GEMINI near-infrared spectroscopic observations of young massive stars embedded in molecular clouds

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ABSTRACT

K-band spectra of young stellar candidates in four Southern hemisphere clusters have been obtained with the Gemini Near-Infrared Spectrograph in Gemini South. The clusters are associated with IRAS sources that have colours characteristic of ultracompact H II regions. Spectral types were obtained by comparison of the observed spectra with those of a near-infrared (NIR) library; the results include the spectral classification of nine massive stars and seven objects confirmed as background late-type stars. Two of the studied sources have K-band spectra compatible with those characteristic of very hot stars, as inferred from the presence of C IV, N III and N V emission lines at 2.078, 2.116 and 2.100 μm, respectively. One of them, I16177 IRS1, has a K-band spectrum similar to that of Cyg OB2 7, an O3If* supergiant star. The nebular K-band spectrum of the associated Ultra-Compact (UC) H II region shows the s-process [Kr III] and [Se IV] high excitation emission lines, previously identified only in planetary nebula. One young stellar object was found in each cluster, associated with either the main IRAS source or a nearby resolved Midcourse Space eXperiment (MSX) component, confirming the results obtained from previous NIR photometric surveys. The distances to the stars were derived from their spectral types and previously determined JHK magnitudes; they agree well with the values obtained from the kinematic method, except in the case of IRAS 15408−5356, for which the spectroscopic distance is about a factor of 2 smaller than the kinematic value.

Key words: stars: early-type – H II regions.

1 INTRODUCTION

Massive star-forming regions are commonly found embedded in high-density molecular clouds. They can be traced, e.g., by the presence of CO (Churchwell, Walmsley & Wood 1992; May et al. 1993; Hofner et al. 2000), CS (Churchwell, Walmsley & Wood 1992; Bronfman, Nyman & May 1996) and NH3 (Cesaroni, Walmsley & Churchwell 1992; Cesaroni et al. 1994), transitions in the radio spectra of the clouds, and are often associated with methanol and water masers. The presence of young massive stars still embedded in their parental molecular cloud can also be inferred from radio continuum and line surveys of IRAS sources selected according to specific colour criteria (Caswell & Haynes 1987; Wood & Churchwell 1989).

Due to the large column density of gas and dust, young clusters are often affected by high visual extinction, sometimes over 30 mag, which makes them undetectable at optical wavelengths. Dutra et al. (2003) identified many previously unknown stellar cluster candidates in the near-infrared (where the extinction is about a 10th of that in the visual window), using the Two-Micron All-Sky Survey (2MASS). The 2MASS images not only have been used to discover new young clusters, but also to obtain physical properties of their members (Borissova et al. 2003; Leistra et al. 2005), although the limited spatial resolution (~2 arcsec) restricts its usage to non-crowded regions. Several authors have taken advantage of the higher spatial resolution provided by the new generation of near-infrared (NIR) array detectors to study clusters with high stellar surface density (Horner, Lada & Lada 1997; Gomes & Kenyon 2001; Figuerêdo et al. 2002, 2005; Hanson, Luhman & Rieke 2002; Massi, Lorenzetti & Giannini 2003; Balog et al. 2004; Kumar, Kamath & Davis 2004; Lada & Muench 2004; Whitney et al. 2004; Arias, Barba & Morrell 2007; Barba & Arias 2007).

Roman-Lopes, Abraham & Lépine (2003), Roman-Lopes & Abraham (2004a,b), Roman-Lopes & Abraham (2006a,b), Ortiz, Roman-Lopes & Abraham (2007) and Roman-Lopes (2007) used the NIR camera CamIV, attached to the telescopes of the Pico dos
Dias Observatory, to study clusters associated with high-density molecular clouds and IRAS sources with colours of ultracompact H\textsc{ii} regions. In these studies, JHK colour–colour (C–C) and colour–magnitude (C–M) diagrams were used to select the cluster member candidates. Their spectral types were estimated by dereddening magnitudes and colours in the C–M diagram up to the point where they intercept the zero-age main-sequence line. This method depends on an accurate knowledge of at least three parameters: (i) the distance to the cluster, (ii) the extinction law in that direction and (iii) the excess emission due to the possible presence of circumstellar material around each individual star, which mainly affects the K-band magnitudes.

Most studies of embedded clusters assume kinematic or statistical distances and make use of a standard interstellar extinction law (Rieke & Lebofsky 1985), even though deviations have been reported in dense molecular clouds (Tapia 1981; Indebetouw et al. 2005; Nishiyma et al. 2006). In addition to that, it is well established that massive young stellar objects (YSOs) have large infrared excess due to the presence of warm circumstellar dust (Grasdalen et al. 1975; Lada & Adams 1992), which will be reflected in an incorrect estimation of their spectral types. To circumvent part of these problems, spectral types of some of the cluster members can be determined from the K-band spectroscopy and can be used to determine the distances to the clusters assuming different extinction laws.

In this work, we present K-band spectra of a sample of southern massive star candidates obtained with the Gemini Near-Infrared Spectrograph (GNIRS). All targets were selected from previous NIR studies (Roman-Lopes et al. 2003; Roman-Lopes & Abraham 2004a,b; Ortiz et al. 2007). With this study we intend to obtain spectral classification of the most massive candidates in these clusters, and from them the cluster distances using the spectroscopic parallax technique. These distances are compared to those derived from kinematical methods, and can be eventually used to improve the rotation model of our Galaxy.

This paper is organized as follows. Section 2 presents a summary of the four studied regions. Section 3 reports the observations, data reduction and results. In Section 4, we discuss the results obtained for each cluster, and in Section 5 we present our conclusions.

2 THE STELLAR CLUSTERS

The sources chosen for this work belong to young stellar clusters in the Southern hemisphere, which are associated with the IRAS 09149–4743, IRAS 15408–5356, IRAS 16132–5039 and IRAS 16177–5018 sources, previously studied using infrared imaging techniques.

The first cluster, associated with IRAS 09149–4743, belongs to the Vela Molecular Ridge (VMR) and is probably related to the optical H\textsc{ii} region RCW 41. Ortiz et al. (2007) obtained JHK photometry of this cluster at 1.3 arcsec spatial resolution. The authors suggested two stars as the more likely candidates to ionize the nebula: IRS1, located at the centre of the IRAS error ellipse, and IRS2, a member of a small ‘subcluster’ containing six stars, situated 1.1 arcmin south-east of the IRAS position and associated to the MSX 6C-G270.2795+0.08353 source. They also found another bright source, IRS3, the reddest object in the cluster. The K-band image of the region obtained by Ortiz et al. (2007) is presented in Fig. 1(a), where these three program stars are identified, together with other stars that fell into the spectrograph slit.

The second cluster is associated with the source IRAS 15408–5356 and the H\textsc{ii} region RCW 95; it is seen against the Sagittarius–Carina and Scutum–Crux spiral arms. This cluster was studied in detail by Roman-Lopes & Abraham (2004b), who obtained JHK photometry of the sources in the region. A nebula is clearly visible in their images, with a clump of embedded stars that include two of the probable ionizing sources of RCW 95, IRS1 and IRS3, as shown in Fig. 1(b).

The third cluster is associated with the IRAS source 16132–5039 and is associated with the H\textsc{ii} region RCW 106. The infrared image obtained by Roman-Lopes & Abraham (2004a), shown in Fig. 1(c), reveals a spheroidal nebula containing a bright star at its centre, IRS1, and a smaller concentration of stars to the south-west of the IRAS source, which coincides with the mid-infrared source MSX 5C G332.5302-00.1171; the brightest source in this subcluster is labelled as IRS3.

The fourth cluster is associated with IRAS 16177–5018 and, together with IRAS 16132–5039, is embedded in the H\textsc{ii} region RCW 106. Roman-Lopes et al. (2003) obtained JHK images and a photometry of the reddest stars, which have visual extinction exceeding 28 mag. The brightest source is IRS1, located at the centre of the infrared nebula, which together with IRS7 seem to play a key role in the energy balance of the compact H\textsc{ii} region (Roman-Lopes et al. 2003). An image of the region, with the two stars indicated, is shown in Fig. 1(d).

3 OBSERVATIONS AND RESULTS

3.1 GNIRS data

K-band spectra of the point sources indicated in Fig. 1 were obtained on different dates using GNIRS (Elia et al. 2006) on the 8-m Gemini South telescope at Cerro Pachon, Chile. Table 1 shows the log of observations. In all cases, the short camera with a pixel scale of 0.15 arcsec pixel$^{-1}$ and a slit size of 0.675 $\times$ 99 arcsec$^2$ was employed. The resolving power of this configuration is 1600, with a theoretical wavelength coverage ranging from 1.90 to 2.50 $\mu$m.

In order to obtain good results in the sky subtraction process, the standard ABBA nodding technique was used to acquire the spectra. The large slit length (99 arcsec) enabled us to perform large node shifts with the target still on the slit. This is especially useful when observing regions where the nebular lines (like Br$\gamma$) are spatially extended, to avoid the overlap of AB positions that would create artefacts in the sky-subtracted images. Individual exposure times at each nod position were 3 min for the science targets; total exposure times are listed in Column 5 of Table 1. In order to correct the science spectra for the effect of telluric atmospheric absorption, a nearby A0$\text{V}$ spectroscopic standard star was observed at similar airmass (Column 7 of Table 1), before or after the set of exposures of each science target.

The GNIRS data were reduced using the GEMINI package within IRAF.$^1$ First, the two-dimensional K-band frames were sky-subtracted for each pair of images taken at the two nod positions, A and B, followed by division of the resultant image by a flat-field. Multiple exposures for each source were combined, followed by one-dimensional extraction of the spectra. Eventually, wavelength

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$^1$IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation
Figure 1. NIR finding charts (taken from previous NIR imaging surveys) of the clusters associated with IRAS 09149−4743 (a), IRAS 15408−5356 (b), IRAS 16132−5039 (c) and IRAS 16177−5018 (d) sources. Each image is about 2 × 2.5 arcmin² in size. North is to the top and east is to the left. In each cluster, we indicate the slit position (dotted lines) and the sources for which we obtained K-band GNIRS spectra. Based on the GNIRS acquisition images, we found that IRAS 09149−4743IRS1 and IRAS 15408−5356IRS3 are in fact double, as shown in the insets in panels (a) and (b), respectively, at plate scale of 0.15 arcsec per pixel.

Table 1. The log-book of the GNIRS observations. The columns are: (1) the associated IRAS source; (2) the identifier of the point source, as designated in the original photometric survey; (3, 4) equatorial coordinates (J2000.0); (5) the total integration time (s); (6) the mean airmass at the time of the observations; (7) the Hipparcos identifier of the associated A0V telluric star; (8) the mean airmass of the telluric star at the time of the observations; (9) lists the Gemini identification program and (10) the corresponding date of observation.

| Source     | IRS | α (J2000.0) | δ (J2000.0) | Time (s) | X Telluric | X ID program | Date          |
|------------|-----|-------------|-------------|----------|------------|--------------|---------------|
| 09149−4743 | 1    | 09h16m43s50 | −47°56′23″ | 540      | 1.07       | HIP40974     | 2005 December 23 |
| 09149−4743 | 2    | 09h16m47s94 | −47°57′18″ | 132      | 1.06       | HIP40974     | 2005 December 23 |
| 15408−5356 | 1    | 15h44m43s40 | −54°05′53″ | 180      | 1.30       | HIP75161     | 2005 December 24 |
| 15408−5356 | 2    | 15h44m43s40 | −54°05′53″ | 180      | 1.34       | HIP75161     | 2005 December 24 |
| 16132−5039 | 3    | 16h16m56s17 | −54°07′18″ | 360      | 1.57       | HIP75161     | 2006 January 22  |
| 16177−5018 | 1    | 16h21m31s60 | −50°25′08″ | 1080     | 1.56       | HIP83818     | 2006 January 24  |

calibration was performed using sky lines; the typical error (1σ) for this calibration was ∼5 Å. A telluric atmospheric correction using the spectroscopic standard stars completed the reduction process. In this last step, we divided the target spectra by the spectrum of the A0 v spectroscopic standard star, already free of photospheric features. In the standard star, the Brγ absorption is the only feature present in the K-band spectrum. It was carefully removed by interpolation across its wings using continuum points on either side of the line while its core was modelled using a Voigt profile. In order to assure good cancellation of the telluric bands, the IRAF task TELLURIC was employed. The algorithm interactively minimizes the rms in specified wavelength regions by shifting and scaling the target relative to the standard spectrum to best divide out telluric features present in the former. Shifting accounts for small errors in the dispersion zero-points, while the intensity scaling corrects for differences of airmass and variations in the abundance of the telluric species. Typical values of the shifts were a few tens of a pixel (equivalent to ∼2 Å) and the scaling factors were less than...
10 per cent. As an example, Fig. 2 shows the spectra of the A0v standard star HIP83818 (already free of the Brγ line), the science target IRAS 16177–5018, and its spectrum corrected from the effects of the telluric absorption bands.

### 3.2 Correcting the science spectra for nebular contamination

As can be inferred from Figs 1b and 1d, the regions associated with IRAS 15408−5356 and IRAS 16177−5018 present strong extended emission. In fact, the K-band spectra of IRAS 15408−5356, IRS1, IRAS 16177−5018, IRS1 and IRAS 16177−5018 are contaminated by Brγ and He I (2.058 μm) nebular components. Since these lines play a fundamental role in the spectral classification, they must be carefully subtracted from the stellar spectrum. To do that, we evaluated the nebular contribution at the position of the point sources by studying the intensity profiles of the Brγ and He I (2.058 μm) lines as function of the position along the slit.

In Fig. 3, we illustrate the procedure used in the case of the sources belonging to the IRAS 16177−5018 cluster. At the bottom panel of this figure, we present the contour diagram made from the GNIRS acquisition image; there we indicate the position on the slit of IRS1 and IRS7, with the spatial coordinate scale measured in pixels. Figs 3(a) and (d) show the spectral intensity at the wavelength of the Brγ and He I (2.058 μm) lines, respectively, which include the continuum emission. After the subtraction of the continuum, taken at ±30 Å (about 6 pixels) off the line centre and shown in Figs 3(b) and (e), we obtained the Brγ and He I (2.058 μm) line contributions, presented in Figs 3(c) and (f), respectively, where we can see the nebular emission at both sides of the stars. In Fig. 3(f), He I (2.058 μm) is clearly seen in absorption at the position of IRS1, while no absorption is present in Brγ in Fig. 3(c). This procedure was used to obtain the spectra of all stars embedded in ionized clouds, even when the nebular contribution was small.

### 3.3 Spectral classification

The GNIRS spectra have been organized in three groups. In the first one, the detected lines are characteristic of hot stars (Brγ, He I 2.058 μm, He I 2.113 μm, He II 2.185 μm, C IV 2.078 μm, N II 2.116 μm, among others); they are shown in Fig. 4 in the order of increasing Brγ equivalent width.

The spectra of the sources in the second group, shown in Fig. 5, present weak Brγ, metallic (Na, Ca, Mg, etc.) and molecular (CO overtones) lines, characteristic of late-type stellar spectra. Finally, the third group shows H and He lines in emission but no photospheric absorption lines, which are characteristic of YSOs; their spectra are shown in Fig. 6.

The library of K-band early-type spectra compiled by Hanson, Conti & Rieke (1996) was used to classify the stars in our sample. Since both spectra have similar resolution, the classification of the stars in Group 1 was made by a direct comparison. For each star, we show the library spectrum that best matches the target one, as well as earlier and later-type library spectra (Figs 7, 8, 9 and 10).

The derived spectral types are presented in Table 2, together with the absolute $M_V$ magnitudes. They were computed considering the $M_V$ magnitudes taken from Hanson, Howarth & Conti (1997) and Walborn (2002), and the intrinsic colours given by Koornneef (1983) transformed into the 2MASS photometric system. Columns 6 and 7 list the intrinsic $(J−H)_0$ and $(H−K)_0$ colours corresponding to each spectral type. Columns 8, 9, 10 and 11 list the measured $J$ and $K$ magnitudes, as well as the $(J−H)$ and $(H−K)$ colours obtained from previous works (Roman-Lopes et al. 2003; Roman-Lopes & Abraham 2004a,b; Ortiz et al. 2007).

### 3.4 Determination of the distances

The distances $d$ to the stars were determined using absolute and measured magnitudes, presented in Table 2, in the equation:

$$m_V - M_V = 5 \log [d(\text{pc})] - 5 + A(\lambda).$$  \hspace{1cm} (1)$$

The absorption $A(\lambda)$ is related to the colour excesses $E(J − H)$ and $E(H − K)$ through the functions $F_J(R) = A(J)/E(J − H)$ and $F_K(R) = A(K)/E(H − K)$ that depend on the ratio of the total to the selective extinction $R = A_V/E(B − V)$. Using the interstellar extinction laws given by Fitzpatrick (1999), it is possible to obtain the ratios $A_J/A_V = f_J(R), A_K/A_V = f_K(R), E(J − H)/E(B − V) = g_J(R)$.
and \( E(H - K)/E(B - V) = g_K(R) \) from which the functions \( F(R) = R f(R)/g(R) \) can be derived.

A source of uncertainty in the distance determination originates from the use of the standard interstellar extinction law, which is represented by \( R = 3.1 \), though it is common to find \( R \) in the range 2.8–5.8 along the Galactic plane (Johnson 1965; Tapia 1981; Fitzpatrick 1999; Indebetouw et al. 2005; Nishiyama et al. 2006). This effect is probably produced by differences in the metallicity and the grain size distribution (Savage & Mathis 1979). It was taken into account by using \( R = 2.8, 3.1 \) and 5.0, and the distance to each star was calculated as the average of these individual values.

Another important source of error comes from the spectral type determination itself, which in our work has an uncertainty of about ± one subtype. For O-type stars, it represents about 0.2 mag in the NIR, whereas for early-B stars it is about 0.6 mag (Hanson et al. 1997). The only exception is the 116177–5018 IRS1 source, for which the true luminosity class is an important source of uncertainty; this issue will be discussed in detail in Section 4.

A third source of uncertainty results from the fact that young stars can be surrounded by disc and/or dust cocoons, which produce excess emission in the NIR (Grasdalen et al. 1975; Glass 1979; Lada & Adams 1992), especially in the \( K \) band. In order to minimize this effect, we used both the \( J \)- and \( K \)-band photometry to derive distances.

Table 3 shows the values of \( E(J - H), E(H - K), A_J \) and \( A_K \) for three values of total to selective extinction ratios (2.8, 3.1 and 5.0). The stellar distances \( d \) were computed as the average of the distances obtained from the \( J \) and \( K \) magnitudes and the three extinction laws. The quoted errors for the distances are the standard deviation of the averaged values, which include the errors associated with the photometry, interstellar extinction law and spectral type, as discussed above. Finally, the distance to each cluster (Column 13) was computed as the average of the distances to each star in the cluster; the total error of these values is the square root of the sum in quadrature of the individual errors.

4 DISCUSSION

In this section, we discuss our main results and compare them with those obtained in the previous works.

4.1 The IRAS 09149–4743 cluster

In this region, three program stars were chosen for observation: IRS1, IRS2 and IRS3. In addition, three other sources located nearby had their spectra taken as well: IRS18, IRS25 and IRS31 (Ortiz et al. 2007). Their relative positions are shown in Fig. 1(a). The source labelled as IRS1 was resolved into two stars in this work: IRS1a and IRS1b (see the inset in Fig. 1a). The spectra of IRS1a and IRS2, shown in Fig. 4, exhibit two important diagnostic lines commonly found in stars earlier than B1: \( \text{H} \beta \) Br–\( \gamma \) at 2.166 \( \mu \)m and the \( \text{He} \)\( \alpha \) line at 2.113 \( \mu \)m. The source IRS1a was classified as a B0\( \text{v} \) star (Fig. 7a), affected by 9 mag of visual extinction (Table 3), which places it at a distance of about 1.20 ± 0.12 kpc.

IRS2, belonging to the nearby subcluster located at 1.1 arcmin to the south-east of IRS1, is probably an O9\( \text{v} \) star (Fig. 7b) affected by about 7–8 visual magnitudes; it is located at 1.27 ± 0.13 kpc, virtually the same distance as IRS1a. IRS31 belongs to the same subcluster as IRS2. Its spectrum (Fig. 7c) exhibits a strong Br–\( \gamma \) line, characteristic of late-B and early-A stars. This source has been classified as a B7\( \text{v} \)–B8\( \text{v} \) star, suffering 5–8 mag of extinction in the \( V \) band (Table 3). Its distance is about 1.37 ± 0.19 kpc, thus reinforcing its membership.

The distances to the three massive stars studied in this region are similar, resulting in a mean cluster distance of 1.3 ± 0.2 kpc. This value can be compared with the photometric distance of 0.7 ± 0.2 kpc quoted by Liseau et al. (1992) for Cloud A in the VMR complex, and the kinematic distance of 1 kpc inferred from CO observations by Murphy & May (1991). The good agreement between our result and that obtained from the Galactic rotation curve is notable, considering the complexity of the VMR and the small radial velocity resulting from its position close to \( l = 270^\circ \).

In Fig. 6, we can see that IRS1b shows no photospheric spectral lines, but Br–\( \gamma \) in emission and some CO overtone band-heads in absorption, characteristic of YSOs (Casali & Eiroa 1996; Hoffmeister et al. 2006). These CO lines are believed to be formed in a warm and dense circumstellar shell, possibly a relic of a former accretion disc. They can be seen in absorption or emission depending on the disc opacity, which in turn depends on the mass accretion rate, as...
shown by Calvet et al. (1991). Ortiz et al. (2007) also pointed out that IRS1a+b shows intense infrared emission beyond 5 μm, usually attributed to warm dust. Based on the present data, we can now state that the observed infrared excess comes from IRS1b, the dusty nearby companion of the IRS1a source.

IRS3 is a highly reddened IR source (Ortiz et al. 2007), located at about 1 arcmin west of IRS1 (Fig. 1a). Its spectrum, shown in Fig. 5, exhibits metallic and molecular absorption lines, such as the CO (2, 0) and (3, 1) transitions at 2.29 and 2.32 μm, respectively, as well as the Ca I and Na I lines at 2.21 and 2.26 μm, typical of K and M giant stars. Assuming its spectral classification as early-K, we can estimate a lower limit for its distance. Its absolute magnitude and intrinsic colour index would be $M_J = -1.9$ and $(J-H) = 0.62$, which implies a colour excess $E(J-H) = 1.42$. If one assumes $R = 3.1$, then $A_J = 4.34$ and $d = 2.5$ kpc. On the other hand, if $R = 5.0$, then $A_J = 4.76$ and $d = 2.0$ kpc. In any case, the distance to this star would be twice as large as the distance to RCW 41. Besides IRS3, two other stars in the neighbourhood have been classified as late-type: IRS18 and IRS25 (Fig. 5). Similar to IRS3, they occupy a position in the $(J-H)$ versus $(H-K)$ C–C diagram consistent with their classification as late-type stars, and their $JHK$ magnitudes given in Ortiz et al. (2007) imply that they must also be the background objects.

4.2 The IRAS 15408–5356 cluster

In this cluster, spectra of four program stars (IRS1, IRS2, IRS3 and IRS4) were obtained. The spectrum of IRS1 is shown in Fig. 4. It presents features typical of very hot stars, such as C IV (at 2.078 μm) and N III (at 2.116 μm) in emission, characteristic of stars with spectral type earlier than O6. A direct comparison with the library templates of Hanson et al. (1996) allowed us to classify it as O5.5 (Fig. 8a). Morisset (2004) found that the relative intensities of mid-infrared emission lines observed by the Infrared Space Observatory require an ionizing source with effective temperature $T_{\text{eff}} = 48 700$ K, equivalent to an O3 star, implying that other stars must be contributing to the total ionizing luminosity.

IRS3, similar to IRS1, was previously suggested to be one of the main ionizing sources of RCW 95 (Roman-Lopes & Abraham 2004b). It actually consists of two stars, labelled as IRS3a and IRS3b, as shown in the inset in Fig. 1(b). The former presents an unexpected spectrum; it does show the hydrogen Brγ and the He I lines typical of hot stars, but also the CO band-head overtone lines in absorption, characteristic of late-type stellar atmospheres. Although CO overtone bands in absorption have been widely reported in low-mass YSO spectra (Straw, Hyland & McGregor 1987; Straw et al. C⃝ 2009 The Authors. Journal compilation C⃝ 2009 RAS, MNRAS 394, 467–478
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2.1 2.2 2.3 2.4
-0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
Mg I Fe I CO (5-3) CO (4-2)

Figure 5. GNIRS spectra of the late-type stars detected in this work. All spectra were continuum flux normalized and are at same scale.

1987; Carr 1989; Casali & Matthews 1992), they have also been found in a few late-O/early-B stars (Hoffmeister et al. 2006). The origin of these CO features is not clear; they might be the signatures of a cold star in the same line of sight or simply neutral gas in the interface between the H\textsc{ii} region and the molecular cloud. Apart from the CO lines beyond 2.3 \( \mu \)m, this star can be classified as O9.5 v, as shown in Fig. 8(b). IRS3b has been classified as a B3/B5 v star (Fig. 8c).

Bik et al. (2005) obtained K-band spectra for two stars in common with the studied region: 15408nr1410 (O5 v-O6.5 v) and 15408nr1454 (O8 v-B2.5 v) and, according to their coordinates (Bik & Thi 2004), these objects correspond to sources IRS1 (O5.5 v) and IRS3a (O9.5 v). Therefore, the spectral classification of the two works agrees with each other within the error bars.

The spectrum of IRS2, seen in Fig. 6, does not present any evident photospheric feature, except for the Br\( \gamma \) emission line, superposed on an absorption profile. Another emission line near 2.27 \( \mu \)m might be due to the 4-3 S(4) H\textsubscript{2} transition. Differently from IRAS 09149\textminus4743 IRS1b, the spectrum of IRS2 does not show any evidence of a CO environment that could be associated with circumstellar discs. However, since this object shows large IR colour excess and is associated with the bright source MSX 6C-G326.6570+00.5912, our result confirms its previous classification as a YSO (Roman-Lopes & Abraham 2004b).

Three additional less luminous stars located near IRS2 fell into the slit: IRS10 and other two sources not included in the previous photometric study of the region, labelled as IRS2\textsubscript{ap2} and IRS2\textsubscript{ap3}. Their spectra, shown in Fig. 5, are characteristic of late-type stars. This result implies that IRS10 is not one of the ionizing sources of RCW 95, as previously proposed considering its JHK magnitudes and colours (Roman-Lopes & Abraham 2004b). Its location in the C–C diagram seems to result from its low effective temperature and the high extinction of the cloud, which together mimic the colour indices of young, massive stars.

The spectrum of IRS4, shown in Fig. 5, is clearly late-type, with strong CO absorption lines in the spectral region between 2.29 < \( \lambda < 2.4 \) \( \mu \)m. One can also see a few metallic lines, probably due to NaI and CaI transitions, which reinforces this classification.

The distances to the early-type sources have been determined from their spectral types, J and K magnitudes and E(J – H) and E(H – K) colour excesses, as described in Section 3.4 and presented in Table 3, with the exception of source IRS3b. Since no photometric data are available for this object, we used the visual absorption calculated for IRS3a instead, and the K magnitude obtained from the GNIRS K-band acquisition image. The instrumental GNIRS magnitudes were calibrated using the combined K magnitudes of IRS3a and IRS3b, obtained from the work of Roman-Lopes & Abraham (2004b). The resulting individual K magnitudes are 9.5 and 12.0 for IRS3a and IRS3b, respectively.

The derived distances to all stars observed in this cluster are similar, like in IRAS 09149—4743, ranging from 1.32 ± 0.20 kpc for IRS3a to 1.34 ± 0.16 kpc for IRS1, giving a mean distance of 1.3 ± 0.2 kpc for the IRAS 15408—5356 cluster. Giveon et al. (2002) derived a kinematic distance of 2.4 kpc using the Galactic
Figure 7. GNIRS $K$-band spectra of IRAS 09149$-$4743 sources (red lines) overlaid on $K$-band spectra (black lines) taken from the library of Hanson et al. (1996).

Figure 8. GNIRS spectra of IRAS 15408$-$5356 IRS1, IRS3a and IRS3b sources (red lines) overlaid on $K$-band spectra (black lines) taken from the library of Hanson et al. (1996).
rotation curve, assuming galactocentric distance of 8.5 kpc and a solar rotation velocity of 220 km s\(^{-1}\). This is about twice to what we have found, showing that at least in this direction, the Galactic kinematic model fails. In fact, differences between the kinematic distances derived from radio observations and those obtained by spectroscopic parallaxes were also found by Blum, Damineli & Conti (1999); Blum, Conti & Damineli (2000) and Figueredo et al. (2005), showing the importance of spectrophotometric studies for a better understanding of the rotation curve of the Galaxy.

### 4.3 The clusters in the RCW 106 region

The two clusters associated with IRAS 16132−5039 and IRAS 16177−5018 are part of the RCW 106 complex. One program target was observed in each star formation region: IRS3 in the former cluster and IRS1 in the latter.

The spectrum of the IRS1 source (Fig. 4) shows C\(IV\), N\(III\) and N\(v\) emission lines at 2.078, 2.116 and 2.100 \(\mu\)m, respectively, He\(\text{II}\) at 2.189 \(\mu\)m in absorption and a weak B\(\gamma\) line. The presence of the N\(v\) line indicates that IRS1 might be a very hot star. In fact, such line is only found in the K-band spectra of O3\(-\text{O}5\)I\(f^+\) supergiant stars (Hanson et al. 2005).

In Fig. 9(a), we compare the IRS1 spectrum with that obtained for O3–O5I\(f^+\) supergiant stars (Hanson et al. 1996). One can note that the GNIRS spectrum resembles well with that of Cyg OB2 7, an O3\(f^+\) star. For completeness, in Fig. 9(b) we also compare the IRS1 spectrum with that of O3–O6 main-sequence stars. In this case, we see a reasonable agreement between the GNIRS spectrum features with that from the HD93250 (O3\(v\)), HD164794 (O4\(v\)) and HD93204 (O5\(v\)). The exceptions are the B\(\gamma\) and He\(\text{II}\) lines, which in the templates appear stronger in absorption.

There are additional constraints indicating that the main ionizing source of the compact \(H\pi\) region probably is an extremely
hot source. From the K-band spectrum of the associated nebular emission, which is shown in Fig. 11, we can see the presence of strong emission lines like the Brγ (2.166 μm), Hei (2.058, 2.113 and 2.161–2.162 μm) and [Fe II], which are normally found in H II regions hosting embedded hot stars. We also found the s-process [Kr III] and [Se IV] high excitation emission lines, previously identified only in the planetary nebula (Sterling, Dinerstein & Kallman 2007), Blum & McGregor (2008) also detected such lines in their study of the ionizing stars associated with the UC H II region G45.45+0.06, suggesting that high-density H II regions excited by the hottest O stars would also produce such emission lines. Indeed, the measured Hei 2.113/Brγ ratio (see Fig. 11) of 0.045 ± 0.003 (not corrected for reddening) indicates the presence of an exciting star whose \( T_{\text{eff}} \) is greater than 40 000 K (Hanson et al. 2002). This would correspond to a star of spectral type earlier than O5, O4.5 III and O4 I (taking into account the luminosity class), as inferred from the new calibration of O star parameters published by Martins, Schaerer & Hillier (2005).

The fact that IRS1 has a K-band spectrum similar to that of Cyg OB2 7, the detection of the s-process [Kr III] and [Se IV] high excitation emission lines (from the associated UC H II region), and the lower limit to the effective temperature (40 000 K) for the main ionizing source in the region, is reasonable to suppose that IRS1 may be an O3 supergiant star (or alternatively a very hot ionizing source). Taking into account the rarity of such type of objects, this is an extraordinary result, which could indicate that RCW 106 may be the birthplace of extremely massive stars.

The presence of a supergiant star in a young massive stellar cluster could be questioned in view of the youth of the sources in the region (Roman-Lopes et al. 2003). In fact, Roman-Lopes (2007) using the fraction of NIR sources showing excess emission in the NIR estimated the age of the cluster as 2.5–3.0 Myr. Indeed, other O-type giants and supergiants have been found in very young stellar clusters. For instance, Massey, DeGioia-Eastwood & Waterhouse (2001) derived ages for several massive early-type stars and found values in the range 1.0–3.0 × 10^6 yr. Recently, Melena et al. (2008) detected several early O-type giant and supergiant stars with similar ages.

Assuming that IRS1 is an O3 f+ supergiant star, we computed its distance as 2.6 ± 0.7 kpc, compatible with that of 2.8 ± 0.6 kpc obtained from the Galactic rotation curve assuming \( R_0 = 8.5 \text{ kpc} \), \( \Theta_0 = 220 \text{ km s}^{-1} \) (Honma & Sofue 1997) and a radial velocity \( V_R = -49.5 \text{ km s}^{-1} \). On the other hand, considering IRS1 as an O3–O5 v star, the distance drops to about 1.2 ± 0.7 kpc. Indeed, further K-band spectroscopic observations of other nearby NIR sources will be necessary to improve our understanding of the Galactic structure in this direction.

Bik et al. (2005) also used the NIR spectroscopy to estimate the distance to this cluster. Three sources were observed (16177nr271, 16177nr405 and 16177nr1020), but unfortunately there are no coordinates or other information that would allow us to perform a cross-correlation between those data with ours. The individual determinations of the distance in that work show somewhat large error bars (1.0–3.7 kpc), but considering its mean value of about 2.4 kpc, their results can be considered consistent with ours.

Another observed point source in this cluster is IRS7 whose spectrum does not show any photospheric spectral feature but shows the Brγ and Hei (2.059 μm) lines in emission, characteristics of a young stellar object (Fig. 6). As pointed out by Roman-Lopes et al. (2003), this object coincides with the mid-infrared source MSX 6C-G333.3072-00.3666, which reinforces this classification. We note a P-Cygni profile in the He1 line at 2.058 μm that may indicate the presence of expanding material inside the region. High-resolution radio observations would be useful to clarify this issue.

The other studied cluster in RCW 106 is IRAS 16132–5039. During the observation of IRAS 16132–5039 IRS3, three stars fell into the slit: IRS3 itself, which has a K-band spectrum similar to O9.5 v/B0 v (Fig. 11a), and two additional sources: IRS3_acp2, identified as a YSO (Fig. 5), and IRS3_acp3, a B8V/B9V star (Fig. 11b). Similar to IRAS 15408–5356 IRS3a, the spectrum of IRAS 16132–5039 IRS3 presents H and He lines as well as CO overtone lines; the possible origin of the CO lines was already discussed in the previous section. The distances to IRS3 and IRS3_acp3 were found to be 2.15 ± 0.50 and 2.64 ± 0.30 kpc, respectively (Table 3). Therefore, it can be concluded that both sources are located at the same distance. The derived spectrophotometric mean distance is about 2.4 ± 0.5 kpc, a value that is compatible with that obtained from the Galactic rotation curve (3.2 ± 0.6 kpc) using the radial velocities taken from the CS (2–1) line (Bronfman et al. 1996) and from the hydrogen recombination lines (Caswell & Haynes 1987).

5 SUMMARY

We report K-band spectroscopic observations of stars in highly reddened young stellar clusters, obtained with GNIRS. We found eight massive main-sequence stars, one possible supergiant, seven late-type stars and four YSOs.

The main-ionizing star in the cluster associated with IRAS 09149–4743 is IRS2 (O9 v), which together with IRS1 (B0 v) are the dominant ionizing sources in the RCW 41 H II region. They
are located in Cloud A of the VMR at a mean distance of 1.3 ± 0.2 kpc, in agreement with the value derived from the kinematic method using CO radial velocities. We found that IRS09149 IRS1 actually consists of two sources: a B0 v star (IRS1a) and a YSO (IRS1b). This result allows us to state that the infrared excess found by Ortiz et al. (2007) comes from the dusty nearby companion of IRS1a. The other bright source in the region, IRS09149 IRS3, is a background giant star located at least twice as far as the cluster, confirming the assumption made by Ortiz et al. (2007), who suggested that this source is a late-type star.

Four K-band spectra were obtained in the cluster associated with RCW 95. IRAS 15408 IRS1 has a K-band spectrum compatible with an O5.5 v star, while IRS3a and IRS3b were classified as O9.5 v and B3-B5 v, respectively. Their distances are similar and have an average value of 1.3 ± 0.2 kpc, in disagreement with the kinematic distance of 2.4 kpc. This seems to indicate that, at least for this star-forming region, the galactic kinematic model fails. Eventually, these results can be used to improve our understanding of the rotation curve of the Galaxy. IRS2, another very bright source in this cluster, is associated with the mid-IR source MSX 6C-G326.6570+0.5912, and was classified by Roman-Lopes & Abraham (2004b) as a YSO candidate. Its K-band spectrum presents Brγ and HeI emission lines characteristic of YSOs, confirming the previous classification.

One of the sources observed in the direction of RCW 106 belongs to the cluster associated with IRAS 16132−5039. Three other stars fell into the spectrograph slit: IRAS 16132 IRS3 (O9.5-B0 v), IRAS 16132 IRS3 ap2 (YSO) and IRAS 16132 IRS3 ap3 (B8-B9 v). The derived mean distance is 2.4 ± 0.5 kpc, a value compatible with that obtained from the kinematic method (3.2 ± 0.6 kpc) using the CS (2-1) and hydrogen recombination lines.

The other cluster in the RCW 106 region is associated with IRAS 16177−5018. The IRAS 16177 IRS1 spectrum presents C IV, N III, and N v emission lines at 2.078, 2.116 and 2.100 μm, respectively, which are seen only in very hot stars. We also detected in the associated nebular K-band spectrum, the s-process [Kr III] and [Se IV] high excitation emission lines, previously identified only in the planetary nebula. In the case of H II regions, such lines seem to be produced only in high-density environment excited by the hottest O stars. Indeed, the measured He I 2.123/Brγ ratio indicates the presence of an exciting star whose T eff is greater than 40 000 K. This would correspond to a single star of spectral type earlier than O5 v, O4.5 m or O4.1, depending on the luminosity class.

We found a good agreement between the IRAS 16177 IRS1 K-band spectrum and that of Cyg OB2 7, an O3If* star. Taking into account the scarcity of supergiants in young cluster (though a few similar occurrences have been reported elsewhere), this is an extraordinary result, which could indicate that RCW 106 is may be the birthplace of extremely massive stars.

Considering IRAS 16177 IRS1 as an O3If* star, the distance to the cluster would be 2.6 ± 0.7 kpc, similar to that of the other massive star formation region in the RCW 106 complex. On the other hand, if IRAS 16177 IRS1 is an O3−O5 main-sequence star, its distance drops to 1.2 ± 0.7 kpc, much smaller than its kinematic distance.

We originally planned to obtain the K-band spectrum for one target in the IRAS 16177−5018 region, but another source also

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Table 2. Derived spectral types for the hot stars in our sample.

| Source   | α (J2000)  | δ (J2000)  | Spectral type | M_J  | (J−H)_ν | (H−K)_ν | J  | (J−H) | K  | (H−K) |
|----------|------------|------------|---------------|------|---------|---------|----|--------|----|-------|
| I09149 IRS1a | 09h16m43s50 | −47°56′23″00 | B0V           | −2.21 | −0.16   | −0.01   | 10.70 | 0.80   | 9.40 | 0.50  |
| I09149 IRS2  | 09h16m47s94 | −47°57′18″00 | O9V           | −3.00 | −0.18   | −0.01   | 9.72  | 0.66   | 8.68 | 0.38  |
| I09149 IRS3a | 09h16m47s77 | −47°57′15″11 | B7/B8V        | −0.270/29.0 | −0.07 | +0.02   | 13.34 | 0.80   | 12.25 | 0.29  |
| I15408 IRS1  | 15h44m43s40 | −54°05′53″7 | O5.5V         | −4.05 | −0.20   | −0.01   | 10.76 | 1.37   | 8.57 | 0.82  |
| I15408 IRS3a | 15h44′56″17  | −54°07′18″1 | O9.5V         | −2.85 | −0.16   | −0.01   | 11.25 | 1.17   | 9.50 | 0.58  |
| I15408 IRS3b | 15h44′56″17  | −54°07′18″1 | O9.5V         | −2.85 | −0.16   | −0.01   | 11.25 | 1.17   | 9.50 | 0.58  |
| I16132 IRS3 | 16h47′50″01 | −50°47′22″7 | O9.5B0V       | −2.85/−2.21 | −0.18/−0.16 | −0.01   | 11.77 | 0.76   | 10.30 | 0.71  |
| I16177 IRS1 | 16h21m31′60 | −50°25′08″3 | O3If*/O3−O5V  | −6.85/−4.95 | −0.21 | −0.01   | 16.65 | 3.92   | 10.21 | 2.52  |

Table 3. Summary of the extinction values and distances to the program stars. For the I16177 IRS1 source we show the distances obtained considering Class I (1) and Class II (2) case.

| Source   | E(J−H) | A_J  | A_J  | A_J  | A_V  | E(H−K) | A_K  | A_K  | A_K  | A_V  | d  | d^2_cluster |
|----------|--------|------|------|------|------|--------|------|------|------|------|----|--------------|
| I09149 IRS1a | 0.96   | 2.5  | 2.6  | 2.8  | 9.1  | 0.51   | 1.0  | 1.0  | 1.1  | 8.9  | 1.20 ± 0.12 | 1.3 ± 0.2 |
| I09149 IRS2 | 0.84   | 2.2  | 2.3  | 2.5  | 8.0  | 0.39   | 0.9  | 0.9  | 1.0  | 6.8  | 1.27 ± 0.13 |          |
| I09149 IRS3 | 0.87   | 2.3  | 2.3  | 2.6  | 8.3  | 0.27   | 0.9  | 0.9  | 1.0  | 4.7  | 1.37 ± 0.19 |          |
| I15408 IRS1 | 1.57   | 4.1  | 4.2  | 4.6  | 14.9 | 0.83   | 1.6  | 1.7  | 1.9  | 14.4 | 1.34 ± 0.16 | 1.3 ± 0.2 |
| I15408 IRS3 | 1.33   | 3.5  | 3.6  | 3.9  | 12.6 | 0.59   | 1.4  | 1.4  | 1.6  | 10.2 | 1.32 ± 0.20 |          |
| I15408 IRS3b | *     | *    | *    | *    | 12.6 | *      | *    | *    | *    | 10.2 | 1.24 ± 0.21 |          |
| I16132 IRS3 | 0.92   | 2.4  | 2.5  | 2.7  | 8.7  | 0.72   | 1.0  | 1.0  | 1.1  | 12.5 | 2.15 ± 0.50 | 2.4 ± 0.5 |
| I16132 IRS3 ap3 | 0.22  | 0.6  | 0.7  | 2.1  | 0.04 | 0.2    | 0.2  | 0.3  | 0.7  | 2.64 ± 0.30 |          |
| I16177 IRS1 | 4.13   | 10.7 | 11.1 | 12.1 | 39.2 | 2.53   | 4.3  | 4.5  | 4.9  | 43.9 | 2.58 ± 0.68 | 2.6 ± 0.7 |
| I16177 IRS1 | 4.13   | 10.7 | 11.1 | 12.1 | 39.2 | 2.53   | 4.3  | 4.5  | 4.9  | 43.9 | 1.22 ± 0.74 | 1.2 ± 0.7 |
fell into the slit: IRAS 16177 IRS7. Its spectrum is typical of an YSO, in agreement with the classification proposed by Roman-Lopes et al. (2003). Its He I (2.058 μm) emission line shows a P-Cygni profile that may indicate the presence of expanding motion. High-resolution radio observations would be useful to clarify this issue.

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