A Massive Star Odyssey, from Main Sequence to Supernova
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The stellar content of obscured compact H II regions

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Abstract. Near-infrared, spectroscopic studies of central ionizing sources of very young H II regions is presented in conjunction with a recently available, sophisticated atmospheric code to constrain the physical conditions and environment of very massive stars at very early stages of evolution. Combining high quality near-infrared spectroscopy of very young massive stars with model atmosphere calculations should allow for the most accurate quantitative determination of $T_{\rm eff}$, rotation, L, and $\log g$, and to search for binaries and possible disk or in-fall signatures in forming or recently formed massive stars. These characteristics make up a vital boundary condition constraining theories on massive star formation.

1. Background

The greatest stumbling block for developing a theory for the formation of massive stars is the lack of direct observations of massive stars at *very early* evolutionary stages. This is due to the very fast contraction time for massive stellar cores. While radio and millimeter observations can directly observe conditions of the collapsing material, only shorter wavelength observations, which become possible later in the formation of massive stars, are capable of directly detecting the star.

The very fast contraction time of massive stars sets up an immense radiation field early in the stars formation, and may reverse the in-fall of additional mass once the star reaches 10 - 20 $M_{\odot}$. This 'radiation pressure problem' is so severe, it has led some theorists to suggest that stars more massive than this cannot form from accretion alone, but instead form from collisions of intermediate-mass stars, which first formed through accretion (Bonnell, Bate & Zinnecker 1998). Our goal is to make observations capable of differentiating between these two current theories for massive star formation: accretion and coalescence. The

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earlier the phase of evolution we can directly observe, the better hope we have of detecting the short-lived characteristics unique to each star formation scenario.

2. Motivation for our program

Unfortunately, by the time a massive star can be observed in the optical, critical signatures present in the spectrum and environment of the star, which yield clues to the formation process, have disappeared. We must observe massive stars before their strong ionizing winds dissipate their accretion disks and outflows, before their stellar atmospheres erase chemical and physical evidence tracing their formation mechanism (due to mixing and spin-down from mass-losing winds), and before the central cluster disperses from destruction of the local molecular cloud. To investigate massive star formation, young massive star systems must be studied while they are still deeply embedded in an environment of gas and dust. The most important observations for this purpose are taken at near-infrared wavelengths because OB stars show few photospheric features at $\lambda > 2.2\,\mu$m. The H- and K-band spectral regions, from 1.5 - 2.2 μm, are thus the most effective wavelengths which can reasonably penetrate the shrouded environment of heavily embedded H II regions and allow us to derive the characteristics of massive stars at their earliest evolutionary phase.

The strategy of our work is to obtain high-quality near-infrared spectra of extremely young and heavily shrouded OB-stars, and to explore quantitative analyses capable of deriving the physical conditions of these very young massive stars while they are still heavily buried in their birth clouds.

Near-infrared imaging studies have identified numerous potential young OB stars, but only a few stars have been observed spectroscopically, and these studies have relied on a comparative analysis (Hanson *et al.* 1997; Watson & Hanson 1997). However, it should soon be possible to derive more accurate stellar characteristics as sophisticated atmospheric models extend their analysis to the near-infrared regime. These characteristics make up a vital boundary condition constraining theories on massive star formation.

3. The near-infrared imaging survey

To locate the rare and very young massive stars needed for our study, Lex Kaper, Fernando Comerón and myself completed a near-infrared imaging survey using the NTT-SOFIA. Our survey comes from a selection of radio and mid-infrared (*IRAS*) identified deeply embedded H II regions in the southern hemisphere. Nearly every field observed showed a star forming region of interest. Forty-five fields where observed in Brγ, H_2, and narrow-band J (1.25 μm) and K (2.2 μm). The nebular images are useful for locating regions of strong ionization (and hence, massive stars). The J- and K-band images are used to identify the stellar constituents in the H II region, and help us in identifying the OB stars contained. These central OB stars will be among the youngest of the most massive stars accessible to near-infrared study and analysis. Furthermore, our images give us a glimpse at the rarely measured, yet highly important, stellar density of very young OB clusters.

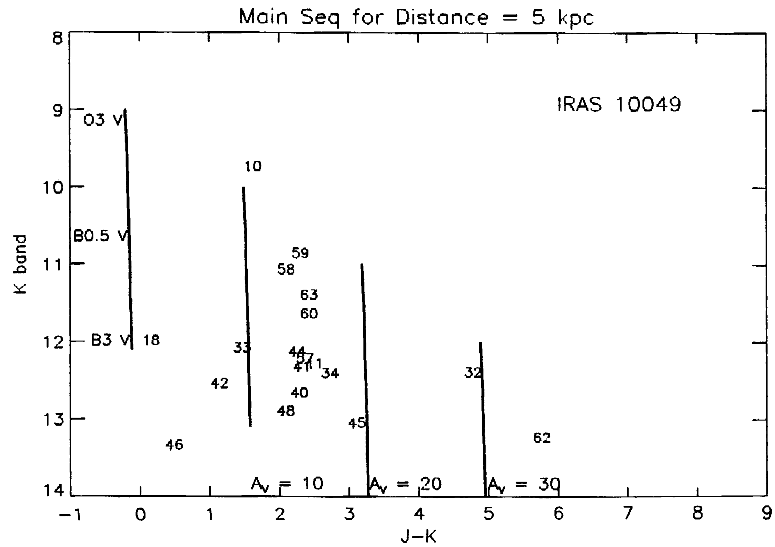

Figure 1. *J–K vs. K* color magnitude diagram of IRAS 10049–5857. The straight line on the left represents the location of the main sequence, without reddening, from O3 V to B3 V (we need to have a distance, but this is merely a guide). The effect of reddening is shown in the placement of the remaining lines, showing the location of the main sequence for $A_V = 10$, 20 and 30 mag. As is seen above, IRAS 10049–5857 shows a distinct main sequence with $A_V \simeq 15$ mag.

3.1. Color-magnitude diagrams

In Figure 1 is shown the color-magnitude (*J–K vs. K*) of the compact H II region IRAS 10049–5857. It shows a clear delineation of sources, lined up at $(J\text{–}K) = 2.0 - 2.5$ mag, indicating the detection of a main sequence behind approximately 15 mag of visible extinction. Not all compact clusters showed such a strong signal in their color-magnitude diagram, but along with morphological information from the nebular images taken of the field, we were able to make reasonable selections of the stars most likely to be the OB stars in field. These sources all became part of a follow up near-infrared spectroscopic study.

3.2. High-resolution near-infrared spectroscopy

Our group was granted time to use the VLT-ISAAC near-infrared spectrometer to obtain high resolution, high signal-to-noise spectra of the ionizing stars for the embedded H II regions. One such set of 2 μm spectra, for cluster IRAS 10049–5857, is shown in Figure 2. At the top is a spectrum of a spectral standard star for comparison. We were required to obtain spectral standards along with our target stars, since near-infrared spectroscopy of standard OB stars at $R \approx 8\,000$ does not exist.

While the spectra for IRAS 10049–5857 are a bit noisy, they show clear evidence of N III 2.1155 μm emission and weak absorption of He I 2.112/3 μm, consistent with an early O-type star. All together 45 compact clusters have been studied in this way and over 100 near-infrared spectra of central ionizing

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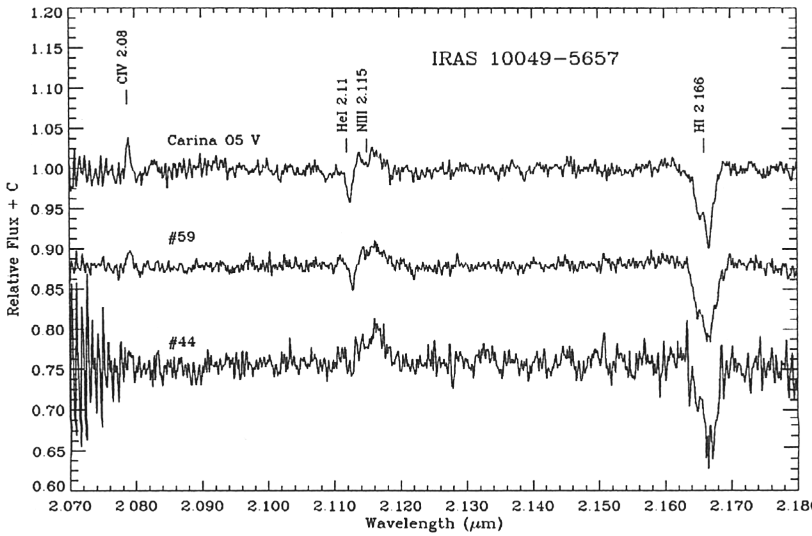

Figure 2. K-band spectra of two O-type stars in IRAS 10049–5857 uncovered in our survey. The top spectrum is a spectral standard, an O5 V in Carina.

stars have been obtained in the near-infrared at high spectral resolution. Not all stars observed showed spectral features consistent with OB stars. A few targets turned out to be foreground. Importantly, a large fraction showed emission features of Brγ and/or CO bandheads, usually without any absorption features, or the targets showed no features whatsoever! Possibly some of these spectra were without sufficient signal-to-noise to detect the weak atmospheric OB lines, but probably most of our featureless sources are likely veiled in the near-infrared from circumstellar material, consistent with the clusters being very young. Arjan Bik, working with Lex Kaper, is completing the reduction and analysis of these data, which will become a major portion of his PhD dissertation.

4. Near-infrared quantitative spectroscopic analyses

A critical component of our program is the concurrent development of sophisticated model atmospheres which can be used with our near-infrared spectra. Puls *et al.* (in preparation) are extending the non-LTE, Unified Model Atmosphere code of Santolaya-Rey, Puls & Herrero (1997) to include near-infrared line formation and the influence of metallic background continua. These models are spherically extended, and include the important effects of winds. They yield the entire sub- and supersonic atmosphere structure and are able to reproduce exactly (pseudo-) hydrostatic non-LTE atmospheres in the limit of very small mass-loss rates, as well as model atmospheres with intermediate to very strong winds.

4.1. Low-resolution spectra

The first step in the analysis is to constrain the stellar and wind conditions by measuring the equivalent widths (W_λ) of several strategic lines. These are

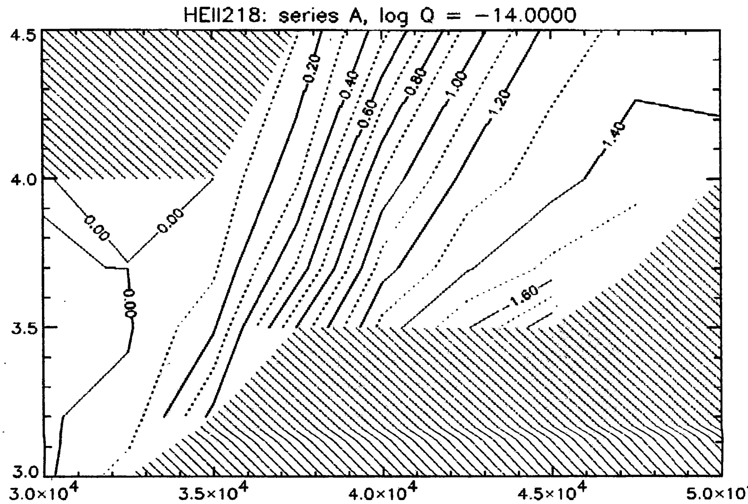

Figure 3. Plotted above are estimated equivalent widths of He II 2.1885 μm as a function of temperature and log g. The near vertical iso-contours of equivalent width indicate that the He II 2.1885 μm line is an excellent temperature indicator, and is not overly sensitive to changes in log g.

compared with model grids of W_λ which have already been calculated for over 500 stellar models, ranging in temperature, $\log g$, wind properties, *etc.* One such grid for the He II 2.1885 μm line is shown in Figure 3. This grid shows how well behaved the He II line is, giving a good estimate of $T_{\rm eff}$ over a fairly wide range of log g values. Likewise, the He I 2.112/3 μm line shows a very consistent measure of $T_{\rm eff}$ over a fairly wide range of $\log g$ values. Once $T_{\rm eff}$ is estimated, other parameters such as $\log g$ and wind properties can be constrained with other near-infrared lines which are equally sensitive to $T_{\rm eff}$.

There are a total of seven helium and hydrogen lines in the H- and K-band spectral regions from 1.6 - 2.2 μm. Our initial results suggest that *using* W_λ *measures alone*, we can usually make fairly good estimates for $T_{\rm eff}$, $\log g$, and some generalized property for the wind.

4.2. High-resolution spectra

Low resolution spectra can get us in the 'ball park', but in order to determine $v \sin i$, L, and more specific characteristics of the stellar wind, and to look for evidence of mass in-fall or circumstellar disks, profile fitting of the features will be necessary. The second phase of the quantitative analysis methods being developed by Puls and collaborators is that of line profile modeling performed on high-resolution ($R \approx 10\,000$) near-infrared spectra. We present here first results from such an analysis for one star, HD 134959, a B2 Ia star in Figure 4. Here the hydrogen series (Br11 1.16806 μm, Br10 1.7362 μm, and Brγ 2.1655 μm) and He I series (1.700 μm, 2.058 μm, and 2.112/3 μm) have been well fit. Some problems still exist in a handful of stars fitting wind-sensitive lines, such as Brγ and He I 2.058 μm. However, $v \sin i$, $\log g$, and $T_{\rm eff}$ have proven to be consistently well constrained via profile modeling.

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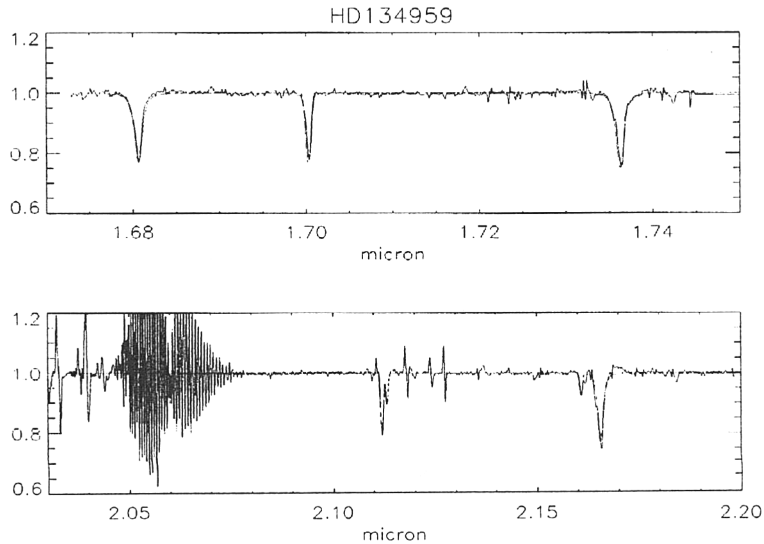

Figure 4. High resolution near-infrared spectra of HD 134959 (B2 Ia) using VLT-ISAAC. The very noisy region centered on 2.06 μm is due to poor telluric matches, but should be reduced with further work on these spectra. Overlayed on top of the observed spectra are theoretical fits obtained by the near-infrared models of Puls *et al.* (in preparation).

Presently, Rolf-Peter Kudritzki and I are completing a high resolution observing campaign using the Subaru Telescope and the IRCS near-infrared spectrometer. More than two dozen O- and early B-type stars covering the full range of luminosity classes will be observed at a resolution of 10 000 and with very high signal-to-noise at both H- and K-bands. This data set will make up a revised set of spectroscopic standards to supplement the lower resolution spectral standards presented in Hanson *et al.* (1996) and will be critical to the testing and implementation of near-infrared quantitative analysis of OB stars.

5. Conclusions

Simultaneously, we are obtaining high-quality spectra on very young massive stars at near-infrared wavelengths, while moving forward on the refinement of existing model atmospheres to be used in the analysis of these unique targets. However, it may be a little while before we can confidently apply quantitative analysis techniques to heavily embedded OB stars. We need first to determine the reliability of near-infrared methods applied to optically visible standard OB stars with a wide range of stellar properties. Such efforts are currently underway.

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Discussion

BLUM: You showed great progress in using higher-resolution K-band spectra in determining stellar parameters. Since most of this is done with equivalent widths, have you tried using the low-resolution spectra from your Atlas to reproduce the high-resolution results? Does it work?

HANSON: Well, we started the comparison of the model predictions using the low-resolution spectra. The high-resolution comparisons were just obtained in the last few months. We have not gone back to see that they are similar to the low-resolution results, but I suspect they will match. Mostly, we are comparing our results with those obtained using optical data of these same stars. But yes, most applications will not need high-resolution spectra. An important part of our work will be to determine what can and cannot be derived with low-resolution spectra and the confidence of those derivations.

LEX KAPER: Very nice talk! Given the small number of lines in the K-band spectrum, it is quite surprising and stimulating to see that both $\log g$ and $T_{\rm eff}$ can be determined with reasonable accuracy. How do you separate $\log g$ and $T_{\rm eff}$ effects using W_λ's?

HANSON: Yes. It was never apparent to me in looking at those spectra that $\log g$ could be derived. $T_{\rm eff}$ is rather obvious in how the helium live behave. However, there are subtle differences occurring in the K-band lines which is giving us information on g, specifically He I 2.112 μm, but also Brγ. The reliability of these measures needs to be investigated.

PULS: Just one comment. In order to derive the stellar parameters from those four lines, we usually have to assume the helium abundance.

HANSON: Yes. Very good. Thank you. I neglected to mention this in my talk.

ZINNECKER: Very nice stuff! I just like to add that we (Apai, Bik, Kaper, *et al.*) have just completed infrared spectroscopic observations at the VLT of some 20 young embedded massive stars to search for radial velocity variability (*i.e.*, tight binaries) using K-band lines. The result may bear on massive binary formation theories.

HANSON: Yes, terrific! Of course this is a very important measure.

NIEMELA: You have shown near-IR model analysis of supergiant stars. Do you expect to find supergiants among newborn stars?

HANSON: No, not at all. These stars were taken as a part of a program to study stars at the Galactic Center. However, to fully calibrate these new near-IR atmospheric models, we are modeling OB stars of all luminosity classes.