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A Large Area Variability Survey in Orion OB1: digging into the fossil record of low-mass star formation

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Abstract.
In an area of $\sim 25\square^o$ we have unveiled new populations of low-mass young stars, from young ($\sim$ 2 Myr) regions in dense molecular clouds like Orion OB 1b, to older ($\sim$ 10 Myr) areas devoid of gas and dust like the sparse OB 1a subassociation. The newly identified young stars are spatially coincident with the high mass O, B and A stars, indicating that little, if any, mass segregation has occured. The absence of dust and gas in Ori OB 1a suggests that star formation is a rapid process, and that molecular clouds do not last more than a few million years after the first stars are born. The lack of accretion indicators or near IR emission from inner dusty disks in Ori OB 1a region suggests that significant disk dissipation has occured in a few Myr, possibly due to the coagulation/agglomeration of dust particles into larger bodies like planetesimals or planets.

1. Introduction

During the last few years our understanding of the formation of low-mass stars and planets has undergone major advances. Dusty disks surrounding very young stars and nearby, more evolved stars, in addition to the burgeoning number of extra solar planets indicate that protoplanetary disks are a common outcome of the star formation process. Evidence is also accumulating in support of a picture of star formation as a rapid process (Hartmann 2001; Briceño et al. 2001).

However, despite significant progress, little is known about star/planet formation in the vast areas spanned by nearby OB associations like Orion OB1, were thousands of young, low-mass ($\lesssim 1M_\odot$) stars are expected to exist but remain undetected yet. Existing optical/IR studies have concentrated mostly on small regions such as the Orion Nebula Cluster (ONC; e.g., Hillenbrand 1997) and the surroundings of the star σ Ori (Walter et al. 1998); a few large scale studies (Wiramihardja et al. 1991; Alcalá et al. 1996) have been done but did not find the more spread out, slightly older lower mass young stars.

Only by identifying and studying somewhat older ($\sim$ 10 Myr), low-mass stars in widely spread stellar populations, can we compare with their younger ($\sim 1-3$ Myr) siblings in dark clouds and ONC-like clusters, in order to answer fundamental questions like the time scale for the coagulation of dust grains into into larger bodies such as planets, and the lifetimes of molecular clouds. But older stellar populations are difficult to find because they are widely spread on the sky; their natal dark, dusty molecular clouds have dispersed and so no longer serve as markers of their positions. Large-scale, spatially-unbiased surveys are needed to find these stars.

To address this problem, we are carrying out a long-term optical variability survey spanning $\sim 120\square^o$ in the Orion OB1 Association ($d \sim 400$ pc), to find, map, and study large numbers of widely-spread, low mass ($\lesssim 1\mathrm{M}_\odot$) stars with ages $\lesssim$ 10 Myr. The survey area (Figure 1) includes young regions of star formation like the Orion Nebula Cluster (ONC; $\lesssim$ 1 Myr), the Ori 1b sub-association (the Orion Belt region, $\sim$ 2 Myr; Warren & Hesser [1977]; Brown et al. [1994]), and older regions devoid of molecular gas like the Ori 1a sub-association ($\sim$ 11 Myr old). In Briceño et al. (2001) we show the potential of our survey to find, in a relatively unbiased way, dispersed young populations.

2. The Variability Survey

The large scale, multiband (BVRIHα), multi-epoch, deep photometric survey is being carried out using an 8000×8000 pixel CCD Mosaic Camera developed by the QuEST collaboration (Quasar Equatorial Survey Team; Baltay et al. 2002), and installed on the 1.0/1.5m Schmidt telescope at The National Astronomical Observatory of Venezuela at Llano del Hato, in the Venezuelan Andes ($8°47'$ N, 3610 m elevation). The 16 2048×2048 UV-enhanced, front illuminated, Loral CCD chips are set in a 4x4 array covering most of the focal plane of the Schmidt telescope, yielding a scale of 1.02" per pixel and a field of view of $2.3° \times 2.3°$. The camera is optimized for drift-scan observing in the range $-6° \leq \delta \leq +6°$: the telescope is fixed and the CCDs are read out E-W at the sidereal rate as stars drift across the device, crossing each of the four filters in succession. This procedure generates a continuous strip (or "scan") of the sky, 2.3° wide; conversely, one can survey the sky at a rate of $34.5\square^o/hr/filter$, down to $V_{lim} = 19.7$ ($S/N = 10$). The raw images are processed with a specially developed automated software pipeline (Baltay et al. 2002). Standard bias subtraction and flatfielding are applied to the raw images. The final output catalogs contain IDs, X,Y coordinates, accurate positions ($\pm 0.2''$), and instrumental magnitudes extracted using aperture photometry.

We have developed tools for identifying variable stars using differential photometry. With a χ^2 test and assuming a Gaussian distribution for the errors, we consider variable only those objects for which the probability that the observed distribution is a result of the random errors is $< 0.01\%$. The minimum amplitude we can detect at a 99.99% confidence level is $\Delta V \sim 0.07$ magnitudes at $V \sim 16$ and $\Delta V \sim 0.4$ magnitudes at $V \sim 19$.

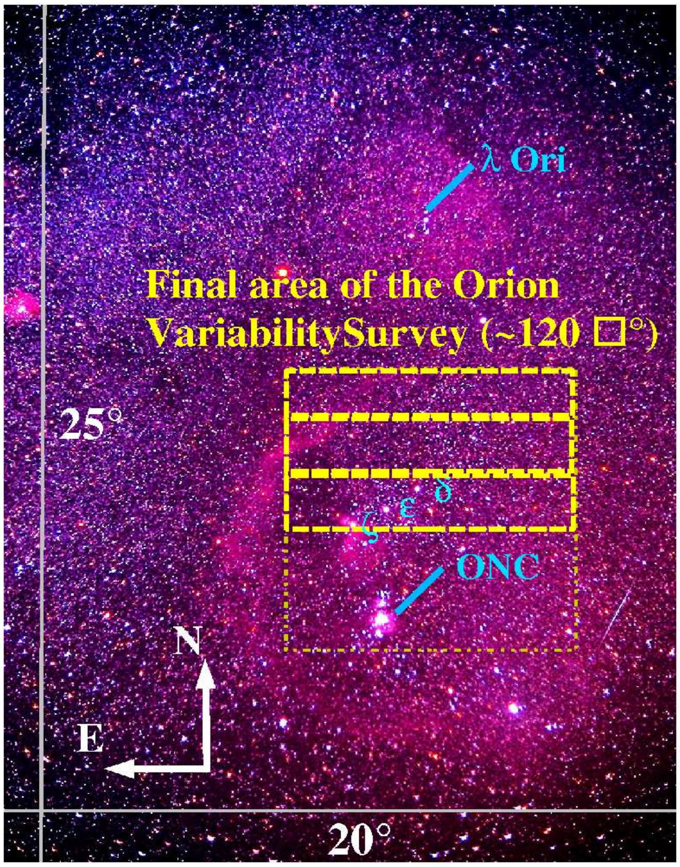

Figure 1. Image of Orion showing the total survey area of 120□° (large yellow dashed-lined box). The first strip, passing over the three Orion belt stars is indicated by thick yellow dashed lines. Two adddi-tional strips covering the northern part of our survey have also been completed, for a total of $\sim 80\square^o$. The Orion Nebula Cluster (ONC) and the bubble around the star λ Orionis are clearly seen.

3. Results

Our first observations consisted of 16 BVR_cI_c scans over a 2.3° wide × 9.7° long strip, centered at declination $\sim -1°$ (Figure 1), obtained during Dec. 98 to early Feb. 99. We selected candidate variable stars located above the zero age main sequence (ZAMS) in a V vs. $V-I$ diagram. Followup spectroscopy was obtained for every object with $V \lesssim 16$ using the FAST spectrograph on the 1.5m telescope of the Smithsonian Astrophysical Observatory (SAO) at Mount Hopkins, with a spectral resolution of 6.5Å covering the spectral range 4000 - 7000Å. Of 350 candidates, 180 are confirmed spectroscopically as low mass pre-main sequence stars (T Tauri stars - TTS), based on the presence of emission lines such as Hα and the absorption line Li I 6707Å, which is an indicator of youth in stars of spectral types later than ~K3 (Briceño et al. 1997, 1998). The newly identified TTS have spectral types K3 - M2, corresponding to masses of

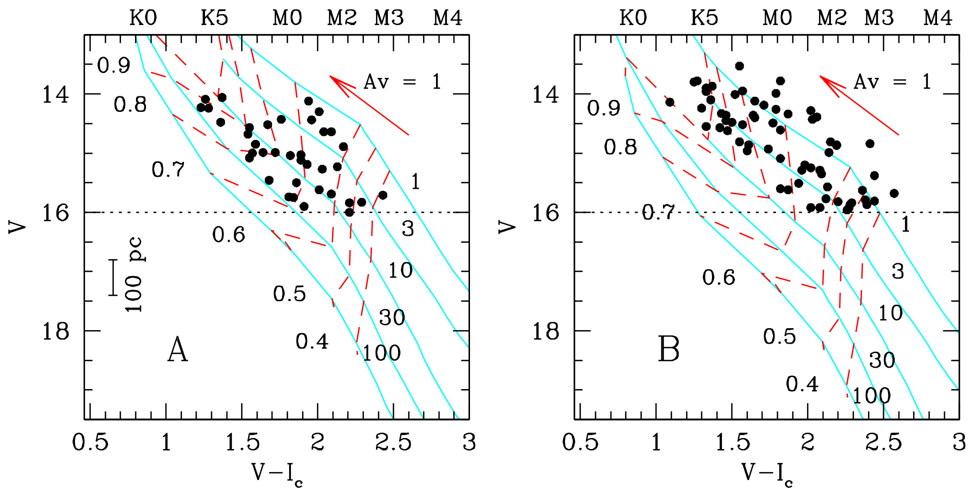

Figure 2. V vs. $(V - I_c)$ diagram for Ori 1a (A) and Ori 1b (B). The assumed distances are 330 pc (1a) and 460 pc (1b). Isochrones (solid lines) for ages 1 to 100 Myr and evolutionary tracks (dashed lines) for masses 0.4 to 0.9 $M_\odot$ (*30*) are indicated. The shifts due to 1 magnitude of de-reddening (arrow) and to a distance change of 100 pc (left vertical bar) are also indicated. The dotted line shows the V=16 limiting magnitude for FAST spectra.

about $0.9 - 0.6\,M_\odot$. The remaining objects are a mixture of mostly background stars of late G - K spectral type (some giants included) and field dMe stars.

Figure 2 shows color-magnitude diagrams for stars in Ori 1a and 1b along with evolutionary tracks for masses 0.3 to 1 $M_\odot$ and isochrones for 1 to 100 Myr (Baraffe et al. 1998). We also indicate the correction in the diagram needed to account for $A_V = 1$. Magnitudes and colors for each star are median values determined from the multiple observations of each object. Because the variations in each star are uncorrelated with the others, they do not affect the location of the sample as a whole in the color-magnitude diagram. It is apparent that stars in 1a are older than stars in 1b. Stars in 1b seem to fall between the isochrones corresponding to 1 - 3 Myr, while stars in 1a seem to fall between 3 and 30 Myr, in agreement with photometric age estimates for the high mass O, B and A stars of the associations (Brown et al. 1994).

According to our present understanding, protoplanetary disks accrete onto their central stars over time scales of millions of years. Accretion results in strong Hα emission (W[Hα]$\gtrsim$ 10Å; Muzerolle et al. 1998), while dust in the innermost disk emits at near-IR wavelengths (Meyer et al. 1997). The disappearance of near-IR dust emission and accretion-related Hα emission may be taken as signposts for the clearing of the inner disk, maybe due to the onset of planet formation.

We have obtained near-infrared JHK magnitudes of the new TTS from the second release of the 2 Micron All Sky Survey (2MASS). Figure 3 shows the $J-H, H-K$ diagram for our sources, along with expected colors for dwarfs and giants. All stars in Ori 1a are within the region expected for purely stellar emission, allowing for small amounts of extinction. In contrast, a significant number of stars in 1b have much larger $H-K$ colors indicating excess disk emission;

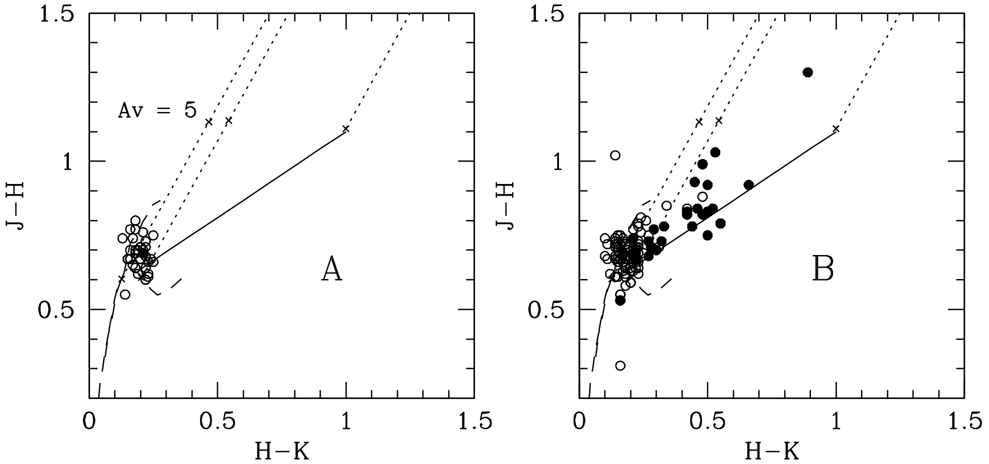

Figure 3. $J - K$ vs. $H - K$ diagram for bright stars in Ori 1a (A) and Ori 1b (B). JHK data from 2MASS. The dwarf and giant standard sequences are indicated (dashed lines), as well as the location of the accreting stars, the CTTS locus (solid lines). Reddening vectors are represented by the dotted lines, with crosses at $A_V = 5$. Reddening shifts are indicated for a K7 star, an M2 star (the approximate later type in out sample), and the red end of the locus. All stars in 1a are inside the reddening line corresponding to M2. In contrast, the CTTS locus is substantially populated in 1b. All but one (probably a binary) of the 1b stars on the locus are CTTS (solid circles), as determined by their W(Hα).

many lie near the locus of young stars with accretion disks (the Classical T Tauri stars - CTTS locus, Meyer et al. 1997). All but one of the stars with infrared excesses have the strong Hα emission associated with accretion. In Figure 4 it can be seen that essentially all the stars in Ori OB 1a are non-accreting weak-lined T Tauri stars (WTTS), while the accreting Classical T Tauri stars (CTTS) are found in 1b. The disappearance of Hα and near-infrared emission in Ori 1a stars indicates that protoplanetary disk accretion stops for almost all solar-type stars on a time scale of a few million years.

Our results have important implications for the star formation history of the region. The east-west boundaries of the low mass members of the association are remarkably well-defined and agree well with the spatial distribution of the higher mass stars (Figure 4). This cannot be a selection effect, because our scans extend well beyond the stellar distribution on either side with similar sensitivity. We find no evidence for a widely spread population of stars dispersed from the present-day molecular clouds in the region; instead, we see a well-defined older association, the fossil remnant of a no-longer existing molecular cloud complex. The absence of molecular gas in Ori 1a supports suggestions that large molecular cloud complexes can form stars and disperse quickly, in only a few Myr (Ballesteros et al. 1999).

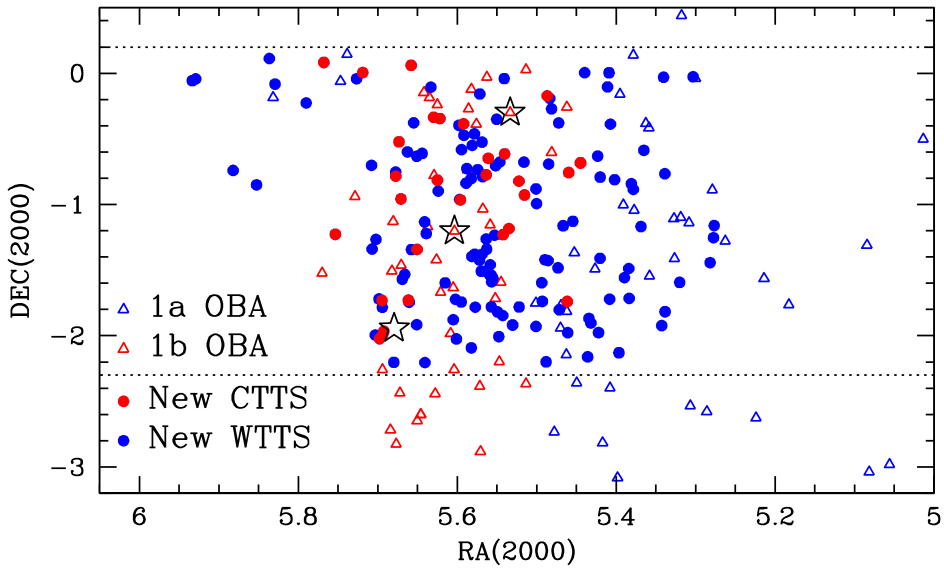

Figure 4. Spatial distribution of new TTS (solid symbols) compared to Hipparcos selected OBA stars in 1a (blue open triangles) and in 1b (red open triangles). The position of the belt stars (black stars) and the limits of the scan (dotted lines) are indicated as reference. Note the sharp cut-off in the low mass star distribution at low RA, consistent with the distribution of high mass stars. Note also the concentration of the new CTTS (solid red dots) towards 1b.

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