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The CIDA Variability Survey of Orion OB1. II. Demographics of the Young, Low-mass Stellar Populations*

César Briceño¹, Nuria Calvet², Jesús Hernández³, A. Katherina Vivas¹, Cecilia Mateu^{4,5}, Juan José Downes^{5,6},
Jaqueline Loerincs⁷, Alice Pérez-Blanco⁸, Perry Berlind⁹, Catherine Espaillat¹⁰, Lori Allen¹¹, Lee Hartmann²,
Mario Mateo², and John I. Bailey III¹²

¹ Cerro Tololo Inter-American Observatory, National Optical Astronomical Observatory, Casilla 603, La Serena, Chile; cbriceno@ctio.noao.edu

² Department of Astronomy, University of Michigan, 311 West Hall, 1085 S. University Avenue, Ann Arbor, MI 48109, USA

³ Instituto de Astronomía, UNAM, Unidad Académica en Ensenada, Ensenada, 22860, México

⁴ Departamento de Astronomía, Instituto de Física, Universidad de la República, Iguá 4225, CP 11400 Montevideo, Uruguay

⁵ Centro de Investigaciones de Astronomía (CIDA), Apdo. Postal 264, Mérida 5101-A, Venezuela

⁶ PDU Ciencias Físicas, Centro Universitario Regional del Este (CURE), Universidad de la República, 27000 Rocha, Uruguay

⁷ School of Mines, University of Colorado, Boulder, CO, USA

⁸ School of Physics and Astronomy, University of Leeds, LS29JT, Leeds, UK

⁹ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

¹⁰ Astronomy Department, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA

¹¹ National Optical Astronomical Observatory, 950 North Cherry Avenue, Tucson, AZ 85719, USA

¹² Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands

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Abstract

We present results of our large-scale, optical, multi-epoch photometric survey across ~ 180 square degrees in the Orion OB1 association, complemented with extensive follow-up spectroscopy. Our focus is mapping and characterizing the off-cloud, low-mass, pre-main-sequence (PMS) populations. We report 2062 K- and M-type confirmed T Tauri members; 59% are located in the OB1a subassociation, 27% in the OB1b subassociation, and the remaining 14% in the A and B molecular clouds. We characterize two new clusterings of T Tauri stars, the HD 35762 and HR 1833 groups, both located in OB1a not far from the 25 Ori cluster. We also identify two stellar overdensities in OB1b, containing 231 PMS stars, and find that the OB1b region is composed of two populations at different distances, possibly due to the OB1a subassociation overlapping with the front of OB1b. A ~ 2 deg wide halo of young stars surrounds the Orion Nebula Cluster, corresponding in part to the low-mass populations of NGC 1977 and NGC 1980. We use the strength of H α in emission, combined with the IR excess and optical variability, to define a new type of T Tauri star, the C/W class, stars we propose may be nearing the end of their accretion phase, in an evolutionary state between classical and weak-lined T Tauri stars. The evolution of the ensemble-wide equivalent width of Li I $\lambda 6707$ indicates a Li depletion timescale of ~ 8.5 Myr. Disk accretion declines with an e-folding timescale of ~ 2 Myr, consistent with previous studies.

Key words: open clusters and associations: individual (Orion OB1 association) – stars: formation – stars: pre-main sequence – surveys

Supporting material: machine-readable tables

1. Introduction

Large star-forming complexes containing early spectral type (SpT) stars, also known as OB associations, are the prime sites for star formation in our Galaxy (Briceño et al. 2007b). These regions can extend to scales of tens up to hundreds of parsecs and span a rich diversity of environments and evolutionary stages in the early life of stars, ranging from young stars still embedded in their natal molecular clouds (ages $\lesssim 1$ Myr), up to somewhat more evolved populations (ages ~ 10 Myr) in areas largely devoid of gas, where the parent gas clouds have already dissipated. Though the most conspicuous members are the few massive O and B stars, the bulk, by number and mass, of the stellar population is composed of solar-like and lower mass pre-main-sequence (PMS) stars, also known as T Tauri stars

(TTSs; Joy 1945; Herbig 1962), whose defining characteristics in the optical wavelength regime are, among others, photometric variability, late SpT (K–M), and emission lines. Because for any reasonable initial mass function (IMF) the TTSs are far more numerous than O and B stars, the low-mass young stars are the best tracers of the spatial extent, structure, and star-forming history of any association. Moreover, they are the only way to study how the early Sun and its planetary system may have evolved. Therefore, building a complete census of the TTS population in an OB association is an essential first step to investigate issues like the degree of clustering, cluster sizes, dispersal timescales, the IMF, disk evolution, and the role of the environment in protoplanetary disks.

However, our knowledge of the full stellar content of most nearby OB associations is still far from complete. This is largely because the majority of existing studies have focused on the most easily recognizable components, that is, the youngest PMS stars, in particular those densely packed in clusters projected on their natal molecular clouds (e.g., the Orion Nebula Cluster—ONC; σ Ori; the NGC 2071, NGC 2068, and NGC 2024 clusters in the Orion B cloud; Tr 37 in Cepheus

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OB2; IC 348 in Perseus; and NGC 2264 in Monoceros, among others). Recent works at the optical (Hsu et al. 2013; Bouy et al. 2014; Kounkel et al. 2017a; Kubiak et al. 2017) and near-IR wavelengths (Megeath et al. 2016) have mapped the youngest populations over larger areas in Orion, but are mostly still limited to the molecular clouds. In regions like Scorpius–Centaurus and Orion, extensive spectroscopy has been done to characterize the young population (Rizzuto et al. 2015; Da Rio et al. 2016, 2017; Pecaut & Mamajek 2016). However, the fact remains that in most regions, the older off-cloud populations have been poorly studied. Only recently, with the advent of large-scale multiwavelength surveys, have we started to build, for the first time, complete pictures of the young stellar populations in these nearby OB associations. The advent of *Gaia* will bring about the exploration of the full extent of OB associations, well beyond the confines of the molecular clouds (Zari et al. 2017; Galli et al. 2018; Wright & Mamajek 2018), though extensive ground-based spectroscopy will still be essential to fully confirm and characterize the young stellar populations, especially for the solar and lower mass stars.

The Orion OB1 association (for reviews, see the various chapters on Orion in Reipurth 2008), located well below the Galactic plane ($-11^\circ \gtrsim b \gtrsim -20^\circ$), at a distance of roughly 400 pc (Genzel & Stutzki 1989; Briceño 2008; Kounkel et al. 2017b), and spanning over 200 deg^2 on the sky, is one of the largest and nearest OB associations. Blaauw (1964) counted 56 massive stars with SpTs earlier than B2, more than Scorpius–Centaurus and Lacerta OB1, and only slightly less than Cepheus. He estimated a total mass for Orion OB1 of $\sim 8 \times 10^3 M_\odot$, though this number is probably best interpreted as a lower limit, because it does not include the lower mass stars. Orion OB1 exhibits all stages of the star formation process, from very young, embedded clusters, to older, fully exposed OB associations, as well as both clustered and distributed populations. Therefore, this region is an ideal laboratory for investigating fundamental questions related to the birth of stars and planetary systems.

From late 1998 to 2012, we carried out the CIDA Variability Survey of Orion (CVSO), a large-scale photometric variability survey (in the optical V-, R-, and I-bands), complemented with an extensive spectroscopic study, encompassing $\sim 180 \text{ deg}^2$ in the Orion OB1 association (Figure 1), with the goal of identifying the low-mass ($0.1 M_\odot \lesssim M \lesssim 1 M_\odot$) stellar populations with ages $\lesssim 12 \text{ Myr}$ (Briceño et al. 2001, 2005, 2007a; Briceño 2008). The CVSO has pioneered the use of large-scale optical synoptic surveys to find and characterize populations of young, low-mass stars, a technique that has been successfully applied in several other studies (McGehee et al. 2005; McGehee 2006; Caballero et al. 2010; Covey et al. 2011; Van Eyken et al. 2011). Though the CVSO goes over the Orion A and B clouds (Maddalena et al. 1986), the real strength of our survey is the detection of the slightly extinguished, optically visible low-mass PMS populations located in the extended areas devoid of cloud material (Figure 2); our completeness in the on-cloud regions is limited to members with low reddening (A_V less than a few magnitudes).

In this work, we present a comprehensive large-scale census of the off-cloud Orion OB1 low-mass young stellar population. We expand the initial results presented in Briceño et al. (2005, hereafter B05) by covering a much larger area, spanning all of the region between $\alpha_{J2000} = 5^{\text{h}}-6^{\text{h}}$, and $\delta_{J2000} = -6$ to $+6 \text{ deg}$. This corresponds to the entire $\sim 117 \text{ deg}^2$ encompassed by the

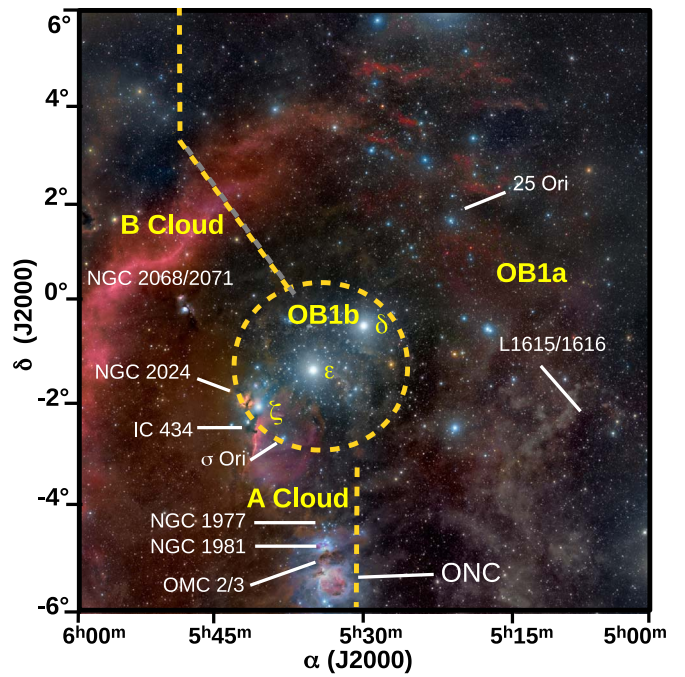


Figure 1. The Orion OB1 association as studied by the CVSO. The most prominent and well-known stellar groups and nebulae found across this extended region are labeled. Throughout this work, we assume the OB1b subassociation to be the area contained within the dashed-line circle roughly centered on ϵ Ori, as defined in Briceño et al. (2005). The OB1a subassociation is all the area west of the straight dashed lines and of OB1b. The B Cloud is considered here as the region east of the boundary with OB1a and OB1b, north of -2° , while the A Cloud is roughly the region east of $5^{\text{h}}28^{\text{m}}$, south of -2° , and excluding OB1b (optical image courtesy of Rogelio Bernal Andreo, DeepSkyColors.com).

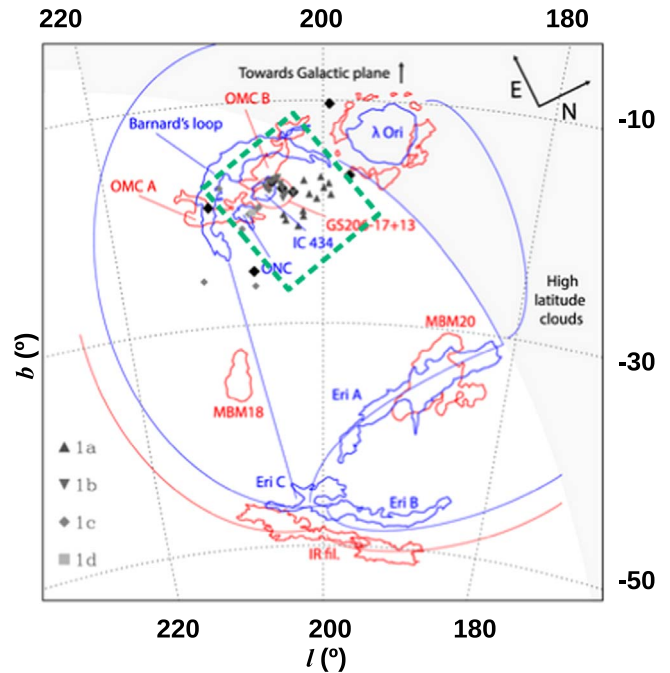


Figure 2. The outline of the CVSO survey area (green dashed-line rectangle) projected in galactic coordinates and overlaid on the large-scale structure of the Orion–Eridanus super bubble, as depicted schematically by Ochsendorf et al. (2015) in their Figure 1(d). The solid red lines map the dust structures, while the blue lines correspond to the rough outlines of gas structures traced by $\text{H}\alpha$ emission (adapted from Ochsendorf et al. 2015).

Table 1
CVSO Observing Log

Year	Month	Day	Obs. No.	Decl. _c (J2000) (deg)	R.A. _i (J2000) (deg)	R.A. _f (J2000) (deg)	Filters	Hour Angle (hh:mm:ss)
1999	12	28	503	+1.0	67.5	97.5	RHIV	01:54:20 E
1999	12	28	504	+1.0	67.5	97.5	RHIV	00:22:26 W
1999	12	28	505	+1.0	67.5	97.5	RHIV	02:52:39 W
1999	12	29	506	+1.0	67.5	97.5	RHIV	00:59:53 W
1999	12	30	507	+1.0	67.5	97.5	RHIV	01:41:07 E
1999	12	30	508	+1.0	67.5	97.5	RHIV	00:44:12 W
1999	12	30	509	+1.0	67.5	97.5	RHIV	03:06:26 W
2002	10	6	510	+1.0	72.5	92.98	VRIV	00:56:00 E
2002	10	13	504	+1.0	72.5	92.5	VRIV	00:38:00 E
2002	11	1	503	+1.0	72.5	93.15	VIRV	00:28:18 W

(This table is available in its entirety in machine-readable form.)

Orion OB1a subassociation and the $\sim 10.2 \text{ deg}^2$ spanned by the OB1b subassociation, both defined as shown in Figure 1, plus $\sim 31 \text{ deg}^2$ on the A and B molecular clouds. We do not consider here other parts of Orion OB1 that fall outside our survey boundaries, such as the L1641 cloud (Allen & Davis 2008), located south of the ONC, or the λ Orionis region (Mathieu 2008). Though located within our survey area, the embedded NGC 2024 (Meyer et al. 2008), 2068, and 2071 clusters (Gibb 2008), and the ONC (Muench et al. 2008) are not discussed here. Neither is the σ Ori cluster (Walter et al. 2008), which has been the subject of a separate study by Hernández et al. (2014).

In Section 2, we describe the optical variability survey, the processing of the observations, the normalization and photometric calibration of the instrumental magnitudes, the CVSO photometric catalog, the selection of candidate low-mass young stars, and our follow-up spectroscopy program. In Section 3, we describe our results, and in Section 4, we present a summary and conclusions.

2. Observations

Here we describe the two-stage methodology of our Orion OB1 large-scale survey, starting with the multi-epoch, photometric variability survey for selecting candidate low-mass young stars, followed by spectroscopic observations in order to provide membership confirmation and derive parameters like SpT, reddening, and type of object.

2.1. The Photometric Survey

The CVSO consists of multi-epoch optical quasi-simultaneous *V*-, *R*-, and *I*-band observations across the entire Orion OB1 association, obtained with the 8000×8000 pixel QUEST CCD Mosaic camera (Baltay et al. 2002), installed on the 1 m aperture Jürgen Stock Schmidt-type telescope at the National Astronomical Observatory of Venezuela. The system is optimized to operate in drift-scan mode: the telescope remains fixed at a given hour angle and declination (decl.), and because of sidereal motion, stars move across the length of each CCD. Up to four separate filters can be fitted at any given time in a special filter holder. A single observation produces four stripes of the sky, since there are four columns in the array of CCDs in the QUEST camera. During drift scanning, stars go consecutively across the four CCDs in the same row, each fitted with a different filter. The total width of the scan area is 2.3 degrees,

including small gaps between columns of CCDs. At a survey rate of roughly 34 deg^2 per hour per filter, large areas can be imaged efficiently. Many of the observations reported here were obtained with two *V* or two *I* filters in the filter holder; therefore, in those cases, two frames in the *V*-band and/or *I*-band were produced for every star in that particular strip of the sky. The typical minimum time between observations in two adjacent filters ($\Delta t_{\min}$) is set by how long it takes a star to go from one detector to the next in the same row of CCDs during a drift-scan observation. In the QUEST Camera, at the equator, $\Delta t_{\min} \sim 140 \text{ s}$, smaller than the timescale of most brightness variations seen in TTSs, which range from $\sim 1 \text{ hr}$ for flare-like events, to days for the rotational modulation produced by dark or bright spots in the stellar surface or changes in accretion flows, to weeks in the case of variations due to obscuration by features in a circumstellar disk. Other variations take place over even longer timescales, like those observed in eruptive young variables like EX Ori and FU Ori objects (Briceño et al. 2004), or the many-year cycles observed in some TTS (Herbst et al. 1994; Grankin et al. 2007, 2008; Herbst 2012). Flaherty et al. (2013) discussed the various causes of variability in TTSs.

Every Orion season (roughly from October to March), we observed as many nights as possible, limited essentially by weather and instrument availability. Usually, on a given night, we concentrated on a particular decl. and made as many drift-scan observations of that stripe of sky as possible during the $\sim 6 \text{ h}$ when Orion is accessible at airmasses $\lesssim 2$ from our equatorial location. Our temporal sampling is very heterogeneous, spanning a wide range of time baselines, from several minutes, to a few hours, days, weeks, months, and years.

The CVSO comprises 337 drift scans, listed in Table 1, performed along strips of R.A. centered at declinations -5° , -3° , -1° , $+1^\circ$, $+3^\circ$, and $+5^\circ$. We included observations obtained specifically for our program, but also for other programs that had targeted the same part of the sky with the QUEST camera (e.g., Rengstorf et al. 2004; Vivas et al. 2004; Downes et al. 2008, 2014). The 4.7 Tb data set corresponds to $\sim 15,000 \text{ hr}$ of observations in the *V*, *R*, and *I* filters, obtained over 190 nights between 1999 and 2008. The nature of the final data set is quite heterogeneous, first, because filters changed position depending on the particular project being executed, which combined with the fact that not all detectors were functional over this many-year period, resulted in some regions having different multi-epoch coverage in any of the *V*-, *R*-, or *I*-band filters. Second, not all declinations were observed as many times in each filter; though

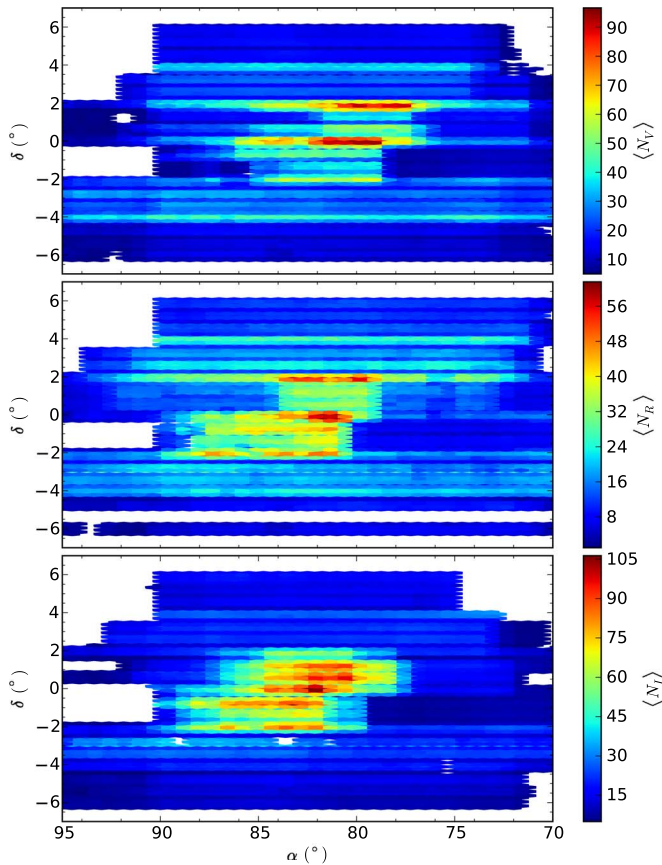


Figure 3. Spatial coverage of the CVSO in the V (top), R (middle) and I_C (bottom) filters. The color-scale bars indicate the number of epochs per filter. Adapted from Mateu et al. (2012).

for the Orion project we planned as uniform a coverage as possible, including additional data from other projects meant that some regions were more densely sampled. However, overall, the entire survey area was observed at least 10 or more times in each band (Figure 3), with roughly 50% of stars having in excess of 10 measurements in at least two photometric bands; on average, a given star has ~ 20 measurements. The average seeing measured in our data is $3''.01$, with $\sigma = 0.64$, which, given our plate scale of 1.02 arcsec/pixel, means that the stellar point-spread function is well sampled.

Because the exposure time in the drift-scan mode observations is fixed, this defines the usable magnitude range for each individual observation. At the bright end, our data saturate at magnitude ~ 13.5 in V , R , and I_C ; at the faint end, the 3σ limiting magnitudes for individual scans are $V_{\text{lim}} \sim 20.5$, $R_{\text{lim}} \sim 20.5$, $I_{C,\text{lim}} \sim 20$, with completeness (magnitude at which the distribution of sources reaches its peak) of $V_{\text{com}} \sim 18.9 \pm 0.06$, $R_{\text{com}} \sim 19.0 \pm 0.07$, $I_{C,\text{com}} \sim 18.0 \pm 0.08$ (Figure 4; also see Mateu et al. 2012 for more details on the photometry).

2.2. Data Processing and Optical Photometry

We used an updated, newer version of the automated QUEST data pipeline described in B05 and Vivas et al. (2004) to automatically process every single drift scan. This software corrects the raw images by bias, dark current, and flat field; masks bad columns and pixels; and then goes on to perform the detection of point sources, aperture photometry, and determination of detector coordinates for each object, independently in

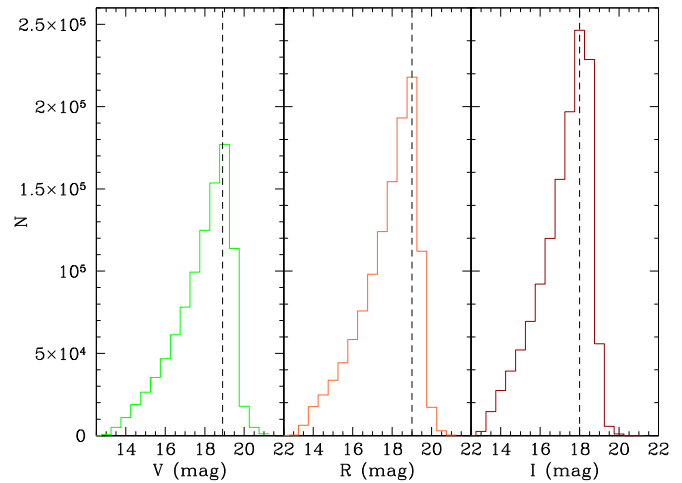


Figure 4. Histogram of magnitudes in the CVSO photometric catalog. The vertical dashed lines indicate the completeness magnitudes: $V = 18.5$, $R = 18.5$, $I = 18.0$.

each of the 16 devices. The software then solves the world coordinate system by computing the astrometric transformation matrices for each CCD of the mosaic, based on the USNOA-2.0 astrometric catalog (Monet 1998), typically with an accuracy of $\sim 0''.14$, sufficient for follow-up work with multi-object fiber spectrographs and cross-identification with other large-scale catalogs. As a result, for every drift-scan observation, there are 16 output catalogs produced, containing for every object the following information: X and Y detector coordinates, J2000 equatorial coordinates, instrumental magnitude and its corresponding 1σ error, and various photometric parameters, like the FWHM of the image profile, ellipticity, the average sky background value and its associated error, and various flags (bad columns, edges, etc.). Because Orion OB1 is well below the galactic plane ($b \gtrsim -12^\circ$), stellar crowding is not an issue, so we could safely perform aperture photometry; in fact, the average spatial density across our entire Orion survey area is 1 point source every 1334 arcsec ^{2} , which translates into a mean distance between stars of $\sim 36''$. We used an aperture equal to the mean FWHM of our images. Following B05, for each filter and decl. strip, we constructed reference catalogs of instrumental photometry, obtained under the best possible atmospheric conditions. All the other catalogs are normalized to these reference catalogs, such that differing sky conditions, like variations in transparency from night to night or a passing cloud causing an extinction of up to 1 mag were accounted for, as shown in Figure 3 of Vivas et al. (2004), where more details of this method are provided.

In order to calibrate our instrumental magnitudes in the Johnson–Cousins system, we followed a several step process (see also B05; Vivas et al. 2004; Mateu et al. 2012). Instead of observing Landolt fields every night at the Venezuela National Observatory, we collected a set of secondary standard star fields evenly distributed in decl., located so that each scan obtained at a given decl. would go over four secondary standard fields, one per row of four CCDs in the QUEST mosaic camera. We refined the calibration done in B05 by defining new 23 arcmin $\times$ 23 arcmin secondary standard fields obtained with the Keplercam $4k \times 4k$ CCD instrument on the 1.2 m telescope at the SAO Whipple Observatory in Arizona. We observed the secondary standard fields during several photometric nights in 2008 February, together with several

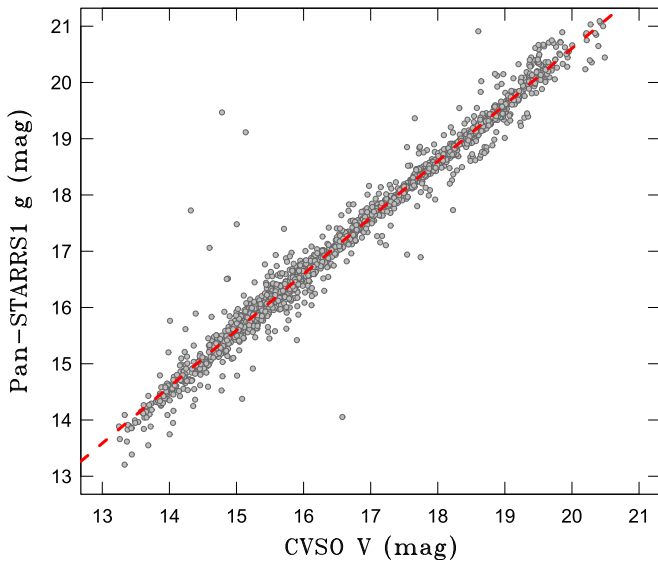


Figure 5. Comparison of our CVSO V magnitudes with the Pan-STARRS1 DR1 g_{PS1} photometry for the TTS sample described in this work. The red dashed line is a least-squares fit to the data.

Landolt standard star fields (Landolt 1983) at various air-masses. Then, using our CVSO observations of the stars in the KeplerCam fields, we selected ~ 125 secondary standard stars per field in the range $13 \leq V \leq 17$, determined to be non-variable at the ≤ 0.02 mag level (the complete V , R , I photometry for the secondary standards is published in Mateu et al. 2012). With such a large number of standards, we were able to derive a robust photometric calibration, with an average rms ~ 0.021 in the V -, R -, and I -bands.

As an external check of our photometry, in Figure 5 we compare our V -band magnitudes with the Pan-STARRS1¹³ (PS1) first data release (DR1) g_{PS1} magnitudes for the full sample of TTSs presented in this work. The agreement is very good. The least-squares fit is $g_{\text{PS1}} = 1.003 \times V + 0.548$, which is consistent within 0.06 mag with the relationship provided by Tonry et al. (2012), for the median $g_{\text{PS1}} - r_{\text{PS1}} = 1.2$ color of our TTS sample. The scatter observed for some stars is likely due to their variability between the CVSO and the PS1 observations.

2.3. The CVSO Photometric Catalog and the Selection of Candidate PMS Stars

2.3.1. The Catalog

Our final CVSO catalog contains 1,702,231 sources located in the region $\alpha_{\text{J2000}} \sim 5^{\text{h}}$ to 6^{h} and $\delta_{\text{J2000}} = \sim +6^\circ$ to -6° . Each source has an arbitrary ID number, α_{J2000} and δ_{J2000} coordinates, at least one measurement in either one of the V -, R -, and I -bands (640,639 objects have photometry in all three bands), with their corresponding errors (the sum in quadrature of the photometric calibration error and the standard deviation in that magnitude bin of all stars determined to be non-variable), the number of measurements in each filter, the maximum measured amplitude of photometric variations in each filter, the standard deviation of photometric variations in each filter, the probability that the object is variable in a

given photometric band based on a χ^2 test, the actual value of χ in each filter, and the Stetson (1996) L_{VR} , L_{VI} , and L_{RI} variability indices with their corresponding weights and the number of pairs of measurements involved in the computation of each index (Mateu et al. 2012).

Though the Stetson variability indices in the CVSO catalog are a valuable new addition to our original B05 photometric variability data set, in order to be able to compare the new results presented here with our previous studies, we used the same variability selection criterion as in B05, namely, we flagged as variable (at a 99.9% confidence level) those objects for which the probability in the V -band χ^2 test that the dispersion of measured magnitudes is due to random errors is very low (≤ 0.001). This criterion yielded 85,011 variable sources (5% of the 1,702,231 objects in the full CVSO catalog). With the adopted confidence level, formally only 85 of the 85,011 objects flagged as variables are expected to be false positives. But in reality, such a sample of variable objects can still potentially contain fake detections due to cosmic rays, bad pixels, or columns not properly corrected for during the data processing, or other artifacts. We dealt with this by requiring that an object have either a counterpart in more than one band, three or more measurements in a single band, or a counterpart in the 2MASS catalog (Skrutskie et al. 2006; see below). Our variability selection also sets the minimum Δmag that we can detect as a function of magnitude: 0.08 for $V = 15$, 0.12 for $V = 17$, and 0.3 for $V = 19$. This means that for fainter stars, we detect only those that vary the most. We cannot decrease the confidence level too much without increasing the contamination from non-variable stars to unacceptable levels, because we are dealing with such large numbers of stars.

Comparing directly the overall fraction of variable stars found in the CVSO with other similar surveys is far from straightforward. The number of variables detected will depend on, among other parameters, the criterion for declaring an object as variable, the wavelength range considered, the time sampling, the general direction on the sky, the survey brightness limits, plate scale, seeing conditions, and methods for source extraction and photometry. Nevertheless, it is useful to place the CVSO results in context with other surveys spanning a similar magnitude range. The Catalina Sky Survey found 2%–4% of variable objects on timescales spanning several years (Drake et al. 2013, 2014), and the PS1 3π survey detects 6.6% variables among 3.8×10^8 sources, in multi-epoch data spanning ~ 3.7 yr (Hernitschek et al. 2016). In Orion, the only other significant variability survey carried out so far is that by Carpenter et al. (2001), which targeted a $0.84 \times 6^\circ$ region centered roughly on the ONC, where they found a $\sim 7\%$ fraction of near-IR variables, similar to our result.

The availability of large-scale astronomical surveys, together with new data mining tools, has made feasible the combination and analysis of multiple data sets containing information across a wide range of wavelengths. We performed a spatial match of the full CVSO catalog against the 2MASS Point Source Catalog (PSC Skrutskie et al. 2006), which helped us weed out artifacts that may still affect the optical catalog, but more importantly, added near-IR photometry that, combined with our optical magnitudes and variability information, provided us with a longer wavelength base for a refined color selection of candidate young stars, and later enabled the determination of fundamental parameters like the stellar luminosity. We used the

¹³ Panoramic Survey Telescope & Rapid Response System, <https://panstarrs.stsci.edu/>.

Tool for Operations on Catalogs And Tables package (TOPCAT—Taylor 2005) and the Starlink Tables Infrastructure Library Tool Set (STILTS—Taylor 2006) to do a positional match, with a $2''$ search radius, between the CVSO catalog and the 2MASS PSC; the mode of the distribution of separations between our catalog positions and 2MASS is $0''.18$ (a significant improvement over the result obtained in B05), of which $0''.06$ comes from a systematic offset between the USNOA-2 catalog and the 2MASS PSC. The resulting combined *VRIJHK* catalog contained 946,934 sources; because of the reduced sensitivity of the 2MASS PSC compared to the CVSO, this match effectively set the limiting depth of our survey, such that the completeness magnitudes dropped to $V_{\text{com}} = 18.2$, $R_{\text{com}} = 17.7$, and $I_{\text{com}} = 17.2$. We could have used the much deeper *YZJHK* data set obtained for the VISTA telescope Galactic Science Verification (Petr-Gotzens et al. 2011), but then we would be limited to a much smaller area ($\sim 30 \text{ deg}^2$, or $\lesssim 20\%$ of our total photometric survey area); the VISTA observations were used by Downes et al. (2014, 2015) and Suárez et al. (2017) in their study of the 25 Ori cluster. Since our purpose was to create a spatially complete map of the low-mass young populations in Orion OB1, we opted to sacrifice depth in favor of a combined optical/near-IR catalog that spanned the full area covered by the CVSO. Even with this modestly deep completeness level, we still are sensitive to PMS stars down to $\sim 0.15 M_{\odot}$ at 10 Myr (Siess et al. 2000), which means that we could still expect to create a rather complete map of the stellar population to very low masses. Also, from a purely observational point of view, this was a reasonable low-mass limit for a feasible spectroscopic follow-up program using existing multi-fiber spectrographs on 4–6.5 m class telescopes (see Section 2.4).

2.3.2. PMS Candidate Selection

In selecting our photometric PMS candidates, we followed a two-step process that produced high- and low-priority targets for follow-up spectroscopy: (1) select objects located above the main sequence in optical and optical–near-IR color–magnitude diagrams (CMDs). (2) Among the PMS candidates from step one, select those identified as variable.

Following the procedure outlined in Briceño et al. (2005), of the 946,934 sources in our combined CVSO–2MASS catalog, we selected 115,071 PMS candidate stars located above the main sequence (Siess et al. 2000), set at a distance of 440 pc, in both V versus $V - J$ and V versus $V - I_c$ CMDs constructed using our robust mean V magnitudes; this is what we call here Candidate Sample 1 (CS1). Formally, Orion spans a range of distances, from ~ 360 pc for the closer OB1a subassociation to ~ 400 pc for OB1b and the molecular clouds, as shown by recent accurate distance determinations from Very Long Baseline Interferometry by Kounkel et al. (2017b) and parallaxes from the *Gaia* Second Data Release (DR2; *Gaia* Collaboration et al. 2018, see Section 3.6.1). However, assuming a slightly farther distance gave us a more relaxed selection criterion, placing the main sequence lower (fainter) in the CMD, and therefore allowing us to gather a more complete candidate sample among the more distant and in the older regions. The disadvantage of this approach is that a fainter main sequence allows more field contaminants, specially for the regions thought to be nearest to us.

Among the objects in CS1, we selected 12,928 stars (11% of the total CS1 sample) as variable objects; this is Candidate

Sample 2 (CS2), which by definition is a subset of CS1. For convenience, we define here as Candidate Sample 3 (CS3) those objects in sample CS1 not flagged as variable and therefore not included in CS2; this is either because they are non-variable, or more likely have variability below our detection threshold for that magnitude. Candidates in CS2 were considered our highest priority targets for follow-up spectroscopy (see Section 2.4). In order to have a general idea of the effectiveness of our PMS candidate selection scheme, we looked up in the SIMBAD database all previously known TTs inside our entire survey region. Though strictly this cannot be considered a quantitative test of our photometric search technique for young low-mass stars, because the PMS objects in SIMBAD constitute a very heterogeneous set, containing objects from a variety of studies with differing biases, techniques, and spatial coverage, it still provides a rough estimate of how much of the low-mass PMS population we can expect to find. Out of 275 SIMBAD objects with a “TT” or “YO” type (excluding sources in the ONC, in σ Ori, NGC 2024, NGC 2068, and those published in B05 and Briceño et al. 2007a, hereafter B07a), in the magnitude range $V = 13.5$ –19, and located in the PMS locus in the V versus $V - J$ CMD, we recovered 85% in CS2. The ones we did not recover were because they coincided with bad columns or fell in gaps between adjacent rows of detectors, in the master reference drift scans used to calibrate the final CVSO catalog (Section 2.2).

2.4. Spectroscopy

A sensitive photometric survey capable of identifying reliable and large samples of candidate PMS stars across the entire Orion OB1 association is the first step in mapping the full young low-mass population. However, follow-up low-resolution optical spectroscopy is paramount for three main reasons: first, to confirm membership, because even the best candidate samples are inevitably affected by contamination from field stars; second, to determine basic quantities for each star like its luminosity and T_{eff} , which can then be compared with evolutionary models to estimate masses and ages; and third, to distinguish between non-accreting weak-line T Tauri stars (WTTSs) and accreting classical T Tauri stars (CTTSs), as shown in Figures 8–10, an important diagnostic for characterizing the disk accretion properties across the full stellar population.

Our spectroscopic low-resolution follow-up program has been carried out with the following facilities:

- (1) The Hydra multi-fiber spectrograph (Barden et al. 1994) on the WIYN 3.5 m telescope at Kitt Peak.
- (2) The Hectospec multi-fiber spectrograph (Fabricant et al. 2005) on the 6.5 m MMT.
- (3) The Michigan/Magellan Fiber System (M2FS; Mateo et al. 2012) on the 6.5 m Magellan Clay telescope at Las Campanas Observatory.
- (4) The FAST Spectrograph for the Tillinghast Telescope (FAST; Fabricant et al. 1998) on the 1.5 m telescope of the Smithsonian Astrophysical Observatory.
- (5) The Goodman High Throughput Spectrograph (GHTS; Clemens et al. 2004) on the 4.1 m Southern Astrophysical Research (SOAR) telescope at Cerro Pachón, Chile.

We obtained spectra of a total of 11,201 candidate PMS stars among all instruments. As a general strategy, we selected our highest priority targets from the CS2 sample (PMS variables), and then added targets from sample CS3 (PMS non-variables).

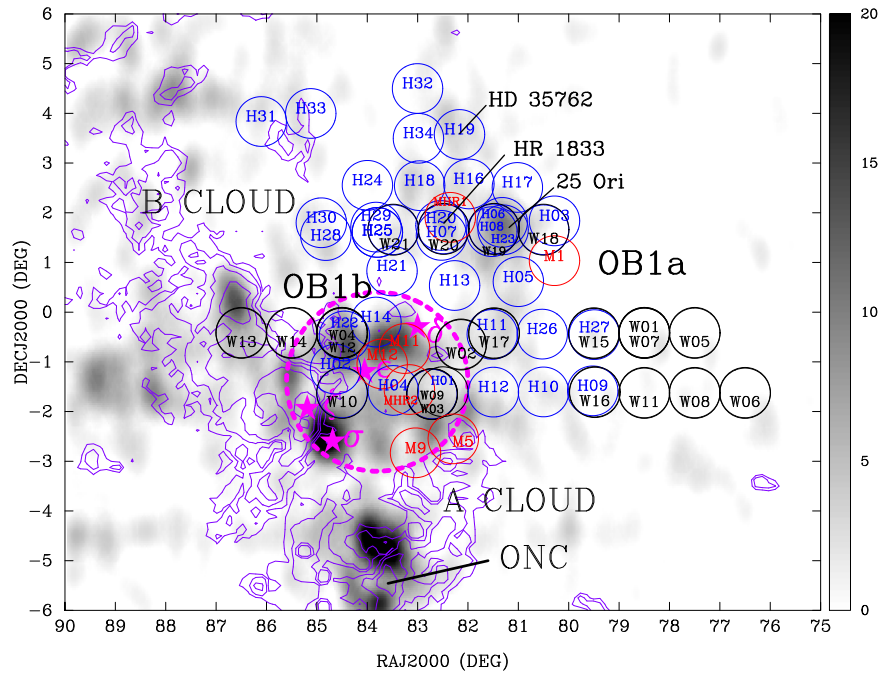


Figure 6. Schematic distribution of our Hectospec, Hydra, and M2FS observations. Circles labeled “H” in blue correspond to the Hectospec fields, “W” black labels to Hydra, and “M” red labels to the M2FS fields (see Table 2). Some fields were observed with both Hydra and Hectospec, so they have both blue and black labels. The grayscale map is the surface density of a candidate TTS in sample CS2, per $1''.6 \times 2''.6$. Contours show the integrated ^{13}CO emissivity of the Orion A and B molecular clouds (Bally et al. 1987), covering the range from 0.5 to 20 K km s^{-1} . The circular dashed region indicates our definition of the Orion OB1b association, as described in B05. The solid starred symbols mark the positions of the Orion belt stars and σ Ori. The locations of the 25 Ori cluster and the new TTS clusterings HR 1833 and HD 35762 (see Section 3.6) are also indicated.

For Hectospec and Hydra, we also included as third priority, whenever there were available fibers, additional candidates selected from the PMS locus in J versus $J - H$ CMDs made from 2MASS data. In Figures 6 and 7, we plot the spatial distribution of all sources observed with the multi-fiber spectrographs and with FAST and SOAR-Goodman, respectively.

2.4.1. Multi-fiber Spectroscopy

A total of 7796 candidates fainter than $V \sim 16$ were observed in our combined multi-fiber spectrograph campaigns. Both Hectospec and Hydra have a 1 deg diameter field of view, while M2FS has a 29.5 arcmin diameter field. Hectospec has 300 fibers, each $1''.5$ on the sky. Hydra with the Red Channel has 90 fibers, each with a projected diameter of $2''.0$, and M2FS offers up to 256 fibers, 128 for each of its twin Littrow spectrographs, each fiber with a projected diameter of $1''.2$ on the sky.

In Table 2, we show the full log of all the multi-fiber spectrograph observations for Hydra, Hectospec, and the Michigan/Magellan Fiber System (M2FS), including those discussed in B05;

WIYN+Hydra—In B05, we reported on 320 targets observed with Hydra in five fields (six fiber configurations) on 2000 November 26 and 27 (W02, W03, W04, W05, W07, and W09 in Table 2). Here we consider an additional 932 objects for which we obtained WIYN-Hydra spectra during the nights of 2000 November 26–28 and February 2, and 2002 November 13–15. These candidates were distributed in 15 fields (see Figure 6), spanning an area of $\sim 11 \text{ deg}^2$; 138 (15%) objects listed in CS2 were selected as priority 1 targets. We used the Red Channel fibers ($2''$ diameter), the Bench Camera with the T2KC CCD, and the $600@10.1$ grating, yielding a wavelength range $\sim 4700\text{--}7500 \text{ \AA}$ with a resolution of $3.4 \text{ \AA}$. The left

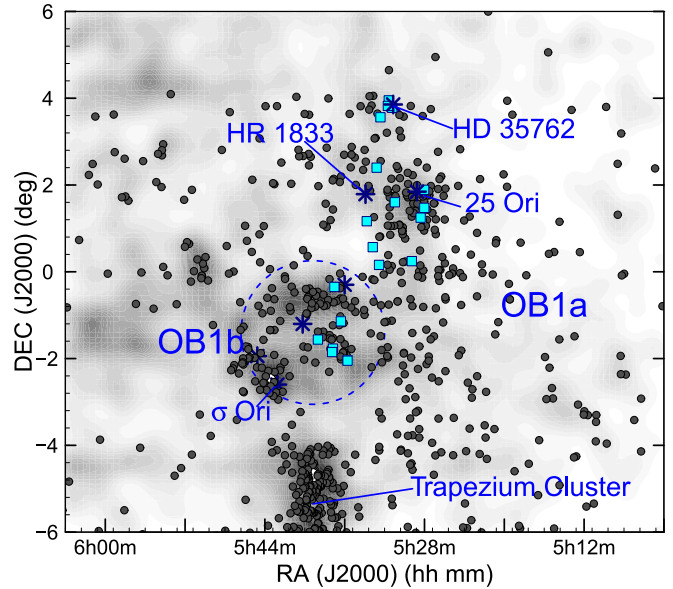


Figure 7. Spatial distribution of TTSs confirmed through FAST and SOAR-Goodman spectroscopy. FAST-confirmed TTSs are indicated with dark dots, while those identified in SOAR-Goodman spectra are plotted as cyan squares. The grayscale background is the surface density of photometric candidate PMS stars in our sample CS2. The main stellar groups and regions are labeled, both the known groups and the new ones discussed in this work.

panels in Figure 8 show TTS spectra obtained with Hydra. All fields were observed with airmasses = 1.0–1.5, and integration times for individual exposures were 1800 s. When weather allowed, we obtained two or three exposures per field. Comparison CuAr lamps were obtained between each target field. In each Hydra field, we assigned fibers to all candidates

Table 2
WIYN-Hydra and MMT-Hectospec Observing Log

UT Date (Year Month Day)	Instrument	Field ID	R.A. _c (J2000) (hh:mm:ss.ss)	Decl. _c (J2000) (dd:mm:ss.s)	T_{exp} (s)	No. Objects	Notes
2000 Nov 26	Hydra	W01	05:14:00.00	−00:25:03.0	1800	57	
2000 Nov 26	Hydra	W02	05:28:33.10	−00:39:00.0	1800	78	Field-1a in B05
2004 Nov 3	Hectospec	H01	05:29:23.28	−01:25:15.3	900×3	235	decml60_7 in D08
2005 Mar 14	Hectospec	H05	05:25:08.04	+00:20:47.0	900×3	273	
2010 Feb 10	Hectospec	H30	05:39:38.67	+01:47:54.9	3600	252	
2013 Nov 30	M2FS	M9	05:32:09.94	−02:49:46.8	3×600	112	
2015 Mar 5	M2FS	M1	05:21:08.02	+01:02:09.1	$3 \times 600 + 180$	63	

(This table is available in its entirety in machine-readable form.)

from CS2 with $V = 16$ – 18.5 , then to candidates from CS3, and with the lowest priority to objects from the 2MASS near-IR CMD. Typically, we assigned 10–12 fibers to empty sky positions and five to six fibers to guide stars. We used standard IRAF routines to remove the bias level from the two-dimensional Hydra images. Then, the dohydra package was used to extract individual spectra, derive the wavelength calibration, and do the sky background subtraction. Since the majority of our fields are located in regions with little nebulosity, background subtraction was in general easily accomplished.

MMT+Hectospec—With Hectospec, we observed 6110 targets distributed in 28 fields (34 fiber configurations), covering 23 deg^2 , during the period 2004 November–2010 February (Table 2 and Figure 6). We excluded the 124 members of 25 Ori from B07a and the 77 very low-mass PMS members in that same cluster already reported by us in Downes et al. (2008, 2014). We assigned the highest priority in the fiber configuration software to the 813 candidates flagged as PMS variables (CS2). The spectrograph setup used the $270 \text{ groove mm}^{-1}$ grating, yielding spectra in the range $\lambda 3700$ – 9000 Å , with a resolution of 6.2 Å . Sample TTS spectra obtained with Hectospec are shown in the right panels in Figure 8. As for Hydra, objects in CS2 had the highest priority, followed by objects from CS3, and the remaining fibers were filled with 2MASS *JH*-selected PMS candidates. On average, we assigned 50 fibers per field to empty sky positions; the majority of our fields are located in regions with little or no extinction, so nebulosity was not an issue for sky subtraction. All of the Hectospec spectra were processed, extracted, corrected for sky lines, and wavelength-calibrated by S. Tokarz at the CfA Telescope Data Center, using customized IRAF routines and scripts developed by the Hectospec team (see Fabricant et al. 2005).

Magellan+M2FS—We used the M2FS instrument to obtain spectra of 434 targets distributed in five fields, spanning a total area of 1 deg^2 , during several runs between 2013 November and 2015 February (Table 2 and Figure 6). As we did for Hectospec, we assigned the highest priority to candidates flagged as PMS variables (CS2). The spectrograph setup used the $600 \text{ lines mm}^{-1}$ grating and $125 \mu\text{m}$ slit, yielding spectra in the range 5670 – 7330 Å , with a resolution of 1.3 Å . Two representative M2FS TTS spectra are shown in Figure 9. Sky fibers were assigned as for Hydra and Hectospec. The raw data were processed using custom Python scripts developed by John Bailey, which apply a bias correction, merge the four files per image produced by each of the four amplifiers, and correct cosmic rays (see Bailey et al. 2016 for a more detailed

description of the software). Extraction of spectra, wavelength calibration, and correction for sky lines were done using the routines in the twodspec and onedspec packages in IRAF.

2.4.2. Single-slit Spectroscopy

FLWO 1.5 m+FAST—We obtained spectra for a total of 3383 bright candidates ($V < 16$) in queue mode at the FAST spectrograph. Out of these 3383 FAST targets, 1235 (37%) objects from subset CS2 were observed as highest priority. We then continued with the remaining 2148 objects from set CS3.

In B05, we presented results for the first 1083 FAST candidates observed from 1999 January through 2002 January. Here we discuss the additional 2300 candidates for which we obtained FAST spectra up to 2013 April. In Figure 7, we show the spatial distribution of the Orion TTS members confirmed with FAST. We obtained a relatively uniform spatial coverage across the entire survey area, except for the decl. band $+4 \text{ deg} \lesssim \delta \lesssim +6 \text{ deg}$. The FAST Spectrograph was equipped with the Loral 512×2688 CCD, in the standard configuration used for “FAST COMBO” projects: a $300 \text{ groove mm}^{-1}$ grating and a $3''$ wide slit, producing spectra spanning the range from 4000 to 7400 Å with a resolution of 6 Å . In Figure 10, we show FAST spectra of two new TTSs. The spectra were reduced at the CfA using software developed specifically for FAST COMBO observations. All individual spectra were wavelength-calibrated using standard IRAF routines. The effective exposure times ranged from 60 s for the $V \sim 13$ stars to $\sim 1500 \text{ s}$ for objects with $V \sim 16$.

SOAR+Goodman—We used the GHTS, installed on the SOAR 4.1 m telescope on Cerro Pachón, Chile, to obtain slit spectra of 23 candidate TTSs that needed confirmation and had not been observed with any other spectrograph. We used available time slots during the engineering nights of 2014 March 19, 2017 September 6, and 2017 December 5. The GHTS is a highly configurable imaging spectrograph that employs all-transmissive optics and Volume Phase Holographic Gratings, which result in high throughput for low- to moderate-resolution spectroscopy over the 320 – 850 nm wavelength range. The 2014 March 3 and 2017 September 6 observations both used the $400 \text{ lines mm}^{-1}$ grating in its 400M2 preset mode combined with the GG 455 order-sorting filter. This configuration provides a wavelength range $\sim 5000 \lesssim \lambda \lesssim 9000 \text{ Å}$, which combined with the $1''$ wide slit results in an FWHM resolution of 6.7 Å (equivalent to $R \sim 800$). Examples of Goodman-SOAR spectra are shown in the two right panels of Figure 10. The 2017 December 5 observations were done with the $600 \text{ lines mm}^{-1}$ grating in the “mid” setup, with the GG385 order-blocking filter and the $1''$ slit. This setup results in an FWHM spectral resolution of 4.4 Å

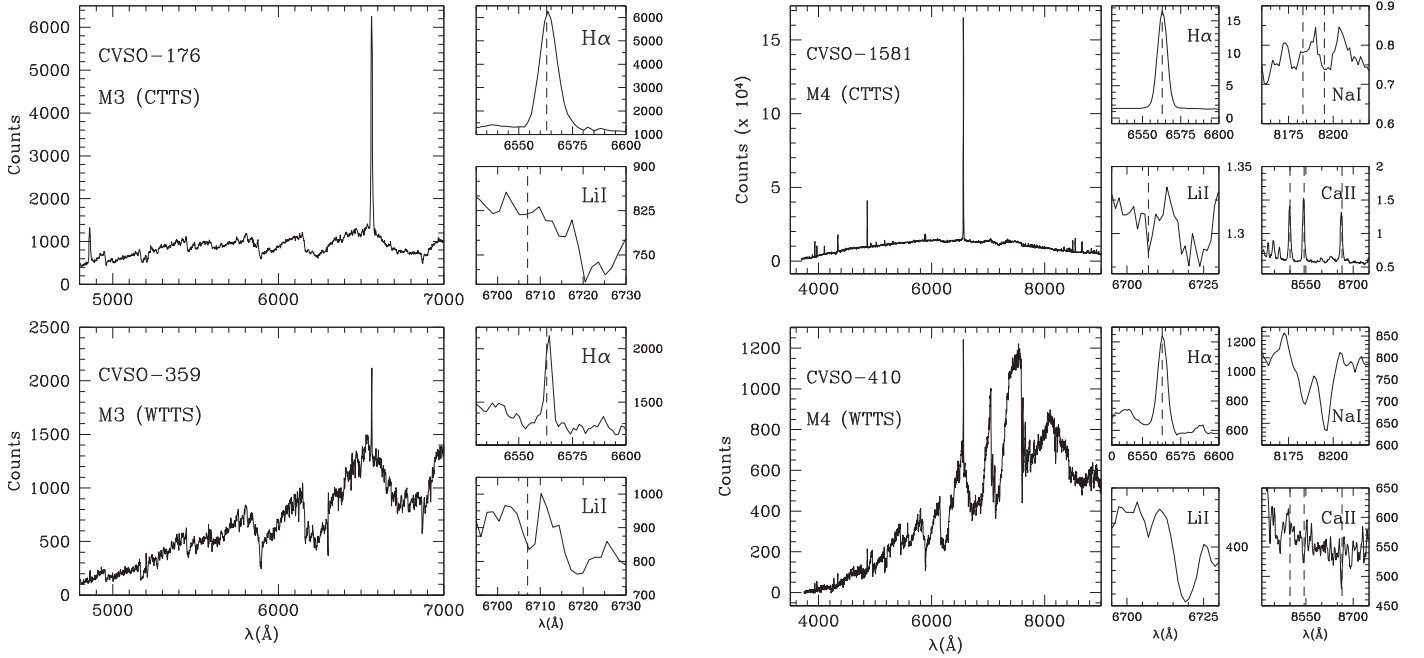


Figure 8. Left: spectra of two M3-type TTs obtained with the Hydra spectrograph on the WIYN 3.5 m telescope. In the upper panel, the CTTS CVSO-176 has a $W(\text{H}\alpha) = -41.4 \text{ \AA}$ and $W(\text{Li I}) = 0.2 \text{ \AA}$. The $\text{H}\beta$ Balmer line is also in emission, as are the He I lines at $5876 \text{ \AA}$ and $6876 \text{ \AA}$. In the lower panels, the WTTS star CVSO-359 has a $W(\text{H}\alpha) = -2.5 \text{ \AA}$ and $W(\text{Li I}) = 0.6 \text{ \AA}$. Other than $\text{H}\alpha$, no other lines are seen in emission. In both stars, the S/N in the region between $\text{H}\alpha$ and Li I is ~ 35 . Right: spectra of two candidates confirmed as new M4 TTS members of Orion, obtained with the Hectospec spectrograph on the 6.5 m MMT. In the upper panel, we plot an extreme CTTS, with $W(\text{H}\alpha) = -83.6 \text{ \AA}$ and $W(\text{Li I}) = 0.1 \text{ \AA}$. The entire Balmer series is clearly in emission, along with the Ca H and K lines ($3933 \text{ \AA}$, $3968 \text{ \AA}$), He I at $5876 \text{ \AA}$ and $6876 \text{ \AA}$, $[\text{O I}]$ $6300 \text{ \AA}$, and $[\text{S II}]$ $6716 \text{ \AA}$, $6732 \text{ \AA}$. In this star, the Na I $5890, 5895 \text{ \AA}$ doublet and the Ca II triplet ($8498 \text{ \AA}$, $8542 \text{ \AA}$, $8662 \text{ \AA}$) are also strongly in emission ($W(\text{Ca II } 8498) = -10.2 \text{ \AA}$, $W(\text{Ca II } 8542) = -11.8 \text{ \AA}$, and $W(\text{Ca II } 8662) = -10.5 \text{ \AA}$). The near-IR Na I doublet has $W(8183) = 0.5 \text{ \AA}$ and $W(8195) = 1.1 \text{ \AA}$. Lower panel: the M4 WTTS shown here has $W(\text{H}\alpha) = -6.1 \text{ \AA}$ and $W(\text{Li I}) = 0.4 \text{ \AA}$. $\text{H}\beta$ and the Ca H and K lines are also in emission. The near-IR Na I doublet has $W(8183) = 0.7 \text{ \AA}$ and $W(8195) = 1.0 \text{ \AA}$, typical of M-type stars with lower than main-sequence gravities (Luhman et al. 2003; Schlieder et al. 2012).

(equivalent to $R \sim 1300$) in the wavelength range of $\sim 4450 \lesssim \lambda \lesssim 7050 \text{ \AA}$. In all cases, we used 1×1 binning, keeping the native pixel scale of $0''.15 \text{ pixel}^{-1}$. For each object, we obtained three integrations, which were median-combined after correcting for bias and spatially registering the second and third exposures to the first one, which we used as reference. Integration times ranged from 300 s for the brightest targets ($V \sim 15$) to 900 s for the fainter ones ($V \sim 18$). The basic image reduction was performed using standard IRAF packages: CCDPROC and IMSHIFT. The one-dimensional spectrum was extracted using routines in the IRAF TWODSPEC and ONEDSPEC packages. For wavelength calibration, we used a HgArNe lamp.

We did not perform flux calibration in any of our spectra, since the main purpose of our follow-up spectroscopy is membership identification and SpT classification. We measured $\text{H}\alpha$ and Li I equivalent widths in all our low-resolution spectra from the various instruments, using the `splot` routine in IRAF and the SPTCLASS tool (Hernandez et al. 2017), an IRAF/IDL code based on the methods described in Hernández et al. (2004). Lines in the far red region of the spectrum were only available for TTs confirmed in Hectospec and SOAR spectra. The signal-to-noise ratio (S/N) of our spectra was typically $\gtrsim 25$ at $\text{H}\alpha \lambda 6563$, sufficient for detecting equivalent widths down to a few $0.1 \text{ \AA}$ at our spectral resolution of $\sim 6\text{--}7 \text{ \AA}$ FWHM. In Figures 8–10, we show sample spectra of Orion OB1 WTTSs and CTTSs observed with the Hydra and Hectospec, M2FS, and FAST and SOAR spectrographs, respectively.

3. Results and Discussion

3.1. Identification of T Tauri Stars

Many methods have been used over the years to identify young, low-mass PMS stars in star-forming regions. From $\text{H}\alpha$ emission in large-scale photometric or objective prism surveys, to X-rays, infrared excess emission, kinematics (e.g., see the review works in Reipurth 2008), and now with the advent of *Gaia*, parallaxes are for the first time available for a large number of candidate young stars in our solar vicinity (Kounkel et al. 2018 and this work). However, in order to confirm the PMS nature of low-mass K- and M-type stars, spectroscopy remains an essential tool, and in particular, no other youth indicator is probably as unambiguous as the presence of the $\text{Li I } \lambda 6707$ line in absorption in K- and M-type spectra. Together with Li I , the Na I $\lambda 8200$ doublet constitutes an additional important indicator of youth, and in young brown dwarfs, in which lithium is no longer depleted, the Na I doublet becomes a main diagnostic (Downes et al. 2008, 2014; Luhman & Muench 2008).

Spectroscopy becomes even more critical when searching for more evolved young stars. Such populations lack the IR-excess emission that make tools like *Spitzer* and *Wide-field Infrared Survey Explorer* (WISE) so effective for mapping the youngest populations in dark clouds (e.g., Megeath et al. 2016) and cannot be identified with X-rays alone, because they share the same X-ray emission properties as young main-sequence stars (Briceño et al. 1997).

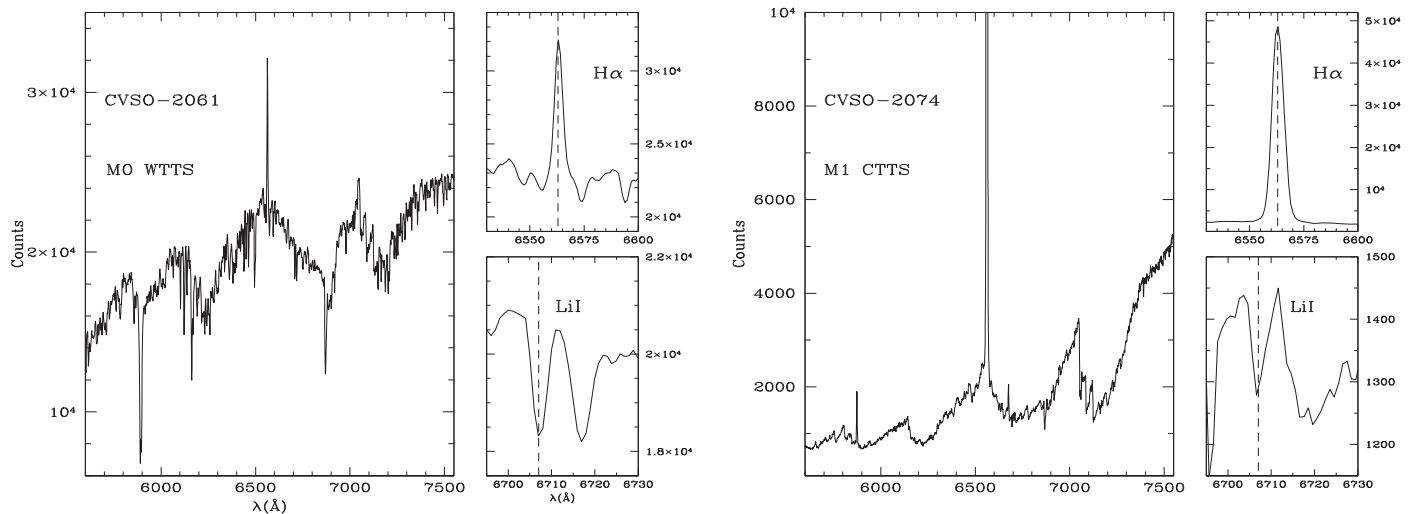


Figure 9. Spectra of two newly confirmed early M-type TTS members of Orion, obtained with the M2FS spectrograph on the 6.5 m Magellan Clay telescope. Left: an M0 WTTS, which has $W(\text{H}\alpha) = -2.2 \text{ \AA}$ and $W(\text{Li I}) = 0.4 \text{ \AA}$. In both spectra, the S/N is $\gtrsim 50$. Right: an accreting CTTS, with $W(\text{H}\alpha) = -139 \text{ \AA}$ and $W(\text{Li I}) = 0.4 \text{ \AA}$. In addition to the strong $\text{H}\alpha$ line, the He I line can also be seen in emission at $5876 \text{ \AA}$ and $6876 \text{ \AA}$, as well as at [O I] $6300 \text{ \AA}$.

In surveys of large areas of the sky, like the CVSO, the majority of K- and M-type field dwarfs are located in front of the region of interest, thus they fall above the main sequence in CMDs, when assumed at the distance of the star-forming region, mimicking PMS stars. This is what we found in our extensive spectroscopic follow-up; almost all contaminants among the variability-selected photometric candidates were K and M dwarfs, many with $\text{H}\alpha \lambda 6563$ emission. Late-type, non-accreting WTTSs (which constitute the bulk of the young populations in the off-cloud regions of OB associations; Briceño 2008) differ from their main-sequence K- and M-type counterparts only in the presence of the Li I $6707 \text{ \AA}$ line in absorption, and the weaker Na I ($8183, 8195 \text{ \AA}$) doublet. Otherwise, they are identical, having the same color, similar median amplitude of photometric variability (see Section 3.7.4 and Figure 32), same SpTs, and weak to modest emission in $\text{H}\alpha \lambda 6563$. With the availability of *Gaia*, most of such foreground contaminants can be readily filtered out, using proper motions and parallaxes. However, even after this there will remain a number of field K and M dwarfs that happen to lie at the same range of distances as the genuine PMS population. Statistically, a number of them will also share similar kinematics to those of the PMS stars. In the end, the detection of Li I at $6707 \text{ \AA}$, as shown in the spectra of Figures 8–10, and its comparison with measurements from young main-sequence clusters stars, as shown in Figure 11, remains the crucial criterion to confirm the PMS nature of K- and M-type dwarfs.

3.1.1. $\text{H}\alpha$ Emission and Li I Absorption

We establish membership based on our low-resolution spectra from FAST, Hydra, Hectospec, M2FS, and SOAR (Figures 8–10). Our criteria to identify PMS low-mass stars are the following:

- (1) SpT between K and M type, which corresponds to the range of colors and magnitudes expected from our photometric survey candidate selection.
- (2) Presence of the Balmer hydrogen lines in emission, in particular $\text{H}\alpha \lambda 6563$, which are characteristic of active late SpT young ($\lesssim 1 \text{ Gyr}$) dwarfs (e.g., Stauffer & Hartmann 1986; Stauffer et al. 1997).

- (3) Presence of the Li I ($6707 \text{ \AA}$) line strongly in absorption (Briceño et al. 1997; Briceño et al. 1998). Li I is our main youth criterion for late-type stars. Since lithium is depleted during the PMS stage in the deep convective interiors of K- and M-type stars, we regarded a candidate object to be a TTS if it had $\text{H}\alpha \lambda 6563$ in emission and Li I $\lambda 6707$ in absorption with equivalent width larger than the upper value for a Pleiades star of the same SpT (Soderblom et al. 1993; Garcia Lopez et al. 1994), which represents the young main sequence for late-type stars (Figure 11). With an S/N $\gtrsim 25$ in our spectra, we could detect Li I $\lambda 6707$ absorption down to $W(\text{Li I}) \sim 0.1 \text{ \AA}$. There are some cases in which Li I could not be reliably measured, but we still classified the star as a TTS. The decision to include the star as a TTS was based on the presence of $\text{H}\alpha \lambda 6563$ clearly in emission, in addition to other lines like $\text{H}\beta \lambda 4861$, Ca H & K $\lambda\lambda 3934, 3969$, He I $\lambda\lambda 5876, 6678$, and in some cases also [O III] $\lambda\lambda 6300, 6364$, [N II] $\lambda\lambda 6548, 6583$, [S II] $\lambda\lambda 6716, 6732$, and Ca II $\lambda\lambda 8498, 8542, 8662$. This generally only applied to strongly accreting CTTSs. Reasons for Li I not being measured could be due to a noisy spectrum, or because the spectrum is heavily veiled by the excess continuum emission from an accretion shock, created by material infalling from the circumstellar disk onto the star. In this latter case, a TTS would exhibit weak Li I absorption, below the Pleiades distribution upper envelope, thus failing our Li I TTS classification criterion, but otherwise fulfilling all other spectroscopic indicators of it being a very active, accreting young star (see (4) below).

- (4) Presence of additional youth signatures, in particular gravity-sensitive features like the Na I $8173/8195 \text{ \AA}$ doublet weakly in absorption (e.g., Martin et al. 1996; Luhman et al. 2003; Martín et al. 2004, 2010; Slesnick et al. 2006; Downes et al. 2008; Lodieu et al. 2011; Schlieder et al. 2012). In strongly accreting young stars, other spectral features like He I $\lambda\lambda 5876, 6678$, [O I] $\lambda\lambda 6300, 6346$, [S II] $\lambda\lambda 6716, 6732$, and the Ca II triplet $\lambda\lambda 8500, 8544, 8665$ can also be seen in emission (Edwards et al. 1987; Hamann & Persson 1990, 1992; Hamann 1994), and we take these as features that confirm and reinforce the PMS nature of a star.

In Figure 12, we show our classification procedure.

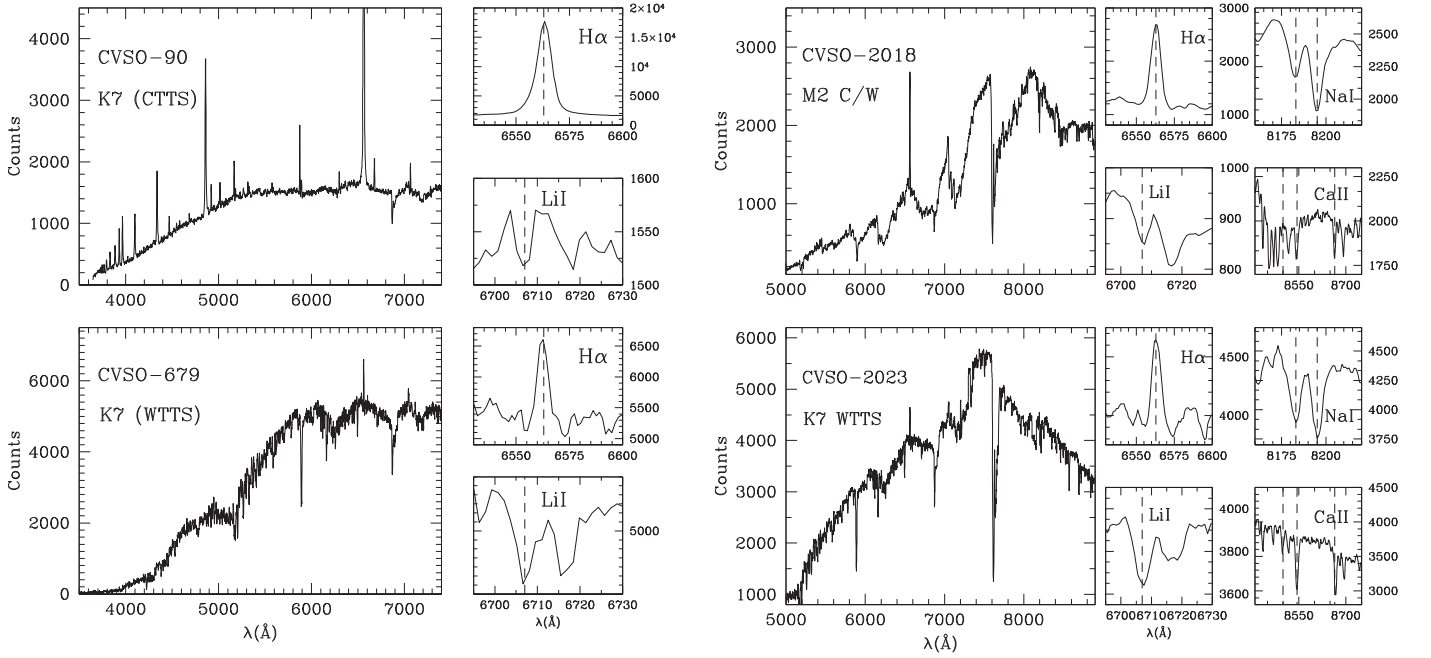


Figure 10. Left: spectra of K7-type TTS obtained with the FAST spectrograph on the SAO 1.5 m telescope. In the upper panels, the CTTS CVSO-90 shows the characteristic extreme emission-line spectrum of a strongly accreting TTS; the equivalent width of the $H\alpha$ emission line is $W(H\alpha) = -97 \text{ \AA}$. The equivalent width of Li I is $W(\text{Li I}) = 0.2 \text{ \AA}$, and the absorption line next to it is the Ca I line at $6716 \text{ \AA}$. The entire Balmer series is seen clearly in emission; also in emission are the Ca H and K lines ($3933 \text{ \AA}$, $3968 \text{ \AA}$), [O I] at $6300 \text{ \AA}$, and He I at $5876 \text{ \AA}$ and $6876 \text{ \AA}$. In contrast, the WTTS CVSO-679 in the lower panels has a weak $W(H\alpha) = -1.6 \text{ \AA}$, and no other emission lines; in this star, $W(\text{Li I}) = 0.4 \text{ \AA}$. Right: spectra of two newly identified TTSs obtained with the GHTS spectrograph on the SOAR 4.1 m telescope. In the upper panels, the C/W type (see Section 3.3) CVSO-2018 shows the characteristic strong emission-line spectrum of a moderately accreting TTS; the equivalent width of the $H\alpha$ emission line is $W(H\alpha) = -9.9 \text{ \AA}$. The equivalent width of Li I is $W(\text{Li I}) = 0.2 \text{ \AA}$, and the absorption line next to it is the Ca I line at $6716 \text{ \AA}$. The K7 WTTS CVSO-2023 in the lower panels has a weak $W(H\alpha) = -1.4 \text{ \AA}$; in this star, $W(\text{Li I}) = 0.5 \text{ \AA}$. In all spectra, the S/N in the region between $H\alpha$ and Li I is $\gtrsim 20$.

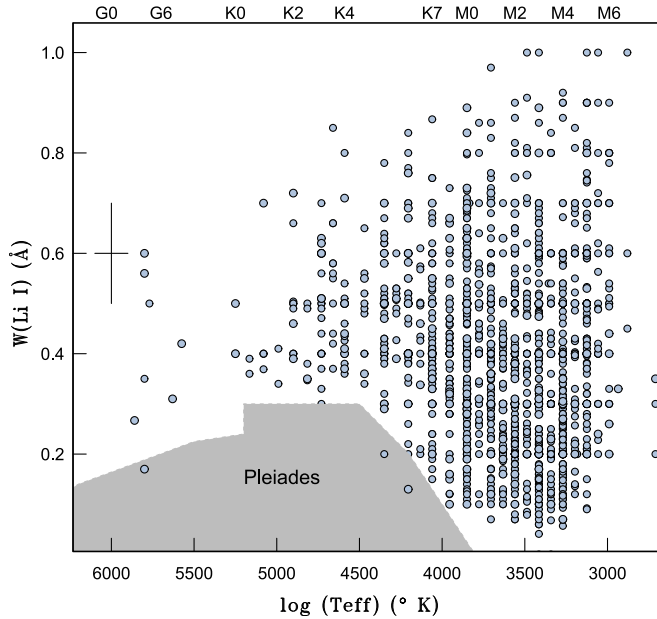


Figure 11. Equivalent width of the Li I $\lambda 6707$ line for the 2062 Orion OB1 TTS. The locus of the Pleiades stars is indicated by the shaded gray region (Soderblom et al. 1993; García López et al. 1994). A candidate young star is considered a TTS if it falls above this part of the diagram (see text). The typical error bar is indicated.

Following this approach, we classified 2062 candidates as confirmed low-mass, PMS stars of K- and M-type, based on our low-resolution spectra (passed $H\alpha$, Li I criterion). The

properties of each TTS are provided in Table 3: ID, designation in Hernández et al. (2007b, hereafter H07) and in SIMBAD (when available), coordinates on the sky, SpT, equivalent width of $H\alpha$, equivalent width of Li I $6707 \text{ \AA}$, total equivalent width of Na I $8183 \text{ \AA} + 8195 \text{ \AA}$, type (WTTS, CTTS, or C/W—see Section 3.3), CVSO photometry and variability information, 2MASS *JHKs* photometry, T_{eff} , A_V , location within the Orion association, and luminosity. There are a few very active CTTSs that show many emission lines in their spectra, but we provide here measurements only for $H\alpha$, Li I, and the Na I 8183 , $8195 \text{ \AA}$ doublet (this last spectral feature only for the 1025 objects observed with Hectospec).

Of the 2062 TTS, 245 were identified in Hydra spectra, 1025 in Hectospec spectra, 49 in the M2FS spectra, 722 in FAST spectra, and 21 in SOAR GHTS spectra. About 50% of the CS2 candidates were confirmed as TTSs, compared to a $\sim 9\%$ success rate for the TTSs confirmed from the CS3 + 2MASS *J-H* color-selected sample. This result highlights the importance of optical variability as a tool for tracing young, low-mass populations of young stars in regions devoid of molecular gas. Since our variability detection rate is highest for the bright ($V \lesssim 16$) sample (because of the smaller measurement errors), we can look at the success rate of the FAST follow-up spectroscopy as an indicator of the best-case efficiency we can expect from our variability selection technique. Of the 1235 variable candidates observed with FAST, 650 ($\sim 53\%$) were classified as TTSs. By contrast, only $\sim 21\%$ of the stars in the entire FAST sample were labeled as a TTS, a number we would expect from a conventional single-epoch color-magnitude selection. In the combined Hydra and Hectospec sample, 428 of 951 PMS candidate variables (45%)

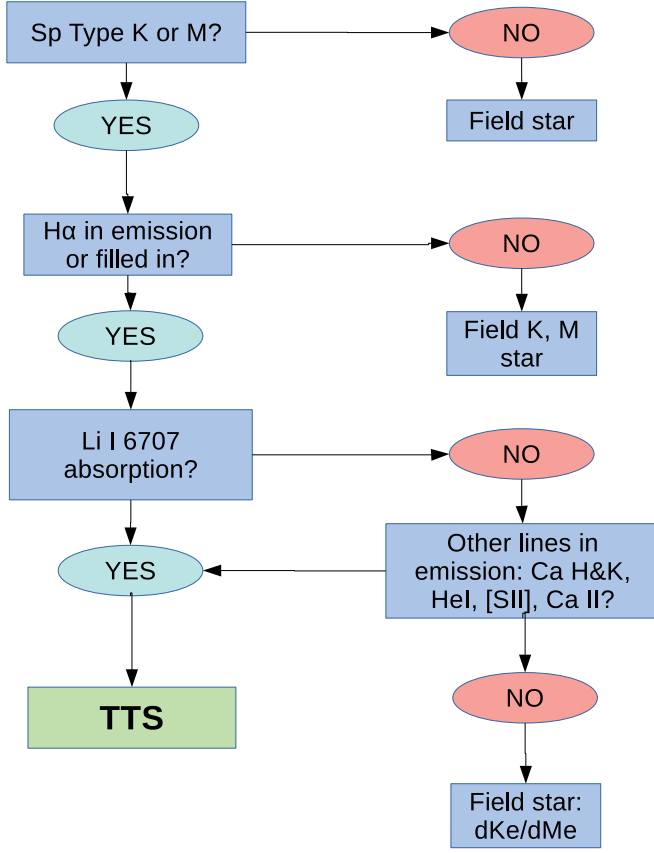


Figure 12. Flowchart of our criteria for spectroscopic confirmation of TTSs in the CVSO.

were classified as TTSs, a slightly lower success rate compared to the FAST sample, but consistent with the fact that as we go to fainter magnitudes, we can detect only those variables that have increasingly larger amplitudes.

3.1.2. The Na I 8200 Doublet as a Youth Indicator

The usefulness of the Na I lines as surface gravity indicators has been known since Luyten (1923) first showed that the sodium D doublet (5890, 5895 Å) was stronger in dwarfs than in giants. The low ionization potential of alkali atoms like sodium, which have a single valence electron, means that they are easily pressure-broadened, and therefore the absorption line strength increases as the gas density gets larger. However, Na I (5890, 5895 Å) is strongly affected by TiO absorption bands in stars later than $\sim$ M2, and absorption by the interstellar medium may also affect the line strength. On the other hand, the Na I subordinate doublet at 8183 Å and 8195 Å is located in a region of high S/N in our Hectospec spectra and not significantly affected by telluric absorption, or by TiO bands up to SpTs as late as M9. This feature has been used many times to discriminate between field dwarfs and younger, late-type objects (Martin et al. 1996; Martín et al. 2004, 2010; Lawson et al. 2009; Lodieu et al. 2011; Hillenbrand et al. 2013; Hernández et al. 2014; Suárez et al. 2017), though with samples of limited sizes. With our spectroscopic follow-up with Hectospec, we have amassed a large number of spectra going out to $\sim$ 9000 Å. Armed with such a

Table 3
T Tauri Stars in the CVSO

Column Number	Column Name	Description
1	CVSO	CVSO number
2	H07	ID from Hernández et al. (2007a)
3	Other ID	Other designation, from SIMBAD
4	R.A.(J2000)	R.A. J2000.0 (hh:mm:ss.ss)
5	Decl.(J2000)	Decl. J2000.0 (dd:mm:ss.s)
6	SpT	Spectral type
7	WHa	Equivalent width of H α 6563 (Å)
8	WLi	Equivalent width of Li I 6707 (Å)
9	WNaI	Total equivalent width of the Na I 8183, 8195 doublet (Å)
10	Type	C = CTTS, CW = C/W, W = WTTS (Section 3.3)
11	$\bar{V}$	V-filter robust mean (mag; Stetson 1996)
12	err(V)	1 σ error of $\bar{V}$, computed from err versus mag diagram (mag)
13	$N(V)$	Number of non-null V-band observations
14	$\bar{R}$	R-filter robust mean (mag; Stetson 1996)
15	err(R)	1 σ error of $\bar{R}$, computed from err versus mag diagram (mag)
16	$N(R)$	Number of non-null R-band observations
17	$\bar{I}_C$	I-filter robust mean (mag; Stetson 1996)
18	err(I_C)	1 σ error of $\bar{I}_C$, computed from err versus mag diagram (mag)
19	$N(I_C)$	Number of non-null I-band observations
20	$\Delta(V)$	V-band peak-to-peak amplitude (mag)
21	$\Delta(R)$	R-band peak-to-peak amplitude (mag)
22	$\Delta(I_C)$	I-band peak-to-peak amplitude (mag)
23	$\sigma(V)$	V-band standard deviation (mag)
24	$\sigma(R)$	V-band standard deviation (mag)
25	$\sigma(I_C)$	V-band standard deviation (mag)
26	V_{prob}	χ^2 probability of variability in V
27	R_{prob}	χ^2 probability of variability in R
28	I_{prob}	χ^2 probability of variability in I
29	L_{VR}	Stetson (1996) variability index for V and R magnitudes
30	L_{VI}	Stetson (1996) variability index for V and I magnitudes
31	L_{RI}	Stetson (1996) variability index for R and I magnitudes
32	J	2MASS J magnitude (mag)
33	err(J)	2MASS J 1 σ combined error (mag)
34	H	2MASS H magnitude (mag)
35	err(H)	2MASS H 1 σ combined error (mag)
36	K	2MASS Ks magnitude (mag)
37	err(K)	2MASS Ks 1 σ combined error (mag)
38	T_{eff}	Effective temperature (K) (1)
39	A_V	Extinction in the V-band (mag) (2)
40	Loc	Location within Orion OB1: 1a, 1b, 25 Ori, HR 1833, A_cloud, B_cloud

Notes.

^a Corresponding to the spectral type interpolated in Table A5 of Kenyon & Hartmann (1995).

^b For 86% of the sample, A_V was derived from the $V - I_C$ color. For an additional 8% of stars which lacked an I-band measurement, we used the $V - J$ color. For the remainder of the stars, we used either the $R - I$, $R - J$ or $I - J$ colors. We adopted the Cardelli et al. (1989) extinction law, and intrinsic colors from Kenyon & Hartmann (1995).

(This table is available in its entirety in machine-readable form.)

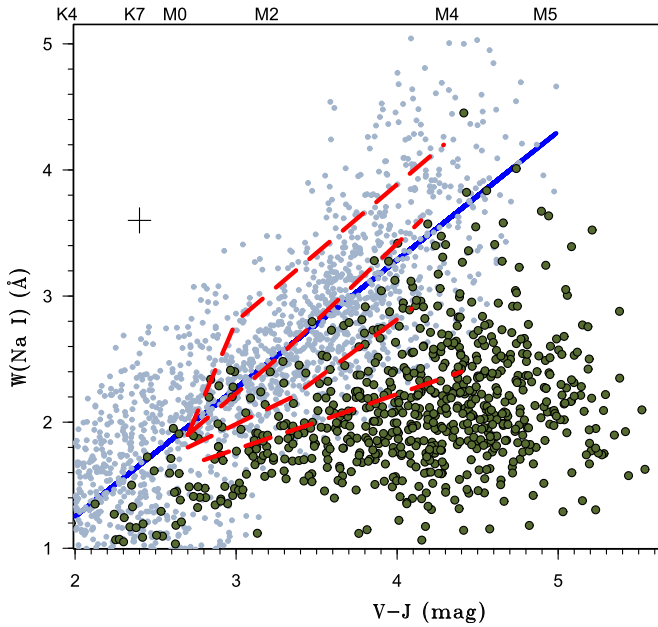


Figure 13. Total equivalent width of the Na I 8183, 8195 Å lines for the new Orion OB1 TTS confirmed with Hectospec spectra, shown as dark green dots. The small light blue dots correspond to stars classified by us as field stars. The blue straight line is the least-square fits to the distribution of those field stars. The dashed red lines are, from top to bottom, the 1 Gyr, 100, 50, and 10 Myr isochrones from Schlieder et al. (2012). A typical error bar is indicated.

large sample of TTSs and field stars, all identified and measured with the same instrumental setup and uniform criteria, we can now explore the behavior of the Na I (8183, 8195 Å) doublet as a youth indicator across the K to M SpT range in a consistent way.

In Figure 13, we show the total equivalent width of the Na I (8183, 8195 Å) doublet as a function of the observed $V - J$ color¹⁴ for 3441 stars: 1025 TTSs (dark green dots) and 2416 field stars (light blue dots). For every object, the equivalent widths of each of the Na I lines were measured both with SPTCLASS (Hernandez et al. 2017) and interactively with the *splo* utility in IRAF, which allowed us to obtain an estimate of the measurement uncertainty, indicated by the error bar in the figure. It is important to point out that the TTSs were identified based solely on the presence of $H\alpha$ in emission and Li I 6707 Å strongly in absorption, above the Pleiades level, as described in Section 3.1.1. Stars lacking Li I were classified as field stars. A least-squares fit to the distribution of field stars is shown as a blue straight line.

As expected from the $V \sim 13$ saturation limit of the photometry, our color selection, the relatively low extinction, and the nature of the stellar mass function in the thin disk of the Galaxy (Robin et al. 2003), the majority (65%) of the field stars in our sample are K- and M-type dwarfs (see Section 3.2 below, and also Downes et al. 2014), with a median SpT of M0 and median $A_V = 0.64$ mag. Among the late-type field stars, 23% were classified as active K- and M-type dwarfs with $H\alpha$ in emission (dKe and dMe stars); this subset is characterized by a later median SpT of M3.

Despite the large scatter of Na I equivalent widths at any given $V - J$, it is readily apparent that the bulk of the TTSs lie distinctly below the distribution of field stars. To quantify this

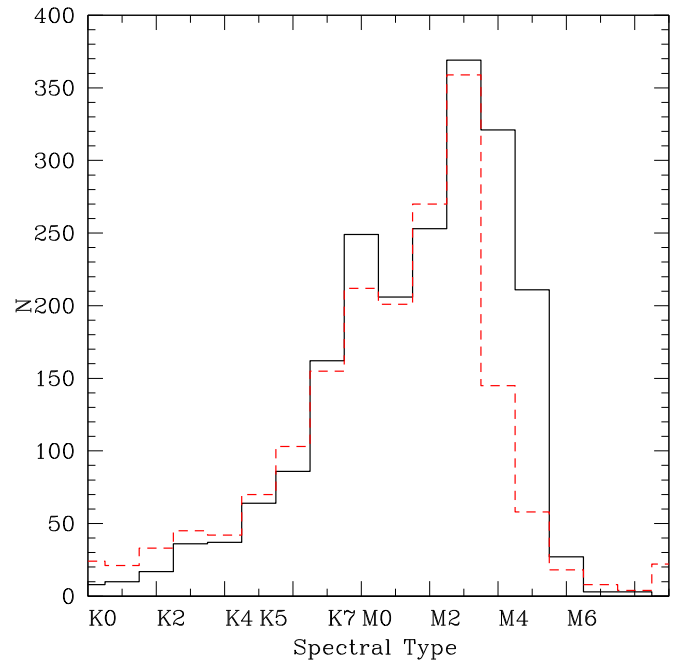


Figure 14. Distribution of spectral types of the 2062 CVSO TTSs. The red dashed line is the distribution of spectral types for K- and M-type stars classified as field stars.

effect, we show in Figure 13 isochrones calculated by Schlieder et al. (2012), using the Siess et al. (2000) evolutionary tracks and the PHOENIX model atmospheres (Hauschildt et al. 1999; Rice et al. 2010). The mean value for the field stars in Figure 13 matches very well the 100 Myr isochrone, and 99.9% of the TTSs fall below this line. Most of the spread seen in the field stars for SpTs later than $\sim M0$ is encompassed within the 50 Myr and 1 Gyr isochrones. It is also noticeable that the TTSs and field stars tend to separate in the $W(\text{Na I})$ versus T_{eff} plane, only for $V - J \gtrsim 3$, corresponding to SpTs later than $\sim M1.5$.

3.2. Determination of SpTs

Our low-resolution spectra provide the large wavelength coverage necessary to measure several temperature-sensitive features like the various TiO bands from ~ 4500 – 8000 Å, which are characteristic of late K- and M-type stars.

We classified our sources using the SPTCLASS package (Hernandez et al. 2017). On average, the uncertainty in SpT is roughly one subclass, but this depends largely on the S/N of the spectrum. The only object in our final TTS table that lacks an SpT is CVSO-157, an extremely active CTTS located in 1b that shows essentially no absorption features in its spectrum and hence no reliable SpT could be determined, so it was classified “C” (a “continuum” object). In Figure 14, we show the distribution of SpTs of our full Orion TTS sample, plotted with the solid black line histogram and with the red dashed line the distribution of SpTs of stars classified as field K and M dwarfs. The distribution peaks at M3 for both samples, and the decline at later SpTs is largely due to the lower completeness for increasingly fainter stars in our spectroscopic follow-up.

3.3. Classification of Accreting and Non-accreting Young Stars: Definition of the New C/W Class

An important result from our extensive spectroscopic observations is the ability to classify in a systematic way a

¹⁴ Because the overall extinction of our sample is small, it is appropriate to use $V - J$ without correcting for reddening; see Table 3.

large number of Orion association young members according to the strength of the $H\alpha$ emission line. In this section, we propose a new type of TTS, the C/W class, objects with $H\alpha$ emission strength intermediate between that of a CTTS and WTTS. We show that the C/W class, defined from a purely spectroscopic criterion, also exhibits intermediate behavior between CTTSs and WTTSs in other properties like IR excesses and variability.

It has long been recognized that $H\alpha$ emission is a telltale signature of accretion in solar-like PMS stars (see Hartmann 2009). Objects showing very strong $H\alpha$ lines are classified as accreting CTTSs, while WTTSs exhibit weak emission, consistent with levels of chromospherically active young stars. The qualitative idea remains a useful classification scheme, especially because by estimating the fraction of accreting stars across different regions and over a range of ages, we can infer fundamental properties like circumstellar disk lifetimes and the effects of the environment on such disks. However, the quantitative criterion to separate the two classes of objects has evolved significantly. The original threshold of $10 \text{ \AA}$ proposed by Herbig & Bell (1988) was revised by White & Basri (2003) and Barrado y Navascués & Martín (2003), based on the fact that the equivalent width of $H\alpha$ due to chromospheric emission is a function of SpT. This is caused by a contrast effect between the emission in the line and the underlying photosphere, such that for equally strong intrinsic line fluxes, the $H\alpha$ equivalent width would be larger in an M-type star than in a K-type star, because of the weaker photospheric continuum near $6500 \text{ \AA}$ in the M star. This had the implication of reducing the number of accreting TTSs (or the number of CTTSs) at later M SpTs.

However, the new criterion introduced by White & Basri (2003) and Barrado y Navascués & Martín (2003) does not account for the fact that $H\alpha$ emission is variable among PMS stars. This variability is greater for the most active, strongly accreting stars, but is present even in the WTTS. The equivalent width of $H\alpha$ can vary by up to factors of a few in CTTS and up to $\times 2$ in WTTS (e.g., Rugel et al. 2018). Therefore, a star classified as a CTTS in one observation may be deemed as a WTTS at some other epoch. Some CTTSs can go through quiescent phases in which they would be confused with a WTTS, unless high-resolution ($R \gtrsim 10,000$) spectroscopy is used to resolve the profile of $H\alpha$ and look for accretion signatures like broad-line wings, or redshifted absorption (White & Basri 2003). To account for such time-variable emission, we introduce here a new class of object, the CTTS–WTTS stars or C/W, which are defined as TTSs falling in the C/W locus in a $H\alpha$ equivalent width versus SpT diagram, as shown in Figure 15. The C/W locus is defined as the region of the diagram contained within the following expressions:

$$W(H\alpha)_{\text{Upper}}^{\text{C/W}} = 10^{(0.09 * \text{SpT} - 5.100)}, \quad (1)$$

$$W(H\alpha)_{\text{Lower}}^{\text{C/W}} = 10^{(0.09 * \text{SpT} - 5.345)}, \quad (2)$$

where the SpT is defined numerically as G0 = 50, G1 = 51, G2 = 52... G9 = 59, K0 = 60, K1 = 61... K7 = 67, M0 = 68, M1 = 69, and M2 = 70... M6 = 74.

We derived the above expressions based on multiple measurements of $W(H\alpha)$ in a set of 95 TTSs with SpTs K4 to M6, for which we had two or more spectra obtained at different epochs. At each SpT, we considered only stars with $W(H\alpha)$ values close to the limit between CTTSs and WTTSs

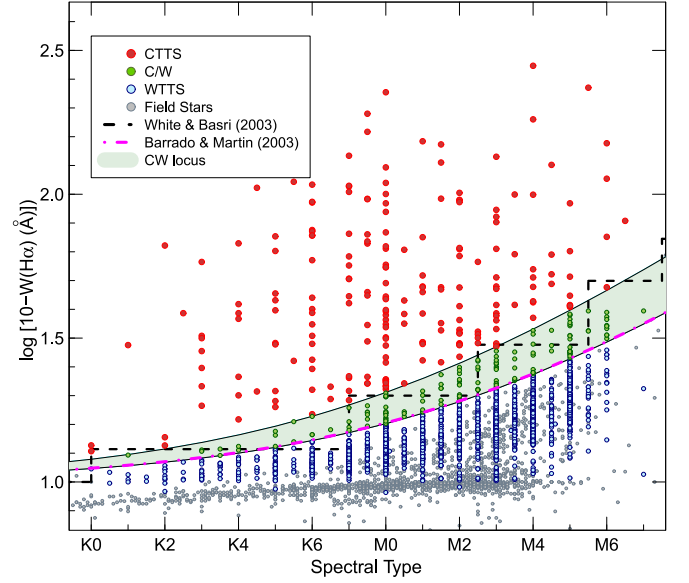


Figure 15. Logarithm of the equivalent width of $H\alpha$ as a function of spectral type for all Orion OB1 members, shifted by $10 \text{ \AA}$. We plot CTTSs as large red dots and WTTSs as smaller blue dots. For reference, we also plot as gray dots stars classified as field objects in our low-resolution spectra. The separation between CTTSs and WTTSs as defined by White & Basri (2003) is shown with the dashed line, while the criterion adopted by Barrado et al. (2011) is plotted as a dashed-dotted magenta line. The boundary we adopt here between CTTSs and WTTSs is shown by the pale green region, which we define as the transition between WTTSs and CTTSs. Objects falling within this area of the plot are classified as C/W objects, objects below it are WTTSs, and objects above it are CTTSs. The height of this transition region was adopted by adding in quadrature the mean variability of $W(H\alpha)$ in CTTSs and WTTSs at each spectral type to the measurement uncertainty.

defined by White & Basri (2003; black dashed line in Figure 15). We then adjusted the width of the C/W locus to encompass the majority ($>85\%$) of the range of variation of $W(H\alpha)$ at each SpT for this subset of TTS close to the CTTS/WTTS dividing line. The classification for each of the 2062 TTSs is indicated under the column “Type” in Table 3: “C” for CTTS, “W” for WTTS, and “CW” for the newly defined C/W objects. Stars in the C/W category may represent objects evolving from an active CTTS accretion phase to a non-accreting WTTS stage. We speculate that this group is likely composed of a mix of objects that are accreting at modest or low levels, constituting the weak tail of the CTTS, and a few objects in a quiescent stage between periods of enhanced accretion. If the newly defined C/W class is indeed TTSs at a stage intermediate between that of actively accreting CTTSs and the WTTSs, which are thought to have ceased accreting from a circumstellar disk (though a fraction of WTTSs likely retain passive, non-accreting disks; Natta et al. 2004; Nguyen et al. 2009a, 2009b; Hernández et al. 2014), we would expect this type of object to also show other properties intermediate between CTTSs and WTTSs.

A well-known indicator of the presence of a circumstellar disk is IR-excess emission, originating in the warm dust heated by irradiation from the central star (Hartmann 2008). In Figure 16, we show the boxplot with the median ($K_s - W1$) color for each type of TTS, and first and third quartiles, where $W1$ is the *WISE* [3.6] band magnitude, obtained by matching the CVSO sample with the ALLWISE catalog (Wright et al. 2010; Mainzer et al. 2011). WTTSs have an average $\overline{K_s - W1} = 0.14 \pm 0.10$ with median ($K_s - W1$) = 0.12; C/Ws have $\overline{K_s - W1} =$

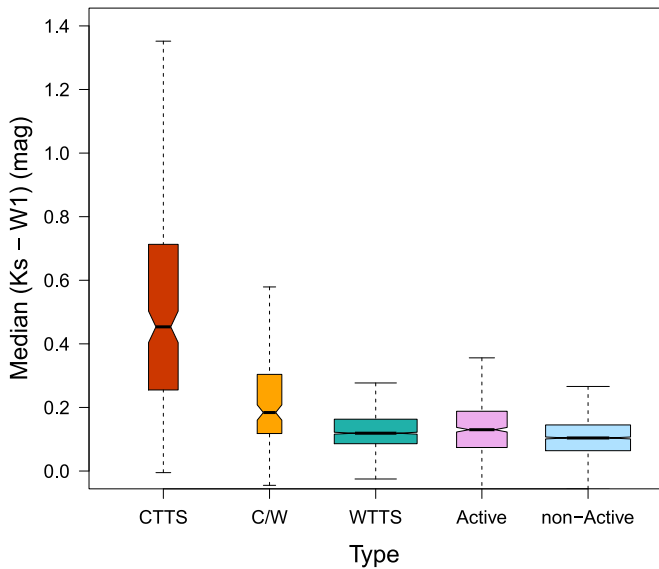


Figure 16. Median $K_s - W_1$ colors for each type of TTS, and for the field star sample. We subdivide the field stars between active (those with $H\alpha$ $\lambda 6563$ in emission) and non-active ($H\alpha$ in absorption). The first and third quartiles are indicated with the dashed vertical bars, and the width of each box is proportional to $\sqrt{N}$, where N is the number of stars in each group. The width of the notches in each box corresponds to the 95% confidence interval, such that if the notches in two boxes do not overlap, it is considered that their medians differ (Chambers 1983).

0.24 ± 0.19 with a median $(K_s - W_1) = 0.19$; CTTs have $\overline{K_s - W_1} = 0.50 \pm 0.32$ with a median $(K_s - W_1) = 0.46$. We have also derived average and median $K_s - W_1$ values for our field star sample, which contains 2814 photometric candidates classified as field stars in our spectra. Of these, 643 are stars with the $H\alpha$ $\lambda 6563$ line in emission ($\sim 27\%$), and almost all are dKe and dMe stars; we call these objects the “active” subset of field stars. These young main-sequence field stars should have ages between ~ 50 and 60 Myr up to a few hundred Myr, as would be expected from the recent history of star formation in the solar vicinity (Briceno et al. 1997). The active field stars have a $\overline{K_s - W_1} = 0.13 \pm 0.16$ with a median value of 0.13 . The “non-active” field stars have $\overline{K_s - W_1} = 0.11 \pm 0.10$ with a median of 0.10 . Clearly, the C/Ws have an intermediate $K_s - W_1$ color between that of WTTs and CTTs, while WTTs have a $K_s - W_1$ color similar to the sample of active field stars, as would be expected from young stars that have largely lost their inner disks, are no longer actively accreting, and exhibit only enhanced levels of chromospheric activity. A noteworthy feature of Figure 16 is that in the lower quartile there seem to be some CTTs with little, if any, $K_s - W_1$ excess. Of a total of 215 CTTs in our survey, 147 stars have *WISE* W_1 , W_2 , and W_3 photometry with errors < 0.1 mag. Among these, 12 CTTs (8%) are found to lack an excess in the $K_s - W_1$ color ($K_s - W_1 < 0.2$). It is interesting to note that among these is the transitional disk CVSO-224 (Espaillat et al. 2008). However, all of these sources do exhibit excess emission in the $W_1 - W_3$ color and would be classified as diskless stars using the diagnostic W_1 , W_2 , and W_3 diagram shown in Figure 4 of Esplin et al. (2018), half of them as transitional disks and the rest at the lower envelope of the full disks. Clearly, these, as the rest of CTTs, have disks, but it appears their inner disks have started developing gaps, so that the warmer dust has been depleted, and they lack $K_s - W_1$ excess emission. Also, while $\sim 25\%$ of the WTTs show

indications of the presence of a disk, as inferred from their location in the *WISE* $W_1 - W_2$ versus $W_3 - W_2$ color-color plane (Esplin et al. 2018), roughly 35% of the C/Ws show evidence of a dusty disk. The median $K_s - W_1$ color for the ensemble of C/W stars and a disk fraction between that of WTTs and CTTs are independent measures that give support to our suggestion of these stars being at an intermediate evolutionary stage between CTTs and WTTs. In an upcoming paper, we will discuss in further detail the IR properties of the C/W sample. High-resolution optical spectroscopy of C/W stars should provide further insight into their accretion state, allowing us to look for accretion-related features in the $H\alpha$ profile. Also, intermediate- to high-resolution near-IR spectra will provide profiles for features like the He I $\lambda 10830$ line, which has been shown to be a sensitive probe of low levels of accretion (Thanathibodee et al. 2018).

3.4. The CVSO Sample in the Literature

3.4.1. Cross-match with SIMBAD

Of our list of 2062 spectroscopically confirmed TTSs, 1484 (72%) are characterized here for the first time, as newly identified members of the Orion OB1 association; 787 have a match within 3 arcsec in the SIMBAD database (the average separation is $0''.31 \pm 0''.33$) and are classified as a star. However, only 433 of the matches (55%) have a SIMBAD type “TT” (TTS), “YO” (young stellar object), “pr” (PMS star), “Or” (variable star of Orion type), “iC” (star in cluster), or “iA” (star in association), and an SpT. We adopt these objects as previously known, confirmed young members of Orion OB1. In Table 3, we provide the SIMBAD identification and type for matching objects.

Among the 433 TTSs in SIMBAD, 225 were published by us in B05, B07a, and Biazio et al. (2011); another 77 in Downes et al. (2014); and 53 in Suárez et al. (2017). The other 78 are from various other studies (see Section 3.4.3). The remaining 354 SIMBAD objects are stars that lacked SpT determination and Li I or Na I measurement. They are either candidate PMS stars from other studies such as Hernández et al. (2007a; 212 objects) and Megeath et al. (2012; 82 objects) or objects classified as an emission-line star, X-ray source, variable star, flare star, irregular variable, star in cluster, or star in association, but lacking membership information. For these, we provide here, for the first time, spectroscopic confirmation of their youth.

Combined with our previous works (B05, B07a), this constitutes the largest sample of low-mass PMS stars with both multiband photometry and optical spectra, obtained in a consistent and systematic way in all of Orion, even when compared to the intensively studied ONC (H97; Carpenter et al. 2001; Slesnick et al. 2004; Tobin et al. 2009; Hillenbrand et al. 2013).

3.4.2. Comparison with Objective Prism and Photometric Surveys

The Orion region has been studied extensively since it was recognized as an OB association by Blaauw (1964). However, few studies have undertaken the task of mapping in detail the young stellar population across the entire complex. In the 1990s, Wiramihardja et al. (1989), Kogure et al. (1989), and Wiramihardja et al. (1991) searched ~ 100 square degrees for $H\alpha$ emission-line stars using photographic plates on the 1 m Kiso Schmidt telescope equipped with an objective prism. They published 759 candidate young stars, but without membership confirmation; 102 are confirmed as members here.

Newer objective prism studies like that of Szegedi-Elek et al. (2013) have focused on the ONC, finding 587 candidate young stars, of which 35 are in our CVSO catalog.

Recent work has revealed large numbers of PMS stars in Orion, but concentrating on the youngest populations on the A and B molecular clouds. Such is the case of the *Spitzer* study by Megeath et al. (2012), which covered the entire Orion A cloud and most of the B cloud. They identified nearly 3500 young stars based on their spectral energy distributions and infrared variability; 82 of these sources match our CVSO catalog, of which 80% are classified by us as CTTs, a result consistent with a search for objects with IR-excess emission. Alves & Bouy (2012) presented a photometric study of the region surrounding the ONC, but their proposed population is based on photometric candidates only; 118 of their sources are in our TTS list. Da Rio et al. (2012) carried out a deep photometric survey of 0.25 deg^2 in the ONC region, proposing 1750 objects as candidate young members; 26 match our CVSO catalog, of which 20 are CTTs. Pillitteri et al. (2013) conducted an X-ray study of the L1641 cloud; they found 716 candidate young stars, of which 16 have a counterpart in our CVSO TTS list, with 12 being WTTs, 3 CTTs, and 1 C/W. Sanchez et al. (2014) carried out a UV-based selection of candidate young stellar objects across $\sim 400 \text{ deg}^2$ encompassing all of Orion, using data from the *Galaxy Evolution Explorer* (GALEX). They identified 111 candidate PMS objects, of which 11 are found in our list. As expected from the UV-excess selection, all but one are CTTs. Spezzi et al. (2015) used the VISTA Orion Mini Survey to identify 186 candidate young objects in the B cloud, including the embedded clusters NGC 2068 and 2071. Ten of their targets match our CVSO catalog, and all but one are CTTs, as would be expected from a selection biased toward IR-excess sources. In the Orion OB1b subassociation, Kubiak et al. (2017) identified 789 candidate young members, based on optical/infrared photometry, with no spectroscopic confirmation. Unfortunately, their target table is not yet available in either SIMBAD, VizieR, or the CDS data services, so we could not cross-match their list with our CVSO sample. For all of the objects in these studies in common with our CVSO catalog, we provide here spectroscopic membership confirmation and characterization of SpT, among other stellar parameters.

Among the few studies targeting the older populations, Van Eyken et al. (2011) used the Palomar Transient Factory survey to look for eclipsing binaries in the 25 Ori cluster. They presented 16 candidate young stars, of which 6 have a counterpart in the CVSO. One is CVSO-35, already known from B05, and the other five are confirmed here as TTSs.

3.4.3. Comparison with Spectroscopic Studies

Work based on optical low-resolution spectroscopic membership confirmation has largely focused on the ONC region and its surroundings in the A cloud. H97 carried the first landmark study of the ONC, producing spectral classification for 675 stars. Then, Hillenbrand et al. (2013) added 254 new stars and reclassified many of the H97 stars; 27 of their sources are found in our TTS list. Hsu et al. (2012) surveyed $\sim 3.25 \text{ deg}^2$ in the L1641 dark cloud, located within the Orion A cloud, south of the ONC. They confirmed 864 low-mass PMS members, 723 of them in common with the Megeath et al. (2012) survey. A total of 22 objects have a match in our CVSO catalog.

After the ONC, the σ Orionis cluster is probably the most studied stellar aggregate in Orion. Among the most recent comprehensive spectroscopic studies is that of Hernández et al. (2014). In our CVSO catalog, we have 16 sources in common with their list of 340 confirmed members. Another cluster that has been the subject of several spectroscopic studies is 25 Ori. Downes et al. (2014) used deep, coadded I_C -band photometry from the CVSO, combined with VISTA data and follow-up spectroscopy, to search for very low-mass TTSs and young brown dwarfs; 65 of their 77 new members are in our catalog. More recently, Suárez et al. (2017) combined optical photometry from the CVSO with spectroscopy from SDSS-III/BOSS to identify 53 new members in an area of $\sim 7 \text{ deg}^2$ roughly centered on the cluster. We find 25 TTSs in common with their study.

The proposed foreground population of NGC 1980 has been studied spectroscopically by Kounkel et al. (2017a), who obtained spectra for 148 young stars. Nine objects are in common with our work; SpTs determined in both studies compare well. Fang et al. (2017) also investigated the “foreground” population to NGC 1980 proposed by Alves & Bouy (2012) and Bouy et al. (2014). They obtained spectra and stellar properties for 691 young stars within ~ 12 square degrees in this region. We found 24 stars in common with our list. In general, few objects in our CVSO catalog match these various studies in the ONC and the A cloud. The main reason is that our south survey limit is close to $\delta = 0^\circ$ – 6° , and we avoided the central region of the ONC, so there is little spatial overlap with these various studies.

After we take into account repeats between the aforementioned studies, there are only 78 objects with existing spectroscopic membership confirmation among the 2062 CVSO TTS ($\sim 4\%$), excluding the 356 sources already published in our previous works (B05, B07a; Biazzo et al. 2011; Downes et al. 2014) and in Suárez et al. (2017). Aside from the stars in 25 Ori and σ Ori, all of the other sources are located south of $\delta = -6^\circ$. Therefore, our survey provides the basis for a consistent and comprehensive characterization of the young stellar population across the Orion OB1 association, north of $\delta = -6^\circ$ and south of $+6^\circ$.

With such a large number of confirmed TTS members, we have the means to derive, for the first time, robust demographics of the populations of low-mass PMS stars in this star-forming complex, across a range of ages and differing environments, with an emphasis on the largely unknown off-cloud component.

3.5. The Large-scale Spatial Distribution of Young Stars across Orion OB1

With the CVSO photometric catalog, complemented with spectroscopic confirmation of a substantial fraction of PMS photometric candidates, we can now examine the spatial distribution of both candidate and confirmed low-mass PMS members. In this section, we start with a qualitative exploration of the large-scale spatial distribution of the photometrically selected PMS population across Orion OB1, which allows us to recognize the major groups and spatial features within each subassociation. Then, in the following sections, we use the properties of the 2062 confirmed members to characterize the general population in each region and conduct demographic studies of the groups and clusters within.

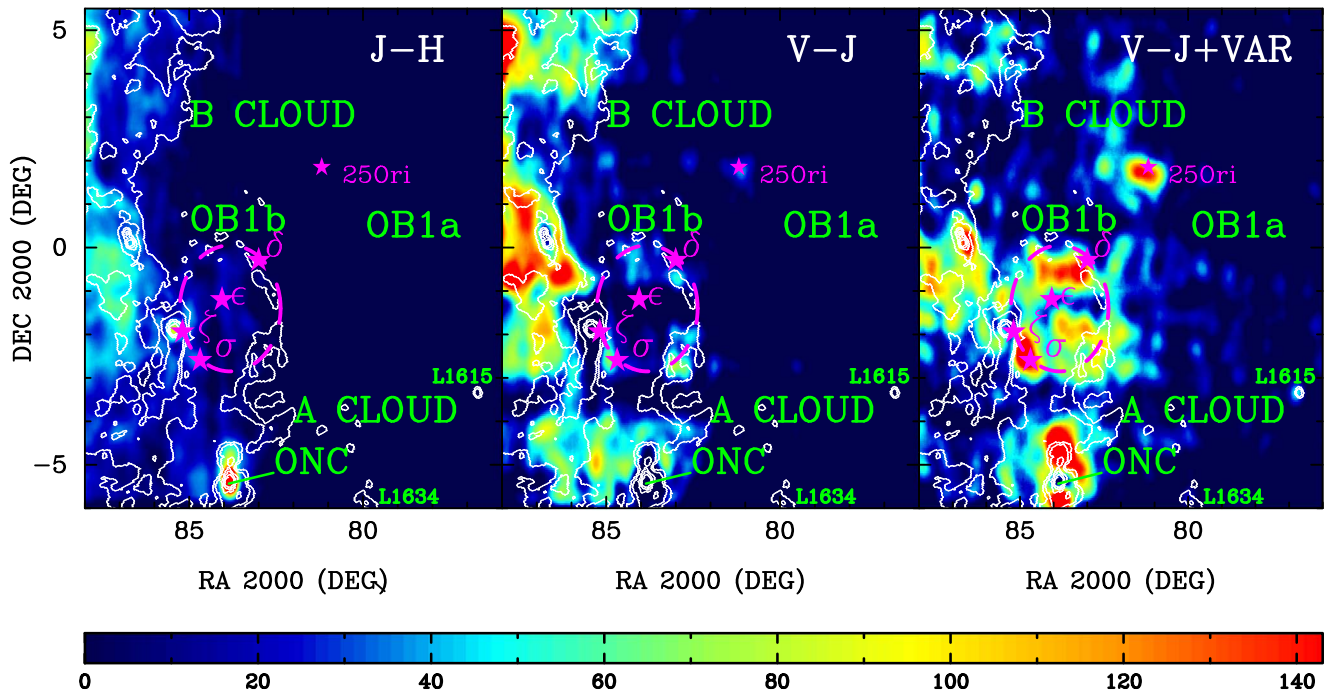


Figure 17. Surface density of PMS candidates selected in different color–magnitude diagrams. Left: surface density (number of stars/4 arcmin²) of PMS candidates in Orion OB1, selected as objects located above the main sequence (Siess et al. 2000, at 440 pc) in the 2MASS J vs. $J - H$ diagram. The maximum value corresponds to a density of 143 stars/deg². The Orion A and B clouds are indicated, as well as the outlying clouds L1615 and L1634. The three belt stars and σ Ori are located within our definition of the OB1b subassociation, indicated by the dashed-line oval. Contours correspond to $A_V = 0.5, 1, 5, 10, 20$ from the IRAS 100 μ m dust map of Schlegel et al. (1998). Middle: surface density (number of stars/4 arcmin²) of PMS candidates selected as objects located above the main sequence (Siess et al. 2000, at 440 pc) in the optical/near-IR V vs. $V - J$ and V vs. $V - I_c$ diagrams (the ONC appears as a hole because we “cut out” this region of dense nebula in the CVSO catalog). Right: surface density (number of stars/4 arcmin²) of PMS candidates selected as objects detected as variable in the V -band and located above the main sequence (Siess et al. 2000, at 440 pc) in the optical/near-IR V vs. $V - J$ and V vs. $V - I_c$ diagrams.

We start here by highlighting the importance of combining optical and near-infrared wavelengths, and more importantly, including photometric variability when searching for the low-mass, slightly more evolved component of the PMS population in regions with little or no extinction, devoid of molecular cloud material. Figure 17 shows how the inclusion of variability from the multi-epoch survey reveals the off-cloud young stellar population in a way single-epoch data cannot. In the left panel, the color map represents the surface density of candidate low-mass PMS stars, selected from the 2MASS J versus $J - H$ CMD. Sources were selected as candidate PMS stars if they fell in the region of the CMD located above the main sequence, plotted for an adopted distance of 400 pc. The middle panel shows the surface density of low-mass PMS candidates selected from a V versus $V - J$ CMD, created by combining the CVSO optical and 2MASS near-IR catalogs. As in the left panel, objects were selected as candidates if they were located above the main sequence placed at 400 pc in the CMD. The right panel shows the surface density of PMS candidates selected from the V versus $V - J$ CMD, as in the middle panel, but with the additional requirement that they be also flagged as variable in the CVSO V -band. These maps were created from the two-dimensional histograms of the spatial distribution of PMS candidates, selected in each case as described above, and then smoothed with a 2° diameter Gaussian kernel. Though it has been long known that the near-IR bands are an ideal tool for locating embedded populations of young low-mass stars, as evidenced by the strong peaks in the surface density of objects at the locations of the ONC and the NGC 2024 cluster (next to ζ Ori), the JH -only selection fails to

detect any off-cloud population of PMS stars, except for a faint trace of a distribution of young stars inside the relatively younger OB1b region; however, it is important to note that recent works have applied improved techniques for finding embedded young populations in near-IR data (e.g., Lombardi et al. 2017), which can also detect the densest overdensities in the older OB1b and OB1a regions. Still, when an optical band is added, the expanded color range offers an advantage for separating young stars in CMDs. The combined optical/IR selection (middle panel) starts to reveal, albeit still faintly, the existence of an off-cloud population of young low-mass stars, appearing in the form of overdensities such as the 25 Ori cluster (B07a; Downes et al. 2014; Suárez et al. 2017), which is largely invisible in the 2MASS-only map. The distribution of young stars within the OB1b subassociation is now more evident and also shows hints of structure; south of OB1b, an extended “halo” of PMS stars appears surrounding the ONC.

When the photometric variability is folded in with the VJ CMDs as a selection criterion, a new and completely different picture emerges. First, a widely spread low-mass, young stellar population is seen to extend well beyond the confines of the molecular clouds, as initially suggested by Briceño et al. (2001) and B05 within a smaller area, where only 25 Ori was apparent. Now, with the full survey area analyzed, it is clear that the young stellar population in the OB1a subassociation extends throughout most of the star-forming complex. The large-scale spatial distribution of this low-mass PMS population can now be used to define the west edge of OB1a, at roughly $\alpha_{J2000} = 5^h16^m$, running from north to south the combined length of the A and B molecular clouds. We can portray this

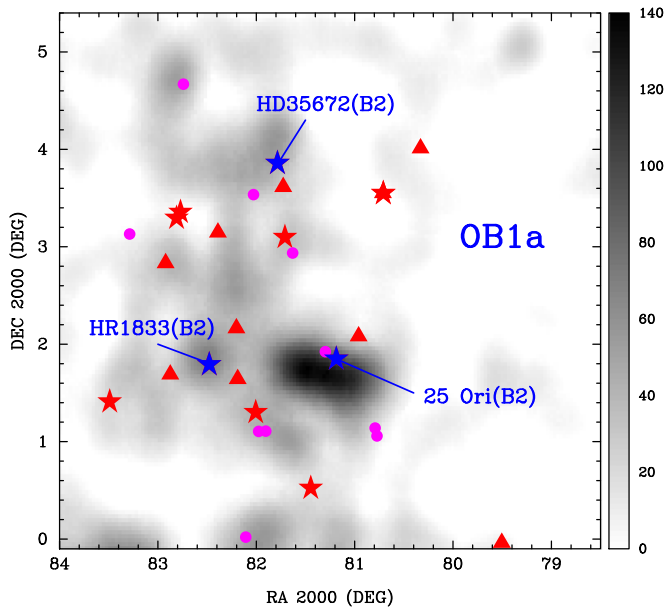


Figure 18. Overdensities of candidate PMS sources in the OB1a region surrounding the 25 Ori cluster. The grayscale map is the surface density of photometric candidate PMS sources selected from the CVSO photometric survey based on their location in the PMS locus of the V vs. $V - J$ CMD and detected as variable in the optical bands. Red stars correspond to early-type stars of B1–B2 spectral type, red triangles to B3–B5 stars, and magenta dots to B6–B9 stars. We have highlighted the B2 stars 25 Ori, HR 1833, and HD 35672 with large blue stars.

boundary as the fossil imprint of the general star formation event that formed Orion OB1a ~ 10 Myr ago. Second, it is evident that in addition to the widely spread, low surface density population of young stars (the “field” population of the OB1a subassociation), there is a significant degree of substructure across all of Orion OB1.

In the OB1a subassociation, there are several evident stellar clumps seen in the grayscale map of Figure 18, which represents the surface density of candidate low-mass young stars selected from the CVSO photometric survey, based on their location in the PMS locus of the V versus $V - J$ CMD and detected as variable in the optical bands. Two were already shown in Figure 7 of Briceño (2008); despite the claim by Lombardi et al. (2017) of having discovered the overdensities of young stars in OB1a). The most prominent of these stellar density enhancements is the 25 Ori cluster (B05; B07a; Downes et al. 2014; Suárez et al. 2017), with a clear elongation in the general E–W direction. This is consistent with the findings by Zari et al. (2017), who noticed an extension in the northward direction in galactic coordinates, corresponding roughly to an eastward direction in equatorial coordinates. The other overdensity is located just east of 25 Ori, at $\alpha_{J2000} = 5^{\text{h}}30^{\text{m}}$, $\delta_{J2000} = +1^{\circ}54'$, ($\alpha_{J2000} = 82^{\circ}5$, $\delta_{J2000} = +1^{\circ}9$), and $4'$ north of the B2 star HR 1833 (HD 36166). This structure may be present very faintly in Figure 15 of Lombardi et al. (2017), and in Figures 3, 8, and 9 of Zari et al. (2017), in both cases with much lower spatial resolution; in fact, it is likely unresolved within the eastward extension of the Zari et al. (2017) maps. However, Lombardi et al. (2017) do not discuss it, because, in their own words, the analysis of the substructure in their density map of OB1a and OB1b was beyond the scope of their study, and Zari et al. (2017) do not mention it, limiting themselves to recognizing the northern (in galactic coordinates) extension to the 25 Ori overdensity. Our more detailed maps show that the HR 1833

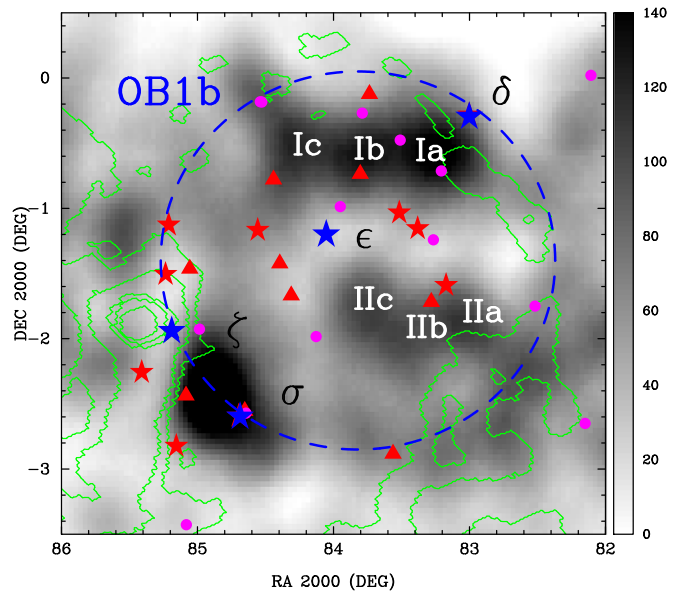


Figure 19. Overdensities of candidate PMS sources in the OB1b region. The background grayscale map is the surface density of photometric candidate PMS sources selected as described in Figure 18. We have highlighted with large blue stars the three Orion belt stars: δ , ϵ , and ζ Ori, and the massive O-type system σ Ori. The large blue dashed circle marks our adopted boundary for the OB1b region, roughly following the contours of the dust extinction map (Schlegel et al. 1998).

density enhancement is a feature distinct from the distribution of sources that can be associated with the 25 Ori cluster. Both the 25 Ori cluster and what we will call henceforth the HR 1833 cluster have been cataloged as clusters by Kharchenko et al. (2005) as ASCC 16 ($\alpha_{J2000} = 81^{\circ}15$, $\delta_{J2000} = +1.80$) and ASCC 20 ($\alpha_{J2000} = 82^{\circ}18$, $\delta_{J2000} = +1.63$), respectively (see also Figure 1 in Suárez et al. 2017). A third density enhancement in the OB1a region is found roughly located at $\alpha_{J2000} = 5^{\text{h}}27^{\text{m}}12^{\text{s}}$, $\delta = +4^{\circ}00'$, ($\alpha_{J2000} = 81^{\circ}8$, $\delta_{J2000} = +4^{\circ}$), $8.8'$ north of the B2 star HD 35762. This structure can be seen in Figure 15 of Lombardi et al. (2017) and also in Figure 4 of Zari et al. (2017). In both studies, it appears as a northward extension of the 25 Ori overdensity (westward in the galactic reference frame), though neither comment further on this feature. Both the HR 1833 and HD 35762 overdensities are shown more clearly in Figure 18. It can be noticed that there is an almost continuous density enhancement going north from HR 1833 up to HD 35762. Also, this last one seems to connect with an overdensity at $\alpha_{J2000} = 82^{\circ}8$, $\delta_{J2000} = +4^{\circ}8$, roughly $8'$ north of the B8IV/V star HD 36310.

Inside the OB1b subassociation, the distribution of stars is also quite clumpy (Figure 19), and some overdensities are found near B-type stars. The σ Ori cluster is by far the densest grouping of stars, but other significant groupings can be seen around ϵ Ori, with the densest being the feature labeled I in Figure 19, located approximately at $\delta \sim -0^{\circ}36'$ ($\delta \sim -0.6$) and $05^{\text{h}}32^{\text{m}} \lesssim \alpha_{J2000} \lesssim 5^{\text{h}}37^{\text{m}}36^{\text{s}}$ ($83.0 \lesssim \alpha_{J2000} \lesssim 84.5$), in which we recognize three distinct structures that we label Ia, Ib, and Ic, starting with the westernmost one. The other major density enhancement in OB1b is roughly located at $\delta \sim -1^{\circ}54'$ ($\delta \sim -1.9$) and $05^{\text{h}}31^{\text{m}}12^{\text{s}} \lesssim \alpha_{J2000} \lesssim 5^{\text{h}}36^{\text{m}}$ ($82.8 \lesssim \alpha_{J2000} \lesssim 84.0$), $\sim 12'$ southwest of the B3V star HD 36646 and $\sim 22'$ southwest of the B2III HD 36591. This overdensity also shows three distinct clumps that we label, from west to east, IIa, IIb, and IIc. These features have already

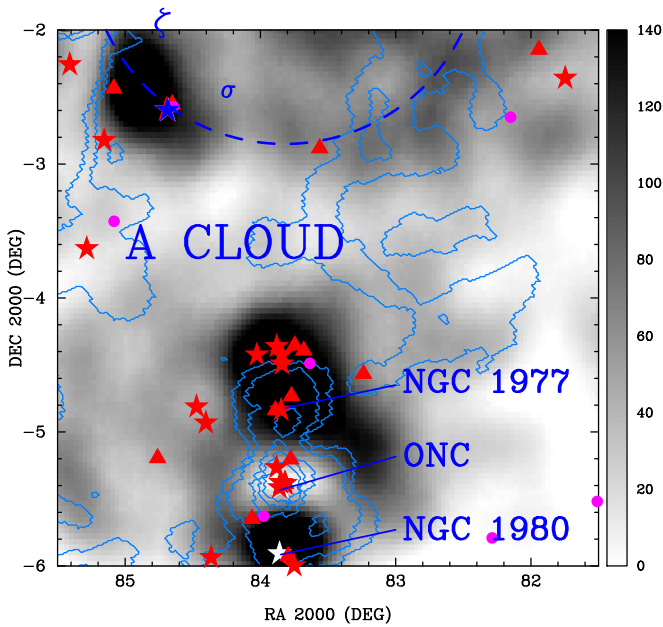


Figure 20. Overdensities of candidate PMS sources in the area surrounding the ONC. The surface density map and symbols are as in Figures 18 and 19. We indicate the location of the ONC, and the NGC 1977 and 1980 stellar aggregates. The lowest blue contour corresponds to $A_V = 0.5$ in the dust extinction map (Schlegel et al. 1998).

been reported by Kubiak et al. (2017), who used a combination of optical data from SDSS and near-IR *JHKs* from 2MASS to identify ~ 800 candidate young objects within Orion OB1b, which they call the “Orion Belt Population.” In the surface density map shown in their Figure 5, aside from the obvious clump corresponding to the σ Ori cluster, they detect the same overdensities I and II, northwest and southwest, respectively, of the central belt star ϵ Ori. They also mention that the density in these structures is clearly not homogeneous, though their data did not allow them to draw further conclusions.

In the Orion A cloud (Figure 20), the most prominent feature is the strong enhancement of candidate PMS stars surrounding the ONC, encompassing to the north the NGC 1977 region and NGC 1980 to the south of the ONC, both known to contain nearly a dozen O to B3 stars (Rebull 2000; Peterson & Megeath 2008; Alves & Bouy 2012). The apparent “hole” in the ONC region is an artifact from the CVSO catalog, which lacks photometry of sources in this region. The “halo” of candidate PMS stars around the ONC extends from $\alpha_{J2000} \sim 5^{\text{h}}31^{\text{m}}12^{\text{s}}$ ($\alpha_{J2000} \sim 82^{\circ}8$) to $\alpha_{J2000} \sim 5^{\text{h}}38^{\text{m}}24^{\text{s}}$ ($\alpha_{J2000} \sim 84^{\circ}6$), and from $\delta_{J2000} \sim -4^{\circ}$ to farther south than $\delta_{J2000} \sim -6^{\circ}$; our data do not allow us to probe beyond this limit. This halo is not uniform; the strongest overdensities correspond to NGC 1977 and 1980, while the areas directly east and west of the ONC have a much lower density of sources. Because this extended structure spans $\sim 4 \text{ deg}^2$ around the ONC, some authors have called attention to the possible contamination of existing censuses of ONC members that extend beyond $\sim 20'$ from the cluster center, and indeed Alves & Bouy (2012) and Bouy et al. (2014) proposed an older, but still young population foreground to the NGC 1977/1980 region, called recently into question by Fang et al. (2017). Kounkel et al. (2017b) obtained spectra for 148 stars in NGC 1980, and they also found that the population is consistent with a younger $\sim 3 \text{ Myr}$ age, also in disagreement

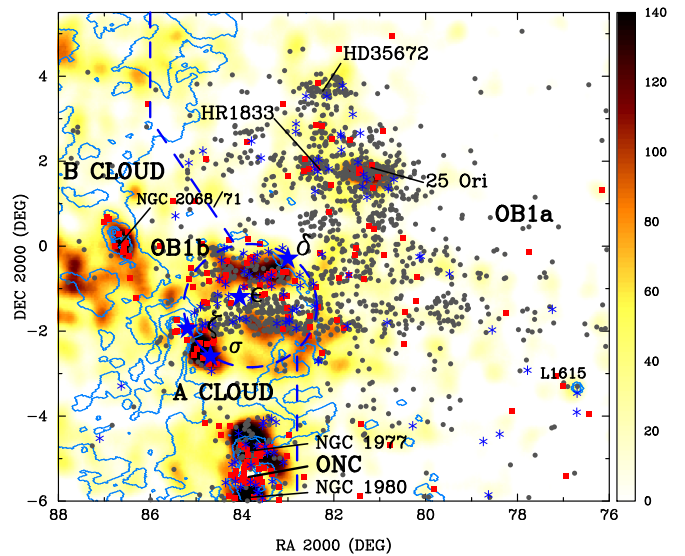


Figure 21. Spatial distribution of the 2062 confirmed TTSs, projected against the surface density of PMS candidates selected as in Figures 18–20; the density scale spans the range 0–143 stars/deg². Gray dots are WTTSs, blue starred symbols are C/Ws, and red solid squares represent CTTSs. The outline of the A and B clouds is delineated by the $A_V = 0.5$ contour from the Schlegel et al. (1998) dust map. Belt stars are indicated with the large blue stars, and the dashed blue circle encompasses the area we assume to be the OB1b subassociation. The dashed lines indicate our adopted boundaries between the OB1a association and the A and B molecular clouds. The off-cloud TTS population stands out very clearly, following the complex structure traced by the surface density of PMS candidates: a low-density component spread out throughout the region, starting at roughly $\alpha_{J2000} = 5^{\text{h}}16^{\text{m}}$, with a number of overdensities that include the 25 Ori cluster, and the HR 1833 and HD 35762 groups in the OB1a subassociation, and the concentrations of TTSs northwest and southwest of ϵ Ori in OB1b. The TTSs surrounding the ONC trace well the underlying density of PMS candidates.

with the Alves & Bouy (2012) and Bouy et al. (2014) studies. What is clear is that these populations of young stars surrounding the ONC will easily contaminate ONC samples, because these stars are essentially at the same distance (Kounkel et al. 2017a, 2017b) and share radial velocities and proper motions, close to zero, similar to the ONC, so they will be difficult to distinguish.

3.6. The T Tauri Population across Orion OB1

Now that we have gained a general picture of how the young, low-mass stars are distributed across the Orion OB1 association, and with the knowledge of the location of the various stellar groupings in each region, we use our large data set of spectroscopically confirmed members to look at the overall characteristics and ensemble properties of the various groups, and compare them in search of trends that can provide insight into the evolution of properties like Li I depletion and disk accretion. In Figure 21, we show the location of the 2062 confirmed TTS members of Orion OB1, projected against the surface density of photometric candidates. We plot WTTSs as solid gray dots, intermediate C/W stars as the six starred blue symbols, and CTTSs as red squares. The low-mass young stars are distributed as follows: 1218 in the 1a region, defined as the general area west of the straight dashed lines in Figure 21 and OB1b; 556 in the 1b region, defined within the dashed circle; 222 projected onto the A cloud; and 68 projected onto the B cloud. Of the 1218 TTSs in OB1a, 374 ($\sim 31\%$) are found within one of the three main stellar aggregates, 25 Ori, HR

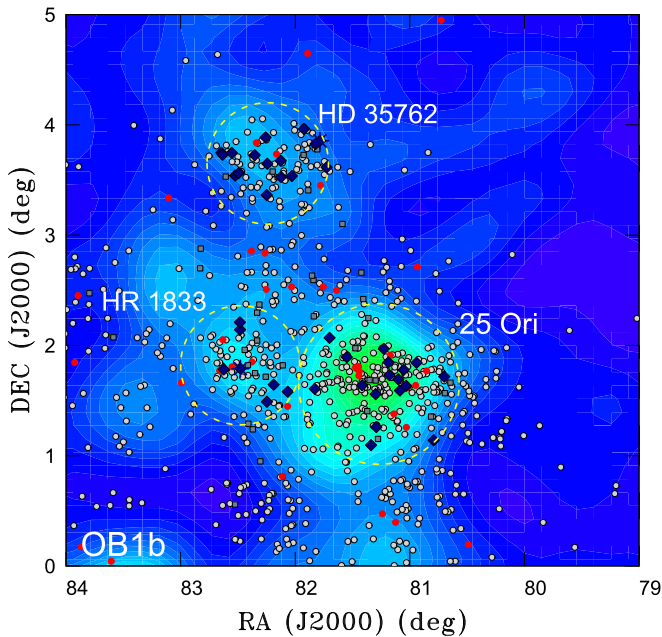


Figure 22. Spatial distribution of confirmed TTSs in the 25 Ori cluster, HR 1833, and HD 35762 groups, projected on the surface density map of PMS candidate stars. Yellow dots are WTTs and red dots are CTTSs. The B- and A-type stars in each group are indicated with the dark blue diamonds. The 25 Ori, HR 1833, and HD 35762 stars are shown as large starred, dark blue, symbols. Circles with our adopted radii of 0.7 for 25 Ori, 0.5 for HR 1833, and 0.55 for HD 35762 are shown with dashed lines.

1833, and HD 35762, and 844 are what we call the OB1a “field” population, stars not associated with any particular stellar overdensity. In OB1b, 231 TTSs ($\sim 42\%$) are associated with either the I or II density enhancements shown in Figure 19.

In order to determine the stellar content and properties of each of the stellar aggregates located in the OB1a subassociation, we defined as members of each group those spectroscopically confirmed TTSs located within a circle encompassing most of the density contour at $\sim 3\sigma$ above the general background in the surface density map (Figure 22). This yielded radii of 0.7 for 25 Ori, 0.5 for HR 1833, and 0.55 for HD 35762.

With this selection criterion, we assigned 223 members to the 25 Ori cluster, 65 to the HR 1833 group, and 86 to the HD 35762 group. The 25 Ori members include 65 from Downes et al. (2014) and 6 from Suárez et al. (2017). In HR 1833, there are five members in common with Suárez et al. (2017); another 13 TTSs in their sample are assigned by us to the OB1a field population. In Figure 22, we show the spatial distribution of all spectroscopically confirmed TTSs in the region around the three stellar aggregates in the OB1a subassociation, together with the location of the early-type stars in each group.

3.6.1. Distances

As is the case for 25 Ori (B07a), we expect these other groupings of TTSs in 1a to be likely younger than ~ 20 Myr. Because of this, we also expect the more massive B- and A-type stars to be located on, or very close to, the zero-age main sequence (ZAMS) in an extinction-corrected CMD. This provides us with the opportunity to derive a photometric parallax for each group by applying the main-sequence fitting

technique instead of simply assuming a common distance for all groups.

A practical advantage of these particular groups is that they are located in an area of very low extinction, well removed from the Orion molecular clouds ($A_V \lesssim 0.3$ for the 25 Ori group; Briceño et al. 2007; Downes et al. 2014; Suárez et al. 2017); therefore, reddening is not an issue when correcting the observed photometry. Within each circular region, we looked up the SIMBAD database and the Kharchenko et al. (2005) catalog of 109 new open clusters for B- and A-type stars. We then cross-referenced these lists with Hernández et al. (2005), using their SpTs whenever available, matched to the *Spitzer* Orion OB1 observations of early-type stars by Hernández et al. (2006) and to the *WISE* catalog (Wright et al. 2010). In each group, we determined which B- and A-type stars showed IR-excess emission typical of circumstellar dusty disks. In the 25 Ori cluster and the HR 1833 groups, where we have *Spitzer* 24 μ m data, we followed the criterion shown in Figure 4 of Hernández et al. (2006): we used the $J - H$ versus $K_s - [24]$ color-color diagram to select objects with $K_s - [24] \geq 0.5$ as disk systems; this selection includes those classified as debris disk systems ($0.5 < K_s - [24] < 5$), and those in the Herbig Ae/Be locus ($K_s - [24] > 5$). In the HD 35762 group, we used the *WISE* W4 band (22 μ m), using only measurements with $S/N \gtrsim 5$ and that had an actual source visible in the W4 image. We further assumed that the disk-bearing B- and A-type stars located within the circular area defined for each group are high-probability early-type members. Once the disk systems were identified in each stellar aggregate, we narrowed our selection to those with SpTs roughly between B9 and A5 (equivalent to $-0.2 \lesssim (V - J)_0 \lesssim 0.25$). This range corresponds to stars that should be on or very close to the ZAMS. At ages of several, up to ~ 20 Myr, they are not so massive as to have started evolving off the ZAMS, and they are not low-mass enough to be located significantly above the ZAMS. In practice, this is equivalent to these stars being located within $\sim \pm 0.12$ mag of the main sequence in a V versus $V - J$ CMD (Siess et al. 2000). We therefore assume that the bright end of the cluster sequence is defined by the $\sim$ B9 to A5 stars with disks. A least-squares fit of the Siess et al. (2000) ZAMS to these stars in each group yielded distances of 337 ± 35 pc for 25 Ori (fit with five stars), 345 ± 35 pc for HR 1833 (fit with five stars), and 343 ± 25 pc for HD 35762 (fit with eight stars). These distances are in agreement with the mean distances derived using available *Gaia* DR1 (Gaia Collaboration et al. 2016) parallaxes for the B9 to A5 stars in each group, regardless of whether or not they were disk candidates, as long as they were located within ± 0.12 mag of the main sequence in the CMD. With the new *Gaia* DR2 release (Gaia Collaboration et al. 2018), we can now derive individual distances for a sizable subset of the 2062 TTSs in the CVSO sample. This provides a sensitive check on the above distances to the various Orion OB1 groups, with statistically robust samples of well-characterized young stars, and enables us to derive for the first time distances to the non-clustered populations in the OB1a and OB1b subassociations, and the populations projected on the molecular clouds. In Table 4, we compare the three distance determinations for the groups and add the *Gaia* DR2 distances to the other regions. We removed a few objects with negative parallaxes and used only stars with parallax errors $< 20\%$. Note that for the distances derived from the *Gaia* parallaxes, we show the standard deviation of all measurements in each group.

Table 4
Mean Distances for Each Region

Region	MS Fit ^a (pc)	<i>Gaia</i> DR1 ^b (pc)	<i>Gaia</i> DR2 ^c (pc)	Adopted pc	N_* ^d
Cloud B	...	...	395^{+68}_{-50}	400	60
Cloud A	...	...	398^{+39}_{-45}	400	206
1b	...	...	398^{+69}_{-51}	400	510
25 Ori	337 ± 35	347^{+58}_{-43}	352^{+34}_{-28}	350	211
HD 35762	343 ± 25	361^{+44}_{-35}	348^{+34}_{-28}	350	78
1a	...	...	358^{+60}_{-43}	360	797
HR 1833	345 ± 35	361^{+45}_{-36}	370^{+52}_{-40}	360	64

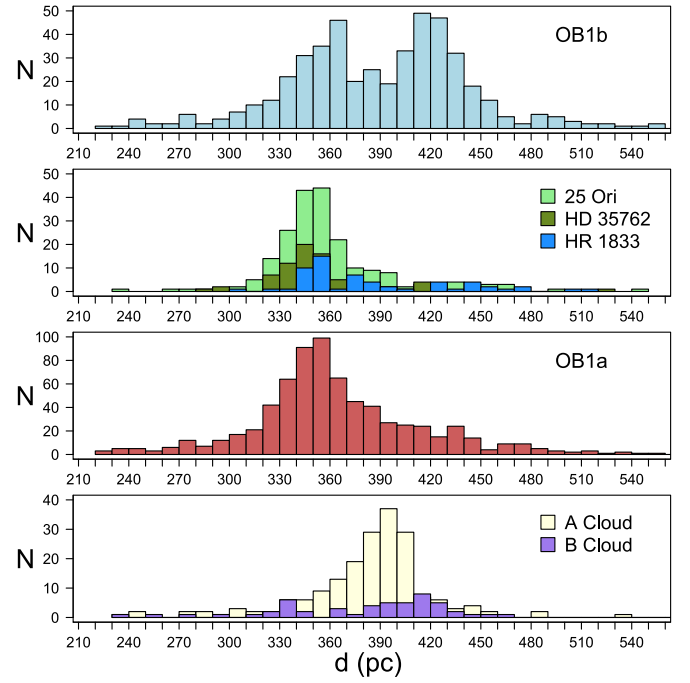
Notes.^a Main-sequence fitting for B9 to A5 stars, with the σ of the fit.^b *Gaia* mean distances derived from DR1 parallaxes of B9 to A5 stars.^c *Gaia* mean distances derived from DR2 parallaxes for CVSO TTSs in each group.^d Number of CVSO TTSs involved in each mean *Gaia* DR2 distance determination.^e The distance distribution in OB1b is bimodal; we find two distinct groups of stars, at two different distances.

The actual typical measurement error in DR2 for our CVSO TTS is $\sim \pm 25$ pc.

The distances derived from our main-sequence fitting, from *Gaia* DR1 parallaxes for the early-type stars, and from the *Gaia* DR2 data for the TTS populations, all agree within $1 - \sigma$. In column 5 of Table 5, we provide our adopted distances for each region, and in Figure 23, we show the distribution of distances derived from *Gaia* DR2. An interesting result is that the OB1b region seems to contain two populations of TTSs, a “near” one at a mean distance of ~ 365 pc and a “far” population located roughly at 420 pc. With a sample of over 500 stars in this histogram, this is a rather robust result. The “near” subset distances peak at ~ 365 pc, essentially the same distance as the field population of OB1a. In retrospect, this is not surprising, given that we would expect some amount of “contamination” of OB1b star samples by stars from the older and closer OB1a subassociation (B05). In fact, this result is consistent with the suggestion by Jeffries et al. (2006) of an older population of stars from OB1a, which has a mean radial velocity of 23.8 km s^{-1} , offset about 7 km s^{-1} from the 30 km s^{-1} mean velocity of the OB1b stars (see also B07a). Further study of the kinematics of these two populations, which is beyond the scope of this work, will help disentangle their nature and origin.

3.6.2. The PMS Population in Orion OB1a

With the distances derived for each group, we proceed to plot all of the stars in reddening-corrected $V - J$ CMDs, along with the Siess et al. (2000) isochrones (Figures 24–26). To derive A_V , we preferentially used the $V - I_C$ color, which uses the robust mean V and I_C magnitudes from our CVSO optical photometry, available for $\sim 86\%$ of the stars. For the remainder of the stars, we used $V - J$ or the $R - I_C$ or $I_C - J$ colors. We used the intrinsic colors from Kenyon & Hartmann (1995), corresponding to the SpT for the star, and the Cardelli et al. (1989) reddening law with $R_V = 3.1$, which is consistent with recent estimates of the extinction toward the Orion region by Schlafly et al. (2016). We used the colors provided by the Siess et al. (2000) isochrone server: <http://www.astro.ulb.ac.be/~siess/pmwiki/pmwiki.php?n=WWWTools.Isochrones>, which are derived in the Cousins

**Figure 23.** Distribution of distances derived from *Gaia* DR2 parallaxes, for confirmed TTSs in the Orion OB1 regions.**Table 5**
Mean Ages for Each Region

Region	Age ^B (Myr)	σ^B (Myr)	Age ^S (Myr)	σ^S (Myr)	N_*	Adopted Myr
Cloud B	2.6	1.3	2.3	1.0	53	2.5
Cloud A	3.2	1.3	3.4	1.6	60	3.3
1b	4.7	1.8	5.2	2.1	489	5.0
25 Ori	6.1	2.4	9.1	2.3	223	7.6
HD 35762	7.9	2.4	8.0	2.5	61	8.0
1a	9.2	2.2	12.3	2.9	811	10.8
HR 1833	11.8	2.5	13.9	2.7	64	12.9

Note. B: Baraffe et al. (1998), S: Siess et al. (2000).

system using the conversion provided by Kenyon & Hartmann (1995) in their Table A5.

It is important to note that because we have extensive variability information in the optical bands for each star, we plot the clipped mean average V magnitudes, so that any spread in luminosity because of variability is minimized. Though ideally we would plot the $V - I_C$ CMDs because they contain the optical photometry and variability information from our own data set, we instead chose here the $V - J$ color, with the caveat that the 2MASS J -band is not simultaneous with our optical photometry, in order to include the early-type stars, which mostly lack I -band data. The CMDs for each group show a well-defined cluster sequence running from the early-type stars all the way to the low-mass PMS members, with a gap in the range roughly corresponding to SpTs F to late G. Stars in this range are saturated in our CVSO survey and are hard to discriminate from contaminating field stars based only on the existing information in the SIMBAD and Kharchenko et al. (2005) samples. Though accreting members of this class of objects are easy to find using tracers like strong $H\alpha$ emission and IR excess, the WTTS counterparts have been traditionally

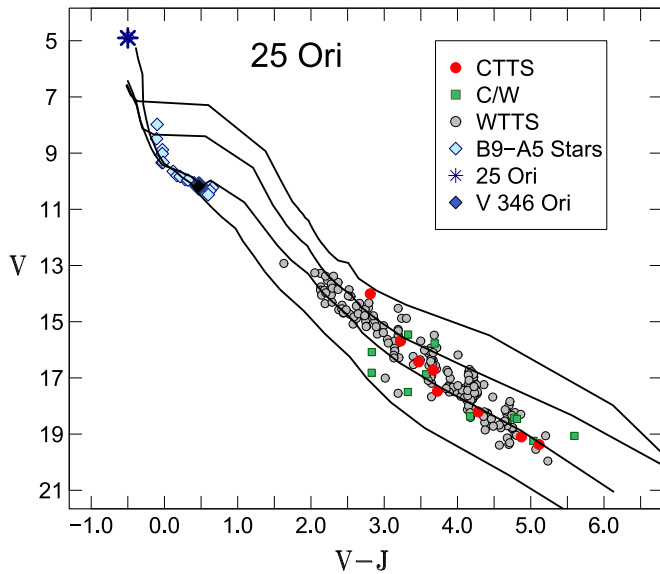


Figure 24. Extinction-corrected color-magnitude diagram for the 25 Ori cluster. Solid lines represent, going down from the topmost one, the 1, 3, 10, and 100 Myr isochrones (Siess et al. 2000), set at the adopted distance of 350 pc. CTTs are plotted with red dots, WTTSs with gray dots, and C/Ws with green squares. The early-type stars are indicated with light blue diamond symbols. The six-pointed symbol marks 25 Ori itself, while the dark blue diamond indicates the A9 Herbig Ae/Be stars in V 346 Ori. An $A_V = 1$ reddening vector is also plotted.

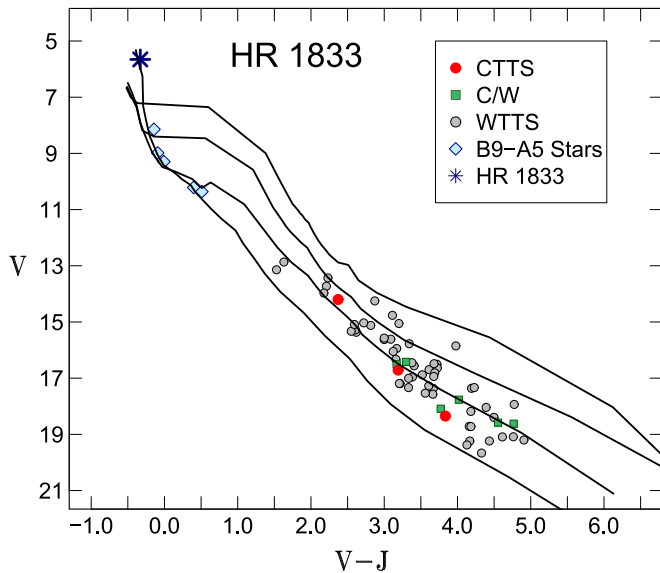


Figure 25. Extinction-corrected color-magnitude diagram for the HR 1833 group. As in Figure 24, solid black lines correspond to the 1, 3, 10, and 100 Myr isochrones (Siess et al. 2000), set at the adopted distance of 360 pc. Symbols are as in Figure 24. The six-pointed symbol marks HR 1833.

difficult to pinpoint. Because of their shallow convective outer zones, G- and F-type stars do not deplete lithium significantly during their PMS phase. Therefore, in contrast with K and M stars, for these earlier type objects, lithium is not a useful youth indicator. Criteria like X-ray activity are not too useful for finding PMS stars among solar-type stars, because X-ray emission decays slowly during the first ~ 100 Myr in G to early-K stars (Briceño et al. 1997). This is an outstanding issue in which parallaxes will be crucial to confirm membership, in

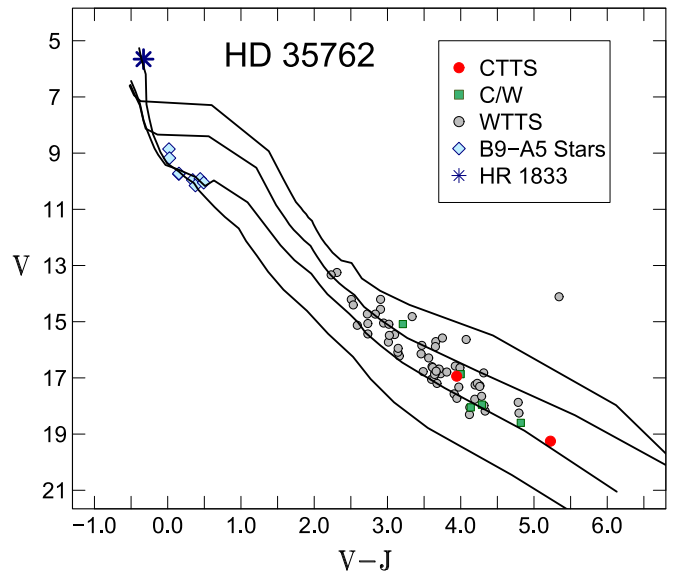


Figure 26. Extinction-corrected color-magnitude diagram for the HD 35762 group. As in Figures 24 and 25, solid lines correspond to the 1, 3, 10, and 100 Myr isochrones (Siess et al. 2000), set at the adopted distance of 350 pc. Symbols are as in Figure 24. The six-pointed symbol marks HD 35762.

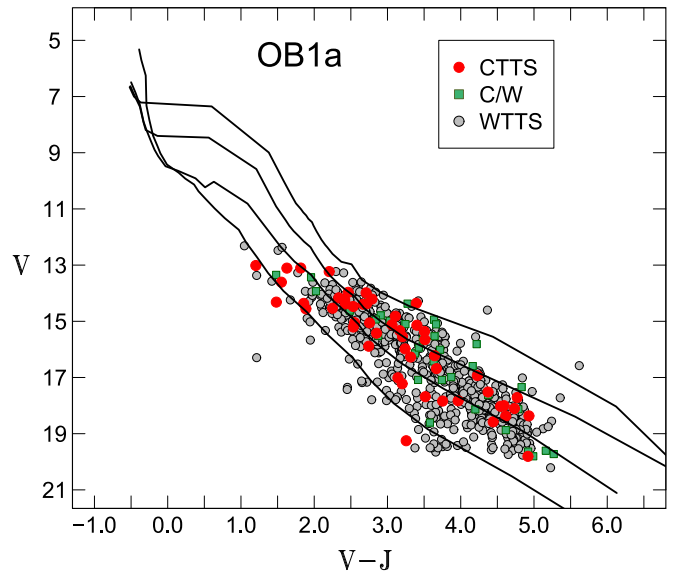


Figure 27. Extinction-corrected color-magnitude diagram for the field population of the OB1a subassociation. As in previous figures, solid lines correspond to the 1, 3, 10 and 100 Myr isochrones (Siess et al. 2000), set at the adopted distance of 360 pc, and the different dot symbols mark the CTTs, C/Ws, and WTTS, as indicated in the legend.

combination with optical photometry and spectroscopy. The *Gaia* DR2 release will be of great help in filling in this region of the CMD.

That the new HR 1833 and HD 35762 TTS clusterings exhibit relatively well-defined sequences in the CMD is a compelling suggestion that they are real stellar aggregates, less massive siblings of the 25 Ori cluster. In contrast, the CMD for the general field population across 1a (Figure 27) is much more spread out in luminosity, as expected from stars that likely span a broader range of distances and ages compared to the population of the three clusterings.

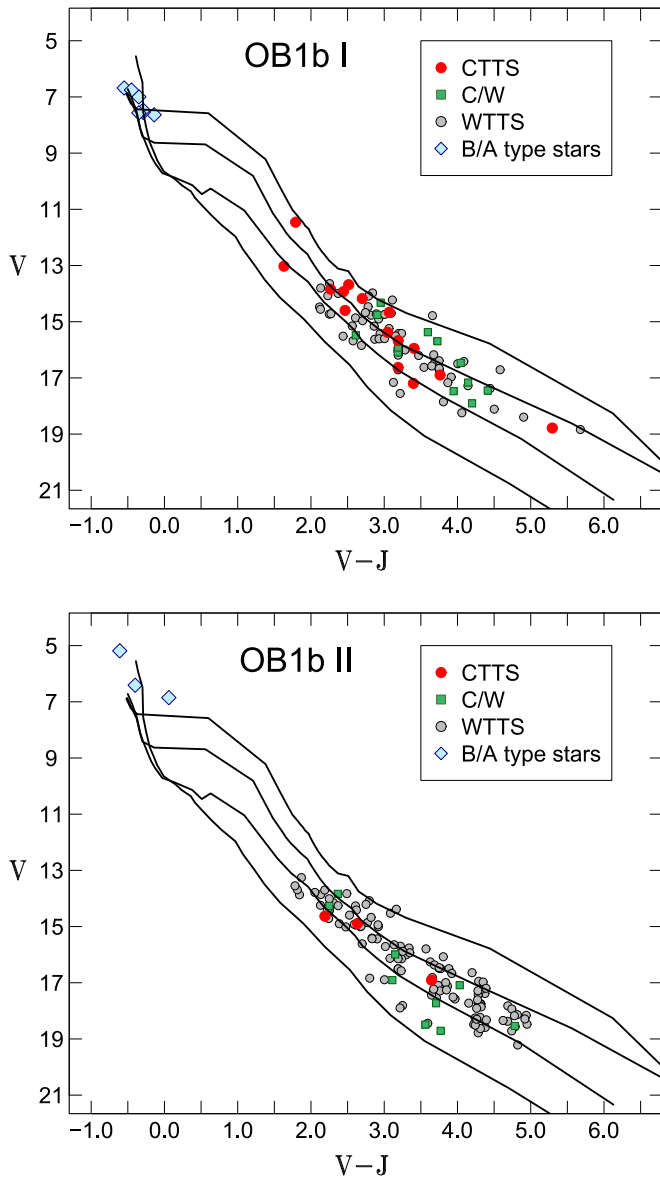


Figure 28. Extinction-corrected color-magnitude diagrams for the population of the two major overdensities in the OB1b subassociation. Upper panel: the I (a through c) overdensity, northwest of ϵ Ori. Lower panel: the II (a through c) group south of ϵ Ori (Figure 19). As in previous figures, solid lines correspond to the 1, 3, 10, and 100 Myr isochrones (Siess et al. 2000), set at the adopted distance of 380 pc, and the different dot symbols mark the CTTSs, C/Ws, WTTSs, and early-type B and A stars, as indicated in the legend.

3.6.3. The PMS Population in Orion OB1b

As discussed in Section 3.5, we identify two major overdensities within the Orion OB1b subassociation, which we labeled I and II, each one showing hints of further substructure, which we identified as subgroups a, b, and c. However, to simplify our discussion and in order to have better statistics, here we will consider these two major structures as two single entities. In Figure 28, we plot the TTSs in the $V-J$ CMDs for each of these two groups, together with the early-type stars found within each overdensity. We assumed a distance of 390 pc, consistent with the latest determinations for the σ Ori cluster (Hernández et al. 2014; Schaefer et al. 2016; Caballero 2017), which is generally assumed to be part of the OB1b region. There are 231 TTSs in these two stellar groups:

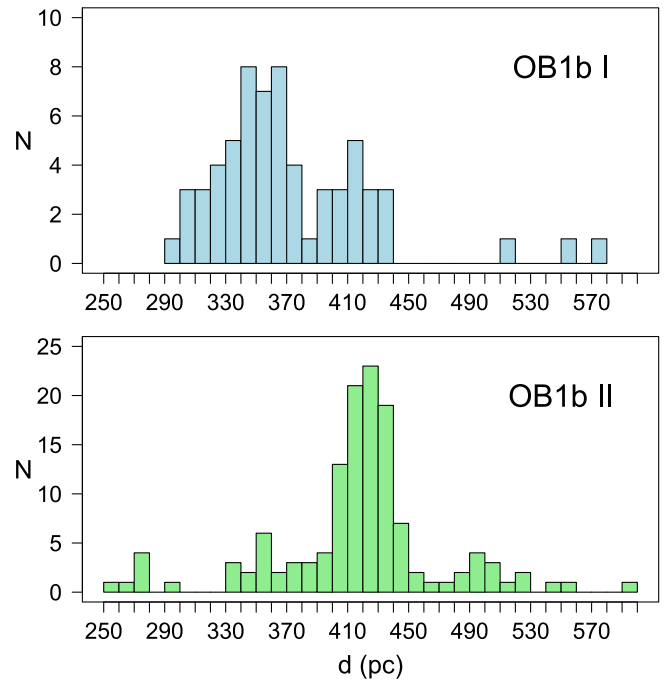


Figure 29. Distribution of distances derived from *Gaia* DR2 parallaxes for the TTSs in groups OB1b I and II.

OB1b I contains 93 TTSs, while OB1b II encompasses 138 TTSs. It is interesting that both OB1b groupings exhibit fairly well-defined sequences and that the early-type stars are also roughly located at their expected location in the CMDs, assuming they form part of these two stellar aggregates, although they are clearly more scattered in the CMD compared with their siblings in the OB1a clusterings, maybe in part because of larger extinction in OB1b compared to OB1a. Also apparent is the fact that OB1b I contains a larger fraction of CTTSs than OB1b II, but we defer further discussion to the next section.

In Section 3.6.1, we showed that the OB1b region is composed of two populations separated in distance. In Figure 29, we show the distribution of distances derived from the *Gaia* DR2 parallaxes for each of the two groups of TTSs in OB1b. This plot shows that the bimodality in the distance (or parallax) distribution in the OB1b subassociation arises from the northern OB1b I group, which has a near (~ 355 pc) component and a far (~ 415 pc) component. By contrast, the majority of the TTSs in the southern OB1b II group are at distances within the range $d \sim 390$ – 450 pc, with a median distance of ~ 420 pc. As we discuss in Section 3.6.1, we speculate that this “near” component may be part of the field population of OB1a stars. If so, we would expect these TTSs to share other properties with their OB1a siblings.

3.7. Demographics of Young Stars in Orion OB1

3.7.1. Ages

In order to study any evolutionary trends, we must first estimate ages for each region and group of stars. The dereddened CMDs provide a useful tool to do this. For each star, we obtained the observed $V-I_C$ color from the CVSO robust mean V - and I -band magnitudes and then derived the color excess by comparing with the intrinsic color

corresponding to our SpT, obtained from Table A5 in Kenyon & Hartmann (1995). We derived A_V assuming the Cardelli et al. (1989) reddening law; we could derive extinctions for over $\sim 88\%$ of the CVSO stars using $V - I_C$. Because $V - I_C$ comes from our quasi-simultaneous CVSO photometry, we adopted this band to perform the reddening correction in preference over the $V - J$ color. The small fraction of stars dropped because of lack of $V - I_C$ information does not affect in a significant way our final mean age estimates. We then performed a linear interpolation within the Baraffe et al. (1998) and Siess et al. (2000) model isochrones, using their published $V - J$ colors and deriving absolute V -band magnitudes with the reddening-corrected distance modulus corresponding to the adopted distances for each group and region shown Table 4. Finally, we computed clipped mean ages to derive a single age for each region. Because the distribution of $\log(\text{age})$ tends to have more symmetric, Gaussian shapes than the distribution in age, we used these to derive the mean age and standard deviations (and perform the outlier rejection). The values, standard deviation of the fits, and number of stars involved in each calculation are provided in Table 5.

The Siess et al. (2000) models yield older ages compared to the Baraffe et al. (1998) ones, but both agree in the sequence of ages, indicating, as expected, that the youngest stars are the ones projected onto the A and B molecular clouds. Within the uncertainties, these two regions can be assumed to be of the same age, ~ 3 Myr, a value which is somewhat higher but consistent with estimates for regions like L1641 in the A cloud (Hsu et al. 2012; given the large uncertainties in age determination, particularly for the youngest star-forming regions). We also point out that because our candidate selection was optical, we are reddening-limited toward the molecular clouds, resulting in a modest number of stars compared to the low-extinction OB1b and OB1a regions. Therefore, we are more susceptible to contamination from OB1b and OB1a. Such slightly older stars would bias the mean age toward a slightly higher value. The second oldest population is located in the OB1b region, and the oldest stars are those in the OB1a subassociation, consistent with the historic picture of the progression of ages across Orion OB1. Within the OB1a region, 25 Ori seems to be the youngest group (~ 6 – 9 Myr), similar in age to HD 35762, while HR 1833 comes out as the oldest one (12–14 Myr). The “field” population has an average age of ~ 11 Myr.

Despite the large uncertainties in the absolute ages of each region, which come from a complex combination of observational errors that include determination of SpTs, transformation to an effective temperature scale, the adoption of dwarf temperatures and colors for PMS stars, the use of a particular reddening law, the uncertainty in the assumed distances, and finally, but not least, limitations in the theory behind model isochrones and differences between various models, for the purpose of our analysis here onwards, what is important is the age sequence between the various regions. Even with the improved distances that will come with the second release of *Gaia*, differences between models or differing methods, and the various other assumptions mentioned above, will likely still introduce significant systematic offsets, in addition to scatter. For example, Bell et al. (2013) found ages that are older by a factor of ~ 2 compared to the most commonly assumed ages for several nearby young regions. Further discussion of PMS ages and their uncertainties is beyond the scope of this work.

3.7.2. PMS Li Depletion

The presence of the Li I 6707 Å line strongly in absorption is a reliable indicator of youth in K- and M-type stars (Section 3.1.1). Because this light element is burned at temperatures of $\sim 2 \times 10^6$ K, which roughly corresponds to the temperature at the base of the convective envelope in a solar-type star at the ZAMS (Siess et al. 2000), lithium is steadily depleted during the PMS phase in low-mass stars, and its surface abundance decreases over time, with the known spread caused by effects like rotation and the details of physical processes used in the stellar interior codes (Sestito & Randich 2005; Tognelli et al. 2012; Bouvier et al. 2016, 2018).

Having measured Li equivalent widths ($W(\text{Li I})$) in a homogeneous way for a large number of PMS K- to M-type stars, we are in a vantage position to explore from a statistical perspective the depletion of Li during the PMS phase. In order to avoid the uncertainties associated with the derivation of Li abundances (see Sestito & Randich 2005; Tognelli et al. 2012), we restrict ourselves to looking at a purely observational measure, $W(\text{Li I})$. This approach was considered by Jeffries et al. (2014) in their discussion of PMS Li depletion. We adopt the ONC data from Sicilia-Aguilar et al. (2005) and the Taurus Li measurements from Basri et al. (1991), as representative of what can be considered as a “pristine” or “undepleted” Li sample of optically visible, 1–2 Myr old, low-mass PMS stars. Both data sets were obtained with similar spectral resolution to that of our spectra, so we expect a reasonable comparison with our own measurements, though it is important to bear in mind that even in very young regions like Taurus and the ONC, there is a considerable spread in Li abundances.¹⁵ Still, past studies indicate that most members in these very young regions have undergone little, if any, Li depletion; see Palla et al. (2005, 2007) and Sestito & Randich (2005). Thus, we define the “undepleted” or “young” Li locus in the $W(\text{Li I})$ – T_{eff} diagram, following Briceño et al. (2007), as the region above the line

$$W(\text{Li I})_{\text{young}} > 1.0591 - (1.52 \times 10^{-4}) \times T_{\text{eff}},$$

with $W(\text{Li I})$ in Å and T_{eff} in K. Over 70% of Taurus and ONC TTSs fall in the young Li locus.

In Figure 30, we show the surface density of Li equivalent widths for two populations at different evolutionary stages, the ~ 5 Myr old OB1b and the ~ 11 Myr old OB1a “field” population. We use these two subsets because they have the largest number of stars, 556 in OB1b and 843 in OB1a, so that statistics are less affected by differences in sample sizes. We derived the surface density using the Two-dimensional Kernel Density Estimation recipe in R (Venables & Ripley 2002). We can see how as we go from a young region to an older one, even allowing for the large spread in $W(\text{Li I})$ at any given T_{eff} , in part intrinsic and in part due to measurement errors, a population-wide trend is evident; the K and M stars slowly

¹⁵ The spread in lithium equivalent widths, or Li abundances, is an open issue. Though age spreads have been proposed as an explanation, it is difficult to argue for clusters like the Pleiades, which have a well-defined age, with little, if any spread, and still exhibit considerable spread in Li abundances at a given T_{eff} , in particular for the later SpTs (e.g., Somers & Pinsonneault 2015). A possibility is mixing induced by rotation, which can be expected given the large spread in rotation rates at a given age during the PMS phase (e.g., see Karim et al. 2016, Figure 11), proposed to originate, at least in part, in variations in the initial conditions under which the individual stars are formed. More recently, radius inflation or magnetic activity have been proposed as explanations for the dispersion in Li (Jeffries et al. 2017).

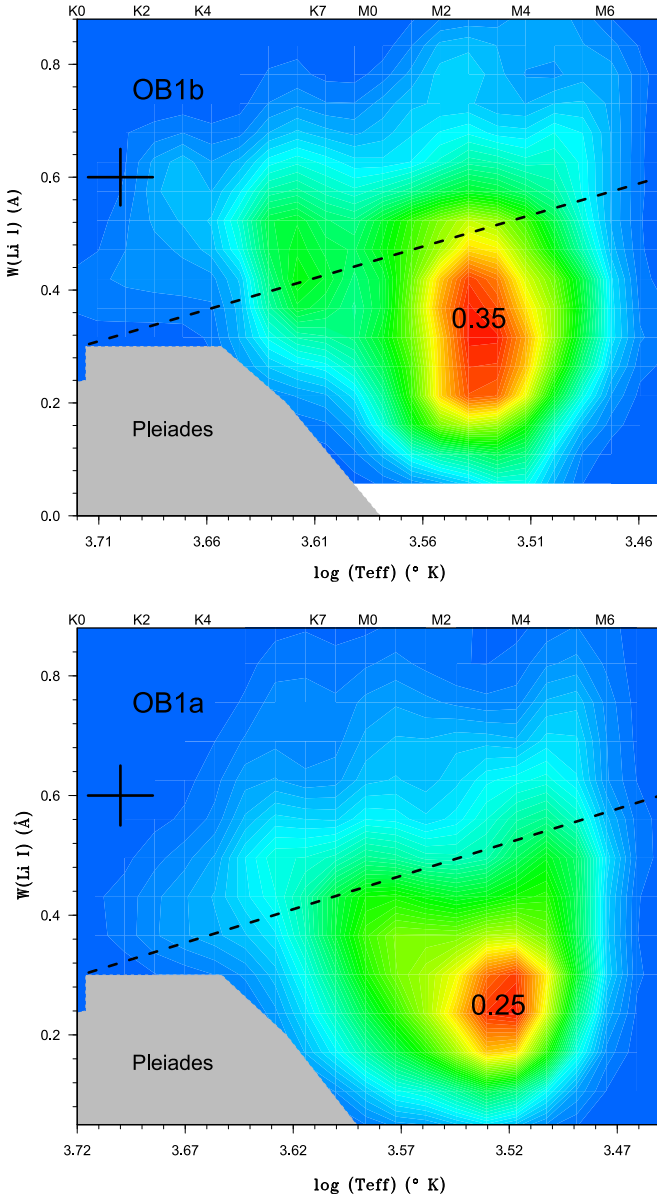


Figure 30. Comparison of the distribution of Li I $\lambda 6707$ equivalent widths, represented as the surface density of values, for the ~ 5 Myr old Ori OB1b TTS and the ~ 11 Myr old OB1a “field” population. The dashed line is the young Li locus lower boundary (see text), above which are the $W(\text{Li I})$ of most optically visible stars in the ONC and the Taurus clouds. In each panel, we label the value of the $W(\text{Li I})$ of the mode of the distribution for the M2–M4 SpT range that contains the most stars in each region (~ 200 ; also see Figure 14). The locus of Pleiades stars is indicated by the shaded gray region (Soderblom et al. 1993; García López et al. 1994). T_{eff} are derived by interpolating our SpTs in Table A5 of Kenyon & Hartmann (1995). The typical uncertainties in each axis are indicated in each panel by the black cross.

move downwards in the diagram, to smaller values of $W(\text{Li I})$. This effect was already suggested by us in Briceño et al. (2007), and later shown by Jeffries et al. (2014) in the γ Velorum cluster. However, here we provide robust observational evidence of Li depletion with large samples of young populations of low-mass stars, all belonging to the Orion OB1 association.

In the left panel of Figure 31, we show the evolution of the ensemble Li I for each population, parametrized by the number of TTSs in each group lying within the “young” Li locus, as

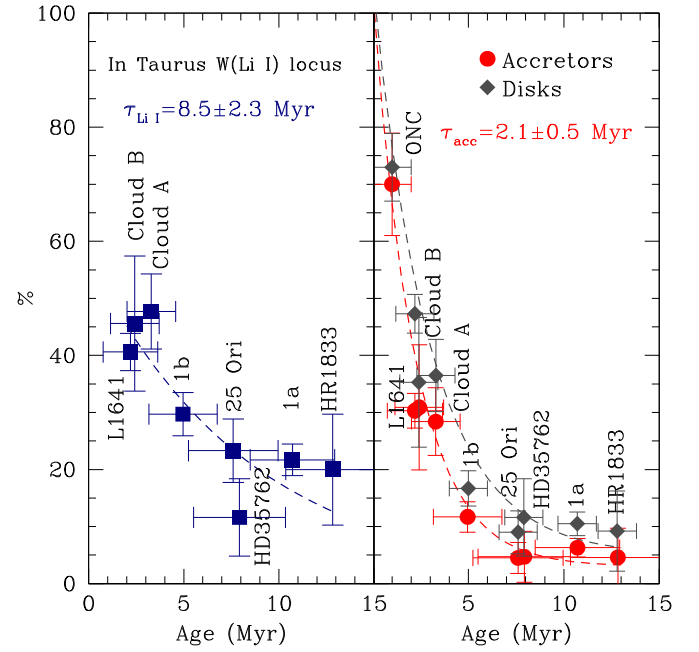


Figure 31. Left: evolution of the fraction of stars with Li I equivalent widths as large as that of K- and M-type T Tauri members of the Taurus star-forming region, which we consider as reference for a pristine, optically visible young population. The blue dashed line is a fit to the data, excluding the point for HD 35762. Right: decline of the accretor fraction as a function of the mean age of each region/group. The red dots indicate the percentage of CTTs in each region, the usual measure of how much of the population is still actively accreting. The red dashed curve is an exponential fit to the data. As a reference, we show with dark diamonds the percentage of disk-bearing stars, determined from the $K_s - W2$ color following Figure 1 of Luhman & Mamajek (2012), with an exponential fit indicated by the dashed curve.

Table 6
Li Depletion in Orion OB1

Region	No. of TTSs	No. in “young” Li locus	Percent in “young” Li locus
L1641 ^a	865	352	41
Cloud B	68	31	46
Cloud A	221	106	48
1b	556	165	30
25 Ori	223	52	23
HD 35762	86	10	12
1a	843	183	22
HR 1833	65	13	20

Note.

^a From Hsu et al. (2012).

indicated in Table 6. The decrease in the ensemble $W(\text{Li I})$ across different populations can be fit by an exponential decline with a characteristic timescale $\tau_{\text{Li}} = 8.5 \pm 2.3$ Myr in M-type stars, which constitute the bulk of the samples shown in Figure 30. This is in rough agreement, within a factor of ~ 2 , with theoretical predictions of Li depletion (Stahler & Palla 2005). For example, Bildsten et al. (1997) estimated that a $0.3 M_{\odot}$ PMS star (approximately an M3 TTS) will have depleted its Li by $\sim 50\%$ at 16 Myr. Though few studies similar to ours have been done, our findings seem consistent with the differences between the overall $W(\text{Li I})$ for M stars shown by Jeffries (2014) in their comparison of the ONC with γ Vel. The HD 35762 group is an outlier in Figure 31, with an unusually low Li-young fraction that does not fit the trend, though it is

Table 7
Accretor Fractions across Orion OB1

Region	TTS	CTTS	C/W	% CTTS	% C/W
ONC ^a	...	...	...	70	...
L1641 ^b	865	262	108	30	12
Cloud B	68	21	2	31	3
Cloud A	221	62	31	28	14
1b	556	65	55	12	10
25 Ori	223	10	11	5	5
HD 35762	86	4	6	5	7
1a	843	53	39	6	5
HR 1833	65	3	6	5	9

Notes.

^a From Hillenbrand et al. (1998).

^b From Hsu et al. (2012).

only a 1σ deviation. This group merits further investigation in order to determine better its full membership and derive better parameters for the stellar aggregate. Large-scale spectroscopic studies in increasingly older populations, carried out in a systematic way, could shed light on the evolution of Li in young stellar populations in the little studied 10–50 Myr age range. If this behavior could be calibrated, it may prove to be a useful tool for dating PMS populations in the next era of large-scale photometric and spectroscopic studies, ushered by the possibility of combining the power of facilities like DECam on the CTIO Blanco telescope, the Zwicky Transient Factory (Smith et al. 2014), and LSST (Ivezic et al. 2008) with highly multiplexed spectroscopic discovery and characterization machines like DESI (DESI Collaboration et al. 2016a, 2016b).

3.7.3. Evolution of Disk Accretion

An important indicator related to the evolutionary state of a population of low-mass PMS stars is the fraction of stars still accreting from their circumstellar disks. As we have discussed in Section 3.3, CTTSs are low-mass PMS stars considered to be actively accreting from a circumstellar disk. We have introduced an additional class of objects, namely, the C/W stars, which we argue are objects in a stage intermediate between that of actively accreting CTTS and the largely diskless, chromospherically active WTTs. These C/W stars are likely undergoing modest and/or variable accretion, in some cases at levels below what can be readily detected in low-resolution spectra. Such low accretors can be diagnosed through high-resolution spectroscopy that can resolve the H α line profile or near-IR spectra that can look at other accretion diagnostics like the He I λ 10830 line (Thanathibodee et al. 2018). In Table 7 we show the accretor fractions derived for each region, in order to gauge how accretion is progressing from one population to another. We determine the percentage of accreting TTS in each region as % Accretors = (No. CTTSs/No. TTSs) $\times$ 100.

The percentage of CTTSs averaged over our full sample is 11%, but this is a strongly location-dependent value, which is due to the very different ages of each group. It varies from at least 70% in the $\sim$ 1 Myr old ONC (Hillenbrand et al. 1998), to $\sim$ 30% in the A and B clouds, decreasing to 14% in the OB1b region and finally down to $\sim$ 5%–8% once we reach the $\sim$ 10 Myr age range of the OB1a subassociation. However, even within the OB1b region, there are considerable

Table 8
Optical Variability in Orion OB1

	TTS	CTTS	C/W	WTTs	Field stars
No. of Stars	2062	218	150	1694	2418
$\Delta(V)$	0.403	0.722	0.474	0.356	0.240
median $\Delta(V)$	0.302	0.500	0.378	0.290	0.191
$\overline{\Delta(R)}$	0.28	0.590	0.349	0.242	0.154
median $\Delta(R)$	0.215	0.381	0.281	0.202	0.113
$\overline{\Delta(I_C)}$	0.244	0.419	0.261	0.225	0.160
median ΔI_C	0.190	0.273	0.218	0.183	0.107
$\sigma(V)$	0.091	0.179	0.118	0.078	0.049
median $\sigma(V)$	0.067	0.136	0.089	0.064	0.036
$\sigma(R)$	0.064	0.145	0.081	0.054	0.032
median $\sigma(R)$	0.048	0.095	0.064	0.045	0.025
$\sigma(I_C)$	0.045	0.091	0.049	0.040	0.027
Median $\sigma(I_C)$	0.033	0.055	0.047	0.032	0.021

differences; the OB1b I group has a much higher fraction of CTTSs ($\sim$ 22%) compared with OB1b II (3.8%).

As disks evolve and dissipate, fewer TTSs are still actively accreting at a given age, and the fraction of CTTSs diminishes as an increasing fraction of the PMS population tends to be composed of non-accreting WTTs. This well-known trend (Hartmann 2008) can now be tested with improved statistics across populations characterized in a uniform and consistent way. In the right panel of Figure 31, we show the decrease of the accretor fraction with age, for all of the populations and groups in our sample. As in previous sections, for this analysis we consider OB1b as a single population, in order to provide more robust statistics. We have included the ONC as reference, taking the value of 70% provided by Hillenbrand et al. (1998), with the caveat that this number has not been derived in the same way as the rest of the regions and groups. Still, this value agrees well with the exponential fit to the data, described by the dashed red line,

$$\% \text{Accretors} = C_{\text{acc}} \times \exp(-t/\tau_{\text{acc}}),$$

with $C_{\text{acc}} = \text{constant}$ and $T = \text{age}$, and C_{acc} normalized so that the percentage of accretors at $t = 0$ is 100%.

This fit gives an accretion e-folding timescale $\tau_{\text{acc}} = 2.1 \pm 0.5$ Myr, consistent with the findings of Fedele et al. (2010), but obtained in a single star-forming region, with $\sim$ 2000 stars measured in a consistent and uniform way. For reference, we also plot the disk fractions for each region, derived using the $Ks - W2$ color, by matching the CVSO sample with the ALLWISE catalog (Wright et al. 2010; Mainzer et al. 2011). Following Luhman & Mamajek (2012; who used $Ks - [4.5]$, from *Spitzer* data), we derived the disk fraction as the number of stars falling above the upper envelope of the distribution of WTTs in a $Ks - W2$ versus $V - J$ color-color diagram, divided by the total number of TTSs with a $Ks - W2$ measurement in each region. The disk fraction is systematically higher than the accretor fraction. A possibility is that at every age, there are systems in which accretion has stopped due to the clearing of an inner gap in the disk, but enough dust remains to produce an IR excess. Alternatively, there may be a number of low accretors that have not yet been found. An exponential fit to the decline in disk-bearing systems as a function of age results in a timescale of 3.2 Myr for the depletion of dust in the innermost parts of the disk. Our derived values for τ_{acc} and τ_{disk} are in very good agreement with

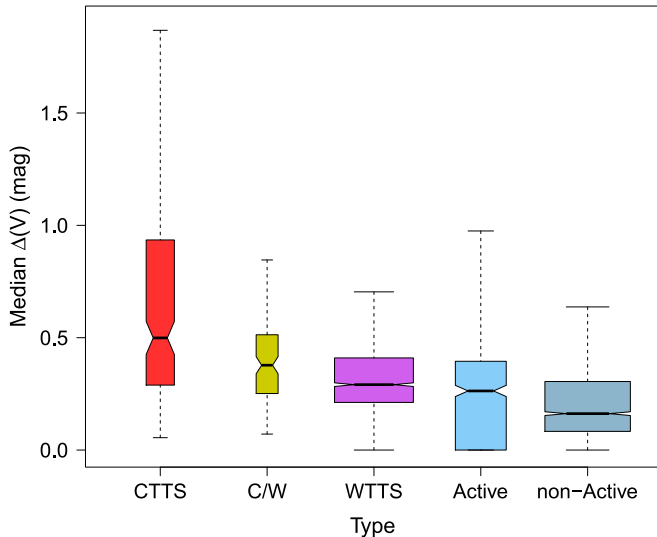


Figure 32. Median amplitude of variability in the V -band for each type of TTS and for field stars. As in Figure 16, this notched boxplot shows the median values together with the first and third quartiles, and the width of each box is proportional to $\sqrt{N}$, with N = number of stars in each group.

previous studies looking at disk fractions using similar indicators (e.g., Fedele et al. 2010), the main differences being that, first, we have derived this result for a large sample within the same star-forming region, thus we can expect the stars to have a common origin, and second, all of the stars in each of the groups spanning the entire ~ 3 – 10 Myr age range have been selected, confirmed as members, and characterized in the same way. We defer further discussion on the ensemble properties of disks in Orion OB1 to a forthcoming paper, in which we carry out an extensive analysis of *Spitzer* and *WISE* infrared data for the CVSO sample.

3.7.4. Variability

We now examine the variability among the various groups of stars in our sample. In Table 8, we show the mean and median amplitudes (peak-to-peak) of the variation in each of the V , R , and I_C bands, together with the mean and median standard deviation of the variability for each type of TTS: CTTS, C/W, and WTTS, as well as for the active and non-active subsets of the field star sample described in Section 3.3. As can be seen in Figure 32, the amplitude of the mean V -band amplitude decreases from the more active CTTSs, to the C/W class, and finally to the more quiescent WTTSs, which are still more variable than the population of active field stars. These active field stars are an important contaminant of photometric surveys like ours, even when folding in variability, because they are active K- and M-type stars, which are significantly variable, so they pass all our selection criteria. They differ from WTTSs only in the lack of the Li I λ 6707 absorption feature, and their weaker Na I $\lambda\lambda$ 8183, 8195 absorption. In fact, the active group of field stars has a higher $\overline{\Delta(V)} = 0.29$ compared to the non-active group ($\overline{\Delta(V)} = 0.22$). A Welch Two-sample T-test finds that the amplitude of variability in these two groups is different at the 95% confidence level. Thus, the active group, defined on the basis of H α emission, also has a higher photometric variability in the V -band; moreover, because these stars are mostly foreground to regions like Orion, they naturally appear above the main sequence in CMDs. These young main-sequence dKe and dMe need to be accounted for when

mapping star-forming regions in future large-scale surveys of the galactic disk.

The trend in Figure 32, combined with that seen in Figure 16, provides support to the idea that the C/W class is indeed a transition stage between the more active CTTSs and the WTTSs, which in turn can be clearly distinguished as a group from their young main-sequence counterparts. Further details on the optical variability of the CVSO TTS sample can be found in Karim et al. (2016), where we presented optical light curves for 1974 stars and derived periods for 564 of them, the large majority WTTSs.

4. Summary and Conclusions

We have carried out a comprehensive synoptic optical photometric survey complemented by extensive spectroscopic follow-up of the majority of the Orion OB1 association, with an emphasis on the off-cloud, little-extincted, and slightly older PMS populations. We have combined photometric variability with the traditional color-magnitude selection, as in Briceño et al. (2001, 2005), and provide further evidence that the resulting candidate selection is sensitive to the young star population in the extended regions beyond the confines of the molecular clouds.

We show the importance of spectroscopic follow-up that includes the Li I λ 6707 line as the only unambiguous diagnostic of youth in K- and M-type PMS stars. With Li I and H α in emission as our main youth diagnostics, we confirm 2062 TTS members across Orion OB1, of which 1485 (72%) are new identifications. We also provide further evidence, with much larger samples than available before in any single star-forming region, of the usefulness of the Na I $\lambda\lambda$ 8183, 8195 doublet as a secondary youth indicator, with the caveat that it has significant overlap with the distribution of field K- and M-type dwarfs.

We provide extensive characterization of the TTS population, including cross-match with SIMBAD, SpT for each star, equivalent widths of the H α λ 6563, Li I λ 6707, and Na I $\lambda\lambda$ 8183+8195 lines; V , R , and I_C robust mean magnitudes; errors and number of observations in each band; amplitude of variability and the standard deviation of the variability of every star in each optical band; the Stetson (1996) variability indices and the variability probability estimates for each band; the 2MASS J , H , and K_S magnitudes; and the T_{eff} , A_V , and group or region to which the star is assigned in Orion OB1. We also compare our study with previous large-scale works in Orion, with both purely survey studies that produced candidate lists and spectroscopic works ending with membership confirmation.

We show that the spatial distribution of the young stars across Orion OB1 is far from uniform, but rather has a significant degree of substructure. Aside from the well-known clusters in the A and B molecular clouds, which we also recover, there are a number of clusterings and stellar aggregates in both the OB1b and the OB1a subassociations. We name the two major stellar overdensities in Orion OB1b, containing 42% of the 556 stars identified within the OB1b region, as OB1b I with 93 confirmed members, and OB1b II, containing 138 confirmed TTSS. The major groups in OB1a are the 25 Ori cluster, with 223 confirmed members, and the new HR 1833 and HD 35762 groups, with 65 and 86 TTS members, respectively. The rest of the 844 TTSS widely spread throughout the OB1a subassociation is what we call the 1a “field” TTS population. For the on-cloud sample, 68 TTSS are projected onto the B cloud, some of them part of the NGC 2068 and 2071 clusters. In the A cloud, we identify 222 stars, most forming a $\sim 2^\circ$ wide halo around the ONC, the northern part of which

corresponds to the NGC 1977 population, and the southern part to NGC 1980, though this group is truncated at $\delta \sim -6^\circ$ due to the southern limit of our survey. These stars likely contaminate many of the ONC censuses, and because they are expected to lie at essentially the same distance as the ONC (Kounkel et al. 2017a), and since the proper motions are likely very similar and all close to zero, it will be difficult to estimate precisely by how much they “contaminate” existing ONC samples.

We derive distances to the three stellar aggregates in OB1a, 25 Ori, HR 1833, and HD 35762, with three methods: using the main-sequence fitting of likely B- and A-type members from *Gaia* DR1 parallaxes for these same early-type stars, and finally, from *Gaia* DR2 parallaxes for the TTS members. We find that the different estimates agree at the $1 - \sigma$ level, indicating a distance of $\sim 350\text{--}360$ pc. With the *Gaia* DR2 data, we also derive distances for the other regions. The ~ 400 pc distance to the A and B clouds agrees with recent determinations using radio interferometric techniques. We find indications of a bimodal distance distribution within the OB1b region, with “near” (~ 350) and “far” (~ 420 pc) components, which we suggest may be the consequence of contamination by the field population of the OB1a subassociation.

With the distances, we use our photometry to place the stars in each group in the CMDs and derive ages by interpolating in the Baraffe et al. (1998) and Siess et al. (2000) model isochrones. We obtain an age of ~ 2 for the B Cloud stars and ~ 3 Myr for the A Cloud stars, with this latter value consistent with the determinations of Fang et al. (2017) and Kounkel et al. (2017a). The groups in the Orion OB1b and OB1a subassociations can be ordered in an age sequence that goes from the older OB1a region (~ 10 Myr), containing 25 Ori, HD 35762, and HR 1833, of which the last one is the oldest; to the intermediate-aged OB1b (~ 5 Myr); to the youngest stars in the A and B molecular clouds. This age sequence agrees with the long-standing idea that star formation in Orion started in the OB1a subassociation $\sim 10\text{--}15$ Myr ago, continuing with OB1b, and ending with the molecular clouds, where the youngest objects and protostars are found today.

We introduce a new class of low-mass PMS stars, the C/W type, which we propose are TTSs going through an intermediate evolutionary stage between that of actively accreting CTTs and WTTs, which have stopped accreting at levels detectable in low-resolution spectra. This new classification is based on the variability of the $H\alpha$ emission-line strength observed in multi-epoch, low-resolution spectra of a subset of our Orion TTS sample. The average disk emission and amplitude of variability of the C/W class fall right between those of CTTs and WTTs, giving support to the idea that these are TTSs at the last stages of their accretion history.

Equipped with an unprecedented large and richly characterized sample of young stars across one of the closest active, massive star-forming regions, we carried out a study of the ensemble-wide properties of each stellar group, the demographics of stellar populations in Orion OB1. This has allowed us to observe, for the first time in a single star-forming region, the depletion of Li during the initial ~ 10 Myr of the PMS phase in K and M dwarfs. By looking at the evolution of the mean $W(\text{Li I})$ for each population, we detected the steady decline of the ensemble-wide strength of the Li I $\lambda 6707$ line. We estimated a timescale of ~ 8.5 Myr for this depletion, roughly in agreement with predictions from theoretical models and with similar work in other nearby star-forming regions

(Jeffries et al. 2014). We also derived the accretor fractions for each region and fit the decline with an exponential function, which yields a characteristic timescale for the decline of accretion of 2.1 Myr, consistent with previous findings. Finally, our data provide the opportunity to look at the optical variability properties of each group of stars. The stellar activity gauged by the mean amplitude of the V-band variability in each type of TTS provides new, robust evidence for the known trend of decreasing activity from CTTs, through the C/W class, to WTTs, through active, likely young, main-sequence stars, and ending with the levels seen in main-sequence, non-active K and M dwarfs.

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Software: IRAF (Tody 1986, 1993), TOPCAT (Taylor 2005), SPTCLASS (Hernandez et al. 2017).

ORCID iDs

César Briceño  <https://orcid.org/0000-0001-7124-4094>
 Nuria Calvet  <https://orcid.org/0000-0002-3950-5386>
 Jesús Hernández  <https://orcid.org/0000-0001-9797-5661>
 A. Katherina Vivas  <https://orcid.org/0000-0003-4341-6172>
 Juan José Downes  <https://orcid.org/0000-0001-6559-2578>
 Catherine Espaillat  <https://orcid.org/0000-0001-9227-5949>
 Lori Allen  <https://orcid.org/0000-0002-7789-5119>
 Lee Hartmann  <https://orcid.org/0000-0003-1430-8519>

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