VLT/ISAAC H-band spectroscopy of embedded massive YSOs

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Abstract. We have performed intermediate resolution (\(R \sim 5000\)), high signal-to-noise H-band spectroscopy of a small, initial sample of three massive embedded young stellar objects (YSOs), using VLT/ISAAC. The sample has been selected from sources characterised in previous literature as being likely of OB spectral type, to be unambiguously associated with bright (\(H \leq 14\)) single point sources in the 2MASS database, and to have no optical counterparts. Of the targets observed, one object shows a \(\sim B3\) spectrum, similar to a main sequence object of the same spectral type. A second object exhibits weak He\(_i\) and H emission, indicating an early-type source: we detect He\(_{ii}\) absorption, which supports a previous indirect derivation of the spectral type as mid-O. The third object does not show absorption lines, so no spectral type can be derived. It does, however, exhibit a rich spectrum of strong, broad emission lines and is likely to be surrounded by dense circumstellar material and at a very early evolutionary stage. Our results from this very small sample are in agreement with those of Kaper et al. (2002), who also find spectra similar to optically visible main sequence stars, together with emission line objects representing a very early evolutionary phase, in their much larger sample of K-band spectra.

Key words. stars: formation - stars: early-type - (ISM): - H\(_{ii}\) region

1. Introduction

Little is known about the earliest stages of the formation of massive stars. It is unclear whether the general picture applicable to the formation of low-mass stars, i.e. an accretion disk and infall onto the central star (Shu et al. 1987) can be scaled up to masses higher than \(\sim 10\,M_\odot\) (in the case of spherically symmetric accretion), as radiation pressure from the high mass stellar core on dust mixed with the infalling gas prevents further accretion. Alternative explanations involving the coalescence of intermediate mass protostars in the dense central regions of rich clusters have been proposed (Bonnell et al. 1998).

Observationally, the earliest stages of massive star formation are only accessible by infrared and radio techniques, because of the presence of \(\sim 10 – 100\) magnitudes of visual extinction. Ultracompact (UC) H\(_{ii}\) regions represent this earliest phase in the evolution of a very massive star. UC H\(_{ii}\) regions are typically identified using radio surveys (e.g. Bronfman et al. 1996; Walsh et al. 1999). Massive YSOs capable of ionizing a UC H\(_{ii}\) region are recognisable by their extremely red IRAS colours (Wood & Churchwell 1989; Osterloh et al. 1997), and the IRAS database has become a rich source to be mined for intermediate and high-mass YSOs using colour selection criteria (e.g. Persson & Campbell 1987; Wood & Churchwell 1989; Campbell et al. 1989; Chan et al. 1996).

Despite this, measurements of the fundamental parameters of UC H\(_{ii}\) regions, and more importantly those of the massive embedded stars which ionize the region, cannot easily be derived from the radio and far-IR observations. This is due principally to uncertainties in distances and in the indirect methods used to convert radio continuum or IRAS fluxes to the physical properties of the embedded, ionizing OB star (Walsh et al. 1997; Kaper et al. 2002) and references therein).

To circumvent these difficulties, observational efforts are now beginning to probe directly the photospheres of massive embedded YSOs using observations in the near-infrared. Such wavelengths are accessible from the ground (1 – 5 \(\mu\)m, JHKL bands) and the extinction owing to the gas and dust in which the YSO is embedded is much less than in the optical. Moreover, at thermal infrared wavelengths, emission from the dust becomes too great, and the flux from the photosphere itself can no longer be detected. The first spectral classification of the ionizing star
of a UC H II region was made by Watson & Hanson (1997) in the K-band.

While an important aim of the present paper is to clarify the status of the three objects discussed here as massive embedded YSOs, a second no less important aim is to show that intermediate resolution spectroscopy in the H-band (where veiling from circumstellar emission is minimal) is a necessary and valuable tool to detect, classify and study the photospheres of such objects. This paper attempts to build on recent work on the classification of OB stars in the H-band, and to apply it to highly obscured objects.

1.1. Classification spectroscopy of OB stars in the H-band

Recent developments in classification spectroscopy of OB stars in the H- and K-bands suggest application to objects too deeply obscured to be optically visible. In the earliest work, both Lancon et al. (1992) and Dallier et al. (1996) presented libraries of stellar spectra in the H-band, but these were largely directed to stellar population analyses. More recently, the most important study directly relevant here has been that of Hanson et al. (1998) who have identified a number of H-band temperature and luminosity diagnostics for OB stars in R=2000 spectra, involving the ratio of Br I (1.681 μm) to He I (1.700 μm) and He II (1.693 μm). Using a full grid of spectra representing both dwarf and supergiant luminosities, these authors find that the presence of all three lines definitively indicates a spectral type earlier than late O. With combinations of only two lines present, in various strengths, dwarfs can be divided into O9 – B1, B2 – B5, and late B – early A type.

This work overlaps with that of Meyer et al. (1998) who have observed 85 MK standards of near-solar metallicity, at R~3000 in the H-band. They find a number of strong T eff and luminosity-sensitive lines in the H-band spectra of stars of spectral type A, and later, all the way down to M5. These two studies show that the classification of heavily embedded YSOs, and the near-IR study of their photospheres, could be carried out in the H-band for all spectral types from O to M, using intermediate resolution, high signal-to-noise spectra. This could be advantageous, since the veiling of photospheric absorption lines by continuum emission from hot circumstellar dust is much less severe than in the K-band (Meyer et al. 1998; Ishii et al. 2001). Taken together, these studies suggest that while K-band spectroscopy has been extremely successful in studies of low-mass YSOs (see Greene & Lada 1996 for one example among many) classification in the range B0 – G0 is best performed in the H-band, as pointed out by Luhman & Rieke (1998).

### Table 1. Basic and derived data for observed targets.

| IRAS     | H   | J-H | H-K | A_v | Sp.T. | Int./s |
|----------|-----|-----|-----|-----|-------|-------|
| 17175-3544a | 14.00 | 2.75 | 3.43 | 13"   | O6-O7 | 7560   |
| 17441-2910b | 10.29 | 3.42 | 2.41 | 30    | O5.5  | 480    |
| 18079-1756c | 11.09 | 2.67 | 1.67 | 74    | B     | 960    |

a. Walsh et al. (1999)
b. Porter et al. (1998), Walsh et al. (1997)
c. Osterloh et al. (1997)
d. Using the given spectral type and using a distance of 2.2 kpc (see text) we derive m_v = 6, yet there is no optical counterpart on DSS plates.

2. Observations and data reduction

2.1. Target selection

Targets for this study were selected from recent literature on UC H II regions and IRAS-selected catalogues of massive YSOs (see Table 1). The main criteria were that such targets would be sufficiently bright in the H-band to be accessible for medium resolution ISAAC spectroscopy in short exposure times, and that they should be present in the publicly available 2MASS dataset, to avoid the need for prior imaging. A further important criterion was that the 2MASS point sources should have no optical counterparts in the GSC2.2 and USNO catalogues. The three selected targets are listed in Table 1 together with 2MASS magnitudes and colours, A_v, and indirect spectral type estimates from the given references. The mid-infrared fluxes are shown in the IRAS colour-colour diagram (Fig. 1), where different locations occupied by sources of various types are indicated. IRAS17175-3544 is too faint in the J-band for 2MASS to give an accurate magnitude in this band. However, this source shows a strong near infrared excess as shown in Fig. 2 where its JHK colours were derived instead from the deeper imaging of Tapia et al. (1996).

Fig. 3 shows the 2MASS H-band images, covering 152” square (the FOV of ISAAC) for each target. Fig. 4 can be usefully compared to Fig. 19 of Walsh et al. (1999) for IRAS17175-3544, who show a K-band image overlaid with the positions of methanol and OH maser sites and 8.64 GHz radio continuum emission, which are shown to be coincident with the near-infrared source. Furthermore, L-band imaging of IRAS17175-3544 by the same authors indicates that the source is extremely bright and red (L=3.8, K-L=4.7). In the cases of IRAS 17441-2910 and IRAS 18079-1756, 2MASS H-band data indicate that the bright sources shown in Fig. 4 lie within 2-3” of the IRAS positions, allowing unambiguous identification of the targets.

The presence of nebulosity associated with all targets is clearly shown in the H-band images and even more
obvious in the K-band (see Fig. 3 which uses the same intensity scales as the equivalent H-band images). This strengthens the identification of the sources in the 2MASS data with the IRAS sources given in the literature. The very bright source IRAS 17441-2910 appears to be multiple, but manipulation of the image indicates that there is one single, major source for which the point spread function in the 2MASS H-band image is symmetric. Therefore it was included as a target under the assumption that this one source would contribute by far the greater flux to the H-band spectrum.

2.2. Data extraction

Observations were carried out at VLT/UT1 (Antu) with the ISAAC spectrograph, in SW mode at medium resolution (R ~ 5000), in service mode, on 2002 May 9 and 10. The total integration time for each object is given in Table 1 and totals 150 min. A central wavelength of 1.71 μm was selected to provide a wavelength range of ~1.67 – 1.75 μm, covering lines diagnostic of an OB spectral type, most importantly H i Br 10 1.7362 μm, Br 11 1.6811 μm, He i 1.7007 μm and He ii 1.693 μm. Data reduction was performed with the ISAAC pipeline package ECLIPSE (version 4.1.2). Firstly, all data and calibration frames were "de-ghosted" using the ghost routine. Next, master flat fields were created for each night using the swflat routine. Co-added spectrum images were then created using
the *sw_spjitter* routine. Full details of the ISAAC reduction pipeline can be found in Amico et al. (2002).

Spectra were then extracted using the standard *APALL* routine in *IRAF*\(^1\), and wavelength calibrated using the sky OH emission lines found throughout the spectra. In all cases \(\sim 17\) OH lines were used, yielding RMS values on the fits to the dispersion of \(<0.1\) Å.

Telluric divisor stars were selected at the time the observations were made, and were typically observed to within 0.05 airmasses of the science objects. Telluric standards were reduced, extracted and wavelength calibrated in exactly the same way as the science data. As the divisor stars are all of spectral type B, Br 11, Br 10 and He\(^i\) profiles were estimated by eye and directly fitted out of the standard spectra, and pure telluric spectra created in these regions by dividing the spectrum by the fit. These sections were then spliced into the rest of the standard star spectra (assumed free of photospheric lines) to create normalised pure telluric spectra, one derived from each standard star observation.

One problem is that in all standard star spectra He\(^i\) is itself blended with a telluric line, too closely for the components to be separated. Therefore the whole He\(^i\) + telluric profile had to be fit, and replaced by a flat ‘continuum’ region. Hence the region around He\(^i\) remains uncorrected for telluric absorption in all target spectra shown in Fig. 5. The problem is dealt with further in Sect. 4, where we have used synthetic spectra to model the telluric standards (see Fig. 6).

Object spectra were divided by those of the appropriate normalised standard (after fitting out photospheric lines) using the *IRAF* package *TELLURIC*. This method retains the same flux scale (number of counts) and spectral slope as the uncorrected spectra. The signal-to-noise ratio (S/N) of the final spectra is \(\geq100\) and in the case of the very bright target IRAS 17441-2910, it approaches 150.

3. Background for individual objects

The three target objects are located in heavily obscured regions in the Galactic plane. Strong extinction in the respective areas is especially obvious from 2MASS K-band images (Fig. 4). This results in a sharp drop in 2MASS K-band detections within a few arcminutes of the target objects. The obscuring material appears to have a filamentary structure, especially visible near IRAS 17441-2910 and IRAS 18079-1756. Neither of these two objects are located within a known massive star forming region or giant molecular cloud.

By contrast, IRAS 17175-3544 lies in the North-Eastern part of the extended molecular cloud complex NGC6334 (photometric distance 1.76 kpc, Neckel 1978). This star forming region is known as NGC 6334 I (Emerson et al. 1973; McBreen et al. 1979) and contains three IR sources IRS-I 1, IRS-I 2 and IRS-I 4 (Harvey & Gatley 1983). IRS-I 1 and IRS-I 2 are within a few arcsec of each other, and both have been proposed to be the driving source of a high-velocity (70 km s\(^{-1}\)) CO bipolar outflow (see Persi et al. 1996).

IRAS 17175-3544 itself appears to be associated with IRS-I 1 (see Fig. 19 of Walsh et al. (1999) and Persi et al. 1996). High resolution near-IR imaging showed IRS-I 1 to be complex, consisting of at least 4 components (Persi et al. 1996). The nearby (6") source IRS-I 2 is a mid-IR source (detected at 20 and 30 \(\mu\)m). Whether or not this
source contributes to the H-band spectrum is determined by its extension and position with respect to the slit, but no source brighter than K ~ 17.5 is detected at the position of IRS-I 2 by Persi et al. (1996), so we consider such a contribution unlikely. This source could however contribute to the IRAS fluxes.

Further evidence for the massive YSO nature of at least two of the objects discussed in this work, namely IRAS 17175-3544 and IRAS 18079-1756, is that both have IRAS low resolution (8 – 23 μm) spectra classified as type H by Kwok et al. (1997). These authors state that the vast majority of IRAS LRS spectra of this type, exhibiting very red continua, are associated with H II regions.

Another noteworthy feature concerning IRAS 17175-3544 is that it is surrounded by an embedded stellar cluster (centred on IRS-I 2), which was detected in the K-band by Straw et al. (1989). The cluster is clearly visible in Fig. 3. Deeper imaging by Tapia et al. (1996) yielded a stellar density estimate of about 1200 pc⁻³, and cluster size of 0.6 pc (for D = 1.74 kpc).

In addition to the cluster near IRAS 17175-3544, our acquisition images revealed that IRAS 18079-1756 is also accompanied by a embedded cluster, which the 2MASS image in Fig. 3 is too shallow to fully reveal. It is not clear whether there is an increase in stellar density near the third source IRAS 17441-2910.

Finally, apart from the location in an obscured region and the presence of a cluster (near at least two sources), a third common characteristic of the target sources is that all are associated with maser emission and/or are known to be outflow sources, as has already been mentioned for IRAS 17175-3544. IRAS 17441-2910 shows evidence for OH masering (Caswell 1998), while IRAS 18079-1756 displays H₂O maser emission located at ~12″ distance and is known to be a CO outflow source (Osterloeh et al. 1997).

To conclude, all three sources show all the characteristics of young, actively forming massive stars.

4. Results from individual spectra

4.1. IRAS 17175-3544

Fig. 6 shows the observed H-band spectrum of IRAS 17175-3544 (upper large panel). As has already been discussed, Walsh et al. (1999) find maser and radio continuum sources exactly coincident with the near-IR source discussed here. IRAS 17175-3544 is one of the few sources for which Walsh et al. (1999) can unambiguously derive a spectral type. As a result of a methanol maser emission survey to identify UC H II regions from an IRAS-selected sample, Walsh et al. (1997) calculated total luminosities and spectral types directly from the IRAS fluxes and the kinematical distances given by the maser emission. However, the large size of the IRAS beam (~1′), may encompass a number of emitting regions, so the IRAS-based spectral types cannot be definitive.

In the case of IRAS 17175-3544, though, extrapolation of the near-IR SED to the far-IR shows that the near-
what different from the methanol maser emission velocity given by Walsh et al. (1997) (−10 km s\(^{-1}\)) and could indicate that the atomic and molecular emission do not arise in precisely the same circumstellar region. However we note that the velocity resolution of our data is insufficient to press this point. It is clear, however, from inspection of the 2D spectrum images for this object, that the H and He emission lines are extended spatially, and hence are of nebular origin.

By themselves, emission lines of H and He suggest an early-type object, but do not allow derivation of a spectral type. We may speculate that, as the emission is much weaker than in IRAS 17441−2910, either the exciting central object is not as luminous in this case, or perhaps the object is in an ‘intermediate’ stage of evolution, displaying nebular emission but not the powerful circumstellar emission of IRAS 17441−2910, nor resembling a main sequence type spectrum like IRAS 18079−1756 (see below).

As this object has previously been characterised as O6 − O7, we have searched the He \(\text{ii}\) region carefully. Fig. 8 shows this region in the telluric corrected spectrum, with the telluric standard star also plotted as a dashed line. The feature in the IRAS 17175−3544 spectrum at \(\sim 1.693 \mu\)m does not appear to be an artifact of the telluric correction process, since the standard star spectrum is featureless across its profile.

We identify this feature as He \(\text{ii}\) absorption. The equivalent width is close to 300 mÅ, compatible with the measurements of Hanson et al. (1998) in their small sample, they measure 0.5±0.2 Å for their latest O-dwarf (HD48279, O8V) and 0.3±0.2 Å for the O7V HD 47839, while they do not detect He \(\text{ii}\) in their O9.5V object.

Moreover, Meyer et al. (1998) include the O7V star HR2546 (15 Mon) in their sample. Even their best spectrum of this object is rather noisy (S/N=50), but clearly exhibits He \(\text{ii}\) absorption. Since the spectrum is noisy, and the continuum level around He \(\text{ii}\) uncertain, we have not attempted to plot the profile in Fig. 8. However, the equivalent width is in the range 150 − 400 mÅ, close to both Hanson et al. (1998) and our measurement. Our He \(\text{ii}\) detection therefore supports the previous classification of IRAS 17175−3544 as O6 − O7. A caveat, however, is that according to Hanson et al. (1998), He \(\text{i}\) should still be strong in absorption (−1 Å) for an O7V type. Such absorption appears to be masked by nebular emission in IRAS 17175−3544.

That IRAS 17175−3544 is located at the centre of the complex star-forming region of NGC6334I has already been discussed. In addition to the H and He features already discussed, it shows absorption features which can be identified as Mg \(\text{i}\) (17113 Å) and the Al \(\text{i}\) triplet (16723, 16755 and 16768 Å). Usually these features are associated with cooler atmospheres, increasing in strength to K-types (Meyer et al. 1998). Inspection of the telluric standard spectrum excludes a telluric nature for this lines (unlike the emission spikes near Br 11 in IRAS 18079−1756), nor a badly determined and subtracted sky spectrum (contamination by other, late-type stars in the slit), since the slit absorption is not a result of imperfect cancellation.

The H-band spectrum does not slope as steeply to the red as the other two objects in the sample, perhaps suggesting it is less embedded; yet the infrared excess is by far the largest of this sample. Narrow, relatively weak emission in IRAS 17175−3544 (dashed line) together with the blended He \(\text{i} + \text{telluric\ line\ derivation\ by}\ division\ of\ the\ two\ spectra\ in\ the\ left\ panel\ (dotted\ line).\ The\ heavy\ line\ shows\ the\ results\ of\ the\ division,\ clearly\ showing\ the\ narrow\ He \(\text{i}\) emission in the IRAS 17175−3544 spectrum.

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position angles were carefully chosen to avoid any other stars along its length. However, a close examination of the VLT acquisition image for IRAS 17175-3544 reveals the presence of a second object, which would have been in the slit at the time the spectrum was obtained. The two sources are not resolved in the 2MASS image.

These two sources are coincident with IRS1-I1E and IRS-I1W of Persi et al. (1996, see also Tapia et al. 1996) where the former source is shown by these authors to be the reddest (H = 15, H-K = 3.9), dominating the emission longward of 2 μm and coincident with the peak of the 30 μm emission. This source is the OB star responsible for the ionization of the compact H II region and for pumping the nearby H2O and OH masers. The second source has H = 14.4 and J-H = 2.3, and clearly also contributes to the H-band spectrum, giving rise to the composite spectrum we observe. The presence of the Mg i and Al i lines, presumed to arise from IRS1-I1W, shows that this source is cooler. We have performed experiments with synthetic spectra which show that the flux emitted by a T eff = 20000 K photosphere is only ~5 times greater than one of T eff = 5000 K in the H-band, so only a very few cooler embedded stars might suffice to cause the appearance of Mg i and Al i. In this scenario, IRS-I1W might be a system of less massive embedded objects associated with IRS-I1E, the embedded OB star which gives rise to the H and Fe features in our spectrum.

Lastly, it might be argued that the observed spectrum could be that of a foreground late-type object, with emission lines from the nebular background. We cannot definitively rule out this possibility using the data presented here, but would point out that there is no optical counterpart to such a putative foreground object, even on the very deep SuperCosmos (UKST I-band, Hambly et al. (2001) and references therein) images.

4.2. IRAS 17441-2910

The very high signal-to-noise (~150) spectrum of this bright (H=10.29) source is shown in Fig. 4 (central large panel). The spectrum exhibits broad, strong emission lines of H i Br 10, Br 11 and numerous other species, notably He i and Fe ii. The emission lines we have been able to identify are labelled in Fig. 4. The object is known to exhibit very strong CO emission in the K-band (Porter et al. 1998). The equivalent widths of the Br 11 and Br 10 emissions are ~6 Å and ~5.5 Å respectively, with FWHM ~180 km s^{-1} and 160 km s^{-1}. Porter et al. (1998) find Br i emission with equivalent width 12 Å. Walsh et al. (1997) have derived a spectral type of O5.5 from the IRAS fluxes, together with the kinematic distance given by the methanol maser (6.67 GHz) emission profile (9.8 kpc), and assuming the source is a single star. However, the lack of photospheric absorption lines precludes a spectral type determination here.

After correction to the LSR velocity, we derive a radial velocity of +44.9 ± 4 km s^{-1} using 4 lines labelled in Fig. 4 which we are able to deblend accurately: Br 11 16811.11, Br 10 17366.85, Fe ii 16877.81 and Fe ii 17115.95. This velocity is somewhat different than that cited by Walsh et al. (1997), and again may indicate that the atomic emission arises in a different region from that producing the methanol maser emission (centred near +23 km s^{-1}). However, owing to the large FWHM of the emission lines measured, and consequent difficulties in accurately measuring the line centre, we do not consider this point further.

Kaper et al. (2002) have drawn attention to a significant population of objects whose K-band spectra also show broad, strong emission lines, up to 100 km s^{-1}, two of which also show CO emission. IRAS 17441-2910 clearly belongs in this category also. Following the suggestion of Kaper et al. (2002), IRAS 17441-2910 appears to be a third object for which strong emission of CO and other species, together with a significant infrared excess (from 2MASS colours), indicate that the exciting object is surrounded by dense circumstellar material. It is clear that the strong emission line objects represent massive stars in the earliest stages of evolution.

4.3. IRAS 18079-1756

Previous literature on this object gave L bol ~ 32000 L⊙ and A v = 74 (Osterloh et al. 1997). This bolometric luminosity would correspond roughly to an early B spectral type. The entire H-band spectrum is shown in Fig. 5 (lower large panel). The plot shows that the continuum slope for IRAS 18079-1756 rises to the red across the length of the H-band spectrum by ~20%, comparable to IRAS 17441-2910, suggesting it is indeed deeply embedded. However, the absence of significant emission, and the general appearance of the spectrum (similar to an unobscured object of the same type) suggests that it could be at a somewhat later evolutionary phase.

The spectrum clearly shows broad He i absorption, which is centred at ~1700 Å, as well as broad hydrogen absorption. In Fig. 6 the normalised spectrum of IRAS 18079-1756 is compared to an H-band spectrum of HR 5191 (ν Uma). This star is one observed by Meyer et al. (1998) who give a spectral type of B3V and v sin i = 205 km s^{-1}. The He i profile is well matched, but the H lines are weaker than in the standard star, presumably because the H profiles are filled in by emission. This is supported by inspection of the Br 10 profile, which clearly shows central emission. The He i profile is contaminated by a telluric line, since it was not possible to correct for telluric absorption over a 50 Å region across the He i profile (see Sect. 2.2). Fig. 10 (left panel, dashed line) shows the blended He + telluric profile in the B-type standard observed for IRAS 18079-1756. In the same way as for IRAS 17175-3544, we have synthesised this spectrum (see Fig. 6) adopting parameters of T eff = 25000 K, log g = 4.0

2 Rest wavelengths from www.pa.uky.edu/~peter/atomic/
and vsini = 100 km s⁻¹ (dotted line). Division yields a pure telluric profile (solid line). In Fig. 11 (right panel), this resultant profile (dotted line) is divided through the uncorrected spectrum for IRAS 18079-1756 (dashed line) to yield the corrected He i profile (heavy line). This profile matches the broad feature in Fig. 11 well, supporting the case that the stellar He i line is the broader feature. Comparing this profile to the galactic standard yields a very close match between the two profiles. It is clear that this match strongly supports an early-B spectral type for IRAS 18079-1756, and furthermore suggests it is a rapid rotator, as expected for very young massive YSOs. However, a rigorous measurement of vsini would require spectra of rather higher resolution.

After telluric correction, the equivalent width of He i (heavy profile in Fig. 11) was measured as 600 ± 100 mA. Comparison with equivalent widths tabulated by Hanson et al. (1998) against optical spectral type, suggest IRAS 18079-1756 is very close to B2, assuming a dwarf luminosity. Comparison with HR 5191 suggests B3V. However, strong He i persists in supergiants to ~B7. If IRAS 18079-1756 is of lower gravity, which would not be unexpected by analogy with low-mass embedded protostars (see Greene & Lada 1996), then a somewhat later spectral type is possible. The equivalent width of Br 11 is ~2.0±0.1 Å, which also suggests early B, although because of the possibility of emission this is not such a reliable indicator.

Furthermore, He i 1.700 μm remains strong into the O-star regime, as far as O7, and the Br 11 widths given by Hanson et al. (1998) for their late O-stars show large scatter, varying non-monotonically from 1.6 to 3.0 Å between O9.5V and O7V. If IRAS 18079-1756 is as early as O8V, however, it should show He ii absorption at 1.693 μm with a strength comparable to that of the observed He i profile. Such a feature is not seen. Hanson et al. (1998) do not detect He ii in their O9.5V object, so in principle IRAS 18079-1756 could be as early as this. Using slightly lower resolution (R=2000), comparable S/N spectra, they give equivalent widths as small as 0.3 Å reliably. Our upper limit on the strength of He ii in IRAS 18079-1756 is smaller than this (~150 mA: we marginally detect a feature of this strength close to the expected He ii wavelength, but it is compatible with the noise). Therefore, it is not possible to say definitively that IRAS 18079-1756 is not an embedded very late O-type photosphere. Nevertheless, since we do not detect He ii with certainty, we adopt a spectral type of B2-B3, provided the luminosity class is nearer than that of a dwarf than a supergiant, which seems likely.

As in the case of IRAS 17175-3544, IRAS 18079-1756 also shows a composite spectrum, with the Al i and Mg i lines. The clear presence of a cluster around the latter object suggests that this spectrum may be composite for similar reasons to IRAS 17175-3544; namely the existence of a small cluster of unresolved low-mass embedded objects around or associated closely with the massive star. For IRAS 18079-1756, there is no suggestion of a second object in the slit which can be identified with a known object, unlike the case of IRAS 17175-3544 (IRSI-I 11W). The acquisition image PSF exhibits some asymmetry, but how many components it contains is unclear. Once again, we note that if the Mg i and Al i lines are to be explained by a chance superposition of a late-type foreground object, there is no optical counterpart at the correct position on the SuperCosmos UKST I-band image.

5. Discussion

5.1. The nature of the three sources

Our sample of three embedded massive YSOs in UC H ii regions has uncovered a variety of objects which may represent different stages of the earliest evolution of massive stars.

IRAS 17441-2910 shows broad, strong emission lines, and is known to show strong CO emission, indicating the presence of dense circumstellar material. While the intrinsic near-infrared excess emission is marginal compared to that of IRAS 17175-3544, the presence of emission lines suggests mass accretion and/or outflow processes. This object appears to be at the earliest evolutionary phase of the three candidate massive YSOs.
IRAS 17175-3544 is in some ways the most enigmatic source, since it has a flat continuum, but the largest near-IR excess of all. Its association with IRS-1 1 in the molecular cloud complex NGC 6334 (see Sect. 3) supports a young evolutionary status. The nebular emission detected (Br 10, Br 11, He i) is narrower and weaker than in IRAS 17441-2910, but still clear. If the rather flat continuum of IRAS 17175-3544 is taken to mean it is relatively less embedded than IRAS 17441-2910, the infrared excess is not explained. Instead, the weakness of the emission lines compared to IRAS 17441-2910 may be indirect evidence that IRAS 17175-3544 is less luminous than IRAS 17441-2910, and that the spectral type of the latter is earlier than O6 – O7, which is supported by the previous derivation of a spectral type of O5.5 (see Table 1). Note however, that the broad emission in IRAS 17441-2910 is most likely of circumstellar rather than nebular origin. We propose that IRAS 17175-3544 may be at an equally early stage of evolution as IRAS 17441-2910.

Finally, the spectrum of IRAS 18079-1756 resembles a main sequence B-star, lacking direct spectral evidence for circumstellar material. The absence of near-infrared emission line features suggests a later evolutionary stage than the other two objects. However, the continuum does slope to the red, rising by \(\sim 20\%\) over the 750 Å range covered by these spectra, similar to the slope exhibited by IRAS 17441-2910. Perhaps tellingly, IRAS 18079-1756 shows little near-infrared excess, while IRAS 17441-2910 does. This supports the hypothesis that IRAS 18079-1756 is more evolved but still obscured, possibly predominantly by intrachuster dust.

While this would explain the slope of the continuum and the location of the source in Fig. 2, the association of the source with a UC H II region and H2O masering, and its identification as a CO outflow source by Osterloh et al. (1997), lend weight to the suggestion that it is an embedded (that is, still surrounded by circumstellar material) YSO.

We note also that the very presence of emission lines does not confirm these sources are massive embedded YSOs; OB supergiants such as P Cygni also exhibit emission lines in the near-infrared (Hanson et al. 1998), but such objects are not generally optically obscured, nor associated with masering phenomena.

### 5.2. Spectral types from H-band data

Where H and He absorption lines are detected, it is possible to obtain unambiguous spectral types, by comparison to galactic standards. He II absorption is detected in IRAS 17175-3544, in close quantitative agreement with the spectral type derived from IRAS fluxes, O6 – O7. From the presence of strong He i and the absence of detectable He ii in IRAS 18079-1756, we also confirm a spectral type of B3, with considerable accuracy (\(\pm \sim 3\) subclasses). These close agreements strongly suggest that near-infrared spectral types could be derived for many of the known UC H II regions for which far-infrared spectral types, derived from bolometric luminosities, are ambiguous (e.g. Walsh et al. 1997).

In a very recent paper, Hanson et al. (2002) have performed a large survey of UC H II regions in the K-band, including spectroscopy at R=1200. Their main finding relevant here is that \(\sim 50\%\) of their radio-selected sample were detectable by Br\(\gamma\) emission, but of those, only for 5 – 10% was it possible to detect photospheric features of the ionizing star, and thus derive spectral type and hence effective temperature directly. However, in the K-band spectroscopic survey of Kaper et al. (2002) at R\(\sim\)8000, these authors detect characteristic K-band OB star features (emission and absorption) in the majority of their sample of 75, of which \(\sim \frac{3}{4}\) are found to be late-type foreground contaminants, and around 20 are found to be extremely strong Br\(\gamma\) emitters with obvious resemblances to IRAS 17441-2910, as discussed above. This suggests that if sufficiently high resolution and high signal-to-noise spectra (R\(\geq\)5000, S/N\(\geq\)100) are used in either the H or K band, the photospheres of massive YSOs, at very early stages of evolution, could be readily detected, and absorption lines analysed. Such spectra would be amenable to similar techniques as those common in optical studies, in particular the derivation of gravities log \(g\) and projected rotational velocities \(v_{\text{sin}i}\), both of which may be expected to differ systematically from that observed on the main sequence. Finally, given suitable line(s) present in the H-band, the detection of a surface enhancement of \(^{14}\)N in young massive stars suggests an observational test of the coalescence formation scenario, by analogy with O-type blue stragglers (Kendall et al. 1995).

### 6. Conclusions

1. We have used high signal-to-noise, intermediate resolution H-band spectroscopy to probe the central, ionizing stars of three UC H II regions. In two of the objects, IRAS 18079-1756 and IRAS 17175-3544, we detect the photosphere directly via absorption lines, allowing the derivation of spectral types which are in close agreement with those found by far-infrared observations.

2. In a third object, we detect no absorption, but a rich emission line spectrum. We identify this object, IRAS 17441-2910, as an additional member of the small subset of massive YSOs displaying strong emission (including CO) and which are likely to be at an extremely early evolutionary stage, surrounded by dense circumstellar material. The large infrared excess of IRAS 17175-3544, coupled with the observation of emission lines, also places it in this category.

3. IRAS 17175-3544 and IRAS 18079-1756 exhibit composite spectra, including absorption lines of neutral metals normally observed in cool stars, as well as H and He lines arising in the OB photospheres of or nebulosity associated with the targets themselves. Both these objects are associated with small clusters, as observed in our acquisition images. For IRAS 17175-3544,
we identify the source of the metal lines as IRS-I 1W (Persi et al. 1996) and suggest that this object is a system of low mass embedded objects associated with the massive source itself. For IRAS 18079-1756 we tentatively suggest a similar scenario, although there is no direct evidence from imaging. In neither case can the spectra presented here rule out a chance superposition of a foreground late-type object causing the composite spectra, but if such a foreground star exists, it does not appear on SuperCosmos UKST I-band images of the two near-infrared sources.

4. H or K-band spectra at a comparable or slightly higher resolution to those in this study, with high signal-to-noise ratio, may be amenable to quantitative analysis; e.g. derivation of projected rotational velocities and perhaps surface gravities, in the same way as for optical spectra. This will open up a new method to study massive YSOs at the earliest stages of their formation. Both bandpasses are likely to be useful: sources will be brightest in the K-band, where CO is also observed, but the H-band promises greatly reduced veiling and is likely to be a better wavelength region to seek weak metal absorption lines.

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