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Quantitative near-infrared spectral analysis of young OB stars

M. M. Hanson[1]†, J. Puls[2] and T. Repolust[2]

[1]Department of Physics, The University of Cincinnati, Cincinnati, OH 45221-0011, USA
email: hanson@physics.uc.edu

[2]Universitäts-Sternwarte München, Scheinerstr. 1, 81679 München, Germany

Abstract. We have recently obtained moderate resolution (R ∼ 8,000–12,000) high signal-to-noise *H*- and *K*-band spectroscopy of a number of optically visible, well studied OB stars (Hanson *et al.* 2005) to test the reliability of a pure near-infrared quantitative analysis (Repolust *et al.* 2005). The analysis of 25 of these OB stars via near-infrared spectra alone using the NLTE line-blanketed model atmosphere code FASTWIND (Puls *et al.* 2005) has proved successful at constraining stellar and wind parameters, consistent with results from previous optical analyses of these stars. This opens the door to quantitative analysis of OB stars at an extraordinarily young age, while they are still heavily enshrouded in their birth cocoons. Because the analysis requires good quality spectra at both *H* and *K* band, present 8-m class telescopes limit us to sources which are not extremely embedded ($A_V < 30$). As a first example, we present a preliminary analysis of the heavily reddened ($A_V = 25$), early-O star ionizing the UCHII region, G29.96-0.02. Challenges facing such an analysis include contributions from excess thermal emission from circumstellar material (disks, etc.) which weaken or even eliminate photospheric lines used in the analysis, nebular contamination in several of the principle H and He lines and crowding or general confusion in these very young and typically complex regions. Spectrographs coupled with state of the art adaptive optics will be extremely useful in minimizing these challenges, and may allow even fairly complex regions to be directly studied.

Keywords. infrared: stars, stars: early type, techniques: spectroscopic, atlases

1. Introduction

Lead by substantial progress in ground-based IR instrumentation in the 1980's and 1990's, IR spectroscopy has grown into an important technique for the study of hot stars and the stellar winds surrounding them. The first in depth studies of OB stars in the *H* and *K* band have been performed by e.g., Hanson *et al.* (1996), Morris *et al.* (1996) and Fullerton & Najarro (1998) providing a vital foundation for quantitative spectral analysis of hot stars. With the use of satellites (e.g., the Infrared Space Observatory (ISO) in 1995 and the Spitzer Space Telescope in 2003) a larger spectral window became accessible, completing the IR regime already observed from the ground. Numerous NIR atlases of OB stars have been published since that time (Wallace & Hinkle 1997, Lenorzer *et al.* 2002, for a recent review of all NIR spectral atlases, see Ivanov *et al.* 2004). The utility of a NIR spectral classification scheme, for hot stars in particular, has proved exceedingly useful for a variety of applications, not least of which includes the study of very young star forming regions and young stellar objects (YSOs, Bik *et al.* 2003).

In light of these successes, our group decided to push NIR spectral studies of OB stars to a new, more sophisticated level. Our goal was to obtain new, higher resolution and very high S/N NIR spectra of OB stars with well understood atmospheric parameters.

† Visiting astronomer, Subaru Observatory

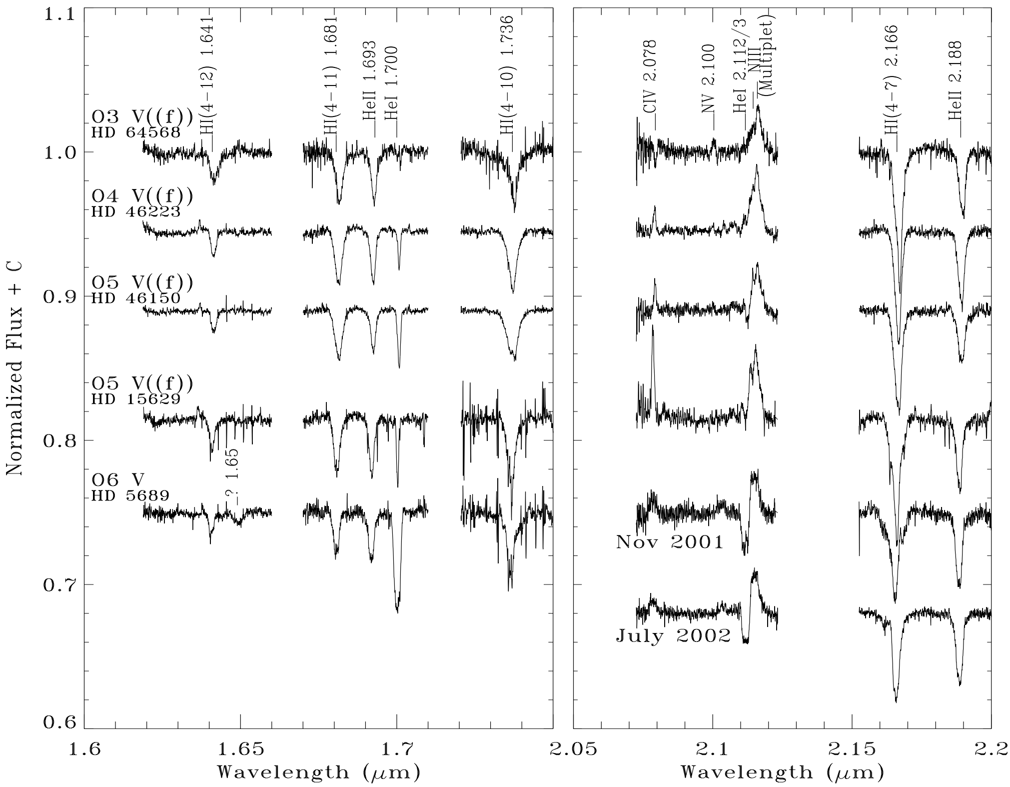

Figure 1. Here we present a subset of the atlas by Hanson *et al.* (2005), showing the early-O dwarf stars. Characteristic lines in this temperature range include strong HeII ($\lambda 1.692\mu$m, 2.188μm), and among the hottest O3, no HeI nor CIV emission (though possibly CIV absorption). All early-O dwarf stars show NIII or CIII emission at 2.115μm.

These standards would then be used to test and guide existing quantitative atmospheric models for OB stars in the NIR regime (Najarro *et al.* 1998; Kudritzki & Puls 2000 and references therein). In turn, once the atmospheric models are able to properly predict stellar characteristics based on the NIR spectra of known, UV- and optically-studied stars, the models may be used to provide accurate constraints to the characteristics of stars observable only in the NIR. The NIR atlas of well known, optically visible OB stars by Hanson *et al.* (2005) makes up the sample of high-quality spectra which are being used by our group for a successful NIR quantitative analysis (Repolust *et al.* 2005).

2. The Spectra

We obtained spectra of 29 standard OB stars (see Fig. 1) and one young massive object, G29.96-0.06*, at the 8.2-m Subaru Telescope, operated by the National Astronomical Observatory of Japan and located at the top of Mauna Kea in Hawaii. We employed the Infrared Camera and Spectrograph (IRCS, Tokunaga *et al.* 1998) installed at the Cassegrain focus. This set up provided a resolution of $R \approx 8,000$ at the H-band and $R \approx 12,000$ at the K band. We strove for very high S/N values, since these spectra were to be used for calibrating sources against the model profiles. Typically, we achieved S/N

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values exceeding 250. For more details on the reduction and to view the entire spectral atlas, see Hanson *et al.* (2005). In Fig. 1 we show just the early-O dwarfs, which are of greatest interest for those studying young massive objects and UCHII regions. The spectral atlas covers a much wider spectral range from O3 to B3 and includes most luminosity classes over that temperature range.

3. The Models

We carried out a spectral analysis for this sample of spectroscopic standards in the near infrared regime (by means of our NLTE, line-blanketed model atmosphere code FASTWIND, cf. Puls *et al.* 2005) and compared it with results already obtained in the optical for these stars. In the end, only the 25 hottest stars from the 29 stars observed could be analyzed, due to missing HeI2.05. In total, eight lines have been investigated, three from hydrogen, including Br_γ serving as a diagnostic tool to derive wind-densities, three HeI and two HeII lines. Apart from Br_γ HeI2.05 and HeII2.18, the other lines are predominately formed in the stellar photosphere, and thus remain fairly uncontaminated from more complex physical processes, particularly clumping.

4. Comparison between synthetic and observed spectra for OB standard stars

From the results of our analysis and in agreement with the predictions from our model grid, we find that an H/K-band analysis is actually able to derive constraints on the same set of stellar and wind parameters as it is known from the optical, e.g., T_{eff}, $\log g$, Y_{He} and optical depth invariant Q, where the latter yields the mass-loss rate $\dot{M}$ if stellar radius (from distance, observed and predicted H/K-band magnitudes and reddening) and terminal velocity are known. For future purposes, when no UV observations will be available, the terminal velocity v_∞ has to be taken from calibrations.

For cooler objects, when HeII is missing, a similar analysis might be possible if HeI2.05 is available (due to the almost orthogonal reaction of HeI2.05 and HeI2.11 on T_{eff} and $\log g$) and the helium content can be adopted, which should be possible for very young objects containing unprocessed material.

For most of our objects, we obtained good fits (see Fig. 2), though the line cores of Br_γ in early O-stars with significant mass-loss are discrepant. First note that this problem is not related to our particular models, since also the results from the alternative NLTE code CMFGEN (Hillier & Miller 1998) exhibit the same shortcoming: Whereas the observations show Br_γ mostly as rather symmetric emission lines, the models predict a P Cygni type line, with a comparably deep core which is never observed. Profiles of this type can be synthesized only if the *ratio* of departure coefficients for the involved levels ($\mathrm{n} = 4 \rightarrow 7$) deviates strongly from unity (cf. Puls *et al.* 1996), whereas a ratio close to unity would just give the observed symmetric emission profile. One might speculate that this is realized by nature due to a stronger influence of collisional bound-bound processes and might be possible in a strongly clumped *lower* wind medium, which has been suggested recently by Bouret *et al.* (2005).

After having derived the stellar and wind parameters from the IR, we have compared them to results from previous optical analyses, in an almost strictly differential way, since most of these results have been obtained also on the basis of FASTWIND (cf. Herrero *et al.* 2002, Repolust et al. 2004). Overall, the IR results coincide in most cases with the optical ones within the typical errors, i.e, an uncertainty in T_{eff} of 5%, in $\log g$ of 0.1 dex and in $\dot{M}$ of 0.2 dex, with lower errors at higher wind densities.

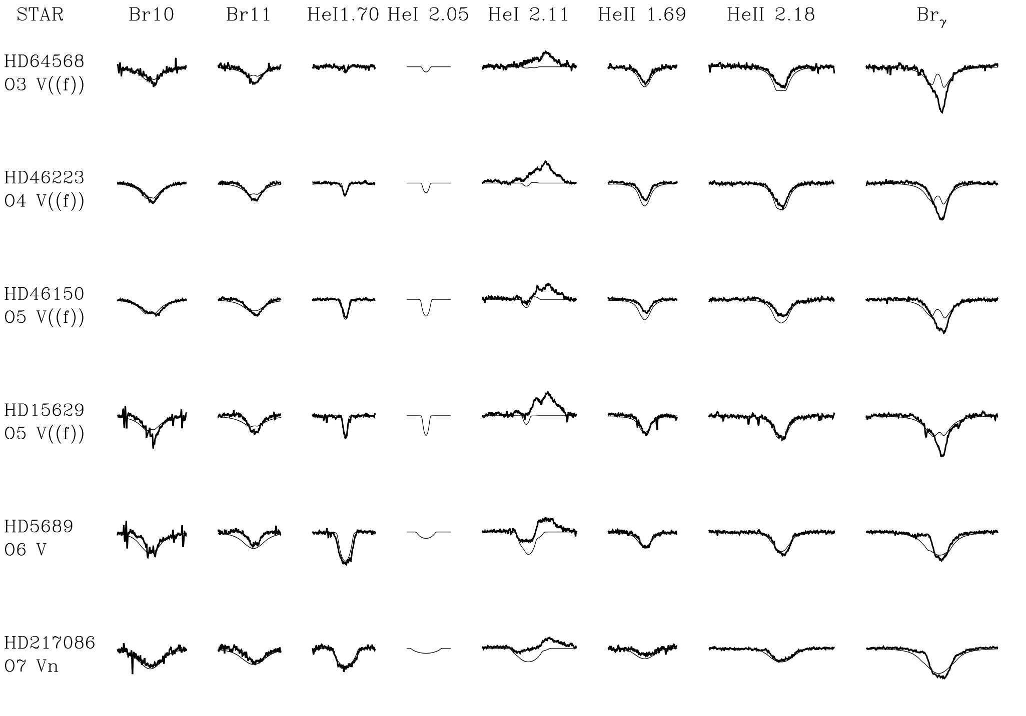

Figure 2. Line fits for hot dwarfs with spectral types ranging from O3 to O7. The HeI line at 2.11 includes contamination from an emission feature at 2.155 μm, thought to be either NIII or CIII, which is presently not included in our model profiles. The horizontal and vertical lines in the bottom right corner indicate the scale used and correspond to 0.01 microns in wavelength and 0.10 in units of the continuum, respectively. Note that the HeI2.05 line was not observed for these stars, though model predictions exist as shown.

In those cases when a star has an extremely weak wind and the core of Br_γ can be resolved (requiring a very low rotational speed), the central emission will give us a clue about the actual mass-loss rate and not only an upper limit, as is true for the optical. An example of this kind of diagnostics is τ Sco. Particularly with respect to recent investigations of young dwarfs with surprisingly weak winds (Martins *et al.* 2004 and these proceedings), this will turn out as an invaluable source of information (even more, if coupled with observations of Br_α, e.g. Najarro *et al.* 1998; **?**).

5. The central ionizing star of the UCHII G29.96−0.02

Having verified our quantitative methods on well known optically visible OB stars, we have turned our attention to deriving the physical characteristics of the central ionizing star of the well studied UCHII G29.96−0.02. The central star was first identified by Watson *et al.* (1997) and its early spectral type established using near-infrared spectral classification (Watson & Hanson 1997). However, more subtle characteristics of the star are not easily derived with just classification. Because the star is a rare example of an observable ionizing source to an UCHII region, the nature of its wind and the exact temperature of the star are important in understanding the evolution and lifetime of UCHII regions in general.

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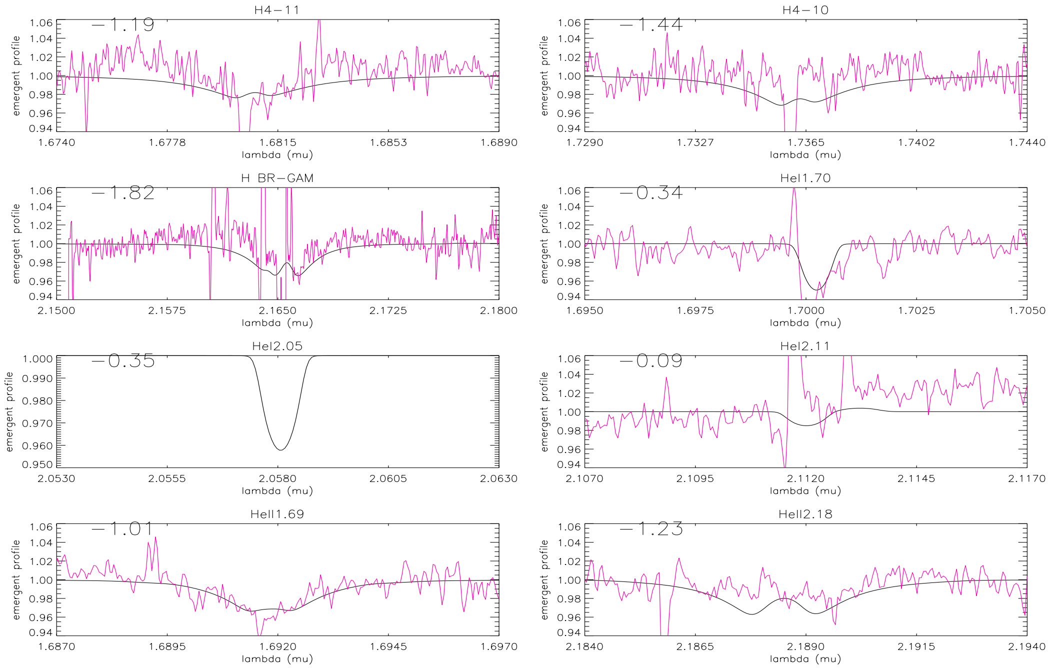

Figure 3. Spectra and synthetic profiles from our near-infrared spectral analysis of the central star ionizing G29.96-0.02. The profiles given are for $T_{\rm eff}$= 41,000 $\pm 2,000$K, $\log g$ = 3.8 ± 0.2 and $v\sin i$ = 80 km s^{-1}. The wind properties derived appear normal for a dwarf star of this spectral type. Assuming $R = 18R_\odot$ and v_∞= 2,200 km s^{-1}, we derive a mass loss rate of $\dot{M} \approx 2 \times 10^{-6} M_\odot$.

We have completed only a preliminary analysis, but already, the numbers are quite interesting (see Fig. 3). The S/N = 60 obtained was far from ideal, we much prefer to work with spectra with S/N > 100 and in fact, S/N > 150 would be best used. However, the mere presence and strength of several lines is highly constraining, particularly with regard to the effective temperature. What is perhaps most remarkable about the NIR spectrum of G29.96−0.02 is how common it is. Compared to the early-O-dwarf stars in the Rosette Nebula, HD 45223 (an O4 V) and HD 46150 (an O5 V) already analyzed (cf. Fig. 2), the G29.96-0.02 star shows absolutely nothing remarkably different from these two optically visible early-O stars. If the central star to G29.96−0.02 is really as young as its UCHII region size suggests (less than one million, and perhaps even less than 500,000 years), it indicates that early-O stars are remarkably quick to lose any signature of a disk or in-falling material and adjust themselves to the main sequence on a very short timescale.

6. Conclusions

Having finished our investigations, we are now able to constrain the observational requirements to perform a pure NIR analysis. Most important, one needs (very) high S/N because most of the lines to be investigated are extremely shallow (few percent of the continuum). Good resolution is also required, similar to the one used here, $R \approx 10,000$, though one may go as low as 5,000, provided the star is not a slow rotator. Because numerous lines are required to constrain the physical conditions, the H band is as critical as the K band in robust analysis. This will become problematic when obtaining high S/N in very high extinction sightlines, as the H-band flux will become quickly attenuated.

The value of a reliable quantitative analysis for hot, massive stars based entirely in the infrared cannot be overstated. Most obvious, it will allow the evaluation of massive star characteristics at an evolutionary stage significantly earlier than has ever been possible before. Circumstellar excess emission may render the photosphere of some very young massive stars inaccessible. Among the most massive stars, mid-O or hotter, we suspect the disk will be destroyed well before even near-infrared studies would be feasible due to the very short disk lifetime (Watson & Hanson 1997). Unfortunately, many of the strategic lines used in our NIR analysis are susceptible to strong nebular contamination, principally Br_γ, HeI2.11, and HeI2.05 (not shown here). High spectral resolution can allow at least part of the profile (see Br_γ in Fig. 3) to be recovered. When considering sightlines with strong nebular emission, high spectral and *spatial* resolution spectroscopy, via adaptive optics, will help to minimize this contamination.

An important challenge to a NIR quantitative analysis include the necessity of providing extremely accurate telluric corrections for ground based spectroscopic observations. While an observer may successfully obtain 10s of thousands of counts at the telescope consistent with very high S/N values, differences of half a percent in the continuum need to be understood and fully accounted for. This requires great care because the temporal variations seen in Earth telluric absorption bands are as great as several percent even in near perfect conditions. Finally, a robust understanding of the line behavior brought about by the extreme sensitivity of the NIR regime to subtle NLTE effects, as outlined, e.g., by Najarro *et al.* (1998) and Repolust et al. (2005) is needed.

A NIR quantitative analysis for OB stars can be applied to any OB star, embedded or not, for which line of sight extinction has made the star beyond reach in the optical. In fact, the volume of our Galaxy for which OB stars are now observable and can be quantitatively studied will grow by an order of magnitude or more when we extend our analysis to the NIR.

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