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NEW T TAURI STARS ASSOCIATED WITH IRAS 05555-1405[1]

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RESUMEN

Se presenta por primera vez espectroscopía de rendija de resolución media ($\Delta\lambda/\lambda = 1320$ Å) y la clasificación espectral MK para las estrellas más brillantes que forman el trapecio estelar asociado con la fuente IRAS 05555-1405, en la nebulosa de reflexión vdB64. Los espectros de los cinco miembros más brillantes del conglomerado presentan la línea del Li I λ6708, característica propia de estrellas de Pre-Secuencia Principal (PMS). Nuestros datos se confrontaron con los reportados en el cercano infrarrojo (NIR) en el 2 Micron All Sky Survey (2MASS) para las estrellas, los cuales confirman nuestros resultados.

ABSTRACT

We present for the first time medium resolution ($\Delta\lambda/\lambda = 1320$ Å) slit spectroscopy and MK classifications for the brightest stars that comprise the stellar trapezium associated with *IRAS* point source IRAS 05555-1405, in the vdB64 reflection nebula. The five brightest members of the trapezium are found through their Li I λ6708 feature to be pre-main sequence (PMS) stars. Our data are compared with those of the near infrared (NIR) 2 Micron All Sky Survey (2MASS) which confirms our results.

Key Words: **STARS: INDIVIDUAL (IRAS 05555-1405) — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

The previous optical information on the infrared source IRAS 05555-1405 and its associated reflection nebula, vdB64, is scarce, contradictory, or inexistent (cf. Racine 1968; Gregorio-Hetem et al. 1992; Magnier et al. 1999; Vieira et al. 2003; and references therein). The mid-infrared (MIR) source IRAS 05555-1405 is embedded in the central and most intense region of vdB64. It is unclear which of the stars associated with the region were observed optically by previous authors, except for the star BD−14°1294 (V= $10^{\rm m}\!.4$, Racine 1968), which van den Berg (1966) associates with the reflection nebula vdB64, and star vdB64a (V= $10^{\rm m}\!.5$, Racine 1968, SpT B8V this work). BD−14°1294 is located about 64″ east and 104″ north of IRAS 05555-1405. Considering the locations of these two bright stars with respect to that of vdB64 and its associated phenomena, including its Bok globule and the infrared source (see Magnier et al. 1999, and Figure 1 here), it is unlikely that these stars are physically related to IRAS 05555-1405. This assertion is further sustained by Hubble's relation for reflection nebulosities (Hubble 1922). Although the star vdB64a could be situated at Orion's OB 1c complex ($d \simeq 770$ pc Racine 1968, this work), it clearly does not follow Hubble's relation between the apparent brightness of the responsible star and the apparent size of the reflection nebulosity (Hubble 1922; Dorschner & Gürtler 1964). Moreover, BD−14°1294's red colors emphasize this star's likely independence from the reflection nebulosity. For the vdB64 reflection nebula, Hubble's relation predicts an illuminating star of $V = 13 - 14$ magnitude; this is significantly fainter than either star, and strongly suggests that the fainter, nebulous stars immersed in the densest part of the nebula may play a role. Unfortunately, no reliable spectroscopic data are available for these stellar objects or for the exciting source of IRAS 05555-1405.

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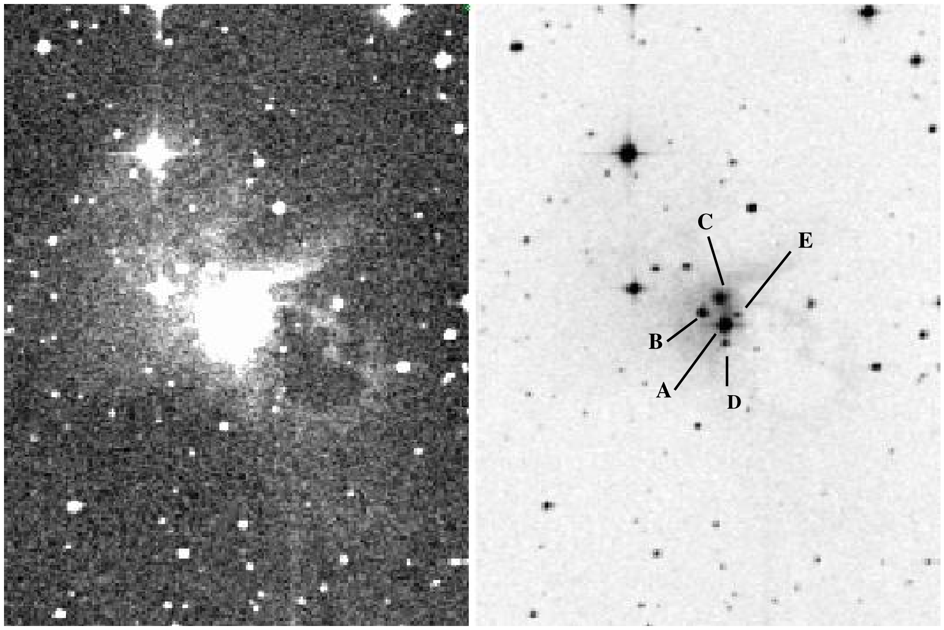

Fig. 1. A 0.14×0.14 degree field centered on the *IRAS* point source IRAS 05555-1405 region containing the Orion-like trapezium, IRAS 05555-1405 and the associated Bok globule to its southwest. The image was taken from the Palomar Observatory Digitized Sky Survey.

The five nebulous stars within or proximate to the error elipse of IRAS 05555-1405 (see Magnier et al. 1999) form a tight Orion-like trapezium[3] ($< D > \approx 0.1 - 0.3$ pc, cf. Gyulbudaghian 1983, 1995). They are unstable to gravitational tides or perturbations and, from their proximity to the Bok Globule nearby and their associated nebulosity, we infer that they have not undergone a significant drift from their birthsite, since the drift velocity is expected to be low, of the order $v_{drift} \approx 1 - 2$ km s^{-1} (e.g., Herbig 1977; Maddalena et al. 1986). Hence, the stellar congregation must necessarily be young (e.g., Ambartsumian 1947; Poveda, Allen, & Warman 1977). Moreover, because of the trapezium's appearance and its similarity to other known young aggregates with ages $\lesssim 10^6$ yr (e.g., trapezia associated with S252, S155, and with HBC498; Chavarría-K, de Lara, & Hasse 1987; Moreno-Corral et al. 1993; Chavarría-K et al. 2005), one expects to find in such a structure PMS intermediate- and low-mass stars. Furthermore, because the cloud-crossing time of a sound wave for such structures is short, $\lesssim 10^6$ yr, the stellar objects can be considered coeval for the purposes of the present work. The pre-main sequence nature of a star is established from key spectral features present in their slit spectrograms (e.g., Herbig 1962, 1977). Astonishingly, recent searches for T Tauri and Herbig Ae/Be stars as well as young stellar objects in the immediate vecinity of IRAS 05555-1405 gave no positive results (cf. Gregorio-Hetem et al. 1992; Magnier et al. 1999). This motivated us to take a closer look at the region.

As a result of our investigation, we found that at least five nebulous stars associated with IRAS 05555-1405 are pre-main sequence (PMS) stars. In the following we report our observations and results. We also discuss the individual stars and this star-forming region.

2. OBSERVATIONS AND DATA REDUCTION PROCEDURES

In the nights of (UT) 1996 February 18 and 2000 February 3 we secured slit spectra of 5 stars embedded in IRAS 05555-1405's reflection nebulosity (see Figure 1) with the *Italian* Boller & Chivens spectrograph attached to the Cassegrain f/7.5 focus of the 2.1 m telescope of the Sierra San Pedro Mártir National Astronomical Observatory (SPMO hereafter). The detector used in both runs was the Metachrome II thinned *CCD TEK* of the SPMO (size = 1024 pixel $\times$ 1024 pixel masked to 275 pixel in the space or "y" direction). For more details about the instrument, see

[3]The distance $< D >$ between any two star members is comparable to the size of the trapezium.

http://haro.astrossp.unam.mx/telescopios/2mt.html. The comparison or "arc" spectra were taken from a He/Ar lamp. The slit width was of 200 μm (= 1.5 arcsec sky-projected). The central wavelength for the spectrograms is $\lambda = 6260$ Å and the spectral range covered is 5100 Å $\leq \lambda \leq$ 7200 Å, with a dispersion of 2.07 Å/pixel and a nominal resolution of 4.1 Å. The true spectral resolution of 5.1 Å, estimated with a Gaussian fit to the arc spectral lines, is smaller because of the slit width used during the observations, but good enough to resolve the Na I-D lines and the Li Iλ6708 resonance doublet from the Ca Iλ6718 photospheric line. The space scale was 0.3 arcsec/pixel. From the width of the bands of the stellar continuum on the spectrograms, we estimated the FWHM size of the (guided) images to be of about $1\farcs2 - 1\farcs4$. The signal-to-noise ratio of the spectrograms was, on the average, 30 (10 or better for the weaker objects, stars D and E, see Fig. 1). According to 2MASS, stars A, B, and C are apparently double, but we did not observe the weaker, northern companions.

Our spectrograms were reduced with the IRAF[4] software package following the usual procedures. Cosmic ray events were removed from the frames, which were then bias- and flat-field corrected. The spectra were extracted and wavelength calibrated with a third order Lagrange polynomial using the apextract task (Massey, Valdes, & Barnes 1992). Once the spectra were reduced and normalized, the MK classifications were found by identifying photospheric lines with help of the multiplet tables by Moore (1945) and by cross-comparison with libraries of stellar spectra with known MK types (e.g., Jacoby, Hunter, & Christian 1984; Alcalá et al. 1996, the SPMO grid of stellar spectral). We interpolated when necessary. From our experience, the spectral types obtained with this procedure from spectrograms with signal to noise ratios S/N $\gtrsim$ 20 in the spectral region of interest are, in the mean, accurate within one subclass. The errors in the MK spectral classification of stars D and E are larger, i.e., $\approx$ 2 subclasses. From a simple quick comparison of our reduced spectrograms of Figures 2 and 3 with the results of Alcalá et al. (1996, their Fig. 1) or Chavarría-K et al. (2005, their Fig. 2), the reader may estimate the goodness of the classification method discussed here. Tracings of the resulting spectrograms of the five nebulous stars are shown in Figures 2, 3, and 4, and in Table 1 we summarize their principal spectroscopic properties. We also supplemented these spectra with data from 2MASS and *IRAS*. The equivalent widths of selected lines given in Table 1 were measured from Gaussian fits to the corresponding lines on the spectrograms. For our case, the largest source of uncertainty of this estimates is given by the signal-to-noise ratio of the spectrograms. These uncertainties are given in Table 1, toghether with the errors of the 2MASS photometric data.

Wichmann et al. (1999) found from a cross-comparison of a representative sample of WTTS and CTTS stars observed with medium and high dispersion resolutions that medium resolution ($\simeq$ 4 Å) spectroscopy of the equivalent width of the Li I resonance line can be a robust tool to single out stars with high lithium content, one of the principal criteria to establish the PMS nature of young stars. None of their Li-rich stars observed with medium resolution proved wrong whith the (follow up) high dispersion data.

3. RESULTS AND DISCUSSION

From the medium-dispersion spectroscopy of the five brightest stars embedded in the densest region of the reflection nebula vdB64, we find the following:

(*i*). The spectrum of star A-south (see Fig. 3) shows photospheric metallic lines of Ca I, Fe I, Fe II, Ti I, Mg I, and Na I with strengths typical of a G5V star and it is the hottest object of the sample. Hα is strong in absorption but slightly filled in with emission when compared with a normal G5V star, and the Li Iλ6708 Å doublet is strong in absorption with an equivalent width of W(Li I) = 0.44 Å. This defines it as a lithium rich star (i.e., its Li content is as abundant or more abundant than its richest-in-lithium counterpart of the Pleiades cluster). These spectral characteristics are typical of weak-line T Tauri stars (e.g., Chavarría-K, Moreno-Corral, & de Lara 1995; Alcalá et al. 1996, and references therein). The star is situated in the immediate vicinity of its birthplace and of its sibling stars (B, C, D, and E of Fig. 1), indicating that it is very young. On the other hand, since weak-line T Tauri stars (WTTSs) have no significant emission line, UV, or IR flux excesses (e.g., Alcalá et al. 1996), its expected IR luminosity is too low by a factor of 10^{-2} or less to account for the infrared flux observed by *IRAS*. The observed IR flux is more in agreement with that of a more luminous star ($L_*/L_\odot > 10^2$, spectral type $\approx$ B8V or earlier). However, if the trapezium is as young as suspected, all the PMS stars

[4]IRAF is the **I**mage **R**eduction and **A**nalysis **F**acility made available by NOAO and operated by AURA, Inc., (NSF-USA).

TABLE 1

EQUIVALENT WIDTHS OF CONSPICUOS SPECTRAL LINES AND NEAR INFRARED PHOTOMETRY OF THE SAMPLE STARS IN IRAS 05555-1406

Star	SpT	Nature	W(Hα)	W(Li I)	W(Ca I)	K	$J-H$	$H-K$
A[a]	G5	WTT	8.59	0.44	0.01[b]	10.06	0.36	0.17
		error (σ ±)	0.014	0.02	0.02	0.02	0.03	0.03
B	K8	WTT	−0.33	0.59	0.56	12.24	0.56	0.12
			0.045	0.045	0.045	0.04	0.06	0.06
C	K6	WTT	−6.33	0.36	0.01[b]	10.21	1.12	0.74
			0.028	0.028	0.028	0.03	0.04	0.04
D	K2	CTT	−28.19	0.43	···[c]	11.09	1.34	1.05
			0.098	0.098	0.098	0.02	0.04	0.03
E	M0	WTT	−2.22	0.24	0.32	13.60	0.63	0.26
			0.075	0.075	0.075	0.05	0.05	0.06

[a]Star associated with nebulosity. [b]Ca I λ6717 is at noise level. [c]Ca I masked by [S II]λ6717.

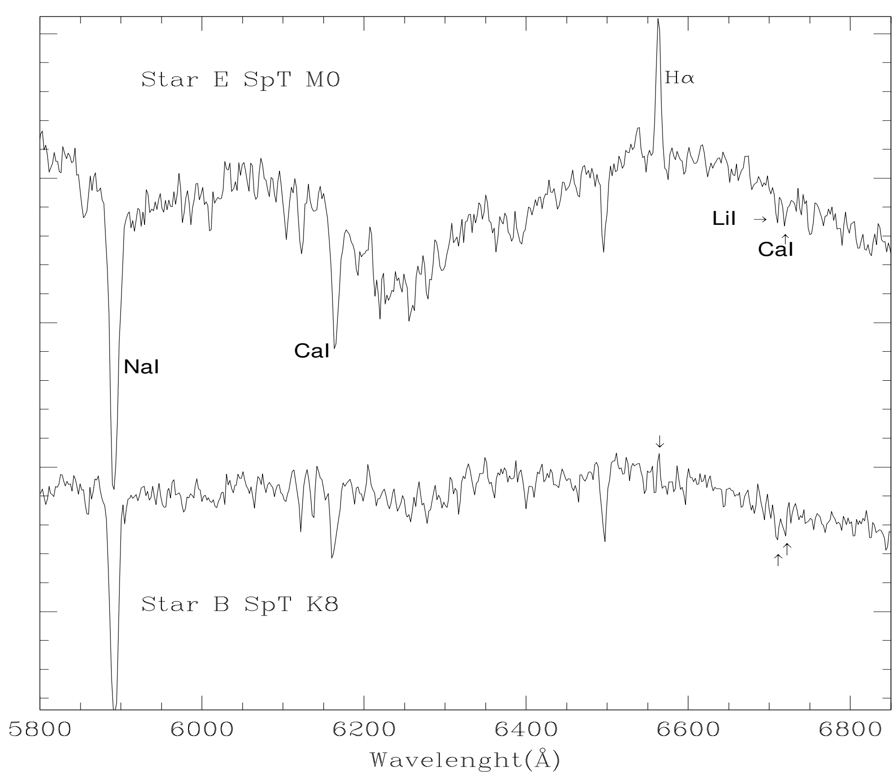

Fig. 2. Weak-line T Tauri stars E and B found in the Orion-like trapezium associated with the reflection nebulosity vdB64 and with the infrared source IRAS 05555-1405.

near the error ellipse of the IR source location may provide the necessary 12 − 100 μm flux observed with *IRAS*.

(*ii*). Similar to case (*i*) above, Star B-south was found to be a K8 star with the Hα line filled-in with emission (see Fig. 2), and the Li Iλ6708 Å

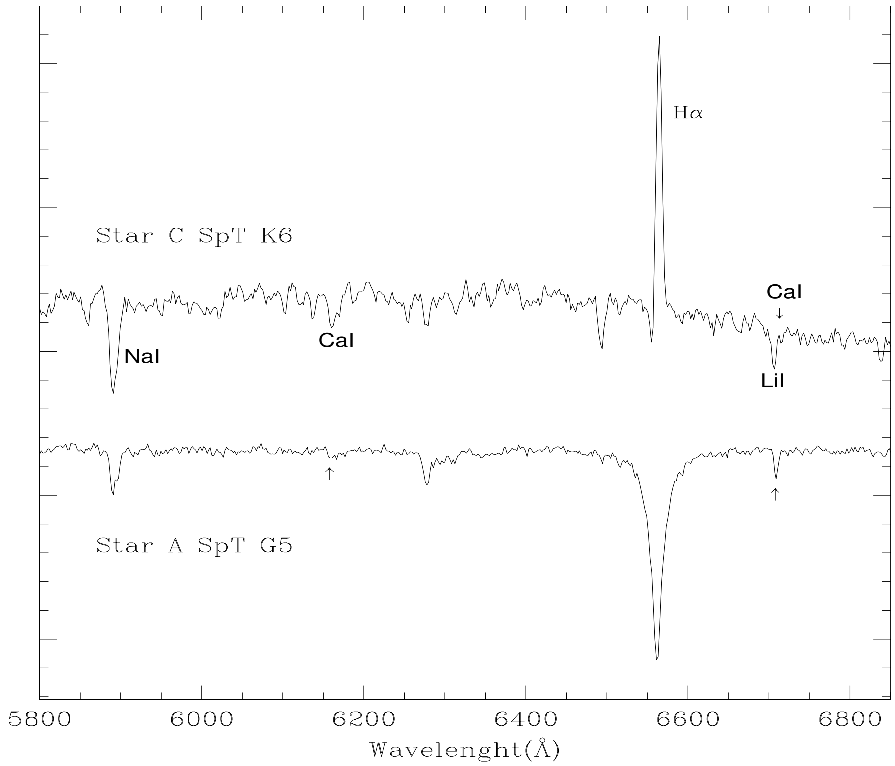

Fig. 3. Weak-line T Tauri stars C and A found in the Orion-like trapezium associated with the reflection nebulosity vdB64 and with the infrared source IRAS 05555-1405.

line strong in absorption but comparable in strength with the nearby Ca Iλ6716 Å line. We conclude that it is a WTTS.

(*iii*). Star C-south is also a late-type star, its spectrum is dominated by neutral metalic lines, Hα is in emission with an equivalent width W(Hα) < 10 Å, and with the resonant Li I λ6708 Å doublet strong in absorption (cf. Fig. 2). Its photospheric spectrum corresponds to a K6 star, and from its morphological and spectroscopic characteristics, it is a WTTS star.

(*iv*). The spectrum of star E shows molecular bands and neutral metallic lines and matches best with that of an M0V star (cf. Fig. 2). Hα is in emission with W(Hα) < 10 Å; Li I λ6708 Å and Ca I λ6716 Å are in aborption. From the equivalent width of the Li I line we find that it is a lithium rich star (see (*i*). above). We conclude that star E is a weak-line T Tauri star. However, in Martín's (1997) scheme, it would be a post T Tauri star (PTTS) since it is situated in the "gap" or empty region between classic T Tauri and (young) main sequence cluster stars in the (EW(Li I), T_{eff}) diagram.

(*v*). The most conspicuous emission line in the spectrum of star D is Hα (EW(Hα) > 10 Å), but also present are the nebular lines [O I] λ6300, [N II] $\lambda\lambda$6548,6584 Å and [S II]$\lambda\lambda$6717,6730 Å, with Li I λ6708 Å strong in absorption (cf. Fig. 4). Its photospheric spectrum corresponds to that of a K2 star. Because of its morphology, its emission spectrum and the intensity of the emission lines, it is a typical classic T Tauri star (CTTS).

(*vi*). No conspicuous NIR source in the IRAS 05555-1405 field is apparent from an examination of the 2MASS data. The survey does reveal that stars A, B, and C are apparent doubles, the secondary components of which (to the north or north-northwest in all cases) are significantly weaker. 2MASS also shows that the CTT star D has NIR flux excess, in agreement with our spectroscopic results.

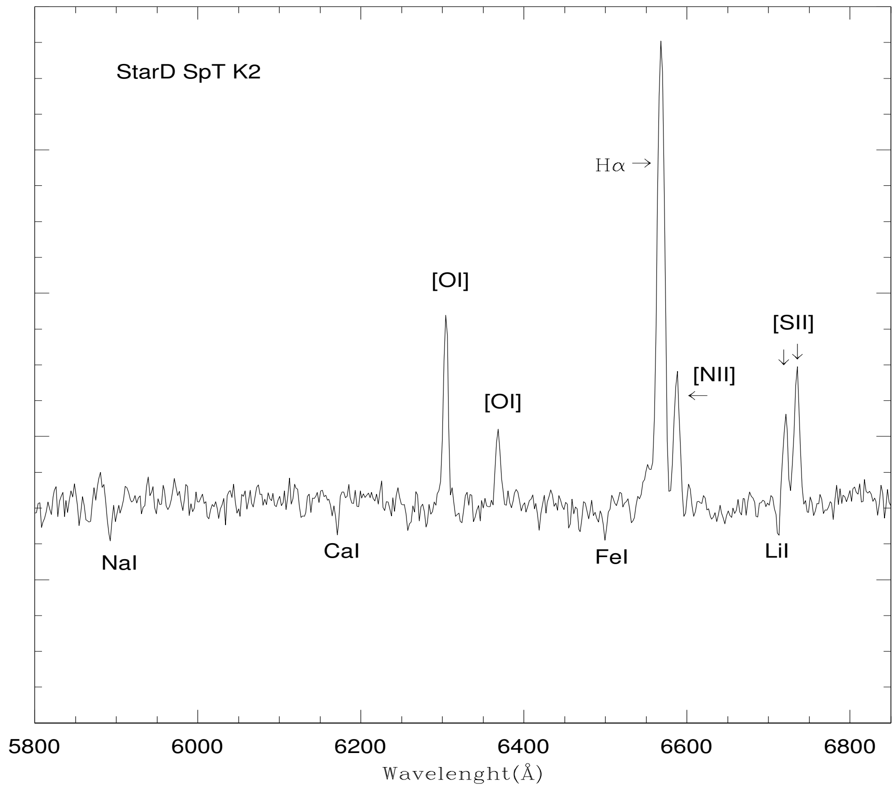

Fig. 4. Spectrogram of the classic T Tauri star D associated with IRAS 05555-1405.

4. CLOSING REMARKS

From our data we conclude that there are, at least, five contemporaneous PMS stars associated with IRAS 05555-1408. We have identified four WTTS and one CTTS that are immersed in the densest part of the reflection nebula vdB64. These stars form an Orion-like trapezium. Their brightnesses and sizes are more in accordance with Hubble's law for reflection nebulosities (Hubble 1922; Dorschner & Gürtler 1964) than the bright stars BD−14°1294 or vdB64a, which others have suggested to be responsible for the reflection nebula (van den Berg 1966; Racine 1968).

Following the procedure outlined by Chavarría-K et al. (2005, their § 3), using our spectral types and the 2MASS data of the trapezium stars given in Table 1 we are able to estimate the bolometric apparent luminosity of the stars by dereddening the NIR photometry and by applying bolometric corrections to the resulting magnitudes. Furthermore, assuming a distance of 460 pc to the complex (see below) we locate the program stars on an HR-diagram, and by comparison with a grid of models of PMS stellar evolution we can find estimates of the masses and ages of PMS stars. From the data we expect their masses to be in the 0.8 − 1.8 $M_\odot$ range, with a coeval age of about 5×10^6 yr, though this last estimate is more uncertain (see Tout, Livio, & Bonnell 1999; Chavarría-K et al. 2005, and literature therein). Moreover, the 2MASS data show that of the five stars we observed, only star D has near IR flux excess, in accordance with its CTTS nature found here. Star C-north, which we did not observe, shows this excess as well. Stars C-south and D are reddened ($E(H-K) = 0.57{\pm}0.05$ and $= 0.92{\pm}0.04$, respectively), while stars A-south, B-south and E are moderately reddened ($< E(H-K) >) = 0.07{\pm}0.02$). This is also in accordance with the morphology of the nebulosity surrounding the stars, in particular stars C-north and C-south.

The flux of the mid-infrared source observed with *IRAS* is equivalent to that of a highly reddened middle to late type B star at Orion's distance, surrounded by a warm envelope, as the increasing flux with wavelength suggests. Apart from the seven low-mass trapezium stars revealed in the 2MASS, no such conspicous NIR source is apparent; however, all the trapezium's low-mass PMS stars could account collectively for the mid-IR flux observed.

Regarding the distance to vdB64, the Bok globule associated with IRAS 05555-1405 (see Fig. 1) has a radial velocity $v_{lsr} = 8.5$ km s^{-1} (Reach, Heiles, & Koo 1993, their source 5937), in agreement with an earlier estimate of the same object ($v_{lsr} = 9.5$ km s^{-1}) and with Orion's A and B molecular clouds ($v_{lsr} = 8.5 \pm 2.8$ km s^{-1} Maddalena et al. 1986, their source 47), which places our region of interest at about 460 pc. From the Q index (Johnson & Morgan 1953) of star vdB64a and assuming luminosity class V and a normal IS extinction law, we situate the star at a distance of 750 pc, which is in fair in agreement with the distance to Orion's molecular clouds, considering the errors involved in the IS extinction law. Anyway, more observations, principally optical photometry of the program stars, are required in order to better understand this low-mass star forming region, in particular its evolutionary state.

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