A NEW Hα EMISSION-LINE SURVEY IN THE ORION NEBULA CLUSTER

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ABSTRACT

We present results from an Hα emission line survey in a 1 deg² area centered on the Orion Nebula Cluster, obtained with the Wide Field Grism Spectrograph 2 on the 2.2 m telescope of the University of Hawaii. We identified 587 stars with Hα emission, 99 of which, located mainly in the outer regions of the observed area, have not appeared in previous Hα surveys. We determined the equivalent width (EW) of the line and, based on this, classified 372 stars as classical T Tauri stars (CTTSs) and 187 as weak-line T Tauri stars (WTTSs). Simultaneous r′, i′ photometry indicates a limiting magnitude of r′ ~ 20 mag, but the sample is incomplete at r′ > 17 mag. The surface distribution of the Hα emission stars reveals a clustered population and a dispersed population, the former consisting of younger and more massive young stars than the latter. Comparison of the derived EWs with those found in the literature indicates variability of the Hα line. We found that the typical amplitudes of the variability are not greater than a factor of two to three in most cases. We identified a subgroup of low-EW stars with infrared signatures indicative of optically thick accretion disks. We studied the correlations between the EW and other properties of the stars. Based on literature data, we examined several properties of our CTTS and WTTS subsamples and found significant differences in mid-infrared color indices, average rotational periods, and spectral energy distribution characteristics of the subsamples.

Key words: ISM: individual objects (Orion Nebula Cluster) – stars: emission-line, Be – stars: pre-main sequence

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

T Tauri type stars are young, low-mass stars. Their typical spectral types are between F and M (Herbig 1960). These stars are still accreting material from a circumstellar disk via magnetic channels. As a consequence of accretion and outflows, pre-main-sequence stars exhibit emission lines, especially strong Hα emission.

Some decades ago these stars were discovered because of their strong Hα emission via low-dispersion objective prism photographic surveys. Nowadays slitless grism spectroscopy with CCD detectors allows simultaneous detection of numerous stars within the field of view, offering a great opportunity to identify Hα emission line stars (see, e.g., Nakano et al. 2012). A good target for such an Hα survey is the young Orion Nebula Cluster (ONC).

The Orion Nebula is one of the best-studied high-mass star-forming regions (Muench et al. 2008; O’Dell et al. 2008). It is situated some 414 pc from the Sun, based on trigonometric parallax (Menten et al. 2007), in the Orion A molecular cloud, which covers 29 deg² and contains 1 × 10⁵ M⊙ of molecular gas. It has a very rich (>2000 members; Hillenbrand 1997) and young (~1 Myr; Hillenbrand 1997) population. At this age many clusters are still embedded, contrary to the ONC, which is observable at optical wavelengths because the parental cloud along our line of sight was removed by the radiation of Trapezium stars. The stellar population centered on the Trapezium stars is traditionally divided into concentric radial zones. These are as follows: the central 0.3 pc (~2 arcmin) is called the Trapezium Cluster, the inner 3 pc (~20 arcmin) is the classical ONC, and the Orion OB1c association extends to more than 25 pc (approximately 3°) in radius.

Haro (1953) found 255 Hα emission line stars in the brightest area of 3.5 deg² of the ONC centered on the Trapezium. Parsamian & Chavira (1982) cataloged 543 Hα emission line stars in a wider 5° × 5° region also centered on the ONC. Wiramihardja et al. (1991) conducted an objective-prism survey of the ONC. The number of Hα emitters was 191 in the observed area A-0975 (5° × 5°, centered at α = 5h20m, δ = −5°) and 415 in the area A-0976 (5° × 5°, centered at α = 5h40m, δ = −5°). In all, the Kiso Survey revealed 606 stars showing Hα emission.

Fűrész et al. (2008) carried out a spectroscopic study of 1215 selected stars covering the ONC and its vicinity. The observations were performed with the Hectochelle multiobject spectrograph at the 6.5 m MMT telescope in Arizona in 2004 and 2005. Narrowband filter photometric techniques have also been used to identify new Hα emission line stars in the ONC. Da Rio et al. (2009) observed the ONC in a field of about 34’ × 34’ with the WFI imager at the ESO/MPI 2.2 m telescope at La Silla Observatory. They identified 638 Hα sources in the region.

The goal of our paper is to assess the power of slitless grism spectroscopy by studying the well-known, nearby, and rich ONC and compare the results with literature data on the same region, derived from various other observing methods. We describe the observations and data reduction, as well as the ancillary data, used during statistical analysis in Section 2. The results and their comparison with literature data are presented in Section 3, and we discuss our results in Section 4. A short summary of the results is given in Section 5.

2. DATA

2.1. Observations and Data Reduction

2.1.1. Slitless Grism Spectroscopy

We observed the ONC, centered on the Trapezium, with the Wide Field Grism Spectrograph–2 (WFGS2) installed on
The equivalent width (EW) of the Hα emission line was computed as follows: first, small stamps with size of 30 × 30 pixels were cut around the core of the emission line. The size of this stamp was derived from the FWHM of the profile and the characteristic lengths of the structures in the grism frames and found to be stable throughout our observations. In each stamp, the background level (which varied significantly due to the intrinsic background of the Orion Nebula complex) was obtained from the upper 30 × 5 and lower 30 × 5 pixels by fitting either a constant level or a plane, depending on the variation level of the background. We found that in most cases, both fits yielded a smooth background; however, in some cases the two methods led to different results. In such cases we accepted the more “stable” solution. The uncertainty of the background level was determined by a simple statistic, i.e., from the fit residuals divided by the square root of the number of involved pixels. Second, these background-subtracted stamps were stacked via the y axis (i.e., almost exactly perpendicular to the grism dispersion), yielding 30 pixel long spectra. The uncertainty of each spectral point was estimated from the photon noise statistic (taking into account the effective camera gain 1.780 e− ADU−1) and by adding quadratically the scaled background scatter. Third, these spectra were fitted with a Gaussian, parameterized by the four free parameters of zero-point level, center, amplitude, and standard deviation. The EW of the emission line was then simply derived from these fitted parameters, i.e., by dividing the integral of the Gaussian (without the zero-point level) by the zero-point level (which is proportional to the instrumental continuum level). The uncertainty of the EWs was obtained from linear error propagation using the fitted results.

Applying the above described method, we could determine the EWs for 452 stars. For the remaining stars in which the Hα emission was clearly detected, this method could not be applied due to faint continuum or the bright and variable nebulous background. In such cases we estimated the EW using the IRAF “splot” package. However, the EWs could not be determined for 28 stars. Due to overlapping fields, 50 of the stars were observed more than once.

Figure 2 shows the distribution of our Hα emission stars over the observed area centered on the Trapezium. Asterisks indicate the classical T Tauri stars (CTTSs), diamonds mark the weak-line T Tauri stars (WTTSs), while triangles represent sources of uncertain nature (see Section 3.1). Figure 3 shows the histogram of EWs.

2.1.2. Photometry

Direct images of each field of the mosaic with the same instrument were obtained through r′ and i′ filters immediately before the spectroscopic exposures. One exposure was taken at each position and in each filter with integration time of 60 s. Aperture photometry was carried out with the PHOT task in the DAOPHOT package. Several stars from the SDSS Photometric Catalog, Release 8 can be found in every frame. In order to transform instrumental magnitudes into the Sloan Digital Sky Survey system, we applied those stars and the following transformation equations:

\[ r_{\text{SDSS}} = C_1 \times r'_{\text{instr}} + C_2 \times \text{airmass} + C_3, \]

\[ r_{\text{SDSS}} - i_{\text{SDSS}} = C_4 \times (r' - i')_{\text{instr}} + C_5 \times \text{airmass} + C_6. \]

The C1 . . . C6 constants are derived from the fitting procedure. Photometric errors of typically 0.1 mag were derived from...
Figure 2. Hα emission stars identified during the present survey overplotted on the DSS2 IR image of the observed area. Red asterisks indicate the 372 CTTSs, green diamonds mark the 187 WTTSs, and blue triangles represent 28 sources without measured EW(Hα).
(A color version of this figure is available in the online journal.)

Figure 3. Distribution of the measured Hα equivalent widths.

Figure 4. Distribution of the r′ magnitudes of the Hα emission stars.

Figure 5. r′, r′ − i′ color–magnitude diagram for the Hα emission stars. The dash–dotted line represents the zero-age main sequence, while the dashed line indicates the 10⁶ yr isochrone (Siess et al. 2000). The arrow shows the direction of extinction.
(A color version of this figure is available in the online journal.)

2.2. Supplementary Data

To characterize the nature of the Hα emission stars and investigate possible correlations between the EW of the Hα line and other stellar properties, we used data available via the VizieR catalog access tool. Equatorial coordinates were determined using the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003) as reference. JHK, magnitudes for all but five stars are found in the same catalog. I magnitudes can be found in the DENIS (Epchtein et al. 1997) data release, and mid-infrared (W1 = 3.4, W2 = 4.5, W3 = 12, and W4 = 22 μm) data in the WISE All-Sky Data Release (Cutri et al. 2012). Spitzer IRAC data can be found for 345 of our Hα emission stars in Megeath et al. (2012). Spectral types for 346 stars can be found in Da Rio et al. (2009), Rebull et al. (2000), Rebull (2001), and Hillenbrand (1997).

A total of 496 of our stars are located within the area observed by the XMM-Newton X-ray observatory, and 257 of them were detected. Their X-ray data can be found in the XMM-Newton Serendipitous Source Catalogue 2XMM-DR3 (Watson et al. 2009). Rotation period measurements are available for 214 stars in Herbst et al. (2002), Cieza & Baliber (2007), and Flaccomio et al. (2005).
Table 1

| 2MASS       | EW (Å)      | r'    | r' − i' | Cross-identification |
|-------------|-------------|-------|---------|----------------------|
| J05333304−0511555 | 49.6(4.9) | 16.3 | 0.46   | RZ Ori, Kiso A-0976 45, [FHM2008] S1-ap75 |
| J0533443−0514177 | 22(1.5) | 16.7 | 0.90   | [FHM2008] S1-ap78   |
| J0533588−0501324 | 148.5(38.9) | 15.8 | 0.85   | VY Ori, Kiso A-0976 50, [FHM2008] S2-ap44 |
| J0533855−0513125 | 60.7(4.3) | 17.0 | 0.96   | Kiso A-0976 51, [FHM2008] F12-ap90 |
| J05334167−0524042 | 57.9(3.1) | 16.4 | 0.60   | Kiso A-0976 52, [FHM2008] F23-ap63 |
| J05334192−0506148 | 293.0(177.9) | 20.3 | 1.39   | [FHM2008] S2-ap37   |
| J05334479−0514098 | 14.7(1.1) | 13.8 | 0.35   | V729 Ori, Kiso A-0976 53 |
| J05334493−0531085 | 44.7(1.4) | 15.2 | 0.73   | [FHM2008] S2-ap44   |
| J05334525−0530498 | 7.7(2.4) | 14.1 | 0.59   | V386 Ori           |
| J05334545−0536323 | 119 (8.8) | 17.9 | 1.89   | V726 Ori, Kiso A-0976 55, [FHM2008] S1-ap42 |

Table 2

| 2MASS       | EW (Å)      | r'    | r' − i' | Cross-identification |
|-------------|-------------|-------|---------|----------------------|
| J0533705−0523069* | 10.1 (4.3) | 16.4 | 0.73   | V725 Ori           |
| J05334954−0536208 | 4.0 (0.3) | 16.5 | 0.62   | V354 Ori, Kiso A-0976 63, [FHM2008] S1-ap60 |
| J05335210−0530284 | 7.2 (1.0) | 16.5 | 1.16   | [FHM2008] F21-ap53 |
| J05340797−0536170 | 7.8 (0.2) | 18.4 | 1.65   | V396 Ori, Kiso A-0976 74, [FHM2008] S1-ap33 |
| J05340835−0514387* | 2.7 | 18.2 | 1.31   | Kiso A-0976 85, [FHM2008] F23-ap240, [H97b] 10075 |
| J05341714−0538168 | 5.4 (1.2) | 16.0 | 1.18   | V1956 Ori, [FHM2008] S2-ap239, [H97b] 3109 |
| J05342616−0526304 | >5.7 | 14.2 | 0.37   | V935 Ori, [FHM2008] F31-ap81 |
| J05342650−0523239 | 11.4 (1.1) | 16.4 | 1.25   | [FHM2008] F23-ap24, [H97b] 3080 |
| J05342751−0528284 | 5.3 (0.6) | 14.9 | 0.70   | [FHM2008] F21-ap54, [H97b] 3120 |
| J05342960−0547247 | 9.4 (0.7) | 16.1 | 0.69   | V386 Ori           |

Note. * Indicates sources, not detected by previous Hα surveys.

3. ANALYSIS

3.1. Classification

CTTSs are pre-main-sequence stars with an accretion disk. Material from the circumstellar disk accretes onto the star via magnetic funnel flows. This accretion process causes broad, often asymmetric Hα emission lines. A WTTS can be either a TTS that evolved and no longer has much circumstellar material to accrete from or a TTS that for some reason is not accreting material from the circumstellar disk accretes onto the star via magnetic funnel flows. This accretion process causes broad, often asymmetric Hα emission lines. A WTTS can be either a TTS that evolved and no longer has much circumstellar material to accrete from or a TTS that for some reason is not accreting much at the moment. Their Hα emission lines are much weaker, and the origin of the line is mostly chromospheric. There are several methods to distinguish accreting and non-accreting young stars from each other. The most widely used method (e.g., Martín 1998) is based on the EW of Hα and classifies each young star with EW(Hα) > 10 Å as a CTTS (accreting). Barrado y Navascués & Martín (2003) defined an empirical classification scheme that takes into account the spectral type as well, while White & Basri (2003) distinguished accreting and non-accreting TTSs based on the width of the Hα emission lines.

To distinguish accreting and non-accreting stars, we applied the criteria by Barrado y Navascués & Martín (2003) for the 346 stars having spectral types in the literature (Da Rio et al. 2009; Rebull et al. 2000; Rebull 2001; Hillenbrand 1997) and adopted EW = 13 Å as a boundary between accreting and non-accreting stars for the unclassified population, which is fainter on average than the classified subsample (⟨J⟩ = 12.39 and ⟨J⟩ = 13.06 for the classified and unclassified group, respectively). This EW value corresponds to the saturation limit of chromospheric activity at M3–M4 type.
Table 3

| 2MASS     | Cross-identification |
|-----------|----------------------|
| J0535074--0503934 | V1902 Ori, [HFM2008] F11–ap39 |
| J05341019–0505155 | [H97b] 12 |
| J05343025–0517012 | V1997 Ori, [HFM2008] F21–ap62, [H97b] 40 |
| J05344197–0545224 | V2009 Ori |
| J05344576–0543439 | V770 Ori |
| J05344922–0504380 | |
| J05351121–0517209 | V2214 Ori, [HFM2008] S1–ap86, [H97b] 358 |
| J05351216–0530201 | V1276 Ori, [HFM2008] S2–ap218, [H97b] 379 |
| J05351376–0539100 | LY Ori, [H97b] 433 |
| J05351405–0519520 | V2252 Ori, [HFM2008] S1–ap57, [H97b] 429 |
| J05351463–0516461 | [HFM2008] S1–ap93, [H97b] 444, [H97b] 20475 |
| J05351534–0519021 | [HFM2008] F21–ap148, [H97b] 469, [H97b] 20341 |
| J05351606–0520363 | V2280 Ori, [H97b] 504b, [H97b] 9125 |
| J05352021–0520569 | TU Ori, [H97b] 640 |
| J05352425–0525186 | V2421 Ori, [HFM2008] S1–ap231, [H97b] 750 |
| J05352469–0524357 | V1400 Ori, [H97b] 762 |
| J05352505–0522585 | [H97b] 766a |
| J05352547–0534028 | [HFM2008] S3–ap197, [H97b] 781 |
| J05352699–0548460 | V2458 Ori |
| J05352986–0525348 | [H97b] 845 |
| J05353340–0539212 | [H97b] 10702 |
| J05354611–0515528 | [HFM2008] S2–ap181, [H97b] 903 |
| J05354002–0502370 | |
| J05355408–0537423 | Kiso A–0976 219, [H97b] 2271 |
| J05361618–0518506 | [H97b] 5069 |
| J05363761–0531189 | |
| J05363404–0534054 | [HFM2008] F21–ap217 |

Note. * Indicates sources, not detected previous Hα surveys.

Stars (Samus et al. 2007–2012), Wiramihardja et al. (1991), Hillenbrand et al. (1998), and Fűrész et al. (2008).

3.2. Discriminant Analysis

To test whether our WTTS and CTTS samples indeed represent physically different objects, we applied a discriminant analysis. It is a common ingredient of professional statistical packages. We used SPSS in the computations. Discriminant analysis aims to find differences between groups in the multivariate parameter space, orders membership probabilities, and one may use this scheme for classifying additional cases not having assigned group memberships. During this process, we used those variables in which a significant number of cases remain after removing missing data. To fit with this requirement, we used the $I – J$, $J – H$, $H – K_s$, $K_s – [W1]$, $[W1] – [W2]$, $[W2] – [W3]$, and $[W3] – [W4]$ color indices, which gives maximal separation between the groups of the cases.

The program calculated the means and standard deviations of quantities included in the analysis, along with the number of cases having valid measurements in all of the variables used in the computation. The results are shown in Table 4. A quick look at the table gives an impression that both the means and standard deviations are greater in the CTT group. The statistical tests show that, except for $[W2] – [W3]$ and $[W3] – [W4]$, the difference between the WTTS and CTT groups is highly significant.

We found that the strongest contribution to the discriminant variable is given by $[W1] – [W2]$, while those of $[W2] – [W3]$ and $[W3] – [W4]$ are negligible. From an astrophysical point of view this result can be interpreted in the following way. The spectral energy distributions (SEDs) of both the WTTS and CTTS classes are built up as a superposition of the photospheric and circumstellar thermal emission over the wavelengths covered by the near- and mid-infrared colors. At shorter wavelengths the contribution of the photospheric emission is the strongest and the opposite is true at the other end of the wavelength domain of the input variables. The wavelengths of $W1$ and $W2$ are between these extremes. The larger average $I – J$ and $J – H$ color indices of the CTTS group possibly indicate greater extinction suffered by these stars, since infrared excesses are less significant in these colors.

Based on the canonical discriminant function (the discriminant variable) resulting from the analysis, one can control the reliability of the original (a priori) classification based on the EW of the Hα emission line. The histograms of the discriminant function for the WTTS and CTTS groups demonstrate that these groups are not disjoint, but rather overlapping with respect to zero, the a posteriori boundary between the two types of TTSs. We found that 25 of our 187 WTTSs have IR colors similar to CTTSs, and 90 of the 372 CTTSs exhibit infrared properties similar to WTTSs.

The discriminant function allowed us to estimate the probable types of the 28 unclassified stars. Although the 2MASS $(J, H, K_s)$ colors of the unclassified sources are complete, a significant fraction of the $WISE$ measurements are missing. The Expectation and Maximization (EM) algorithm of the Missing Value Analysis procedure, implemented in the SPSS statistical package, was used to generate a maximum likelihood estimation for the missing values. The discriminant analysis suggests that 13 stars from the 28 unknown sources are WTTSs, while the remaining 15 sources can be classified as CTTSs.

3.3. Comparison with Previous Hα Emission Surveys

We compare our sample of Hα emission stars with those detected by the Kiso survey (Wiramihardja et al. 1991), Fűrész et al. (2008), and Da Rio et al. (2009) in Figure 6. The Kiso survey and the survey by Fűrész et al. (2008) covered the whole area of our survey, while the photometric Hα survey of Da Rio
et al. (2009) covered just the central 34′ × 34′. Due to the bright nebulosity, we could barely detect sources in the densest central region of the ONC, and for the few detected sources EW(Hα) could not be determined, therefore comparison with previous Hα surveys is justified only outside the central area of ∼5′ in right ascension and ∼10′ in declination.

Based on the VizieR database, 92 Hα stars identified by the Kiso survey are located in the area covered by our observations. Out of these 92 stars 79 show emission in our images. Comparison of these two surveys suggests that most of the stars detected by Wiramihardja et al. (1991) were strong emitters. A total of 763 stars observed by Fűrész et al. (2008) are located in the area of our survey. Among those, we detected Hα emission in 337 stars. A detailed comparison shows that, outside the central region, we detected most stars for which Fűrész et al. (2008) measured EW(Hα) > 10 Å, and their low-EW stars, when detected, appeared as WTTSs in our survey as well.

A total of 274 of the 638 Hα emission stars identified by Da Rio et al. (2009) coincide with our emission stars. Figure 6 shows that most of our Hα emission stars, located within the area observed by Da Rio et al. (2009), are found in their database. Those of their Hα stars that were missed by our survey are either located within the central 5′ × 10′ area or are fainter than V ∼ 19 mag.

A total of 99 of our Hα emission stars were detected by neither the above surveys nor earlier surveys. The distribution of these stars can be seen in Figure 7. Most of them are located outside the central, thoroughly studied region of the ONC. Forty-eight stars belong to the CTTS group, 44 to the WTTS group, and the remaining 7 stars to the third group of uncertain nature. Several of them are known variable stars or cluster members. In particular, 15 of the near-infrared variables studied by Carpenter et al. (2001) appear in this sample. Figure 8 shows the $H$ versus $H − K_s$ color–magnitude diagram of the newly identified Hα emission line stars, based on the 2MASS data. Diamonds indicate M-type cluster members identified by Hillenbrand et al. (1998). The diagram suggests that the new emission line stars may be pre-main-sequence stars located at the distance of the ONC.
Figure 9. Surface distribution of our Hα emission stars (symbols are the same as in Figure 2) and the Spitzer sources identified as young stars by Megeath et al. (2012; small plus signs).

(A color version of this figure is available in the online journal.)

3.4. Comparison with Other ONC Surveys

The most complete census of the disk-bearing population of the ONC can be found in the Spitzer database (Megeath et al. 2012), whereas the diskless young stars down to 0.1–0.2 $M_\odot$ were identified by the Chandra Orion Ultradeep Project X-ray survey (Preibisch et al. 2005a, 2005b). To test whether our Hα emission stars represent a typical subsample of the cluster population or not, we examined the number and ratio of the infrared emission stars and the infrared-excess stars of the same area. This sample contains 86 CTTSs and 15 WTTSs. Our data show an apparent CTTS fraction of 85%, indicating that our survey, as expected, is biased toward disk-bearing stars.

Since both infrared excess and Hα emission in young stellar objects (YSOs) are disk indicators, overlapping of the samples of Hα emission stars and the infrared-excess stars of the same region is expected. In Figure 9 the surface distribution of our stars is displayed together with the mid-infrared excess stars identified by Megeath et al. (2012), based on Spitzer observations. It can be seen that numerous sources are in common, but of course there are sources that were detected in only one of the surveys. Both Figures 6 and 9 show that outside the cluster core our results overlap well with those of other surveys and reveal new cluster/association members in the outer, lower density regions of the ONC. Although the $r'$ versus $r' - i'$ color–magnitude diagram (Figure 5) indicates a limiting magnitude of $r' \sim 20$ mag, Figure 4 shows that our sampling starts to be fairly incomplete beyond $r' \sim 16$–17 mag.

3.5. Surface Distribution of the Hα Emission Stars

A look at the surface distribution of the Hα emission stars in Figure 2 gives the impression of clustering of the stars. The surface distribution of the merged YSO samples (Figures 6 and 9) also suggests the presence of small apparent stellar groups in the outer regions of the field, sampled by our survey. We examined the reality of the clusterings in our sample by an appropriate statistical procedure. To test our impression, we generated a fully random case with the same numbers of CTTSs and WTTSs as in the real case and used the Fast Nearest Neighbor Search Algorithms and Applications (FNN) package of the R project to prove the reality of the clustering in the surface distribution. We compared the cumulative distributions of the nearest neighbor distances in the real and random samples applying a Kolmogorov–Smirnov (K-S) test. The results of K-S statistics indicate that the distribution of the Hα emission stars in the observed area indeed shows some clustering with respect to the fully random surface distribution.

To study the nature of the clustered and distributed population and reveal the possible difference between their measured properties, we first defined clusters in the surface distribution. Based on the maximum departure of the real and random distribution, we assigned an object to a cluster if its fourth nearest neighbor had a distance of $d < 130''$. Comparison of the cluster members and outliers has shown that the mean brightness of the cluster stars is greater at all wavelengths. The difference is increasing toward the longer wavelengths. It is about 0.5 mag in the near-infrared and reaches about 1 mag at $W4$. For testing the significance of the difference between the corresponding groups, we applied a statistical $T$-test. According to the applied $T$-test, these differences are highly significant. In contrast, however, there is no significant difference in EW(Hα).

Regarding the cluster members, a $T$-test demonstrates that the difference between the CTTSs and WTTSs in the cluster environment is smaller than the standard error of the mean in the $K_s$ brightness. In the $J$ band, however, the CT class is fainter. This may be accounted for by the greater extinction of the circumstellar matter or, alternatively, may indicate that the weak Hα emission of the fainter WTTS population remained undetected.

3.6. Variability of the Equivalent Width of the Hα Line

The strength and shape of the Hα emission line can show temporal variability due to variable accretion rate and wind. EW(Hα) can change even in the absence of flux variations, due to the photometric variations of the stellar continuum. The subsample of Hα sources observed several times due to overlapping of the images allowed us to examine the short timescale (hours to months) variability. Seven stars were observed twice within a few hours. They showed significant short timescale variations in the Hα EW. Of these seven stars, six possess a flat or rising (Class I) SED (Figure 10). This suggests that these stars are very young and may still be surrounded by an envelope, and this can lead to significant variability of the accretion rate and accretion-related wind. Nine of the 11 stars that were observed twice or more within a few days showed no significant variation, and the remaining 2 exhibited small (some 30%) variations in EW(Hα). Stars observed on longer timescales (some weeks or months) show a wide range of variations in EW(Hα) (see Table 1).

We compared the derived EWs with those published by Fűrész et al. (2008) and Da Rio et al. (2009). This comparison allowed us to study the changes of the EWs on timescales of a few years. Part of the observed differences may originate from the
fact that the EWs in the compared works were determined with different methods. To check this point, we selected all of the sources common among these three surveys (Figure 11) and calculated the significance of correlations using Kendall’s tau statistics. Based on the statistics, we find that the surveys of Fűrész et al. (2008) and Da Rio et al. (2009) are less correlated, while our survey and the survey of Da Rio et al. (2009) are well correlated. The comparison between the measurements of Fűrész et al. (2008) (high resolution) and our survey (low resolution) suggests a quite good correlation at lower EW values.

The results are presented in Figures 12 and 13. The histogram with upward diagonal hatching (red in the online version) represents the CTTSs, while the histogram with horizontal hatching symbolizes the WTTSs. It can be seen that the amplitudes of variations are moderate in the greater part of the sample: most of the observed changes in EW are within a factor of two to three, whereas changes as high as ten- to twenty-fold appear in a few cases. The greater EW ratios in Figure 13 reflect the lower level of correlation between these data sets.

4. DISCUSSION

4.1. Accreting and Non-accreting Stars

The classical and weak-line subclasses of TTSs are generally correlated with the infrared signature of the accretion disks. Figure 14 is the $J - H$ versus $H - K_s$ two-color diagram for the stars listed in Tables 1–3 with the colors from 2MASS Point Source Catalog. This figure shows that only a few of the
low-EW stars (diamonds) exhibit near-infrared excess, while a significant part of the high-EW population (asterisks) and a few stars without EW data (triangles) are distributed over the region occupied by reddened stars associated with accretion disks. Stars that are lying below the CTTS locus and right from the zero-age main sequence can be explained by the circumstellar disk models of Lada & Adams (1992). The models take into account the surface temperature, disk inclinations, and radial temperature profiles. The modeled systems with stellar surface temperature from 3000 to 12,000 K can explain this part of the two-color diagram. Our sample mainly consists of stars of K and M spectral type, but we detected Hα emission in four known Herbig Ae/Be stars too.

Figure 12. Distribution of the changes in EW(Hα) compared with EW data from Da Rio et al. (2009). The histogram with red upward diagonal hatching indicates the CTTS sample, while the histogram with green horizontal hatching symbolizes the WTTS sample. (A color version of this figure is available in the online journal.)

Figure 13. Same as Figure 12 but compared with data from Fűrész et al. (2008). (A color version of this figure is available in the online journal.)

Figure 14. Hα emitters on the 2MASS J − H vs. H − Ks diagram. The solid curve shows the colors of the zero-age main sequence, and the dotted line is the giant branch. The long dashed lines delimit the area occupied by the reddened normal stars (Cardelli et al. 1989). The dash-dotted line is the locus of unreddened TTSs (Meyer et al. 1997), and the gray shaded band indicates the area of the reddened Ks-excess stars. Red asterisks indicate the CTTSs, green diamonds mark WTTSs, and blue triangles are unclassified Hα emission stars. (A color version of this figure is available in the online journal.)

Figure 15 shows the WISE [3.4]–[4.6] versus [4.6]–[12] color–color diagram of our CTTS and WTTS sample. The boundaries dividing Class I, Class II, and Class III sources (Koenig et al. 2012) are indicated. Comparing this plot with the similar diagram of the Taurus star-forming region (Koenig et al. 2012) shows that the [4.6]–[12] color indices of our stars are unusually high. The reason for this may be that due to the wide point-spread function of WISE and the strong background of the Orion Nebula at 12 μm, fluxes measured in the W3 band are seriously contaminated by emission from small nebular clumps or faint neighboring stars (Koenig et al. 2012). To test this hypothesis, we examined the positions in the WISE [3.4]–[4.6] versus [4.6]–[12] color–color diagram of all Chandra sources (Getman et al. 2005) of the ONC without Spitzer detection. The strong X-ray emission and lack of mid-infrared excess ensure their diskless young star nature. We found that these X-ray-selected cluster members also exhibited high [4.6]–[12] color indices, supporting that the 12 μm flux probably originates from the environment. The [3.4]–[4.6] colors indicate that most of our CTTSs are Class II infrared sources. Most of the WTTSs exhibit no excess in these bands, but, in contrast with the case of the J − H versus H − Ks diagram, a significant subgroup of them (37 stars) exhibit quite large excesses in the [3.4]–[4.6] color.

Based on the WISE [3.4]–[4.6] color (Koenig et al. 2012) or, where they are available, Spitzer IRAC [3.6]–[4.5] colors (Gutermuth et al. 2008), we identified a subsample of low-EW Hα emission stars exhibiting infrared excess indicative of an optically thick accretion disk. We checked the VizieR catalogs and omitted the stars having known neighbors within the angular resolution of the WFGS2 instrument. The stars, selected in this manner and listed in Table 5, are apparently not accreting, in spite of their primordial accretion disks (Figure 16). Most of them are known variables (see Table 2). Comparison of their
Figure 15. WISE [3.4]–[4.6] vs. [4.6]–[12] color–color diagram. Dashed lines indicate the boundaries between Class I, Class II, and Class III sources adopted from Koenig et al. (2012). Red asterisks indicate the CTTSs, while green diamonds represent the WTTSs. (A color version of this figure is available in the online journal.)

Table 5

| 2MASS | W1 – W2 | EW (Å)     | This Survey | Fűrész et al. | Da Rio et al. |
|-------|---------|------------|-------------|---------------|---------------|
| J05334964–0536208 | 0.53     | 0.51       | 4.0 (0.3)   | 5.2           | ...           |
| J05335210–0530284 | ...      | 0.31       | 7.2 (1.0)   | 6.5           | 3.6           |
| J05340797–0536170 | 0.64     | 0.81       | 7.8 (0.2)   | 24.3          | 78.0          |
| J05340835–0514387 | ...      | 0.40       | <2.7        | ...           | ...           |
| J05342616–0526304 | 0.56     | 0.73       | >5.7        | 42.2          | 230           |
| J05342650–0523239 | ...      | 0.36       | 11.4 (1.1)  | 45            | 46            |
| J05342960–0547247 | 0.09     | 0.31       | 9.4 (0.7)   | 8.5           | ...           |
| J05343203–0511248 | ...      | 0.55       | 5.9 (0.8)   | 19.5          | ...           |
| J05343417–0505170 | 0.16     | 0.53       | 3.6 (0.3)   | 4.7           | ...           |
| J05344172–0536488 | 0.45     | 0.58       | >6.5        | 12.8          | 30            |
| J05344239–0512381 | ...      | 0.88       | 5.5 (0.3)   | 25.3          | ...           |
| J05344244–0543256 | 0.32     | 0.50       | 8.0 (2.9)   | 3.9           | ...           |
| J05344789–0530465 | 0.21     | ...        | 9.2 (0.9)   | 22.2          | 10            |
| J0534815–0542289 | 0.24     | 0.54       | 6.7 (3.0)   | 3.1           | 23            |
| J05345825–0541498 | 0.39     | 0.68       | 5.3 (1.1)   | ...           | 28            |
| J05345881–0547334 | 0.32     | 0.74       | 9.7 (3.5)   | ...           | ...           |
| J05350085–0509389 | ...      | 0.34       | 9.2 (1.6)   | ...           | ...           |
| J05350532–0534285 | 0.37     | 0.46       | 7.7 (1.3)   | 7.2           | 11.0          |
| J05351205–0547296 | 0.36     | 0.49       | <7.0        | ...           | ...           |
| J05351236–0543184 | 0.10     | 0.45       | 3.8 (0.4)   | ...           | ...           |
| J05351464–0502251 | 0.26     | 0.45       | 5.8 (0.7)   | 4.8           | ...           |
| J05351715–0541538 | 0.28     | 0.48       | 5.7 (2.8)   | ...           | 14            |
| J05353047–0549037 | 0.28     | 0.30       | 8.8 (0.7)   | 8.6           | ...           |
| J05353070–0518071 | 0.50     | 0.76       | 2.4 (0.2)   | 65.8          | 190           |
| J05353385–0538206 | ...      | 0.33       | 4.9 (1.8)   | ...           | 1.6           |
| J05353554–0506585 | ...      | 0.78       | 2.8 (0.5)   | 5.1           | ...           |
| J05354130–0538329 | 0.31     | 0.44       | 7.6 (1.6)   | 5.6           | 15            |
| J05355109–0507088 | 0.29     | 0.42       | 6.7 (0.4)   | 6.0           | ...           |
| J05355232–0512569 | 0.23     | 0.63       | 4.8 (2.8)   | ...           | ...           |
| J05355276–0512590 | 0.27     | 0.48       | 5.3 (0.8)   | 3.8           | 30            |
| J05360276–0515269 | ...      | 0.43       | 11.8 (0.6)  | 13.3          | 11            |
| J05361010–0522050 | ...      | 0.31       | 6.1 (0.7)   | 6.0           | ...           |
| J05361975–0514386 | 0.30     | 0.37       | 10.0 (0.3)  | 3.0           | ...           |
| J05362627–0518301 | 0.29     | 0.53       | 14.2 (2.6)  | 10.7          | ...           |
| J05363167–0526356 | ...      | 0.42       | 4.5 (0.8)   | 9.9           | ...           |
| J05364005–0512231 | 0.25     | 0.37       | 4.5 (1.3)   | 3.1           | ...           |
| J05364932–0533205 | 0.42     | 0.39       | 9.9 (2.8)   | ...           | ...           |
Figure 16. Spectral energy distribution for stars classified as WTTS, but exhibiting near- and mid-infrared excesses characteristic of CTTSs. Symbols are the same as in Figure 10.

(A color version of this figure is available in the online journal.)

EWs, measured by various surveys and shown in Columns 4–6 of Table 5, shows that 7 of the 37 stars exhibited much stronger Hα emission in 2005, at the epochs of the observations of Fűrész et al. (2008) and Da Rio et al. (2009), that is, their accretion and wind activities are highly variable on a few-year timescale.

One star, exhibiting an extreme EW value around 500 Å in Figure 3, deserves attention. It is V421 Ori, associated with the proplyd 280-931 (Ricci et al. 2008). Da Rio et al. (2009) also measured very strong emission, EW(Hα) = 420 Å from this object, in which the emission from the externally ionized disk contributes to the observed Hα.

4.2. Clustered and Distributed Hα Emission Stars

To test whether the apparent clusters and voids in the surface distribution reflect patchy interstellar extinction, we plotted the cluster members and outliers, defined by their nearest neighbor distances, with different symbols onto the SPIRE image of the Orion region, downloaded from the Herschel Science Archive. The data are part of the Guaranteed Time Key Program “Probing the origin of the stellar initial mass function: A wide-field Herschel photometric survey of nearby star-forming cloud complexes” (Herschel Gould Belt Survey; PI: P. André; André et al. 2010). The structures in the
500 μm radiation of the cold dust correlate well with those seen in the extinction maps of the region (Rowles & Froebrich 2009; Scandariato et al. 2011). We chose the far-infrared image to display the surface distribution of the absorbing dust since its angular resolution is higher than those of the available extinction maps. Figure 17 suggests that variable extinction alone cannot account for the surface inhomogeneities of the stars. An apparent void can be seen next to the Trapezium where the bright background prevented us from detecting any emission line. The clustered stars (those having at least four neighbors within 2.16′) are found near the cold dust structures, suggesting that they are probably younger than the distributed population, and are closely associated with their natal clouds. Figure 17 suggests that variable extinction cannot result from a greater extinction along their line of sight.

The difference in brightness between the clustered and distributed stars suggests that we observe two populations of pre-main-sequence stars that differ from each other in both age and location in space. The lower average brightness of this scattered population suggests greater distance, higher age, or lower average mass of these stars. Since the presence of the massive molecular cloud, associated with the ONC, efficiently blocks the background stars, the greater distance is less probable than the older age and lower average mass. The increase in the brightness difference toward longer wavelengths points to a greater amount of circumstellar matter in cluster members with respect to the field stars, indicating a younger age of the clustered population. The presence of two overlapping populations toward the line of sight of ONC was suggested by the radial velocity survey of Fűrész et al. (2008) and is demonstrated by the recent work of Alves & Bouy (2012). The distribution of our Hα emission stars also reflects the presence of two, probably unrelated populations of pre-main-sequence stars.

4.3. Correlations of Hα Equivalent Width with Other Stellar Properties

4.3.1. Hα Equivalent Width and Infrared Excess

The study of the slope of a young star’s SED offers a great possibility to characterize the disk population of young stars. This method was applied, e.g., by Lada et al. (2006) and Teixeira et al. (2012). They measured the slope of the SED between 3.6 μm and 8 μm and, using this so-called αIRAC index, sorted the disks into an evolutionary sequence. To get an idea of the evolutionary stages of the disk population in our sample, we applied this method for the stars having Spitzer data in the literature. Figure 18 shows that most of our CTTSs have −1.8 < αIRAC < −0.5, characteristic of optically thick accretion disks. The stars at αIRAC ≲ −2.5 exhibit low EWs, suggesting an overlap between our CTTS and WTTS classes. The WTTS sample clearly splits into a group of diskless stars at αIRAC < −2.0 and temporarily non-accreting disked stars at −1.8 < αIRAC < −0.5.

4.3.2. Hα Equivalent Width and Rotation Period

Theoretical predictions suggest that the rotation rate of young stars may be influenced by magnetic interactions with the
accretion disk: the star is forced to corotate with the inner edge of the disk (see, e.g., Königl 1991). If this disk locking is real, CTTSs should have longer rotational periods than WTTSs.

Of the 587 TTSs listed in Tables 1–3, 214 were found to be periodic variables by Herbst et al. (2002), Cieza & Baliber (2007), and Flaccomio et al. (2005). Of the periodic variables, 144 are CTTSs and 70 WTTSs. The period histograms for the whole Hα emission star sample, CTTSs, and WTTSs are shown in the upper, middle, and lower panels of Figure 19, respectively, using the rotation data from Herbst et al. (2002), Cieza & Baliber (2007), and Flaccomio et al. (2005), binned into 1 day intervals. It can be seen clearly that there are two peaks at 2 and 8 days in the top panel. Herbst et al. (2002) showed a similar bimodal distribution for stars having masses greater than 0.25 $M_\odot$ in their rotational study. There is only one weakly defined peak at 8 days in the middle panel, while in the bottom panel there is another peak at 2 days.
peak at 2 days. Applying the statistical Welch’s test, we found a significant difference between the rotation periods of CTTSs and WTTSs. The mean rotation period of the CTTS sample is statistically longer than that of the WTTS group, as expected.

4.3.3. Hα Equivalent Width and X-Ray Emission

X-ray luminosity of main-sequence stars shows a tight correlation with rotational period. This correlation confirms the existence of a solar-like dynamo as the origin of the X-ray activity (Pizzolato et al. 2003). Pre-main-sequence stars show much greater X-ray emission than main-sequence stars. The origin of this emission is still debated, but presumably originates from the coronal magnetic activity (Preibisch et al. 2005a). There are still some unanswered questions about X-ray emission of pre-main-sequence stars.

Studies based on observations from the Chandra X-Ray Observatory indicated that CTTSs in the ONC may have lower levels of X-ray activity than WTTSs (Flaccomio et al. 2005; Preibisch et al. 2005b). Similar results were published for the Taurus–Auriga association (Neuhäuser et al. 1995; Stelzer & Neuhäuser 2001). Telleschi et al. (2007) found a significant difference in the X-ray luminosity functions of CTTSs and WTTSs based on the measure of XMM-Newton Extended Survey of Taurus molecular cloud in the Taurus–Auriga molecular cloud. The CTTSs are weaker in X-rays by about a factor of two. In the open cluster IC 348, Stelzer et al. (2012) found that for the lowest examined masses (0.1–0.25 M⊙) there is an important difference between accreting and non-accreting stars. Explanations for this phenomenon are either disk locking (Neuhäuser 1997) or distortion of the magnetic field structure (Preibisch et al. 2005b). In contrast with these results, Feigelson et al. (2002) found no evidence for the influence of an accretion disk on the activity levels of ONC stars.

To test this relationship in our sample that contains both CTTSs and WTTSs, we used X-ray data from the XMM-Newton Serendipitous Source Catalogue. A simple way to compare the X-ray luminosity for CTTSs and WTTSs is the statistical Welch’s test. The t variable is used for testing the significance of the difference between the corresponding groups. Applying this test for comparison between the X-ray luminosity for CTTSs and WTTSs shows that there is no difference between the mean X-ray luminosity of our CTTSs and WTTSs. However, since our Hα emission stars represent a strongly biased and incomplete sampling of the cluster population, this result does not conflict with those established for the whole ONC.

We examined the ratio of detected and non-detected stars within the XMM-Newton field of view and found that whereas 151 of the 342 CTTSs in the XMM-Newton field were detected (44.2%), 106 of the 154 WTTSs (68.8%) were above the detection threshold of the X-ray observatory. A chi-square test demonstrated that this difference is significant at a reasonably high level. According to this test, the hypothesis that the difference in the detection rate (detected/non-detected) is independent of the type can be rejected with a very low error probability. In other words, the fraction of X-ray-detected WTTS-type objects is significantly greater than that of the CTT group.

We examined the differences between X-ray-detected and non-detected objects in other measured quantities, such as EW(Hα), rotation period, and WISE, Spitzer, and 2MASS magnitudes. First we studied the whole sample and then the case of the CTT and WTTS groups, separately. The results, summarized in Table 6, show that the EW values of the stars not detected in X-rays are greater than those of the detected ones. The rotational periods are somewhat longer for the X-ray-detected TTs; the differences, however, exceed only slightly the standard error of the mean. As far as the 2MASS, Spitzer, and WISE fluxes are concerned, the X-ray-detected objects are systematically brighter in all bands. The brightness difference between the X-ray-detected and non-detected objects decreases with the increasing wavelength. We applied Welch’s test to study the significance of these values. We carried out this test for each parameter separately. The results demonstrate that, except for the rotational period, all the variables have significant differences between the X-ray-detected and non-detected stars. The most striking difference appears in EW(Hα). The greater infrared fluxes of the stars above the X-ray detection limit suggest that they are more massive than those below the detection limit.

5. SUMMARY

We identified 587 stars with Hα emission in a 1 deg² area centered on the ONC, 99 of which have not appeared in previous Hα surveys. We determined the EW of the line for 559 stars and, based on it classified 372 stars as CTTSs and 187 as WTTSs. The Hα line is strongly biased toward the minority population of CTTSs and misses the majority of the population of WTTSs reported in the Chandra X-ray sample. Compared with published data, we found 2–3-fold variations in the EW of the Hα line for the greater part of our sample. In a few cases the variations are ten- to twenty-fold.

We examined the surface distribution of the Hα emission stars and, based on the angular distance of their fourth nearest neighbors, defined a clustered and distributed population. We compared the properties of the clustered and distributed sources and found the mean brightness of the clustered stars to be statistically greater in all photometric bands. The clustered population is associated with cold dust structures, suggesting that these stars are younger than the dispersed population. The dispersed stars may be lower mass foreground objects, possibly associated with another, older subsystem of the Orion star-forming complex.

We studied the correlation between the EW of the Hα line and other properties of the stars and found the following:

1. According to the slope of their SEDs over the 3.6–8 μm wavelength region, our CTTSs show Class II SEDs, characteristic of optically thick accretion disks. The non-accreting WTTS sample splits into a diskless (Class III) and a disked (Class II) subgroup, suggesting that phases of very low accretion rate occur during the evolution of protorotating protoplanetary disks.
2. The CTTSs of our sample have longer rotational period than WTTSs, in accordance with theoretical results.
3. We examined the X-ray counterparts of the Hα emission stars in the XMM-Newton database. We found that, although the detection threshold in the X-ray regime is the same for the CTT and WTTS classes, a much higher fraction of WTTSs have been detected in X-rays than of CTTSs. We found that except for the rotational period all measured variables have significant differences between the X-ray-detected and non-detected stars. The most striking difference appears in the EW(Hα): the X-ray-detected CTTSs show much lower mean EW than the non-detected ones.

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### Table 6

| Quantity | Class          | Mean  | Std. Dev. | Std. Error Mean | Number of Stars |
|----------|----------------|-------|-----------|-----------------|-----------------|
|          |                | All   | CTT       | WTT             | All             |
|          |                | All   | CTT       | WTT             | All             |
|          |                | All   | CTT       | WTT             | All             |

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