Low-Mass Star Formation Induced by the Orion–Eridanus Bubble

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Abstract

During a spectroscopic survey performed with the Nordic Optical Telescope in La Palma we found five classical T Tauri stars in the small, high latitude molecular clouds associated with the reflection nebula IC 2118. The star-forming clouds are located at the outer boundary of the Orion star forming region, at a mean galactic latitude of -28°. Their positions in space and cometary shapes suggest their interaction with the Orion SFR. Using spectroscopic and near-infrared photometric data we determined the positions of the newly discovered pre-main sequence stars in the HRD. Comparison of the results with evolutionary models has shown that the masses of these stars are between 0.3–0.8 $M_{\odot}$ and their ages are close to 10^6 yrs. They are roughly coeval and significantly younger than the known WTTS of the same region. We conclude that the birth of the molecular clouds and the stars was probably induced by the interaction of the Orion–Eridanus Bubble with some small, diffuse high-latitude HI clouds.

KEYWORDS: *ISM: supershells, high-latitude molecular clouds, Orion–Eridanus Bubble, star formation–stars: pre-main sequence*

1. Introduction

The Orion–Eridanus Bubble is a giant supershell blown by the high-mass stars of the oldest subgroup of the Orion OB1 association, Orion OB1a (Brown et al., 1995). Its present radius is about 140 pc, and has a mean expansion velocity of $\sim$40 km s^{-1}. It shows up as a fragmented HI shell with angular extent more than 40°, associated with several Hα loops and filaments, including the Barnard Loop. The interior of the bubble is filled with low density ionized gas which is traced by soft X-ray emission and by ultraviolet absorption lines in the spectra of background stars. This large volume of tenuous gas surrounding Orion OB1 is often referred to as *Orion's cloak* (Cowie, 1982). The total mass of the H I shell is estimated to be about $2.3 \times 10^5\,\mathrm{M}_\odot$, and its kinetic energy is about 3.7×10^{51} erg (Brown et al., 1995). The supershell expands into the surrounding interstellar medium, thereby creating favorable circumstances for induced star formation. Identification of individual interstellar features associated with the bubble, hovewer, requires careful study of distances of the objects in question, because the size of this supershell is comparable with its distance from us.

The reflection nebula IC 2118 near Rigel (*Witch head nebula*) is a region associated with the nearest wall of the supershell. Its galactic coordinates are $205^\circ \leq l \leq 210^\circ$, $-30^\circ \leq b \leq -25^\circ$. The distance of the nebula from the Sun is 210 ± 20 pc (Kun et al., 2001).

In this case the well-known distance of the illuminating star makes it possible to determine the distance of the illuminated clouds. Molecular clouds associated with IC 2118 were described by Yonekura et al. (1997) and Kun et al. (2001). The wind-blown appearance of the bright reflection nebula and the cometary shapes of the associated molecular clouds suggest that the region is dynamically influenced by the association Orion OB1: though the main source of illumination is Rigel, the heads of the cometary clouds point towards the north-east, to the centre of the association. This morphology suggests the scenario in which the H I clouds have been compressed from the direction of Orion OB1. The association, however, is some 150 pc more distant than IC 2118. Therefore the interaction of these objects is probably mediated by the high pressure of the bubble surrounding the association.

Objective prism search for Hα emission stars in the region of IC 2118 suggested that low-mass stars might have been born in these high-latitude molecular clouds (Kun et al., 2001). In this paper we present the results of spectroscopic observations that confirm the presence of pre-main sequence stars in the molecular clouds associated with IC 2118.

2. Observations

We observed the spectra of stars selected as possible Hα emission objects in objective prism Schmidt plates in January 2001 with ALFOSC (*Andalucia Faint Object Spectrograph*) on the Nordic Optical Telescope in La Palma. Using grism 8 with a 1 arcsec slit provided a spectral resolution $\lambda/\Delta\lambda \approx 2200$ in the wavelength interval 5800–8300 Å. This spectral region contains both the Hα and the Li I λ6708 lines, crucial for identification of T Tauri type stars, as well as several absorption features suitable for spectral classification (Kirkpatrick et al., 1991). Spectra of helium and neon lamps were observed before and after each stellar observation for wavelength calibration. For spectral classification purposes we observed a series of spectroscopic standards. We reduced the spectra using the standard IRAF routines. Spectral and luminosity classes were determined using the criteria established by Kirkpatrick et al. (1991) and Martín & Kun (1996).

3. Results

We found five stars closely confined to the clouds which have shown several characteristics of pre-main sequence nature, as well as two stars having weak Hα emission ($EW(H\alpha)$ <5 Å) but no Li I absorption. Figure 1 displays the distribution of the pre-main sequence stars identified during the spectroscopic survey with respect to the molecular clouds, and Fig. 2 shows their spectra, normalized to the continuum. Several emission lines attributed to circumstellar matter can be observed in the spectra, such as the [O I] lines at 6300 and 6360 Å, [N I] at 6583 Å, [S II] at 6717 and 6731 Å, as well as the emission lines of neutral helium at 5875 Å and 6678 Å.

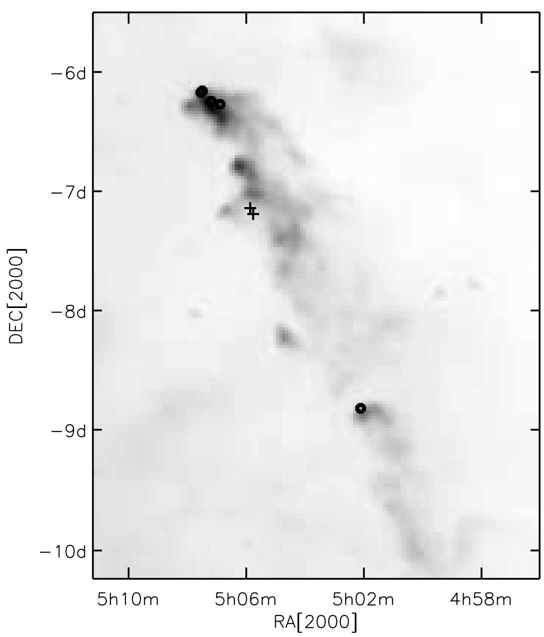

Figure 1: Location of classical T Tauri stars (circles) and weak-line Hα emission stars (crosses) with respect the molecular clouds indicated by the distribution of 100 μm emission observed by IRAS in the region of IC 2118.

Table 1: T Tauri stars in IC 2118

2MASS	Sp.T.	J	$J-H$	$H-K$	$W(\mathrm{H}\alpha)$	$W(\mathrm{LiI})$
0502063−085046	M2IV	10.987	0.782	0.441	−60.72	0.28
0506030−071547	M4V	11.535	0.538	0.285	−4.11	0.03
0506091−071239	M3V	10.888	0.557	0.246	−0.97	0.00
0506535−061712	K7IV	11.182	1.255	0.754	−112.35	0.53
0507115−061509	M0V	13.009	1.730	1.225	−293.20	1.19
0507301−061015	K5IV	10.839	1.254	0.963	−79.35	0.37
0507306−061059	K7IV	10.127	1.081	0.743	−13.47	0.41

J, H, and K magnitudes of the pre-main sequence stars were obtained from the 2MASS Second Incremental Survey Catalog (IPAC, 2000). We used these data to place the stars on the Hertzsprung–Russell diagram. Table 1 shows the 2MASS identifications, spectral types, J, H, and K magnitudes, Hα and LiI equivalent widths of the new pre-main sequence objects. Figure 3 displays their positions on the $(H-K)$ vs. $(J-H)$ color-color diagram together with the lines indicating the position of zero-age main-sequence, the giant branch, direction of the interstellar reddening and the locus of classical T Tauri stars determined by Meyer et al. (1997).

In order to place the stars on the HRD their effective temperatures and bolometric luminosities are to be determined. T_{eff} comes from the spectral type, according to *e.g.* Kenyon & Hartmann (1994), whereas L_{bol} can be determined from the near-infrared photometric data. For this purpose we make the widely used assumption that the total emission of our target stars in the J band originates from the photosphere (e.g. Hartigan et al., 1994). Thus the color index $J-H$ can be written as

$$J - H = (J-H)_0 + E_{\mathrm{CS}}(J-H) + E_{\mathrm{IS}}(J-H),$$

where $(J-H)_0$ is the true photospheric color of the star, $E_{\mathrm{CS}}(J-H)$ is the color excess due to the emission from the circumstellar disk in the H band, and $E_{\mathrm{IS}}(J-H)$ is the color excess originating from the interstellar extinction in the H band.

The locus of unreddened T Tauri stars in the $H-K$ vs. $J-H$ color-color diagram (Meyer et al., 1997) allows us to determine $E_{\mathrm{IS}}(J-H)$, the interstellar

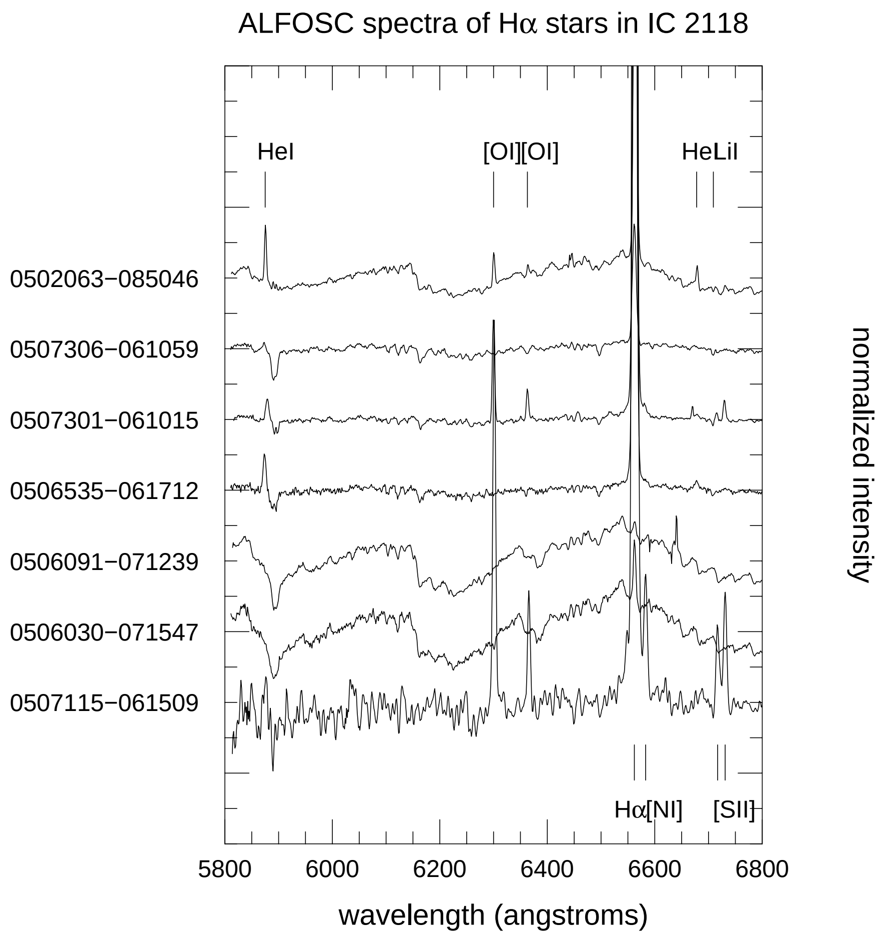

Figure 2: Spectra of the new pre-main sequence stars in IC 2118 in the wavelength region 5800–6800 Å.

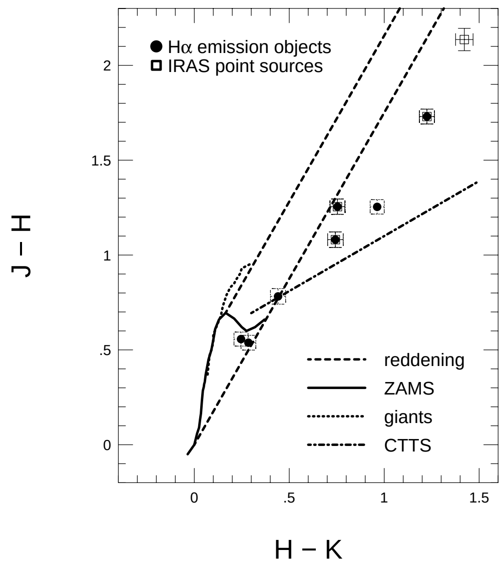

Figure 3: Positions of the T Tauri stars in IC 2118 in the $J-H$ vs. $H-K$ diagram. Loci of zero-age main sequence, giant branch, and classical T Tauri stars, as well as the slope of interstellar reddening are indicated.

component of the $E(J-H)$ color excess. The bolometric luminosities of the stars were derived by using the interstellar extinction law $A_{\rm J} = 2.65 \times E_{\rm IS}(J-H)$, given by Rieke & Lebofsky (1985) and the bolometric corrections tabulated by Hartigan et al. (1994).

The positions of our target stars in the HRD are shown in Fig. 4 together with evolutionary tracks and isochrones given by D'Antona & Mazzitelli (1994) (model 1). It can be seen that the masses of these stars are in the 0.3–0.8 $M_\odot$ interval, and they are grouped along the isochrone corresponding to a mean age of 10^6 years, comparable to the age of the youngest subgroup of Orion OB1.

4. Conclusions

We found five classical T Tauri stars in the molecular clouds associated with IC 2118. We estimated their masses and ages, and found them to be nearly coeval, at a mean age of 10^6 yrs. Our results suggest that the T Tauri stars associated with IC 2118 are significantly younger and less massive than most of the weak-line T Tauri stars discovered by ROSAT (Alcalá et al., 1998) in the Orion–Eridanus region. Both the small, high-latitude clouds and the low-mass stars in them have most probably been produced by the interaction of the Orion–Eridanus Bubble with diffuse H I clouds.

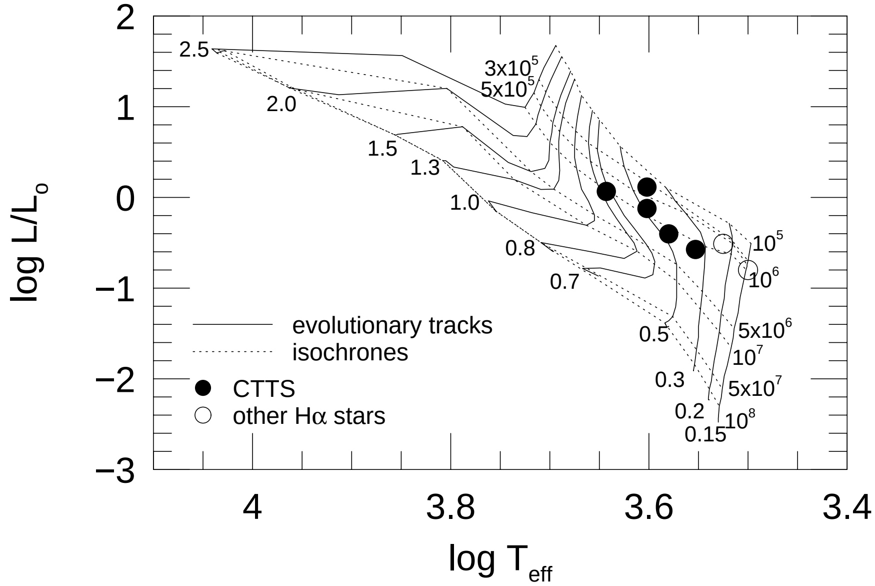

Figure 4: The T Tauri stars of IC 2118 in the HRD. Solid lines indicate the isochrones and dashed lines show the evolutionary tracks from D'Antona & Mazzitelli's (1994) model 1.

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