Near-Infrared Observations of Hot Stars, and Applications to Galactic H II Regions

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Abstract. We outline recent progress in the establishment and application of hot-star spectral classification through near-infrared (1–5μm) spectroscopy, and show how this new tool may be coupled with near-infrared photometry of Galactic H II regions to study the properties of these regions and their exciting stars (including application to Galactic structure). We also present some preliminary observations aimed at accomplishing these goals.

1. Introduction

Massive stars, those spectroscopically identified as hot O-type, are mostly born within giant molecular clouds (GMCs), regions that contain substantial concentrations of interstellar gas and dust. The large *optical* extinction of the dust in the clouds and (in our Galaxy) along the lines of sight to these objects has often precluded *visual* observation. The dust and gas ionized by hot stars can be studied in infrared (IR) and radio wavelengths (μm–cm), where the extinction is small or zero. The properties of the local environment are used to infer the numbers and types of hot, massive (and luminous) stars contained within the GMC. Soon after the massive stars are born (the exact timescale is still uncertain), their intense radiation fields and stellar winds dissociate and blow away the dust and molecular gas out of which they were born. At this point they become visible optically, and as such have been the subject of much work in the previous decades (see Maeder & Conti 1994 for a recent review).

New advances in astronomical instrumentation in near-infrared (NIR) wavelengths (1–5μm), where the dust extinction is only a fraction of that in the optical, has now opened the door to direct observation of the massive stars in their birthplaces. Radiation from hot stars is, of course, over a hundred times fainter in the K band (2.2μm) than in the blue band where classification is normally made. Hot stars in our Galaxy are typically confined to the plane where the dust absorption dominates, but the extinction in K is small, $A_K \simeq 0.1 \times A_V$. Given practical considerations of instrumental efficiencies and elimination of sky noise, once the A_V is more than $7^{\rm m}$, observations at K are more efficient than in the blue. Absorption features due to Brγ, He I, and He II transitions, and emission lines from C IV and N III, have been identified. Spectral classification in the K band utilizes the line ratios of the 2.113μm He I and 2.189μm He II lines (analogous to 4471Å He I and 4541Å He II used by Conti & Alschuler 1971) for the quantitative classification of O stars. The Brγ (7–4) line is found in absorption in most OB stars and plays a role as a luminosity indicator. The absorption lines behave in a relatively smooth fashion along the O to early B-type spectral sequences, thus laying the foundation for a classification in this wavelength band.

Hanson (1995) and Hanson, Conti & Rieke (1996) obtained *high-quality* K-band spectra for over 180 hot stars of all OB-type luminosity classes. These data, at very high signal-to-noise (S/N), detect absorption lines down to 1–2% of the continuum (this is, in many cases, better than published optical spectra of the same stars!). This Atlas will form the basis for subsequent classification of hot stars in the K band.

Once the hot stars are present, they ionize the nearby interstellar medium, producing an H II region. These objects are nearly entirely found in the Galactic plane and our optical view of all but the nearest is obscured by dust absorption in and along the line of sight. The overarching motivation for this work is to identify the hot stars in H II regions in our Galaxy (those that are otherwise optically obscured) through NIR photometry and follow-up NIR spectroscopy of suitable candidates. With spectral types in hand, we will then be able to connect the stellar census with the properties of the H II region. Obtaining spectra in a sample of such H II regions will also allow us to probe Galactic structure accurately.

2. The Stars of M17

2.1. K-Band Spectroscopy

Hanson, Howarth & Conti (1997) have obtained K-band spectra of twenty-eight of the brightest stars in the star-forming H II region M17. Ten stars showed the 2.3μm CO bands in *absorption,* suggesting they are late-type stars. These objects are likely foreground or background stars seen along the line of sight to M17. Eight O-type stars were identified within M17, seven of which are ‘early’ type from comparison to our Atlas spectra; two B-type stars were found. Figure 1 shows spectra of ‘normal’ O stars and several of those detected in M17, indicating the procedure. The O stars identified fully account for the radio recombination-line spectrum (of the H II region of M17).

Finally, nine other stars showed *no* photospheric features at all in the K band but five of them showed the 2.3μm CO-band *emission,* a feature seen in a number of Young Stellar Objects (YSOs). Examples are shown in Fig. 2. It is suspected that these stars all have dusty disks surrounding them, as the observed spectral-energy distributions (SEDs) showed a ‘bump’ near 2μm, corresponding to excess emission from warm dust near to the star (Hanson et al. 1997). This dust emission would dilute the weak stellar absorption features in the K band. The luminosities of these stars in M17 are such that they would nominally be late-O or B type. Several of these YSO candidates were bright enough to obtain spectra at shorter wavelengths, although one is then dealing with ever increasing interstellar dust *extinction.*

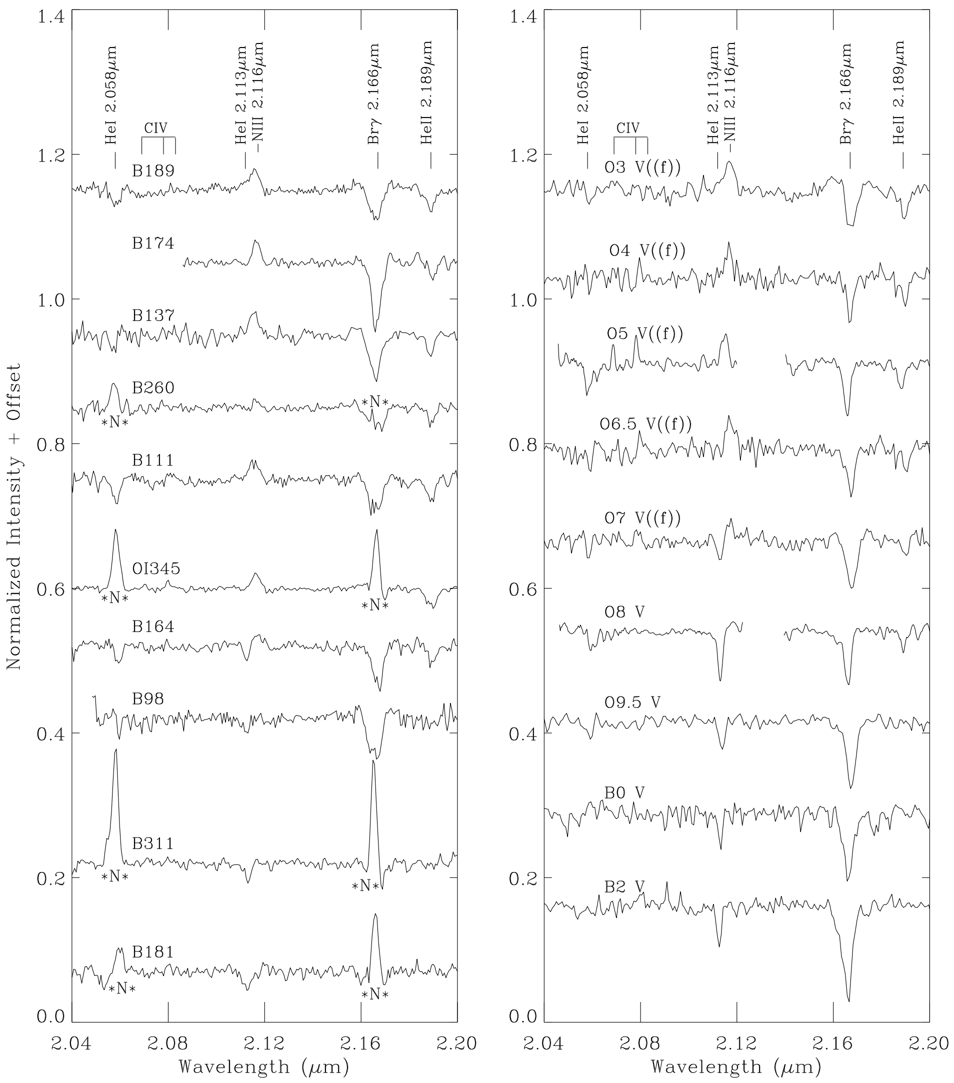

Figure 1. Examples of K-band spectra of normal O-type stars (right) and stars identified in M17 (B numbers – left). By eye inspection, it is clear that the absorption features and the line ratio of 2.113μm He I to 2.189μm He II nicely define the spectral types in the K-band region. 2.116μm emission is seen in the earliest O-types. '*N*' indicates *nebular* contamination. From Hanson et al. (1997).

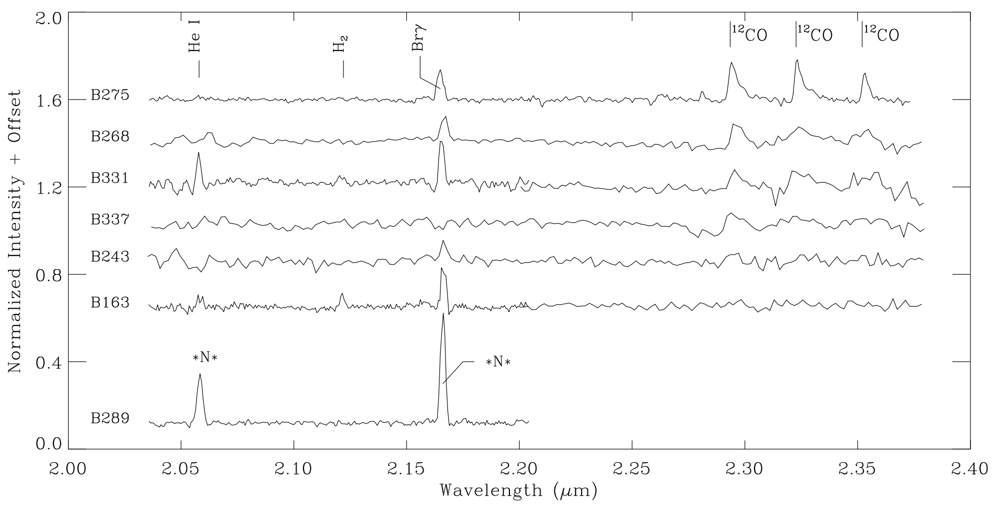

Figure 2. Examples of spectra of M17 stars (B numbers) with CO emission and/or weak or absent photospheric features in the K band. These stars are YSO candidates. In this figure, the 2.058μm He I line and Brγ features are, in some cases, contaminated with nebular emission. From Hanson et al. (1997).

2.2. Optical and 1μm Spectroscopy

Hanson et al. (1997) obtained obtained spectra in the blue, and in the 1-μm region, of a few of the M17 O-type stars and the YSO candidates. The O stars identified in the K band are consistently O types in these shorter-wavelength bands, but can be more quantitatively classified. Examples of M17 stars with O-type spectra are shown in Fig. 3. Among the YSO candidates, *all* those bright enough to be observed showed absorption features in the 1μm and the blue spectral regions. Examples of their optical spectra are shown in Fig. 4. Aside from one star with 'washed out' Balmer lines, the others could consistenly be classified as early- to mid-B types in the MK system.

Spectra were obtained near 1μm for some of the M17 O stars and YSO candidates by Hanson et al. (1997) and are shown in Fig. 5. In addition to Pδ being in absorption in the O stars, the (4–5) He II transition at 1.0124μm is also seen. In the YSO candidates, Pδ has absorption wings with a central emission feature, double in the case of B243. As B-type stars, these objects would not show the He II feature at 1.0124μm. Thus while some stars still within their birth clouds might have significant excess emission in the K band, which dilutes the stellar absorption features in some circumstances, photospheric lines *might be visible* in shorter-wavelength bands (e.g., I' [1.10μm, $A_{I'} \simeq 0.4 \times A_V$]; J [1.25μm, $A_J \simeq 0.3 \times A_V$], and H [1.65μm, $A_H \simeq 0.2 \times A_V$]). Thus we need to consider these other NIR wavelength bands for spectroscopy.

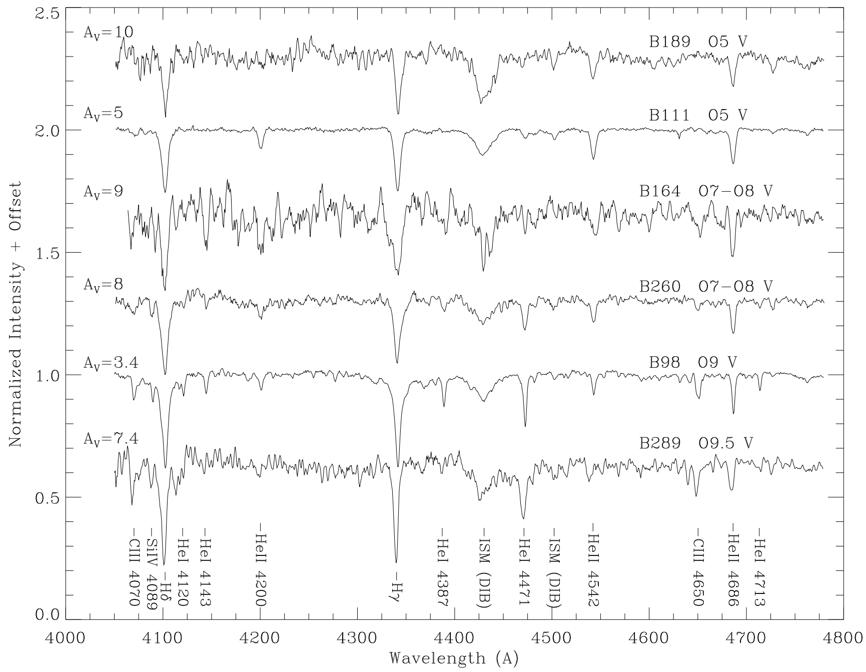

Figure 3. Examples of blue spectra of M17 stars (B numbers), all of O spectral type. B289, a YSO candidate, is 'featureless' in the K band (see Fig. 2). From Hanson et al. (1997).

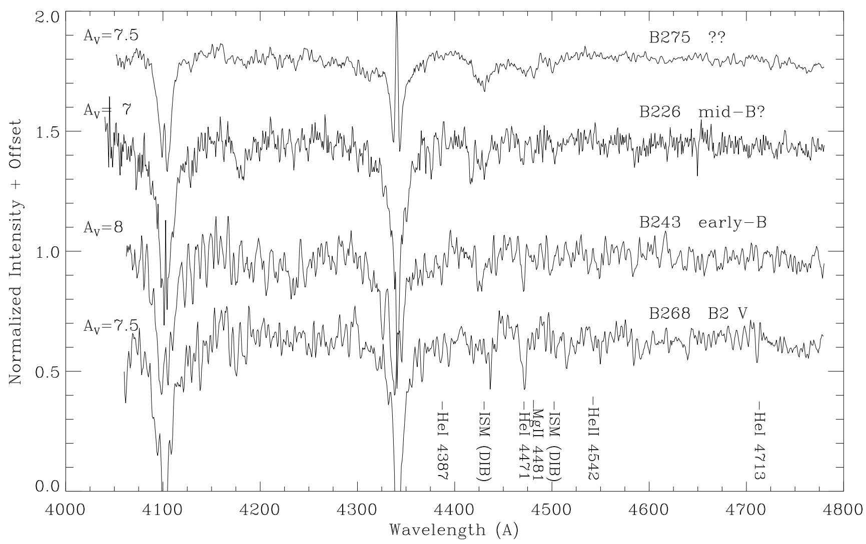

Figure 4. Examples of blue spectra of M17 YSO candidates (B numbers), all of which have absorption features of B-type stars. B275 is strongly 'veiled' and has central narrow emission in the Balmer lines. In contrast to nebular contamination in Brγ, the Balmer emission shown here is stellar. From Hanson et al. (1997).

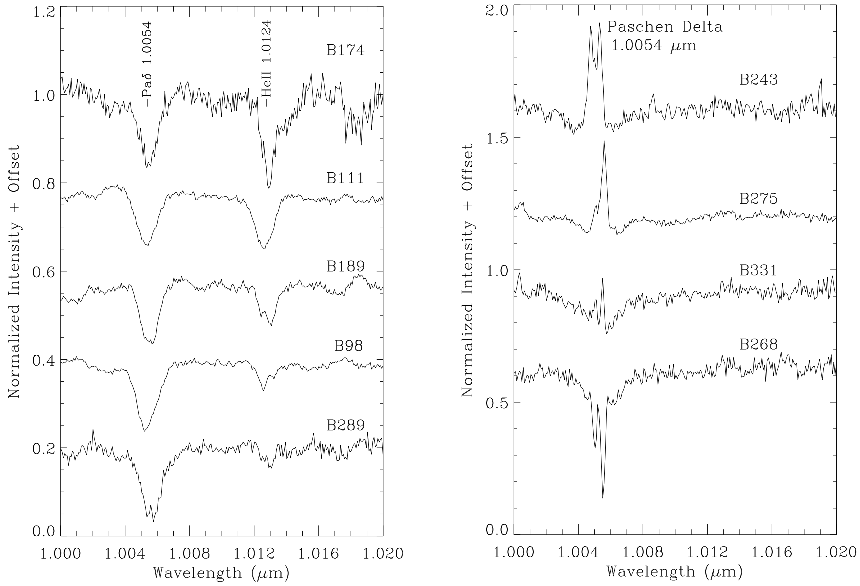

Figure 5. 1-μm spectra of M17 O-type stars (left) and YSO candidates (right). Note the central emission in Pδ in the latter objects; this is double in B243, direct evidence of the presence of a disk. In contrast to the Brγ nebular contamination, the Pδ emission shown here is associated with the stellar disk. From Hanson et al. (1997).

3. $I'JH$-Band Spectroscopy of Normal OB Stars

Absorption lines of hydrogen and helium are found in the I'-, J-, and H-band windows of hot stars. The advantage of these shorter wavelengths over the K band is the lack of circumstellar excess emission due to dust and/or an accretion disk; the disadvantage will be the greater extinction by dust along the line of sight. As with the K band, 'standard stars' would first need to be observed and an analogous I'-, J-, and H-band 'atlas' prepared. We have already obtained preliminary I', J, and H spectra of several OB stars (Blum et al. 1997) and found that while the H band can provide a rough guide to spectral classification of hot stars, the J and I' bands by themselves just don't have enough promising lines for this purpose. Thus, while ideally, the investigations of other star-forming and H II regions will utilize spectroscopy in all the NIR bands, I', J, H, and K together, the practical application of classification will probably be K and H only.

Fig. 6 shows representative spectra of northern OB stars at H (Blum et al. 1997). The primary lines used for classification of the hot stars are indicated in the figure. Briefly, the H I Brackett lines, the He I 1.70-μm line, and He II 1.57-μm lines in the H band will be used to sort out O- and B-type stars. Paschen lines at I' and J could be used for secondary classification purposes, as well as for comparison to model predictions, as can be seen from Fig. 7.

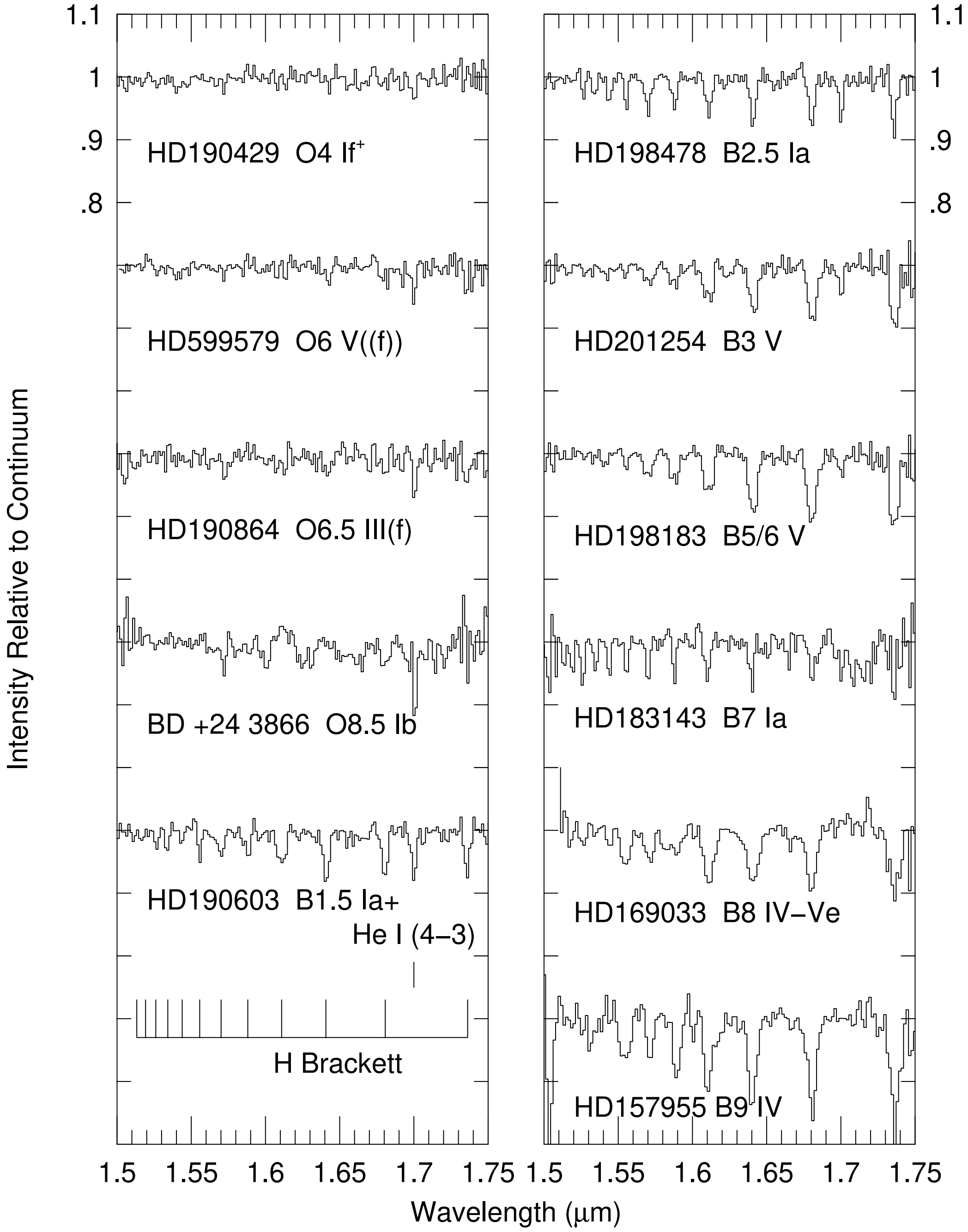

Figure 6. H-band spectra of a sample of OB stars. The hydrogen Brackett lines, He I 1.70μm line, and the He II 1.57μm line can be used for classification; note how the upper Brackett-series lines disappear in the hotter O stars, while the He II absorption becomes apparent. From Blum et al. (1997).

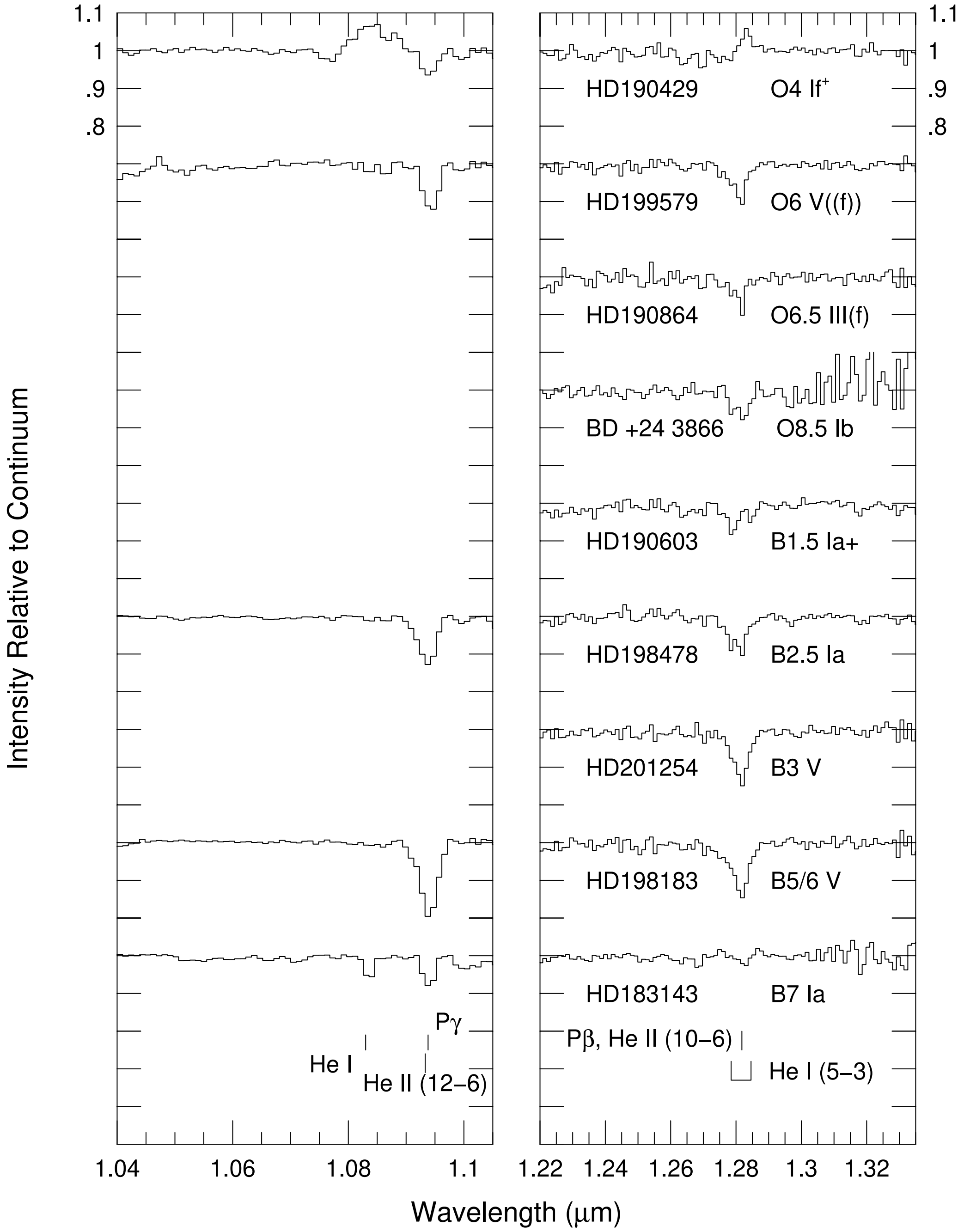

Figure 7. I'-, J-band spectra of a sample of OB stars. The hydrogen Paschenβ and γ lines are prominent, but no suitable He I or He II features are found. While He I 1.083μm is located within the I' band, it is *not* well behaved. From Blum et al. (1997).

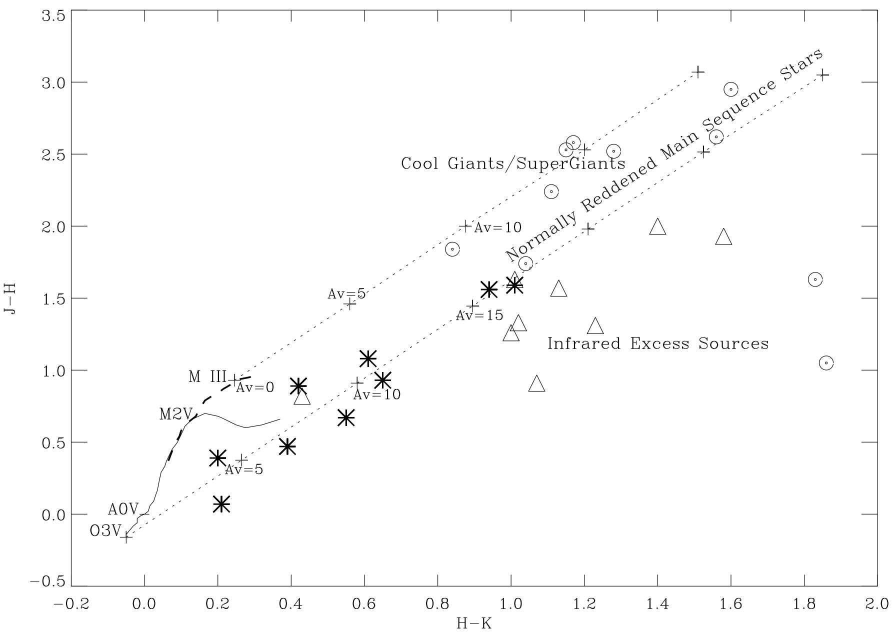

Figure 8. $J-H, H-K$ colour–colour plot of those stars in M17 that have K-band spectroscopy as follows: '*', OB stars; triangles, YSO candidates; circle with dot, cool stars (giants and supergiants). Figure provided by Dr. Margaret Hanson.

4. Preliminary NIR Photometry of Galactic H II Regions

NIR spectroscopy is the tool with which we will investigate the most massive stars in H II regions. To accomplish this goal, we need first to identify potential massive hot stars (and YSOs), by obtaining JHK images. Suitable candidates for follow-up spectroscopy can be selected based on their position in a $J-H$, $H-K$ colour–colour diagram. Normal cool giants ought to follow along a reddening line distinct from the hot stars (see below). Hot stars are reddened by variable amounts of interstellar dust, but some may have circumstellar excesses, as indicated by redward $H-K$ positions in the colour–colour diagram.

Figure 8 plots the $J-H, H-K$ colours of those stars in M17 for which *K-band* spectra have been obtained (Hanson et al. 1997). It very nicely indicates that a preliminary separation of cool stars, normal OB stars, and stars with NIR 'excesses' may be made *on the basis of their JHK photometry.* Of course, this selection is not foolproof since, for example, two cool giant stars lie along the reddening line for OB stars, as do two YSO candidates. This is not a serious problem. We may unintentionally observe a few cool background giants, but finding YSO candidates can only be considered useful!

In Fig. 9, we show preliminary H- and K-band images (roughly $1' \times 1'$) of the region of the Galactic radio source G351.6−1.3. Nebulosity (from the Brγ emission) is apparent in the K-band image, along with several star clusters. These highly reddened objects (barely visible in H) are undoubtedly the exciting objects of this radio source. The H- and K-band images were used to construct

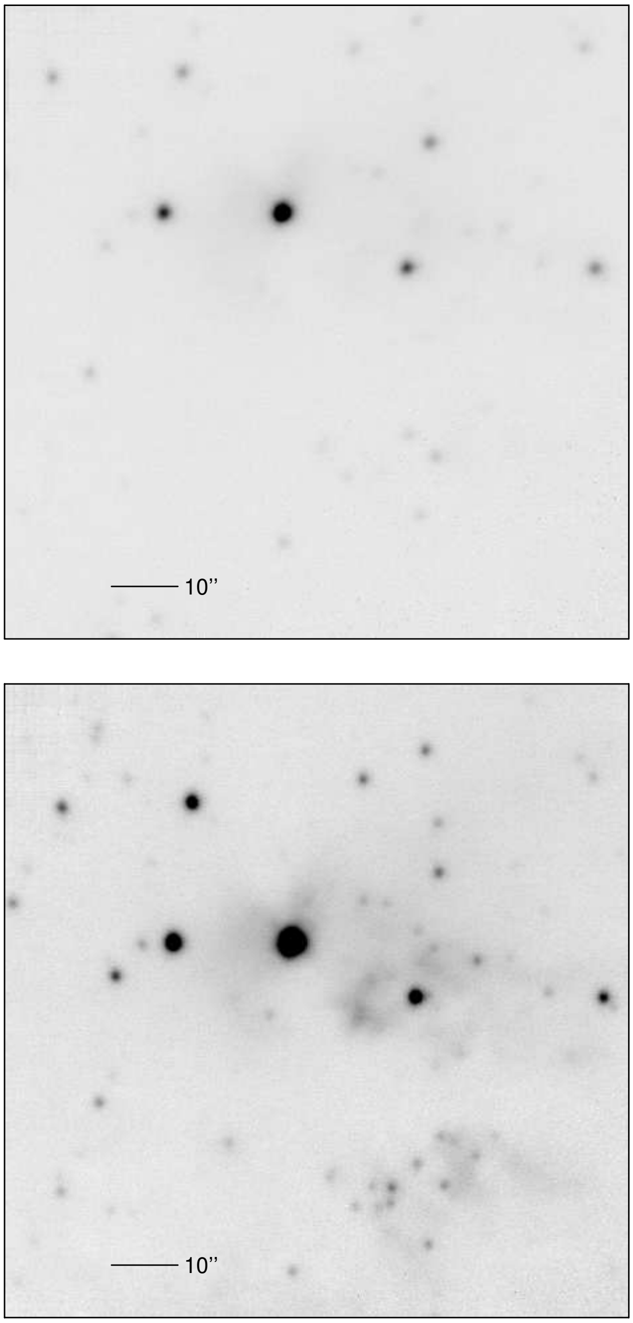

Figure 9. H-band (top) and K-band (bottom) images of the region near the Galactic radio source G351.6−1.3. Notice the appearance of star clusters connected with the nebulosity, visible in the K band from the Brγ emission. The brightest object may be a small unresolved multiple system, but higher spatial resolution will be needed to demonstrate this. Some sources might be unrelated cool stars.

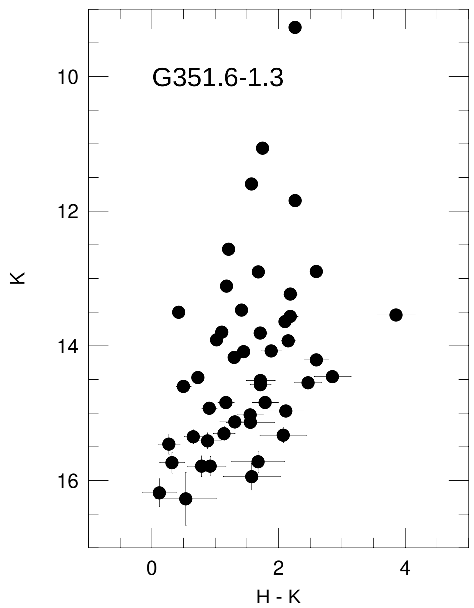

Figure 10. $H-K$, K colour–magnitude diagram for stars (solid dots) in the region near the Galactic radio source G351.6−1.3. Stars with $H-K$ larger than $1^{\rm m}$ may be cluster members. The brightest object may be an unresolved multiple system.

the colour–magnitude diagram (CMD) shown in Fig. 10. The CMD indicates that nearly all the sources in the field are highly reddened and may be associated with G351.6−1.3. Several very red objects appear to have IR excesses and may be YSO candidates. The acquisition of K-band spectra of the brighter sources is planned.

5. Preliminary K-Band Spectroscopy of Galactic H II Regions

Hanson and Conti have obtained K-band spectra of ten hot-star candidates in W 51, but generally with insufficient S/N to detect photospheric features. *All* the spectra showed *nebular* Brγ and 2.058 μm He I emission lines; in several cases these were centred on the star and extended only a short physical distance from it. Clearly these are separate 'compact' H II regions, which are excited by individual O-type stars. Going to shorter wavelengths, as was done for the stars in M17, might show photospheric features. Unfortunately, for W 51, with its A_V of roughly 30 magnitudes, such spectroscopy will be impossible shortward of 1μm. However, we believe it will be possible to study the ionizing stars of W 51, and other similar internally dusty environments, with H-band spectroscopy. Such efforts are planned. A very recently acquired high-S/N K-band spectrum of star #6 in W 51 (Goldader & Wynn-Williams 1994) is shown in Fig. 11. While lacking obvious photospheric absorption features, the presence of N III emission indicates this object is an early O-type star. This is the first stellar spectrum obtained for an exciting star of W 51.

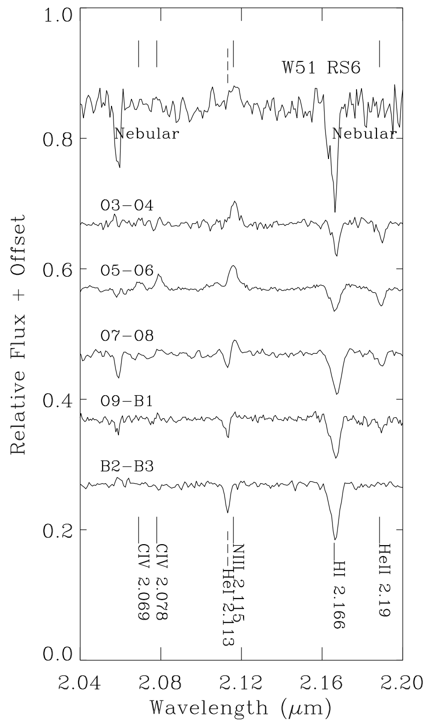

Figure 11. *K*-band spectrum of star #6 in W 51, with several OB standard stars. The presence of 2.115μm N III emission indicates the spectral type to be early O. Plot courtesy of Dr. Margaret Hanson.

As a further example of the possibilities of classification of highly obscured Galactic H II regions, in Fig. 12 we show a *K*-band spectrum of star #9 in W 33 ($K = 11, H - K = 1.5$). While no stellar absorption features are present, Brγ is in emission. A nebular contribution has been subtracted, so this compact emission is likely associated with the star. One is tempted to consider W 33#9 to be a YSO candidate and attribute this feature to a disk. It would be interesting to obtain a spectrum of W 33#9 near 2.3μm to look for emission in the CO feature, as was found for a number of the M17 objects.

6. Future Directions

The eventual goal of the work we have described here is to identify the potential exciting stars of the H II regions in our Galaxy (e.g., those listed by Georgelin & Georgelin 1976; Smith et al. 1978). Spectroscopy will then be used to classify and categorize the hot, luminous stars and relate their presence in each H II region with the already well-known nebular recombination spectrum. Using stellar models one can predict the number of Lyman continuum photons from the statistics and compare this to the radio results. Is there any substantial leakage of these photons from the nebulae? Does local dust absorption play any role?

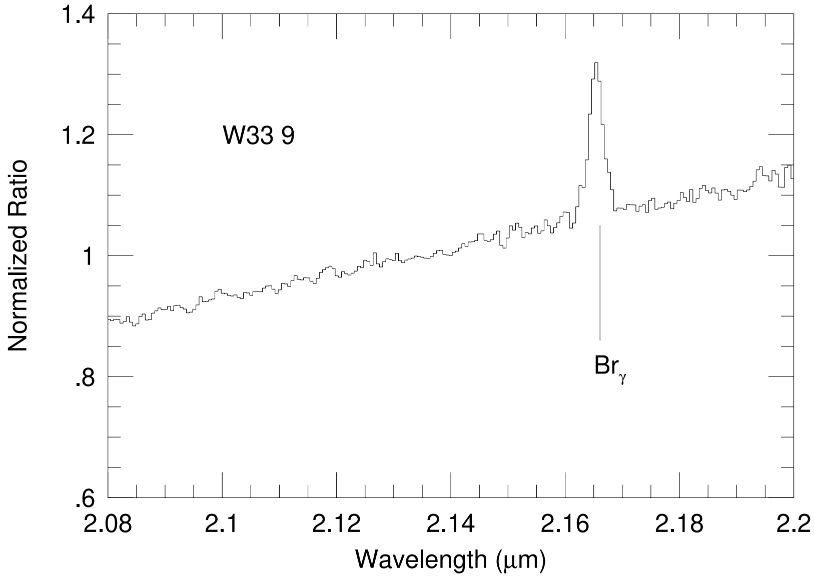

Figure 12. K-band spectrum of star #9 in W 33. While no stellar absorption features are seen, the presence of stellar Brγ emission strongly suggests the a disk morphology and a YSO candidate. Unlike the situation in M17, the nebular contamination near this star is small and has been subtracted.

One necessarily begins this programme by obtaining NIR photometry of H II regions. Ground-based observations can be used for some objects (e.g., Figure 9), but the brighter, or more distant, giant H II regions may well be too crowded and will need HST NICMOS photometry (a collaborative proposal has been submitted). Once the hot-star candidates are identified from the JHK colours (e.g., Figure 8), H- and K-band spectra will be obtained. These can be used to classify the stars into their OB spectral types, and the presence of compact emission features (e.g., Figure 12) may be noted as indicating YSO candidacy. The distribution of OB subtypes, and the presence or absence of YSO candidates among each H II region, ought to tell us something about some of the earliest stages of the formation of massive stars.

It should be possible to obtain distances to the H II regions from the photometry and the OB spectral types. These can then be used to investigate the uniform Galactic rotation model, which is the fundamental assumption under which the kinematic distances to these H II regions has been inferred. The similarities and differences between the spectroscopic and kinematic distances will test the model and might help our understanding of Galactic structure.

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Discussion

Kudritzki: What's the minimum useful spectral resolution?
Conti: 1200 is a sort of 'optimum minimum'; 800–900 is pretty marginal, but of course if you can go higher, so much the better. And the S/N needs to be at least 70, even with $R \simeq 10^3$; 30 isn't going to do it.
Langer: Does this work provide some clues for the theory of the formation of O stars?
Conti: Yes, it ought to. To remind you, in M17 we found 5 stars that have CO emission, which almost certainly means a disk. Those stars have luminosities corresponding to a mass range of late-O to early-B ($\sim$10–20$M_{\odot}$; we didn't go much below about 10$M_{\odot}$). Now, we found a bunch of early O stars that don't have any evidence of disks, so it *appears* that the earliest, most massive O stars have the disk phenomenon behind them (or possibly it didn't happen, although I think that's less likely). We also have 4 objects with no lines, which we also interpret as having disks but no CO emission; just about all these stars have IR excesses.
Langer: What about radio emission? I always though about O stars being labelled as these ultracompact H II regions...
Conti: I think in M17 we're after the ultracompact phase. Margaret [Hanson] will talk about the ultracompacts [p. 1].
Kudritzki: Are you able to say something about rotational velocities?
Conti: No, we'd like to do that but we really need higher spectral resolution – it would take $R \simeq$ 3000–4000.
Najarro: What is the longest wavelength you're reaching?
Conti: Some of the things we were getting were down towards 2.3μm.
Najarro: Okay, so you're getting the N III lines at 2.24 and 2.25μm. These are more useful than N III 8–7 at 2.11μm, which is blended with H I and C III 8–7.