THE CIDA VARIABILITY SURVEY OF ORION OB1. I. THE LOW-MASS POPULATION OF ORI OB1A AND 1B1,2

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ABSTRACT

We present results of a large-scale, multipoch optical survey of the Orion OB1 association, carried out with the QUEST camera at the Venezuela National Astronomical Observatory. We identify for the first time the widely spread low-mass, young population in the Ori OB1a and OB1b subassociations. Candidate members were picked up by their variability in the V band and position in color-magnitude diagrams. We obtained spectra to confirm membership. In a region spanning ~68 deg2, we found 197 new young stars; of these, 56 are located in the Ori OB1a subassociation and 141 in Ori OB1b. The spatial distribution of the low-mass young stars is spatially coincident with that of the high-mass members but suggests a much sharper edge to the association. Comparison with the spatial extent of molecular gas and extinction maps indicates that the subassociation Ori OB1b is concentrated within a ringlike structure of radius ~2~ (~15 pc at 440 pc), centered roughly on the star ε Ori in the Orion belt. The ring is apparent in 12CO and corresponds to a region with an extinction A_V ≥ 1. The stars exhibiting strong Hα emission, an indicator of active accretion, are found along this ring, whereas the center is populated with weak Hα-emitting stars. In contrast, Ori OB1a is located in a region devoid of gas and dust. We identify a grouping of stars within a ~3 deg2 area located in Ori OB1a, roughly clustered around the B2 star 25 Ori. The Herbig Ae/Be star V346 Ori is also associated with this grouping, which could be an older analog of σ Ori. Using several sets of evolutionary tracks, we find an age of ~7–10 Myr for Ori OB1a and of ~4–6 Myr for Ori OB1b, consistent with previous estimates from OB stars. Indicators such as the equivalent width of Hα and near-IR excesses show that the number of accreting low-mass stars decreases sharply between Ori OB1b and Ori OB1a. These results indicate that although a substantial fraction of accreting disks remain at ages ~5 Myr, inner disks are essentially dissipated by 10 Myr.

Key words: stars: formation — stars: pre–main-sequence — surveys

Online material: machine-readable tables

1. INTRODUCTION

The Orion OB1 association, located at roughly 400 pc (see review by Genzel & Stutzki 1989) and spanning over 200 deg2 on the sky, is one of the largest and nearest regions with active star formation. With a wide range of ages and environmental conditions, Orion is an ideal laboratory for investigating fundamental questions related to the birth of stars and planetary systems. Blaauw (1964) identified four major subgroups that differ in age and their content of gas and dust: Ori OB1a, 1b (which roughly encompasses the belt stars δ, ε, and ζ Ori), 1c, and 1d (where the Orion Nebula Cluster [ONC] is located). Within this vast region there are extremely young groupings of stars still embedded in their parent clouds, such as NGC 2068, 2071, 2023, and 2024 in the Orion B molecular cloud, observed mostly at IR and submillimeter wavelengths (Dahari & Lada 1999; Haisch et al. 2001; Motte et al. 2001); the young, dense, and partially embedded ONC (Herbig & Tercrul 1986; Ali & Depoy 1995; Hillenbrand 1997, hereafter H97); clusterings of intermediate age (~3–5 Myr) stars including the σ Ori (Garrison 1967; Walter et al. 1997) and λ Ori groups (Murdin & Penston 1977; Dolan & Mathieu 1999, 2001, 2002); and older populations like the ~10 Myr old 1a subassociation, located in an area essentially devoid of gas and dust.

Whereas the earliest stages of stellar evolution must be probed with infrared and radio techniques, many fundamental questions, including lifetimes of molecular clouds, cluster dispersal, protoplanetary disk evolution, and triggered star formation, can only be addressed by optical surveys of older populations with ages ~3–20 Myr. To make progress on these issues, wide-field studies of stellar populations in and near star-forming regions are required. In the past, studies of OB associations have been used to investigate sequential star formation and triggering on large scales (e.g., Blaauw 1991 and references therein). However, OB stars are formed essentially on the main sequence (e.g., Palla & Stahler 1992, 1993) and evolve off the main sequence on timescales of 1–3 Myr. Moreover, we cannot investigate cluster structure and dispersal or disk evolution without studying low-mass stars. Wide-field

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studies of the low-mass populations have been carried for some portions of the Upper Scorpius OB association (Preibisch & Zinnecker 1999; Preibisch et al. 2002). In Orion, many young individual clusters have been studied at both optical and infrared wavelengths (e.g., Lada 1992; Prosser et al. 1994; H97; Stassun et al. 1999), but these only represent the highest density, and often youngest, regions. Little is known about the more widely spread low-mass stellar population in these OB associations.

A few large-scale surveys have tried to map the widely distributed low-mass pre–main-sequence population in Orion. The Kiso objective-prism Hα survey (Wiramihardja et al. 1989, 1991, 1993; Kogure et al. 1989; Nakano et al. 1995) covered 225 deg² around the clouds but was biased toward the strongest Hα-emitting stars. The ROSAT All-Sky Survey (Alcalá et al. 1996) detected many X-ray–strong young stars widely distributed across Orion; however, this selection was strongly affected by older foreground field stars unrelated to the young population of Orion (Bricén et al. 1997), and because of its shallow limit it did not reach the fainter K and M stars. Walter et al. (1998) carried out a detailed photometric and spectroscopic study of the region around the O9.5-type star σ Ori, belonging to 1b, and found a large concentration of pre–main-sequence low-mass stars down to \( V \sim 19 \). Similar high densities of young low-mass stars have been found in other selected small regions in 1a and 1b by Sherry et al. (1999) and Sherry (2003), indicating that many low-mass stars remain undiscovered.

Until recently, it was not possible to conduct unbiased, large-scale optical surveys, but technological advances have now made it possible, building on the availability of cameras with multiple CCDs and multiobject spectrographs on telescopes with wide fields of view. One such survey is the optical variability study we have conducted over \( \sim 173 \) deg² in the Orion OB1 association with the purpose of finding, mapping, and studying large numbers of widely dispersed, low-mass (\( \leq 1 M_\odot \)) stars with ages from 1 to \( \sim 20 \) Myr.

Optical photometric variability is one of the defining characteristics of pre–main-sequence stars (Joy 1945; Herbig 1962). However, because of limitations in the size of CCD detectors, past work on photometric variability of young stars has concentrated on follow-up studies of selected samples that had been identified as pre–main-sequence objects by some other means. Only very recently has the potential of variability as a technique to pick out young stars among the field population started to be realized (Bricén et al. 2001; Lamm et al. 2004).

In this contribution we present results from our variability survey in an area of nearly 68 deg² that includes the Orion OB1b subassociation, a large fraction of Ori OB1a, and part of the Orion B molecular cloud (Maddalena et al. 1986), with the young clusters NGC 2023, 2024, 2068, and 2071. In § 2 we describe the optical variability survey and follow-up spectroscopy. In § 3 we describe our results, and in § 4 we present a discussion and conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The QUEST Camera

The multiband, multiphoto photometric survey was carried out using an \( 8000 \times 8000 \) CCD mosaic camera built by the QUEST collaboration and installed on the 1 m (clear aperture) Schmidt Telescope at the Llano del Hato National Astronomical Observatory, located at an elevation of 3610 m in the Venezuelan Andes, close to the equator (8°47' north) and under dark skies. The 16 2048 × 2048 Loral CCD devices are set in a 4 × 4 array covering most of the focal plane of the Schmidt telescope. The chips are front illuminated, with a pixel size of 15 \( \mu m \), which corresponds to a scale of \( 100 \) pixel\(^{-1} \). Because of the gaps between rows of CCDs in the east-west direction, the effective field of view is 5.4 deg². (See Baltay et al. 2002 for a detailed description of the instrument.)

The camera has been designed for observing in drift-scan mode: the telescope is fixed and the CCDs are read out east-west at the sidereal rate as stars drift across the device. This procedure results in the generation of a continuous strip (or “scan”) of the sky, 2.3 wide; the sky can be surveyed at a rate of 34.5 deg² hr\(^{-1} \). In addition to its high efficiency for covering large areas in a short time, drift scanning offers other significant advantages: The telescope does not have to be moved so there is no time lost for reading out the CCDs. In addition, flat-fielding errors are minimized, since each stellar image is obtained by averaging over many pixels as it travels over the CCD, and astrometric precision is enhanced because the zenith angle is constant throughout. One of the limitations of drift scanning is that the sky motion is only parallel on the equator, so the rate of drift on the focal plane is a function of the declination. To address this effect, each row of CCDs is mounted on a separate “finger,” which pivots at one end, allowing the row to be independently aligned perpendicular to the star paths by moving an eccentric cam at the opposite end. The chips are clocked out at separate rates to compensate for the change in sidereal rate as a function of declination; even so, the size of the devices and the image scale limit the declination range available for drift scanning. To minimize image smearing to \( \leq 0.5 \) pixels, drift scanning is restricted to \( -6^\circ \leq \text{decl.} \leq +6^\circ \). The drift-scan mode allows us to obtain quasi-simultaneous multiband photometry, since each column of chips, oriented north-south, can be fitted with separate filters; stars successively cross over four chips in a column, each with its own filter.9 Several filters are available, including \( BVRI \) and Hα. The exposure time (and hence the limiting magnitude) are set by the time a star needs to cross a single chip (140 s at \( \delta = 0^\circ \)). Deeper images can be obtained by combining several scans. This combination of exposure time with the typical seeing at the site (see below) results in a 10 \( \sigma \) limiting magnitude of \( \sim 19.5 \) in the \( V \) band. Saturation occurs at \( V = 13.0-14.5 \), depending on the CCD, since they have differing well depths. The data acquisition system is described in Sabbey et al. (1998).

2.2. The Optical Variability Survey

The location of the telescope, together with the advantages of the drift-scan technique, make this an ideal survey instrument for large-scale studies of regions close to the celestial equator like Orion. Our photometric survey spans the region from \( 5^\circ \) to \( 6^\circ \) in R.A. and decl. = \( -6^\circ \) to \( +6^\circ \), shown in Figure 1 of Bricén et al. (2001). We covered this large portion of the sky in six strips at constant declination, centered at decl. = \( -5^\circ \), \( -3^\circ \), \( -1^\circ \), \( +1^\circ \), \( +3^\circ \), and \( +5^\circ \), for a total area of \( \sim 173 \) deg². (Because of the \( \sim 50^\circ \) gaps between CCDs in declination, we lose about 1.1 deg² per scan.) Here we present results for two strips at

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8 The QUEST (Quasar Equatorial Survey Team) collaboration (Snyder 1998) included Yale University, Indiana University, CIDA, and Universidad de Los Andes (Venezuela). The main goal of QUEST was to perform a large-scale survey of quasars, but the impressive capabilities of this instrument prompted a variety of other studies.

9 In 2001 August lightning struck the 1 m Schmidt dome and damaged the CCD mosaic camera, resulting in the loss of an entire row of CCDs. Therefore, starting in the fall of 2001, we only could obtain data simultaneously in three filters.
decl. = -1° and +1°, encompassing an area of nearly 68 deg² and spanning the range from I’ ~ 200'' to ~210'' and h = -10° to -22°. This part of Orion includes the region around the belt stars, δ, ε, and ζ Ori, that constitutes the OB1b subassociation (Warren & Hesser 1977, 1978, hereafter WH), the region north and west of it, the OB1a subassociation, and part of the Orion B molecular cloud (Maddalena et al. 1986), with the young clusters NGC 2023, 2024, 2068, and 2071.

Our scans start on average a little before R.A. = 5h and end a little beyond R.A. = 6h, in order to have complete coverage in all filters in the range R.A. = 5h–6h. Some of our observations were shared with other projects; therefore, a number of our scans, especially at decl. = -1°, start at R.A. ~ 3h–4h. In practice, the start time and length of each drift scan was determined by the sky conditions; some scans had to be cut short of R.A. = ~ 6h. The temporal spacing between observations was mostly determined by weather and scheduling constraints because of other ongoing projects with the instrument. We obtained 23 scans at decl. = -1° during 18 nights from 1998 December through 1999 January and February and then from late 1999 through early 2000; the 33 scans at decl. = +1°, collected over 17 nights, are more sparsely distributed in time, starting in 1999 December, continuing in 2002 October, 2003 January and February, with the final data obtained in 2003 October. The observation log is shown in Table 1. The general observational strategy was to observe as close to the meridian as possible with a maximum hour angle of 2.5°; because of this and the equatorial location of Llano del Hato, the air mass for most of our observations is ≤ 1.3. The typical seeing during our observations ranged from 1.8° to 2.5°; however, because of the expected degradation introduced by drift scanning (Gibson & Hickson 1992) combined with the pixel size, most scans have images with FWHM ~ 2.5°–3.7°. Thus, with a pixel scale of 1.0’’2, the point-spread function is well sampled.

2.3. Data Processing and Variable Star Identification

In order to effectively process the approximately 30 Gbyte per night of raw data produced by this instrument, QUEST developed its own software. The whole process is completely automated with minimum interaction from the user. The QUEST offline software performs the basic reduction with overscan subtraction, flat fielding (one-dimensional flats are used to correct the response variations along the north-south direction), and object detection and seeing determination (by measuring an average FWHM for ~10²–10³ of stars in each frame); determines the positional offsets between CCDs (recognizes a single star in all four fingers [or rows]); and performs aperture photometry with an aperture radius based on the FWHM of the particular frame (several apertures are used: 1 x FWHM, 2 x FWHM, etc.). Finally, astrometry is done by matching the objects with the USNO-A2.0 catalog (Monet et al. 1998). Positions are internally accurate to ±0.7”. Each catalog for every drift scan is stored in binary format and contains, among others, J2000 positions, instrumental magnitudes in four bands, errors, fluxes within several apertures, and flags (bad columns, edges, etc.). A detailed description of the data pipeline is given in Rengstorf et al. (2004).

We have used differential photometry to identify variable stars among this large number of objects. Our main interest is picking out candidate pre–main-sequence stars among the general field population. Low-mass (M ≤ 2 M☉) young stars (T Tauri stars [TTSs]) are known to vary on timescales from hours to weeks, with variations of up to a few magnitudes. Usually, the variations are larger in the V band than in the I band. This variability can be irregular and is thought to originate in flarlike activity or in nonsteady accretion for the strong Hβ-emitting objects (classical T Tauri stars [CTTSs]); the periodic variations, seen mostly in weak Hβ-emitting TTSs (WTTSs), are proposed to be the result of rotational modulation by hot or cool stellar spots on the star’s surface (Herbst et al. 1994). Therefore, our choice of the V filter allows us to sample a wavelength range where TTSs are expected to vary the most. In addition, because we are not aiming at obtaining light curves or deriving periods for our stars, our irregular temporal sampling is not a major limitation; in fact, since our data span timescales from hours (in a few cases) to days, months, and years, we expect to detect most of the TTSs within our survey area and down to our sensitivity limits.

In order to derive the relative photometry, we first chose as reference catalogs those corresponding to scans obtained during clear nights, which showed a stable behavior of the sky background as a function of right ascension as measured from the average value for the ensemble photometry of thousands of stars in each frame. For the decl. = -1° strip we used observation 512 from 1999 January 6, and we used observation 502 from 1999 December 26 for decl. = +1°. After doing a positional matching, within a 2° search radius, of all stars in each reference scan with respect to the other scans, we obtained a final combined catalog for the decl. = -1° and +1° strips containing 340,532 objects, which had a minimum of three good measurements. This master catalog incorporated data from 21 out of the 23 scans at decl. = -1° and 31 of the 33 scans at decl. = +1°. Some scans had to be discarded because of excessive cloud cover during the observation.

The instrumental magnitudes were normalized to each reference scan in order to remove variable atmospheric extinction due to differences in air mass and sky transparency. This normalization to reference magnitudes was done in bins of 0.25 of right ascension, equivalent to ~1 minute of time in drift-scan mode. Then we calculated the magnitude differences between each scan and the reference scan for all stars in each bin of right ascension, and an ensemble-clipped mean was produced. Since each bin typically contains several hundred stars, especially at the relatively low Galactic latitude of our survey area, this procedure gives a robust estimate of the zero-point difference between each scan and the reference one. With this approach, variable sky conditions like a passing cloud causing an extinction of up to 1 mag can be corrected, as shown in Figure 3 of Vivas et al. (2004), in which more details of this method are provided.

Since a large number of stars have been measured, the random errors of the differential magnitudes are well determined. These amount to ~0.005 mag for V < 17 and increase to ~0.08 mag at V ~ 19.7 as photon statistics dominate the noise. Because of the larger errors when progressing toward the limiting magnitude of our observations, fainter variables are biased toward larger values of ΔV. In Figure 1 we show the dispersion in the normalized instrumental V-band magnitudes for a subsample of the data corresponding to an area of 5.2 deg² containing ~30,000 stars. Each point represents the statistics of up to 32 measurements. Objects detected as variables are indicated with a cross. Most objects are nonvariable and populate the curved region; points above the curve are likely variable stars.

Following Vivas et al. (2004), we applied a χ² test on the normalized magnitudes to select variable stars, which is appropriate because nonvariable stars follow a Gaussian distribution of errors (Fig. 5 in Vivas et al. 2004). If the probability that the dispersion is due to random errors is very low (≤ 0.01),
the object is flagged as variable. Before running the \( \chi^2 \) test, we eliminated measurements that are potentially affected by cosmic rays by deleting points that were more than 4 \( \sigma \) away from the mean magnitude for that particular object. We flagged all objects with a 99\% confidence level of being variable [\( P(\chi^2) \leq 0.01 \)]. This confidence level sets the minimum \( \Delta \)mag that we can detect as a function of magnitude: 0.06 for \( V = 15 \), 0.09 for \( V = 17 \), and 0.30 for \( V = 19 \). This means that for fainter stars we detect only those that vary the most. We cannot decrease the confidence level very much without increasing the
contamination from nonvariable stars to unacceptable levels because we are studying hundreds of thousands of stars. Following this scheme we detected 20,729 variables in the decl. = −1° and +1° strips, a ~6% fraction of variable stars. The selection criterion we used still allows ~3400 possible spurious variables. The fraction of variables we find is larger than that found by other variability surveys, e.g., 0.4% in the All Sky Automated Survey (Pojmanski 2003) and 0.8% in the Robotic Optical Transient Search Experiment variability survey (Akerlof et al. 2000). However, the fraction of false variables in our data may be quite higher than the number expected from the confidence level of the $\chi^2$ test alone. This could be the result of close neighbors and blends, especially at the Galactic latitude of Orion. We did not attempt to identify these false variables because our selection criteria include additional constraints, particularly spectroscopy, that will further reject contaminants. At this point we proceeded to plot the variables in color-magnitude diagrams (CMDs) to select pre–main-sequence candidates.

For the calibration of the photometry we used the Smithsonian Astrophysical Observatory (SAO) 1.2 m telescope equipped with the 4SHOOTER CCD mosaic camera (Caldwell & Falco 1993) at Mount Hopkins, Arizona, during the nights of 2002 December 3 and 4. The 4SHOOTER is an array of four CCDs, covering a square ~25′ on a side, with the four chips each approximately 12′ on a side. We used a binning of 2 × 2, yielding a plate scale of 0.66 pixel$^{-1}$. We obtained $I$- and Cousins $I'$-band images of selected fields at R.A. = 5°–6°, with declinations such that they would fall on parts of the sky overlapping each of the four columns in our QUEST camera scans. Throughout each night we observed the Landolt (1992) standard fields PG 0231+051, SA 92, and SA 98 at air masses 1–1.5. We centered all our target fields on chip 3, the detector with the best cosmetics. Raw images were bias-subtracted and flattened (with dome flats) using standard IRAF$^{11}$ routines. We then performed aperture photometry on all our frames. Typically we had 12–20 standard stars per night. Our photometric solution was derived with an rms of 0.02 mag for $V$ and 0.03 mag for $I_C$. In each of the secondary standard fields we selected stars in the range $V = 15$–18, much fainter than our saturation limit, and bright enough to yield a good signal-to-noise ratio (S/N). Positions within 0.5′ were obtained using the CM1 program (Stock & Abad 1988) to produce a plate solution for each frame after comparing with about six reference stars from the Guide Star Catalog.$^{12}$ This accuracy is enough for positional matching with our QUEST camera catalog. Finally, we kept only those stars with more than seven measurements and not flagged as variable by our variability selection scheme (see below). Our final list contains 390 secondary standards, a robust set of comparison stars that we used to calibrate the normalized magnitudes computed by our variability programs from the QUEST camera scans.

2.4. Selection of Candidate Pre–Main-Sequence Stars

Traditional multicolor photometric surveys for pre–main-sequence stars have relied mainly on color-magnitude and color-color diagrams to select candidate young stars. This approach has been feasible for previous studies that dealt with regions spanning small areas. However, because of the large number of potential pre–main-sequence stars in our survey and the contamination by large numbers of field stars, this selection method is too inefficient. We therefore use variability to select candidate association members.

In Figure 2 of Briceño et al. (2001) we showed that even in a modest region of ~10 deg$^2$ toward Ori OB1b there can be of order 4000 objects above the zero-age main sequence (ZAMS) down to $V \sim 19.5$; after object lists are filtered by our variability criterion, only ≤10% remain above the ZAMS. Moreover, selection of variable stars above the ZAMS clearly picks a significant fraction of the young stars in Orion, as shown in Figure 2, where we compare CMDs for a region in OB1b ($l \sim 203°$, $b \sim 18°$) and a control field ($l \sim 195°$, $b \sim 31°$), located well off Orion; the Orion field exhibits an excess of objects above the ZAMS not present in the control field, even after taking into account that the Orion region has a higher density of stars because it is closer to the Galactic plane. In the Orion field the fraction of variables above the ZAMS is 19%, compared with 10% in the control field, a factor of ~2 overdensity. However, the densest concentration of points in the CMD for the Orion field occurs at roughly 1 mag above the ZAMS. If we compare this locus in both panels of Figure 2, the fraction of variables above the ZAMS in the Orion field is a factor of 3 larger than in the control field.

We tested the reliability of the technique by recovering as variables the 15 out of 19 previously known pre–main-sequence objects (Herbig & Bell 1988) among the stars selected as variable above the ZAMS (see § 3.1). We also used our results to estimate the minimum number of observations required to detect a star as variable. We took the data for five of the Herbig & Bell (1988) stars in our sample and at random took out data points from each star’s light curve, running the $\chi^2$ test each time. Accounting for points rejected because of objects falling

$^{10}$ See http://linmax.sao.arizona.edu/help/FLWO/48/4CCD.primer.html.
$^{11}$ IRAF is distributed by NOAO, which is operated by AURA, Inc., under cooperative agreement with the NSF.
Fig. 2.—CMDs for stars selected as variable. Left: All variables detected in the decl. = −1° strip with R.A. > 5h. Right: Control field off Orion; stars in the same strip and with R.A. = 4⁰48ᵐ−5⁰00ᵐ.

Fig. 3.—Sample FAST spectra of newly identified low-mass young stars in Orion. The left panels show the entire spectra from ~3800 to 7300 Å, from weak Hα-emitting TTSs at top to CTTSs, with their characteristic strong emission in Hα, Hβ, and other lines, in the two bottom left panels. In the right panels we show an expanded view of the wavelength range around the Li i line at 6707 Å; the Ca i line next to it (6718 Å) is also clearly visible.
The number of variables in the left panel of Figure 2 decreases with increasing \( V \) and \( V - I \). This is a result both of the decreased sensitivity in the \( V \) band for redder objects and of our selection criteria for variables. We selected a total of 3744 objects flagged as variable down to our limit of \( V \sim 19.7 \) and located above the ZAMS (Baraffe et al. 1998) in the \( V \) versus \( V - I_C \) diagram. Within this sample we selected objects located above the 10 Myr isochrone as our highest priority candidates. (We excluded from this list the previously known TTSs in the region.) We established a magnitude cutoff at \( V = 16 \). Brighter than this magnitude, we included all variables above the ZAMS; here we discuss follow-up spectroscopy for 1083 of them. In the magnitude range \( V = 16-18.5 \) we assigned the highest priority to all variables above the ZAMS. We then added a number of nonvariable stars in the same region of the CMD. We adopted this strategy in order to circumvent the problem of missing a significant fraction of low-mass, young stars at fainter magnitudes. A total of 320 of the \( V = 16-18.5 \) objects are discussed in this work.

In summary, our selection scheme of candidate Orion members started with 20,729 objects flagged as variables from 340,532 detections. We then selected 3744 of the variables that were located above the ZAMS in the CMD. Finally, we obtained spectra for a subset of those. Here we discuss follow-up spectroscopy for 1403 objects.

2.5. Spectroscopy

Follow-up spectra are necessary to provide confirmation of pre–main-sequence low-mass stars. Optical spectra of TTSs are characterized by emission in the Balmer lines, particularly H\( \alpha \), and other lines like Ca I H and K, as well as the presence of the Li i \( \lambda 6707 \) line in absorption. Weak H\( \alpha \) emission lines and Li i can be reliably measured in low-resolution spectra, which are easiest to obtain at many moderate-aperture telescopes (Briceno et al. 1998, 2001). In addition, low-resolution spectra usually span a large wavelength range, which provides a reasonable number of features (like TiO absorption bands in K- through M-type stars) for reliable spectral typing, from which \( T_{\text{eff}} \) can be derived.

Optical spectra were obtained in queue mode for 1083 of the brighter candidates (\( V < 16 \)) during the period 1999 January through 2002 January, using the 1.5 m telescope of the FLWO with the FAST spectrograph (Fabricant et al. 1998), equipped with the Loral 512 × 2688 CCD. The spectrograph was set up in the standard configuration used for “FAST COMBO” projects, a 300 groove mm\(^{-1} \) grating and a 3" wide slit. This combination offers 3400 Å of spectral coverage centered at 5500 Å, with a resolution of 6 Å. The spectra were reduced at the Center for Astrophysics (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 \( \sim 1500 \) s for objects with \( V \sim 16 \). The S/N of our spectra is typically ≥25 at H\( \alpha \), sufficient for detecting equivalent widths down to a few tenths of an angstrom at our spectral resolution. In Figure 3 we show examples of typical FAST spectra.

We obtained optical spectra for a sample of faint targets (\( V = 16–18.5 \)) using the Hydra multiobject spectrograph on the KPNO 3.5 m WIYN telescope, during the nights of 2000 November 26 and 27 with clear weather. We discuss here spectroscopy of 320 candidate objects distributed in five fields spanning an area of ~4 deg\(^2 \); details are shown in Table 2. (Note that field 2b is the same region as field 2a but with fibers located on different sets of objects.) We used the blue channel fibers (3.1 diameter), the Simmons camera with the T2KC CCD, the 400@4.2 grating, and G3 GG-375 bench filter, yielding a wavelength range ~4000–7000 Å with a resolution of 7.1 Å. All fields were observed with air masses of 1.0–1.5, and exposure 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.

Following the strategy outlined in § 2.4, in each Hydra field we first assigned fibers to all variables above the ZAMS and with \( V = 16–18.5 \) and then filled the remaining fibers with nonvariable objects located in the pre–main-sequence region of the \( V \) versus \( V - I_C \) diagram and with \( V = 16–18.5 \). When possible we also assigned fibers to bright \( V < 16 \) TTSs confirmed from FAST spectra. 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 dohydro 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.

3. RESULTS

3.1. New Members

Table 3 lists the 197 new members of Ori OB1 found in the survey so far (56 in Ori OB 1a, 135 in 1b, and six in 1c). Column (1) gives the CIDA Variability Survey of Orion (CVSO) running number. Column (2) gives the name of the counterpart in the All Sky release of the Two Micron All Sky Survey (2MASS) catalog, and columns (3) and (4) give the 2MASS positions.
| CVSO          | 2MASS (J2000) | R.A. (J2000) | Decl. (J2000) | $V$  | $V - I_c$ | $\sigma(V)$ | $\Delta V$ | Spectral Type | $W$(Hα) (Å) | $W$(Li) (Å) | Class | OB | $J$ | $J - H$ | $H - K$ |
|---------------|---------------|-------------|---------------|------|-----------|-------------|------------|--------------|-------------|-------------|-------|----|-----|-------|-------|
| 05105877−0008030 | 05 10 58.78   | −00 08 03.0 | 17.30         | 2.69 | 0.06      | 0.23        | M3         | −37.80       | 0.40        | C           | 1a    | 12.82 | 0.68 | 0.25   |
| 05152615−0038067 | 05 15 26.15   | −00 38 06.7 | 15.88         | 2.16 | 0.10      | 0.34        | M1         | −3.80        | 0.40        | W           | 1a    | 12.55 | 0.67 | 0.23   |
| 05152669−0038070 | 05 15 26.69   | −00 38 07.0 | ...           | ...  | ...       | ...         | ...        | ...          | ...         | ...         | ...   | ... | ... | ...   | ...   |
| 05154362+0157310 | 05 15 43.62   | +01 57 31.1 | 16.25         | 2.25 | 0.03      | 0.10        | M3         | −5.90        | 0.30        | W           | 1a    | 12.69 | 0.67 | 0.26   |
| 051181171−0001356 | 05 18 11.71   | −00 01 35.8 | 14.62         | 1.78 | 0.06      | 0.17        | M0         | −3.70        | 0.20        | W           | 1a    | 11.72 | 0.67 | 0.20   |

**Notes.**—Column (2) gives the 2MASS ID of the counterpart. In some cases (stars 34, 114, and 186), more than one possible counterpart is shown (see text). Columns (3) and (4) give the 2MASS coordinates. Spectral-type errors are 1–2 subclasses for stars with FAST spectra and 2–3 subclasses for stars with Hydra spectra. Equivalent widths $W$ in columns (10) and (11) are in angstroms. The classification in column (12) (C = CTTS, W = WTTS) is based on the spectral-dependent threshold $W$(Hα) following White & Basri (2003). Assignation to a given subassociation in column (13) follows discussion in § 3.2. Table 3 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

* Star observed with the Hydra spectrograph.

* Pair not resolved in QUEST photometry.
The association between QUEST and 2MASS was made as follows. Positions obtained with the QUEST camera are internally accurate to 0".2. We used a 5" search radius to match our positions for 165,530 objects in the decl. \( \equiv \) C0/C14 strip with 2MASS; we found a median offset of 0".67 \( \pm 0".22 \). However, because the object surface density increases toward the Galactic plane, confusion starts to be an issue at R.A. \( \geq 5^h30^m \); the automated pipeline is not designed to deal with objects that are separated by less than 2 \( \times \) FWHM. The result is that candidate lists have to be collated manually for blends. Thus, we inspected visually the Digitized Sky Survey (DSS) red plate images for each selected candidate. With a plate scale of 0".5, the DSS can resolve close pairs better than our QUEST camera images. Still, some close pairs were observed spectroscopically (see below). Once we determined the new members, we searched in the 2MASS catalog for all sources within 10" from the QUEST position. We calculated the expected J magnitude of the counterpart from V and extinction estimated from V/I using the interstellar reddening law (\( \equiv 3.4 \)). For 191 stars, we found only one source within this search radius with J within 0.5 mag of the expected J. However, for six stars (2, 34, 59, 114, 170, and 186 in Table 3), we found two 2MASS sources with comparable J magnitudes within the search radius. These stars were not resolved in the QUEST photometry, shown in columns (5) and (6) of Table 3, so we list in the table the two possible counterparts and note that the optical photometry corresponds to the blend of both sources.

Figure 4 shows the distribution of \( \Delta V \) for the stars in our sample. The average \( \langle \Delta V \rangle \) for the WTTSs is 0.26 mag with an rms = 0.08 mag; for CTTSs we measure \( \langle \Delta V \rangle = 0.58 \) mag with an average rms = 0.17 mag. CTTSs exhibit a wider range of \( \Delta V \), with variations as large as \( \leq 24 \) mag, while the majority of WTTSs vary by less than 0.5 mag. These values are consistent with those found in the comprehensive study by Herbst et al. (1994). Columns (7) and (8) of Table 3 list the standard deviation and the measured \( \Delta V \), respectively. Twenty-three stars do not

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**TABLE 4**

**OTHER DESIGNATIONS OF NEW MEMBERS**

| CVSO | Other Identification |
|------|----------------------|
| 40   | Kiso A-0903 132      |
| 41   | Kiso A-0903 133      |
| 47   | Kiso A-0903 142      |
| 48   | Kiso A-0903 143      |
| 58   | Kiso A-0903 176      |
| 75   | Kiso A-0903 191      |
| 82   | IRAS 05284–0042      |
| 90   | Kiso A-0904 1, Kiso A-0903 20 |
| 104  | Haro 5-64, Kiso A-0903 220 |
| 107  | Kiso A-0904 4        |
| 109  | V* V462 Ori, Haro 5-66, Kiso A-0904 5 |
| 143  | Kiso A-0904 36, SVS 1272, NSV 2328 |
| 146  | V* V499 Ori, Kiso A-0904 40, Haro 5-73, SVS 1238 |
| 152  | Haro 5-79            |
| 155  | Kiso A-0904 60       |
| 157  | Kiso A-0904 65       |
| 164  | Kiso A-0904 73       |
| 165  | Kiso A-0904 76       |
| 171  | Haro 5-87, Kiso A-0904 8 |
| 176  | Haro 5-91, Kiso A-0904 104 |
| 177  | Kiso A-0904 106      |
| 178  | V* V513 Ori, Haro 5-92 |
| 180  | Kiso A-0904 115      |
| 181  | RX J054132.6–015658, [FS95] 14 |
| 182  | Haro 5-59, NGC 2024 HLP 4 |
| 184  | LkHβ 288             |
| 187  | Kiso A-0904 131      |
| 190  | V* V518 Ori, Haro 5-93, Kiso A-0904 148 |
| 192  | LkHβ 293, Haro 5-95, Kiso A-0904 165 |
| 193  | LkHβ 298, GSC 00116-01169, CSI +00-05435, Kiso A-0904 176, RJHA 11, SSV LDN 1630 51 |
have measurements for \(\sigma(V)\) or \(\Delta V\). These were objects located above the ZAMS in the CMD but not detected as variable, to which we allocated fibers in the WIYN-Hydra observations.

In columns (10) and (11) of Table 3 we show the equivalent width of \(\text{H}\alpha\) and \(\text{Li}\ i\ \lambda 6707\). In column (12), we show the classification of the star according to the equivalent width of \(\text{H}\alpha\). We follow White & Basri (2003) and use a limiting value between strong emission, or CTTSs (“C” in Table 3), and WTTSs (“W” in Table 3) that depends on spectral type: 8 Å if the spectral type is K5 or earlier, 10 Å if the spectral type is between K5 and M2.5, and 20 Å if the spectral type is between M3 and M7.5. Unlike other regions of Orion, we are not affected by nebular emission, so the measurements of \(W(\text{H}\alpha)\) are fairly reliable. Our main limitation is the low spectral resolution, but even for the earlier type stars in the survey the value of \(\sim 3\) Å is within our detection limit at our typical S/N.

Columns (14)–(16) of Table 3 list \(J\) and the colors \(J - H\) and \(H - K\) for the 2MASS counterparts of each star. We give the near-IR magnitudes of both possible counterparts for stars that were blended in the QUEST photometry. The \(J\) magnitude of star 34 has a flag in the 2MASS catalog indicating deblending problems; only the \(H - K\) color is listed, for each of the counterparts, and the actual magnitudes are given in a note to the table. Similar deblending problems are listed for \(J\), \(H\), and \(K\) of the possible counterparts of star 186.

In Table 4 we indicate previously existing identifications for each star (if any). Many of these were identified in the Kiso survey of \(\text{H}\alpha\)-emitting stars. This survey contains 451 objects in the region we have studied. Of these, 25% are located above the ZAMS, and 50% of this subset are flagged by our software as variable. Only 6% of the Kiso objects below the ZAMS are variable.

There are 19 previously known TTSs within our survey area that have \(V \geq 13.5\). We detected 15 of them, all flagged as variable (Table 5); they are located in the L1622, 1627, and 1630 clouds associated with the embedded clusters NGC 2024, 2068, and 2071, respectively. Stars LkHo 314, 315, 336/c, and 337 were not detected by the QUEST automated pipeline. In the case of 336/c, its proximity (5′′) to LkHo 336 results in the images being too close to be separated as two distinct objects. The remaining stars fell on bad columns in the reference scan, so they were flagged as having problems by our software and not included in the resulting object catalogs.

The depth \((V \sim 19.7)\) and wide spatial coverage of our study offers several advantages when compared to other large-scale surveys aimed at finding pre–main-sequence stars. The ROSAT All-Sky Survey (RASS) was used to search for pre–main-sequence stars over 450 deg\(^2\) in Orion (Alcalá et al. 1996). However, in Bricen˜o et al. (1997) we showed that the shallow limit of the RASS results in significant incompleteness for distances \(d \geq 100\) pc, which corresponds to \(V \sim 12\) for solar-type
stars with no extinction. Deep X-ray observations can detect many young low-mass stars, but they are limited to small selected fields (e.g., the Chandra deep pointings in the ONC; Garmire et al. 2000). The Kiso Schmidt H/C11 survey covered a large area in Orion down to V/C24 but is biased toward CTTSs and did not confirm membership of their sources. Finally, while 2MASS has been an important tool to look for young stars embedded in their natal clouds, it is not effective for finding the older, widespread populations we are starting to unveil here.

3.2. Spatial Distribution
Blaauw (1964, 1991) was the first to recognize the existence of different subassociations in Orion, which he named 1a to 1d. As inferred by the hottest star in each subassociation, Blaauw assigned an age of a few megayears to 1b and a few times 10 Myr to 1a and suggested that these groups were one of the best examples of sequential star formation. WH carried out a detailed photometric study of Blaauw’s subassociations and were the first to formally assign boundaries between them. Figure 5 shows these boundaries in the region of our survey. We also show in this figure the distribution of the new TTSs, indicating the CTTSs and WTTSs with different symbols. It is apparent that the low-mass stars are not distributed uniformly throughout the survey area; rather, they are located in distinct regions: in particular, the CTTSs are concentrated toward the 1b subassociation.

Figure 5 also shows the distribution of the OB stars in the subassociations (Hernández et al. 2005). These OB stars were selected from the Hipparcos catalog using proper-motion criteria given in A. G. A. Brown (1999, private communication), in addition to photometric and parallax limits (cf. Hernández et al. 2005). These stars are indicated with squares in Figure 5. The low- and high-mass stars appear to be similarly located in the sky.

One interesting structure is the grouping or “clump” of low-mass stars in 1a, located roughly at R.A. = 5h23m and decl. = 1°45' Its elongated form in the east-west direction could be the result of this structure lying at the northern limit of our decl. = +1° strip. Analysis of the decl. = +3° strip (in a forthcoming paper) will clarify whether it extends farther north. This stellar group is clustered around the B1 Vpe star 25 Ori, a star with Hα emission but no significant excess in the JHK bands. However, the A2 star V346 Ori (HIP 25299) is also in the cluster. This star has a strong near-IR excess and Hα emission, for which it has been classified as a probable member of the Herbig Ae/Be class (van den Ancker et al. 1998; Mora et al. 2001; Hernández...
et al. 2004). The low-mass members of the group are mostly WTTSs, with only one CTTS discovered so far, CVSO 35, which at $W(H\alpha) = -10.3$ Å and a spectral type K7 is barely on the dividing line we have adopted for WTTS/CTTS.

WH and Brown et al. (1994) used main-sequence fitting for the OB stars in the subassociations to estimate distances and ages. They confirmed the age difference indicated by the early studies of Blaauw. Moreover, they found a difference between 1a and 1b, with 1b having a similar distance as that of the molecular cloud, $\sim 440$ pc (Genzel et al. 1981), while 1a is closer, $\sim 330$ pc. Stars in Brown et al. (1994) were observed by Hipparcos; Brown et al. (1994) confirmed the distance difference between 1a and 1b, although there were substantial observational errors in the parallaxes of individual stars.

To reconsider the question of the distance of 1a, we considered a subsample of the Hipparcos stars close to the clump of low-mass stars in 1a discussed above. The average parallax of this subsample is 3.1 mas with a dispersion of 1.3 mas, compared with 3.11 mas with dispersion of 1.9 mas for the much more dispersed Brown et al. (1994) sample (Hernández et al. 2004). The corresponding mean distances are $323^{+23}_{-96}$ and $322^{+504}_{-122}$ pc, so the distance of the subsample is slightly better constrained.

We adopt this estimate for the mean distance of 1a, noting that the large dispersion may suggest that the subassociation have a significant depth, comparable to the large spread in the sky. This will result in a large spread in the positions of the stars in the color-magnitude or the H-R diagram when using mean distances.

To further investigate the nature of the subassociations, we compare the location of our new members with the distribution of gas and dust in the area. Figure 6 shows the stellar positions, together with maps of $^{13}$CO from Bally et al. (1987), which have enough resolution and probe the densest gas regions. This map is shown in color halftone scale. We also show the isocontour of color excess $E(B-V) = 0.3$ from Schlegel et al. (1998) as an indicator of the dust distribution in the area. The gas and dust distributions follow each other closely.

The boundaries of the survey observations presented in this work are indicated, as well as the WH boundaries. It can be seen that 1a corresponds generally to regions devoid of gas and dust, outside the boundaries of the Orion molecular clouds. In contrast, 1b is located at the boundary of the clouds, in regions of intermediate concentration of gas and dust between 1a and the clouds. In particular, a ringlike structure with a radius of $\sim 2^\circ$, which corresponds to $\sim 15$ pc at the 1b distance, can be seen in low $^{13}$CO emission and especially in the color excess isocontour. The center of the ring is located near the B0 Iae star $\epsilon$ Ori, in a region of low $A_V$.

The part of the ring at $l \sim 203^\circ - 204^\circ$ falls on the region of the decl. $= +1^\circ$ observations, where the sampling is poor because spectroscopic follow-up was delayed by the damaging of the
some of the CCDs in the QUEST camera (see § 2.1). The part of the ring at \( l \gtrsim 206\degr \) falls outside the survey limits presented in this paper. However, the middle part of the ring is very well sampled by our observations at decl. \( \approx -1\degr \). A clear pattern can be seen in the distribution of CTTSs and WTTSs. While WTTSs can be found in the entire region, the CTTSs concentrate toward the regions of higher extinction and gas density delineating the ring. This distribution is similar to that found in the molecular ring around \( \kappa \) Ori, which has comparable dimensions to the 1b ring (\( 16–20 \) pc; Dolan & Mathieu 2001, 2002). Dolan & Mathieu (1999) found that only 5% of the stars near the center of the \( \kappa \) Ori ring are CTTSs, while most CTTSs concentrate near the molecular ring. These authors suggested that the lack of accreting stars near the center of the region could be the result of photoevaporation of disks by the nearby OB stars. Dolan & Mathieu propose that the CTTSs along the ring were formed by the effects of a supernova at the center of the ring, which snowplowed preexisting molecular material into concentrations dense enough to trigger star formation. On a smaller scale, a similar situation is also found by Sicilia-Aguilar et al. (2004) in a study of the young cluster Trumpler 37, where the CTTSs are strongly concentrated in a region away from the central O star.

We speculate that Ori OB 1b corresponds to a population formed by a supernova event that occurred near \( \epsilon \) Ori \( \sim 5 \) Myr ago (§ 3.3). The reality of this scenario will be tested by forthcoming radial velocity studies of the low-mass population. Nonetheless, we have redefined the boundaries of 1b so that it roughly follows the outer \( A_V \sim 0.5 \) contour at \( l \sim 203\degr -205\degr \) and is limited by the cloud at \( l \gtrsim 205\degr \). This is the definition used in Table 3. Obviously, whether a star belongs to 1a or 1b near the boundary is very uncertain.

Finally, there are six stars in Table 3 that have R.A. \( \leq 5\text{h}44\text{m} \) and decl. \( \sim 0\degr \), which places them around the boundary between the 1a and 1c subassociations as defined by WH; they are located on the molecular cloud. We have assigned them to 1c.

3.3. Color-Magnitude Diagrams

In Figures 7 and 8 we show the CMD of 1a and 1b, together with theoretical isochrones from Siess et al. (2000) and Baraffe et al. (1998). Isochrones are represented assuming a distance of 330 pc for 1a and 440 pc for Ori OB 1b. Members are plotted with their observed magnitudes and colors (not corrected for reddening).

A large spread in ages is observed in Figures 7 and 8, due in part to uncertainties in the distance (§ 3.2). To restrict this
somehow, we plot in Figures 7b and 8b only those stars located in the clump in 1a. The spread is considerably reduced, showing an age of 3–10 Myr for 1a. The spread is much larger in 1b, where, in addition to the distance, there are uncertainties due to lack of extinction corrections and overlap with 1a. In any event, it is apparent that 1b has a much higher fraction of 1–3 Myr stars than 1a. We have included the 1c stars together with the 1b members in the CMDs (labeled as “1b+1c”) because they are few and do not impact our conclusions on the ages of each region.

3.4. Stellar Properties

We have applied the spectral classification method of Hernández et al. (2003), extended to include indices around the TiO bands for the late spectral types of our stars. The resulting spectral types are given in column (9) of Table 3. Errors in spectral type are typically ±1 subclass for stars observed with the FAST spectrograph and 2–3 subclasses for stars observed with Hydra. We have then obtained the effective temperature \( T_{\text{eff}} \) by

\[
\text{Table 6}
\]

| CVSO | \( T_{\text{eff}} \) (K) | \( A_V \) (mag) | \( L \) (\( L_{\odot} \)) | \( R \) (\( R_{\odot} \)) | \( M(B) \) (\( M_{\odot} \)) | Age (B) (Myr) | \( M(S) \) (\( M_{\odot} \)) | Age (S) (Myr) | Class |
|------|-----------------|----------------|-----------------|-----------------|-----------------|--------------|-----------------|--------------|-------|
| 1......| 3470            | 0.53           | 0.16            | 1.12            | 0.42            | 4.60         | 0.33            | 4.53         | CTTS  |
| 2a......| 3720            | 0.48           | 0.22            | 1.14            | 0.65            | 7.47         | 0.47            | 6.07         | WTTS  |
| 3......| 3720            | 0.48           | 0.18            | 1.01            | 0.65            | 10.81        | 0.47           | 7.97         | WTTS  |
| 4......| 3470            | 0.00           | 0.16            | 1.11            | 0.42            | 4.73         | 0.33           | 4.68         | WTTS  |

\text{Notes.}—“B” and “S” refer to quantities determined using the Baraffe et al. (1998) and Siess et al. (2000) evolutionary tracks. Table 6 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

\* Properties have been determined for each of the two 2MASS counterparts using the corresponding \( J \) magnitude.
using the calibration of Kenyon & Hartmann (1995, hereafter KH95). Using the \( V - L \) color, intrinsic colors from KH95, and the Cardelli et al. (1989) extinction law with \( R_V = 3.1 \), we calculate the extinction \( A_V \). We dereddened the \( J \) magnitude and calculate the stellar luminosity using the calibration in KH95. These stellar properties are shown in Tables 6–8 for 1a, 1b, and 1c, respectively.

The top panels of Figures 9 and 10 show the location of stars in 1a and 1b in the H-R diagram, with evolutionary tracks and isochrones from Siess et al. (2000) and Baraffe et al. (1998), respectively. We calculate mass and ages using both sets of tracks and consider the difference between them as the biggest uncertainty in the determination of these quantities. The derived quantities are given in Tables 6–8. As can be seen in Figure 10, the Baraffe tracks cover a more restricted range of parameter space than the Siess tracks, so for a number of objects, only the Siess values are given.

Although there is a large spread of the stars in the H-R diagram, on average stars in 1a are older than in 1b. Table 9 shows the average age and standard distribution of the ages of 1a and 1b. An uncertainty of 100 pc in the distance results in an uncertainty of \( \log (\text{age}) \) of approximately 0.75, since \( L \propto \text{age}^{-2/3} \) (Hartmann 1998). The age difference between both associations is larger than this uncertainty, in both determinations.

Stars in 1b show a larger spread in the H-R diagram than those in 1a. Since most of the stars in 1a are WTTSs, any contamination of stars of 1a into 1b would appear mostly in the WTTSs. In Figures 9 and 10 we present H-R diagrams for only the CTTSs of 1b, and in Table 9 we show the average age of 1b derived using only the CTTSs. Eliminating the possible contamination of 1a stars by selecting only the CTTSs makes the age of 1b 2–3 Myr, significantly younger than 1a.

In addition, we expect that stars with high values of \( A_V \) are more likely to belong to 1b than to 1a. We show in the lower right panels of Figures 9 and 10 H-R diagrams for all the CTTSs and the WTTSs that have \( A_V > 0.4 \). The distribution of stars in the H-R diagram is not significantly different from that of the entire sample, maybe reflecting a larger range of ages in the WTTSs than in the CTTSs, possibly related to the formation scenario discussed in § 3.2.

3.5. Near-IR Excesses

We have used the near-IR colors in Table 3 to locate the stars in the \( JHK \) diagram, shown in Figure 11. Also shown are the standard main-sequence and giant relations, the reddening vectors, and the CTTS locus, the location of the stars surrounded by accretion disks (Meyer et al. 1997). For 1b, the WTTSs concentrate around the reddened standard sequence up to early M, consistent with the spectral type of the sample and lack of reddening toward 1a. Three out of the four CTTSs in 1a show infrared excesses. We note that two of these stars, 40 and 41, are close to the 1a/1b boundary and could very well belong to 1b. However, star 35, with \( H - K = 0.41 \), is a bona fide CTTS in 1a (see Table 3).

Much higher near-IR excesses are found in 1b, as one would expect from the larger number of CTTSs. Figure 11 shows that stars with excesses generally are CTTSs, consistent with locations along the CTTS locus.

4. DISCUSSION AND CONCLUSIONS

A large fraction of the stars in our galaxy were formed in OB associations (Walter et al. 2000). Adams & Myers (2001) suggest that many, if not most, stars form in stellar groups with \( 10 < N < 100 \) stars. These small groups are not strongly bound like more massive entities destined to become open clusters, and they

### Table 7

| CVSO | \( T_{\text{eff}} \) (K) | \( A_V \) (mag) | \( L \) (\( L_\odot \)) | \( R \) (\( R_\odot \)) | \( M(B) \) (\( M_\odot \)) | Age (B) (Myr) | \( M(S) \) (\( M_\odot \)) | Age (S) (Myr) | Class |
|------|-----------------|----------------|-----------------|-----------------|-----------------|----------------|-----------------|----------------|-------|
| 37   | 3850            | 0.00           | 0.41            | 1.43            | 0.72            | 3.62           | 0.58            | 3.59           | WTTS |
| 48   | 4590            | 0.83           | 1.23            | 1.76            | ...             | ...            | 1.28            | 6.71           | CTTS |
| 50   | 4205            | 0.00           | 1.51            | 2.31            | ...             | ...            | 0.91            | 1.68           | WTTS |
| 52   | 4060            | 0.00           | 0.40            | 1.28            | 0.86            | 6.01           | 0.80            | 8.10           | WTTS |
| 56   | 4060            | 0.00           | 0.47            | 1.38            | 0.84            | 4.49           | 0.80            | 6.61           | WTTS |

**Notes.**—“B” and “S” refer to quantities determined using the Baraffe et al. (1998) and Siess et al. (2000) evolutionary tracks.

### Table 8

| CVSO | \( T_{\text{eff}} \) (K) | \( A_V \) (mag) | \( L \) (\( L_\odot \)) | \( R \) (\( R_\odot \)) | \( M(B) \) (\( M_\odot \)) | Age (B) (Myr) | \( M(S) \) (\( M_\odot \)) | Age (S) (Myr) | Class |
|------|-----------------|----------------|-----------------|-----------------|-----------------|----------------|-----------------|----------------|-------|
| 192  | 4205            | 1.95           | 1.53            | 2.33            | ...             | ...            | 0.91            | 1.65           | CTTS |
| 193  | 4205            | 1.21           | 1.53            | 2.33            | ...             | ...            | 0.91            | 1.64           | CTTS |
| 194  | 4730            | 0.00           | 0.70            | 1.25            | ...             | ...            | 1.05            | 18.70          | WTTS |
| 195  | 4730            | 0.42           | 0.44            | 0.99            | ...             | ...            | 0.92            | 29.70          | WTTS |
| 196  | 4205            | 0.00           | 0.42            | 1.21            | ...             | ...            | 0.93            | 10.83          | WTTS |
| 197  | 5800            | 2.32           | 0.86            | 0.92            | ...             | ...            | ...             | ...            | WTTS |

**Note.**—“B” and “S” refer to quantities determined using the Baraffe et al. (1998) and Siess et al. (2000) evolutionary tracks.
Fig. 9.—Location of the CTTSs (filled circles) and WTTSs (open circles) in the H-R diagram. Also shown are the Siess et al. (2000) evolutionary tracks (solid lines) for masses 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.5 $M_\odot$ from left to right, and isochrones (dotted lines) of log (age) = 5.5, 6, 6.5, 7, and 7.5 from top to bottom. The lower isochrone is the ZAMS. Top left: stars in 1a; top right: stars in 1b; bottom left: 1b CTTSs; bottom right: CTTSs and WTTSs in 1b with $A_v > 0.4$. 
Fig. 10.—Similar to Fig. 9, using Baraffe et al. (1998) evolutionary tracks and isochrones. From left to right, evolutionary tracks (solid lines) are for masses 0.2, 0.4, 0.6, 0.8, 0.9, and 1.0 $M_\odot$. From top to bottom, isochrones (dotted lines) are for log (age) = 6, 6.5, 7, 7.5, and 8.
evolve and disperse much more rapidly than clusters do. Sparse, low-density regions like Taurus and Chamaeleon are more representative of what Adams & Myers (2001) call isolated star formation, whereas the $N \sim 100$ groups are expected to form in OB associations. These groups are also expected to consist mostly of solar-type and less massive stars; thus, they are not necessarily picked up by the existing studies of massive stars in these regions. Few studies exist that have been capable of mapping the low-mass, young population over wide enough areas in nearby OB associations (e.g., Mamajek et al. 2002; Preibisch et al. 1997; Dolan & Mathieu 2002).

We show here that multiepoch surveys over very large areas of the sky are powerful tools for identifying young, low-mass stars in the older, extended regions of nearby OB associations where the molecular gas has dissipated and no longer serves as a marker of recent star formation. This new type of survey builds on the availability of CCD mosaic cameras on wide-field telescopes of small to moderate size.

We have identified about 200 low-mass ($M \sim 0.12\text{–}0.9$ M$_\odot$) pre–main-sequence stars widely spread over nearly 70 deg$^2$ in the Orion OB1 association. The spatial distribution of the newly identified young stars indicates two large star-forming events within this large area, supporting previous studies that recognized two distinct regions, the younger Ori OB1b and the older Ori OB1a. However, our sample is much more numerous, providing a better estimate of the properties of each subassociation than studies of the more massive stars. We find that 1b is almost completely confined to a large bubble of gas of $\sim2$" radius roughly centered on the B0 Iae star $\epsilon$ Ori. We also note that there seems to be a rather well-defined edge to the OB association in the east-west direction, with essentially no TTSs found at R.A. $\leq 5^\circ10^\text{m}$, although many of our scans started further west than this. Another striking result is the discovery of a concentration of stars in 1a, located around an early-type star, which also includes a possible member of the Herbig Ae/Be class. This is similar to, but more numerous than, other small clusters like $\chi$ Cha in the Sco-Cen association (Lawson et al. 2001), possibly an example of the grouped type of star formation proposed by Adams & Myers (2001).

Within present uncertainties (distances and depth of each association, differences between theoretical evolutionary models, etc.) we find an age of $\sim4\text{–}6$ Myr for 1b and $\sim7\text{–}10$ Myr for 1a. The fact that almost all accreting TTSs (those with strong H$_\alpha$ emission), which are also the ones exhibiting near-IR excesses,
are concentrated in 1b, together with the environmental characteristics of each region, supports the idea of 1b being much younger than 1a, consistent with previous estimates from the massive stars.

In Figure 12 we plot the inner disk frequency as a function of age for a number of clusters and associations, including our new data. The disk frequency has been determined by different methods. Haitsch et al. (2001) measured the excess in the near-IR bands JHKL in a number of young clusters, spanning the age range 0.3–30 Myr. The disk frequency in Ori OB1a and 1b has been determined by the fraction of CTTSs; these fractions are ~11% and 23%, respectively. We estimate the fraction of accreting stars in the TW Hya association, using the breadth of the Hα profile from Muzerolle et al. (2000, 2001) as an indicator of accretion and adopting 24 as the total number of members from Song et al. (2003). In general, there is a close correlation between the presence of inner disks, as indicated by near-infrared excesses, and the existence of accretion onto the central star (Hartmann 1998). While not all T Tauri inner disks exhibit K-band excesses, depending on inclination and magnetospheric hole size (Meyer et al. 1997; Muzerolle et al. 2003), the use of L-band data by Haisch et al. (2001) should yield much more complete detections of disk excesses (Hartigan et al. 1990).

The new data for 1a and 1b are consistent with the previously determined decrease of the disk fraction with age (Hillenbrand & Meyer 1999; Haisch et al. 2001) and with the much more elaborate determination by Hillenbrand et al. (2005, in preparation), supporting the idea of a timescale of ~10 Myr for the dissipation of inner disks around low-mass, young stars.

Finally, the discovery of a significant population of low-mass, pre–main-sequence stars in a region devoid of gas such as 1a favors the growing general idea that molecular clouds disperse over times of less than 10 Myr (Hartmann 2001). This work has been supported by NSF grant AST 99-87367 and NASA grant NAG5-10545. C. B. acknowledges support from grant S1-2001001144 of FONACIT, Venezuela. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the NSF. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We are grateful to Susan Tokarz at CFA, who is in charge of the reduction and processing of FAST spectra. We also thank Robert W. Wilson of the CFA Radio and Geoastronomy Division for making available to us the $^{13}$CO map shown in Figure 6. We thank the invaluable assistance of the observers and night assistants at the Venezuela Schmidt telescope that made possible obtaining the data over these past years: A. Bongiovanni, C. Castillo, O. Contreras, D. Herrera, M. Martinez, F. Molina, F. Moreno, L. Nieves, G. Rojas, R. Rojas, L. Romero, U. Sánchez, L. Torres, and K. Vieira. We also acknowledge the support from the CIDA technical staff, and, in particular, of Gerardo Sánchez. Finally, we acknowledge the comments from an anonymous referee, which helped improve this article.

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