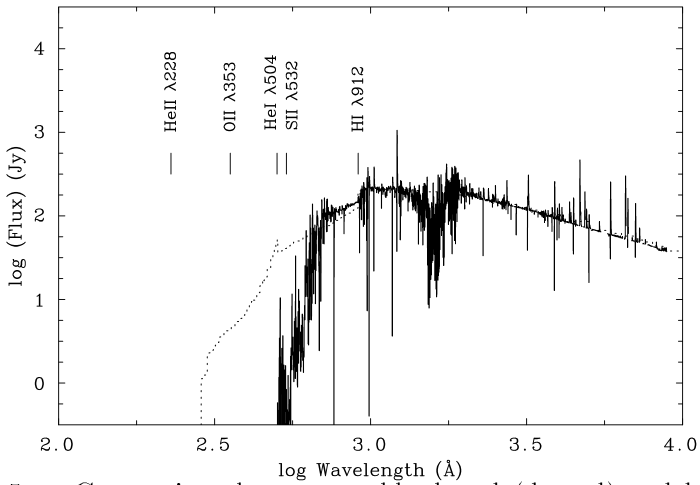

Figure 5. Comparison between unblanketed (dotted) and blanketed (solid) flux distributions for 209 BAC (WR124, WN8) using stellar parameters obtained by Crowther et al. (1995b), together with an indication of various important ionization edges.

particular, unblanketed models with $T_* \leq 30$kK were required to reproduce the low ionization observed in the nebula M1–67, while Crowther et al. (1995b) obtained a higher stellar temperature of $T_* = 33$kK from a detailed spectroscopic analysis of its central star 209 BAC (WR124, WN8).

We now follow Esteban et al. except that both unblanketed and Fe IV–VI blanketed model flux distributions at solar metallicity (Hillier & Miller 1997) are used as input into photoionization codes (Harrington et al. 1982). Theoretical flux distributions are compared in Fig. 5, demonstrating major differences in EUV flux distributions. While the ionizing fluxes in the Lyman continuum is barely affected in the blanketed model (decreasing from $\log (Q_0/\mathrm{s})$=48.9 to 48.8), that in the He I continuum ($\lambda \leq 504$Å) decreases by 10^3 (!) to $\log (Q_1/\mathrm{s})$=44.8.

In Table 2 we compare theoretical predictions with nebular observations of M1–67. It is clear that the unblanketed model fluxes poorly reproduce the observed nebular properties, such as the T_e and ionic ratios, while the line-blanketed flux provides good agreement with observed nebular quantities. In particular, the absence of nebular [O III] 5007Å and the low T_e are now reproduced. Differences in predicted [O III] 5007Å strengths can easily be understood since they depend on the flux shortward of the O^+ edge at 353Å (Fig. 5). Although some deficiencies remain, such as the sulphur ionic ratio and nebular He I line intensity (assuming a reasonable He abundance of He/H=0.2 by number), these results give us greater confidence in the validity of current Wolf-Rayet models, especially when models considering more complete blanketing become available in the near future.

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Discussion

Kudritzki: When considering emission-line strengths in nebulae around WRs, stellar models which include line blanketing fix some problems, but, as your Table 2 shows, still leave some helium lines in error by more than a factor of 10.
Crowther: Yes, that's a known problem... Linda, do you want to comment?
Smith: The electron temperature of a given nebula is known, and in some cases indicates that most of the helium is neutral and unobservable. The helium abundance then becomes a free parameter, and you can get agreement just by adjusting the abundance until the He I line intensities are correctly reproduced. This hasn't been done for the table that Paul showed.
Schmutz: Paul, in Bali I pointed out that there's always a problem with the 1.0124-μm He II line. Has this gone away, or is it still there?
Crowther: Still there. As you mentioned in Bali, it's not there for the very hot WNE stars, but it is for the cooler WN stars.
Gies: Alex Fullerton has shown that He I 5876Å shows huge variations in HD 152408. When you modelled that star, did you use just a single spectrum?
Crowther: 'Fraid so! We're trying to get more observations.
Owocki: Another TAC problem!