The Low-mass Populations in OB Associations

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Low-mass stars ($0.1 \lesssim \mathrm{M} \lesssim 1\ \mathrm{M}_{\odot}$) in OB associations are key to addressing some of the most fundamental problems in star formation. The low-mass stellar populations of OB associations provide a snapshot of the fossil star-formation record of giant molecular cloud complexes. Large scale surveys have identified hundreds of members of nearby OB associations, and revealed that low-mass stars exist wherever high-mass stars have recently formed. The spatial distribution of low-mass members of OB associations demonstrate the existence of significant substructure ("subgroups"). This "discretized" sequence of stellar groups is consistent with an origin in short-lived parent molecular clouds within a Giant Molecular Cloud Complex. The low-mass population in each subgroup within an OB association exhibits little evidence for significant age spreads on time scales of $\sim$ 10 Myr or greater, in agreement with a scenario of rapid star formation and cloud dissipation. The Initial Mass Function (IMF) of the stellar populations in OB associations in the mass range $0.1 \lesssim \mathrm{M} \lesssim 1\ \mathrm{M}_{\odot}$ is largely consistent with the field IMF, and most low-mass pre-main sequence stars in the solar vicinity are in OB associations. These findings agree with early suggestions that *the majority of stars in the Galaxy were born in OB associations*. The most recent work further suggests that a significant fraction of the stellar population may have their origin in the more spread out regions of OB associations, instead of all being born in dense clusters. Ground-based and space-based (Spitzer Space Telescope) infrared studies have provided robust evidence that primordial accretion disks around low-mass stars dissipate on timescales of a few Myr. However, on close inspection there appears to be great variance in the disk dissipation timescales for stars of a given mass in OB associations. While some stars appear to lack disks at $\sim$1 Myr, a few appear to retain accretion disks up to ages of $\sim$10-20 Myr.

1. INTRODUCTION

Most star formation in normal galaxies occurs in the cores of the largest dark clouds in spiral arms, known as Giant Molecular Clouds (GMCs). A GMC may give rise to one or more star complexes known as OB associations, first defined and recognized by *Ambartsumian* (1947) as young expanding stellar systems of blue luminous stars. These generally include groups of T Tauri stars or T associations (*Kholopov*, 1959; *Herbig*, 1962; *Strom et al.*, 1975) as well as clusters, some containing massive ($\mathrm{M} \gtrsim 10\ \mathrm{M}_{\odot}$) stars, but all teeming with solar-like and lower mass stars.

Though we now recognize OB associations as the prime sites for star formation in our Galaxy, much of our knowledge of star formation is based on studies of low-mass (M $\lesssim 1$ M$_\odot$) pre-main sequence (PMS) stars located in nearby T associations, like the $\sim 1-2$ Myr old Taurus, Lupus and Chamaeleon star forming regions. The view of star formation conveyed by these observations is probably biased to the particular physical conditions found in these young, quiescent regions. In contrast, the various OB associations in the solar vicinity are in a variety of evolutionary stages and environments, some containing very young objects (ages $\lesssim 1$ Myr) still embedded in their natal gas (e.g., Orion A and B clouds, Cep OB2), others in the process of dispersing their parent clouds, like λ Ori and Carina, while others harbor more evolved populations, several Myr old, which have long since dissipated their progenitor clouds (like Scorpius-Centaurus and Orion OB 1a). The low-mass populations in these differing regions are key to investigating fundamental issues in the formation and early evolution of stars and planetary systems:

1) *Slow vs. rapid protostellar cloud collapse and molecular cloud lifetimes.* In the old model of star formation (see *Shu et al.*, 1987) protostellar clouds contract slowly until ambipolar diffusion removes enough magnetic flux for dynamical (inside-out) collapse to set in. It was expected that the diffusion timescale of $\sim$ 10 Myr should produce a similar age spread in the resulting populations of stars, consistent with the $\lesssim$ 40 Myr early estimates of molecular cloud lifetimes (see discussion in *Elmegreen*, 1990). Such age spreads should be readily apparent in color-magnitude or H-R diagrams for masses $\lesssim 1$ M$_\odot$. However, the lack of even $\sim$ 10 Myr old, low-mass stars in and near molecular clouds challenged this paradigm, suggesting that star formation proceeds much more rapidly than previously thought, even over regions as large as 10 pc in size (*Ballesteros-Paredes et al.*, 1999), and therefore that cloud lifetimes over the same scales could be much shorter than 40 Myr (*Hartmann et al.*, 1991).

2) *The shape of the IMF.* Whether OB associations have low mass populations according to the field IMF, or if their IMF is truncated is still a debated issue. There have been many claims for IMF cutoffs in high mass star forming regions (see e.g., *Slawson and Landstreet*, 1992; *Leitherer*, 1998; *Smith et al.*, 2001; *Stolte et al.*, 2005). However, several well investigated massive star forming regions show *no* evidence for an IMF cutoff (see *Brandl et al.*, 1999 and *Brandner et al.*, 2001 for the cases of NGC 3603 and 30 Dor, respectively), and notorious difficulties in IMF determinations of distant regions may easily lead to wrong conclusions about IMF variations (e.g., *Zinnecker et al.*, 1993; *Selman and Melnick*, 2005). An empirical proof of a field-like IMF, rather than a truncated IMF, has important consequences not only for star formation models but also for scenarios of distant starburst regions; e.g., since most of the stellar mass is then in low-mass stars, this limits the amount of material which is enriched in metals via nucleosynthesis in massive stars and which is then injected back into the interstellar medium by the winds and supernovae of the massive stars.

3) *Bound vs. unbound clusters.* While many young stars are born in groups and clusters, most disperse rapidly; few clusters remain bound over timescales > 10 Myr. The conditions under which bound clusters are produced are not clear. Studies of older, widely-spread low-mass stars around young clusters might show a time sequence of cluster formation, and observations of older, spreading groups would yield insight into how and why clusters disperse.

4) *Slow vs. rapid disk evolution.* Early studies of near-infrared dust emission from low-mass young stars suggested that most stars lose their optically thick disks over periods of ~ 10 Myr, (e.g., *Strom et al.*, 1993), similar to the timescale suggested for planet formation (*Podosek and Cassen*, 1994). However, there is also evidence for faster evolution in some cases; for example, half of all ~ 1 Myr-old stars in Taurus have strongly reduced or absent disk emission (*Beckwith et al.*, 1990). The most recent observations of IR emission from low-mass PMS stars in nearby OB associations like Orion, suggest that the timescales for the dissipation of the inner disks can vary even in coeval populations at young ages (*Muzerolle et al.*, 2005).

5) *Triggered vs. independent star formation.* Although it is likely that star formation in one region can “trigger” more star formation later in neighboring areas, and there is evidence for this from studies of the massive stars in OB populations (e.g., *Brown*, 1996), proof of causality and precise time sequences are difficult to obtain without studying the associated lower mass populations. In the past, studies of the massive O and B stars have been used to investigate sequential star formation and triggering on large scales (e.g., *Blaauw*, 1964, 1991 and references therein). However, OB stars are formed essentially on the main sequence (e.g., *Palla and Stahler* 1992, 1993) and evolve off the main sequence on a timescale of order 10 Myr (depending upon mass and amount of convective overshoot), thus they are not useful tracers of star-forming histories on timescales of several Myr, while young low-mass stars are. Moreover, we cannot investigate cluster structure and dispersal or disk evolution without studying low-mass stars. Many young individual clusters have been studied at both optical and infrared wavelengths (c.f. *Lada and Lada* 2003), but these only represent the highest-density regions, and do not address older and/or more widely dispersed populations. In contrast to their high mass counterparts, low-mass stars offer distinct advantages to address the aforementioned issues. They are simply vastly more numerous than O, B, and A stars, allowing statistical studies not possible with the few massive stars in each region. Their spatial distribution is a fossil imprint of recently completed star formation, providing much needed constraints for models of molecular cloud and cluster formation and dissipation; with velocity dispersions of $\sim$1 km s^{-1} (e.g. *de Bruijne*, 1999) the stars simply have not traveled far from their birth sites (~ 10 pc in 10 Myr). Low-mass stars also provide better kinematics, because it is easier to obtain accurate radial velocities from the many metallic lines in G, K and M type stars than it is from O and B type stars.

2. SEARCHES FOR LOW-MASS PMS STARS IN OB ASSOCIATIONS

Except for the youngest, mostly embedded populations in the molecular clouds, or dense, optically visible clusters like the Orion Nebula Cluster (ONC), most of the low-mass stellar population in nearby OB associations is widely spread over tens or even hundreds of square degrees on the sky. Moreover, it is likely that after ~ 4 Myr the stars are no longer associated with their parent molecular clouds, making it difficult to sort them out from the field population. Therefore, a particular combination of various instruments and techniques is required to reliably single out the low-mass PMS stars. The main strategies that have been used to identify these populations are objective prism surveys, X-ray emission, proper motions and, more recently, variability surveys.

2.1 Objective Prism Surveys

The TTS originally were identified as stars of late spectral types (G-M), with strong emission lines (especially Hα) and erratic light variations, spatially associated with regions of dark nebulosity (*Joy*, 1945). Stars resembling the original variables first identified as TTS are currently called ”strong emission” or Classical TTS (CTTS). Subsequent spectroscopic studies of the Ca II H and K lines and the first X-ray observations with the *Einstein* X-ray observatory (*Feigelson and De Campli*, 1981; *Walter and Kuhi*, 1981) revealed surprisingly strong X-ray activity in TTS, exceeding the solar levels by several orders of magnitude, and also revealed a population of X-ray strong objects lacking the optical signposts of CTTS, like strong Hα emission. These stars, initially called ”naked-T Tauri stars” (*Walter and Myers*, 1986), are now widely known as ”weak-line” TTS after *Herbig and Bell* (1988). The CTTS/WTTS dividing line was set at W(Hα) $= 10$Å. In general, the excess Hα emission in WTTS seems to originate in enhanced solar-type magnetic activity (*Walter et al.*, 1988), while the extreme levels observed in CTTS can be explained by a combination of enhanced chromospheric activity and emission coming from accretion shocks in which material from a circumstellar disk is funneled along magnetic field lines onto the stellar photosphere (Section 5). Recently, *White and Basri* (2003) revisited the WTTS/CTTS classification and suggested a modified criterion that takes into account the contrast effect in Hα emission as a function of spectral type in stars cooler than late K.

The strong Hα emission characteristic of low-mass young stars, and in particular of CTTS, encouraged early large scale searches using photographic plates and objective prisms on wide field instruments like Schmidt telescopes (e.g., *Sanduleak*, 1971, in Orion). These very low resolution spectroscopic surveys (typical dispersions of ~ 500Å/mm to ~ 1700 Å/mm at Hα; c.f. *Wilking et al.*, 1987; *Briceño et al.*, 1993) provided large area coverage, allowed estimates of spectral types and a qualitative assessment of the strength of prominent emission lines, like the hydrogen Balmer lines or the Ca II H & K lines. *Liu et al.* (1981) explored a 5×5 deg region in Per OB2 and detected 25 candidate TTS. *Ogura* (1984) used the 1m Kiso Schmidt to find 135 Hα emitting stars in Mon OB1. *Wilking et al.* (1987) detected 86 emission line objects over 40 square degrees in the ρ Ophiuchi complex. *Mikami and Ogura* (2001) searched an area of 36 square degrees in Cep OB3 and identified 68 new emission line sources. In the Orion OB1 association, the most systematic search was that done with the 1m Kiso Schmidt (e.g., *Wiramihardja et al.*, 1989, 1993), covering roughly 150 square degrees and detecting ~ 1200 emission line stars, many of which were argued to be likely TTS. *Weaver and Babcock* (2004) recently identified 63 Hα emitting objects in a deep objective prism survey of the σ Orionis region.

The main limitation of this technique is the strong bias towards Hα-strong PMS stars; few WTTS can be detected at the resolution of objective prisms (c.f. *Briceño et al.*, 1999). *Briceño et al.* (2001) find that only 38% of the 151 Kiso Hα sources falling within their ~ 34 square degree survey area in the Orion OB 1a and 1b sub-associations are located above the ZAMS in color-magnitude diagrams, and argue that the Kiso survey is strongly contaminated by foreground main sequence stars (largely dMe stars). The spatial distribution of the Kiso sources has been useful to outline the youngest regions in Orion, where the highest concentrations of CTTS are located (*Gómez and Lada*, 1998), but these samples can be dominated by field stars in regions far from the molecular clouds, in which the CTTS/WTTS fraction is small. Therefore, as with other survey techniques, objective prism studies require follow up spectroscopy to confirm membership.

2.2 X-ray surveys

Young stars in all evolutionary stages, from class I protostars to ZAMS stars, show strong X-ray activity (for recent reviews on the X-ray properties of YSOs see *Feigelson and Montmerle*, 1999 and *Favata and Micela*, 2003). After the initial Einstein studies, the ROSAT and ASCA X-ray observatories increased considerably the number of observed star forming regions, and thereby the number of known X-ray emitting TTS. Today, XMM-Newton and $Chandra$ allow X-ray studies of star forming regions at unprecedented sensitivity and spatial resolution.

X-ray observations are a well established tool to find young stars. For nearby OB associations, which typically cover areas in the sky much larger than the field-of-view of X-ray observatories, deep and spatially complete observations are usually not feasible. However, large scale shallow surveys have been conducted with great success. The ROSAT All Sky Survey (RASS) provided coverage of the whole sky in the $0.1 - 2.4$ keV soft X-ray band. With a mean limiting flux of about $2 \times 10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{2}}$ this survey provided a spatially complete, flux-limited sample of X-ray sources that led to the detection of hundreds of candidate PMS stars in star forming regions all over the sky (see *Neuhäuser*, 1997).

The X-ray luminosities of young stars for a given age, mass, and bolometric luminosity can differ by several orders of magnitude. Until recently it was not even clear whether all young stars are highly X-ray active, or whether an "X-ray quiet" population of stars with suppressed magnetic activity may exist, which would have introduced a serious bias in any X-ray selected sample. The $Chandra$ Orion Ultradeep Project (*Getman et al.*, 2005), a 10 day long observation of the Orion Nebular Cluster, has provided the most comprehensive dataset ever acquired on the X-ray emission of PMS, and solved this question by providing definitive information on the distribution of X-ray luminosities in young stars. It found no indications for "X-ray quiet" TTS, and established that 50% of the TTS have $\log{(L_{\rm X}/L_{\rm bol})} \geq -3.5$, while 90% have $\log{(L_{\rm X}/L_{\rm bol})} \geq -4.5$ (*Preibisch et al.*, 2005; also see chapter by *Feigelson et al.*). Since the RASS flux limit corresponds to X-ray luminosities of about 5×10^{29} erg s^{-1} at the distance of the nearest OB associations ($\sim$ 140 pc), this implies that the RASS data are essentially complete only for $M \geq 1$ M$_\odot$ PMS stars in those regions, while only a fraction of the X-ray brightest sub-solar mass PMS stars are detected. A caveat of the RASS surveys for PMS stars is that these samples can be significantly contaminated by foreground, X-ray active zero age main sequence stars (*Briceño et al.*, 1997). These limitations have to be kept in mind when working whith X-ray selected samples; at any rate, follow-up observations are necessary to determine the nature of the objects.

2.3 Proper Motion surveys.

The recent availability of ever-deeper, all-sky catalogs of proper motions (like *Hipparcos* and the Tycho family of catalogs) has aided the effort in identifying the low-mass members of the nearest OB associations. The proper motions of members of a few of the nearest OB associations are of the order of tens of mas yr^{-1} (*de Zeeuw et al.*, 1999). With proper motions whose errors are less than a few mas yr^{-1}, one can attempt to kinematically select low-mass members of nearby associations. The nearest OB association, Sco-Cen, has been the most fruitful hunting ground for identifying low-mass members by virtue of their proper motions. Current proper motion catalogs (e.g., Tycho-2, UCAC) are probably adequate to consider kinematic selection of low-mass stars in at least a few other nearby groups (e.g., Vel OB2, Tr 10, α Per, Cas-Tau, Cep OB6). The very small ($<$10 mas yr^{-1}) proper motions for some of the other nearby OB associations (e.g., Ori OB1, Lac OB1, Col 121) will preclude any attempts at efficient selection of low-mass members via proper motions, at least with contemporary astrometric catalogs.

The *Hipparcos* survey of the nearest OB associations by *de Zeeuw et al.* (1999) was able to identify dozens of FGK-type stars as candidate members. *De Zeeuw et al.* (1999) predicted that $\sim$37/52 (71%) of their GK-type *Hipparcos* candidates would be bona fide association members, and indeed *Mamajek et al.* (2002) found that 22/30 (73%) of a subsample of candidates, located in Sco-Cen, could be spectroscopically confirmed as PMS stars. *Hoogerwerf* (2000) used the ACT and TRC proper motion catalogs (p.m. errors $\simeq$ 3 mas yr^{-1}) to identify thousands of candidate Sco-Cen members down to V ~ 12. Unfortunately, the vast majority of stars in the ACT and TRC catalogs, and their descendant (Tycho-2), do not have known spectral types or parallaxes (in contrast to the *Hipparcos* catalog), and hence the contamination level is large. *Mamajek et al.* (2002) conducted a spectroscopic survey of an X-ray and color-magnitude-selected subsample of the Hoogerwerf proper motion-selected sample and found that 93% of the candidates were bona fide PMS association members. The high quality proper motions also enabled the estimate of individual parallaxes to the Upper Centaurus Lupus (UCL) and Lower Centarus Crux (LCC) members, reducing the scatter in the HR diagram (*Mamajek et al.*, 2002). In a survey of 115 candidate Upper Sco members selected solely via STARNET proper motions (p.m. errors of $\sim$5 mas yr^{-1}), *Preibisch et al.* (1998) found that *none* were PMS stars. The lesson learned appears to be that proper motions *alone* are insufficient for efficiently identifying low-mass members of nearby OB associations. However, when proper motions are used in conjunction with color-magnitude, X-ray, spectral type, or parallax data (or some combination thereof), finding low-mass associations can be a very efficient task.

2.4 Photometric surveys: Single-epoch observations

Single epoch photometric surveys are frequently used to select candidate low-mass members of young clusters or associations. Most studies use broadband, optical filters that are sensitive to the temperatures of G, K and M-type stars. Near-IR color-magnitude diagrams (CMDs) are not as useful for selecting low-mass PMS stars because NIR colors are similar for all late type stars.

Candidate low-mass association members are usually selected by their location in the CMD above the zero-age main sequence (ZAMS). This locus is usually defined by either a known (spectroscopically confirmed) population of PMS stars or because the PMS population of the association is clearly visible as a concentration on the CMD (e.g., Fig. 1). Single epoch photometry is most effective in regions such as σ Ori or the ONC where the proximity and youth of the cluster make the low-mass PMS members brighter than the bulk of the field stars at the colors of K and M-type stars.

The main advantage of photometric selection is that for a specified amount of time on any given telescope a region of the sky can be surveyed to a fainter limit than can be done by a variability survey or a spectroscopic survey. Also, photometric selection can identify low-mass association members with very low amplitude variability. The disadvantage of single epoch photometric selection is that

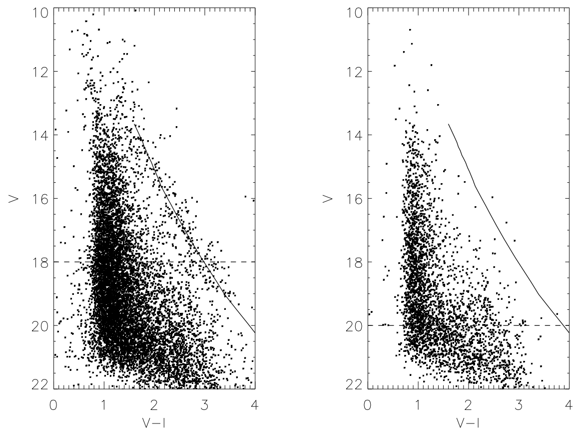

Fig. 1.— The left panel shows the V vs. V$-$I$_C$ color-magnitude diagram of 9556 stars in 0.89 deg^2 around σ Ori (from *Sherry et al.*, 2004). The solid line is a 2.5 Myr isochrone (*Baraffe et al.*, 1998; *Baraffe et al.*, 2001) at a distance of 440 pc (*de Zeeuw et al.*, 1999), extending from $1.2\ \mathrm{M}_\odot$ at V~ 13.5 down to $\sim 0.2\ \mathrm{M}_\odot$ at V~ 18 (the completeness limit, indicated by the dashed line). This isochrone marks the expected position of the PMS locus for Orion OB1b. There is a clear increase in the density of stars around the expected position of the PMS locus. The right panel shows the same color-magnitude diagram (CMD) for the 0.27 deg^2 control fields from *Sherry et al.* (2004). The isochrone (solid line) is the same as in the left panel. The dashed line marks the fainter completeness limit of the control fields.

there is inevitably some contamination by foreground field stars and background giants. As with the other techniques, it is impossible to securely identify any individual star as a low-mass member of the association without spectroscopic follow-up. In small areas with a high density of low-mass association members such as the σ Ori cluster or the ONC, single epoch photometry can effectively select the low-mass population because field star contamination is fairly small (*Sherry et al.*, 2004; *Kenyon et al.*, 2005). But in large areas with a lower density of low-mass association members, such as Orion OB1b (Orion's belt) or Orion OB1a (NW of the belt) the field star contamination can be large enough to make it difficult to even see the PMS locus.

2.5 Photometric surveys: Variability

Variability in T Tauri stars has been intensively studied over the years (e.g., *Herbst et al.*, 1994), but mostly as follow up observations of individual young stars that had been identified by some other means. Building on the availability of large format CCD cameras installed on wide-field telescopes it has now become feasible to conduct multi-epoch, photometric surveys that use variability to pick out candidate TTS over the extended areas spanned by nearby OB associations. In Orion, two major studies have been conducted over the past few years. *Briceño et al.* (2001, 2005a) have done a VRI variability survey using the Quest I CCD Mosaic Camera installed on the Venezuela 1m Schmidt, over an area of $\gtrsim 150$ square degrees in the Orion OB1 association. In their first release, based on some 25 epochs and spanning an area of 34 square degrees, they identified ~ 200 new, spectroscopically confirmed, low-mass members, and a new 10 Myr old clustering of stars around the star 25 Ori (*Briceño et al.*, 2006). *McGehee et al.* (2005) analysed 9 repeated observations over 25 square degrees in Orion, obtained with the Sloan Digital Sky Survey (SDSS). They selected 507 stars that met their variability criterion in the SDSS g-band. They did not obtain follow up spectra of their candidates, rather, they apply their observations in a statistical sense to search for photometric accretion-related signatures in their lower mass candidate members. *Slesnick et al.* (2005) are using the QUEST II CCD Mosaic Camera on the Palomar Schmidt to conduct a BRI, multi-epoch survey of ~ 200 square degrees in Upper Sco, and *Carpenter et al.* (2001) has used repeated observations made with 2MASS in a 0.86×6 degree strip centered on the ONC to study the near-IR variability of a large sample of young, low-mass stars.

With more wide angle detectors on small and medium sized telescopes, and projects like LSST coming on line within less than a decade, variability promises to grow as an efficient means of selecting large samples of candidate low-mass PMS stars down to much lower masses than available to all-sky X-ray surveys like ROSAT, and without the bias towards CTTS of objective prism studies. However, as with every technique there are limitations involved, e.g., temporal sampling and a bias toward variables with larger amplitudes, especially at the faint end, are issues that need to be explored.

2.6 Spectroscopy.

As already emphasized in the previous paragraphs, low to moderate resolution follow-up spectroscopy is essential to confirm membership of PMS stars. However, the observational effort to identify the widespread population of PMS stars among the many thousands of field stars in the large areas spanned by nearby OB associations is huge, and up to recently has largely precluded further investigations. With the advent of extremely powerful multiple-object spectrographs, such as 2dF at the Anglo-Australian Telescope, Hydra on the WIYN 3.5 m and the CTIO 4 m telescopes, and now Hectospec on the 6.5 m MMT, large scale spectroscopic surveys have now become feasible.

One of the most powerful approaches to unbiased surveys of young low-mass stars is to use the presence of strong 6708 Å Li I absorption lines as a diagnostic of the PMS nature of a candidate object (e.g., *Dolan and Mathieu*, 1999, 2001). Because Li I is strongly diminished in very early phases of stellar evolution, a high Li content is a reliable indication for the youth of a star (e.g., *Herbig*, 1962; *D'Antona and Mazzitelli*, 1994). However, Li depletion is not only a function of stellar age, but also of stellar mass and presumably even depends on additional factors like stellar rotation (cf. *Soderblom*, 1996). Not only PMS stars, but also somewhat older, though still relatively young zero-age main sequence stars, e.g. the G and K type stars in the $\sim 10^8$ years old Pleiades (c.f. *Soderblom et al.* 1993), can display Li absorption lines. In order to classify stars as PMS, one thus has to consider a spectral type dependent threshold for the Li line width. Such a threshold can be defined by the upper envelope of Li measurements in young clusters of main-sequence stars with ages between ~ 30 Myr and a few 100 Myrs such as IC 2602, IC 4665, IC 2391, α Per, and the Pleiades. Any star with a Li line width considerably above this threshold should be younger than ~ 30 Myrs and can therefore be classified as a PMS object.

In addition to Li, other spectroscopic signatures can be used as youth indicators, such as the K I and Na I absorption lines that are typically weaker in low-mass PMS objects compared to field M-type dwarfs (*Martín et al.*, 1996; *Luhman*, 1999), and radial velocities (if high resolution spectra are available).

3. AGES AND AGE SPREADS OF LOW-MASS STARS

Stellar ages are usually inferred from the positions of the stars in the HR-diagram by comparison with theoretical PMS evolutionary models. Photometry of young clusters and associations has shown that low-mass members occupy a wide swath on the CMD or the H-R diagram (NGC 2264; ONC; σ Ori). A common interpretation has been that this spread is evidence of an age spread among cluster members (e.g., *Palla and Stahler*, 2000). This interpretation assumes that the single epoch observed colors and magnitudes of low-mass PMS stars accurately correspond to the temperatures and luminosities of each star. However, it has to be strongly emphasized that the masses and especially the ages of the individual stars read off from their position in these diagrams are generally *not* identical to their true masses and ages. Several factors can cause considerable deviations of an individual star's position in the HR-diagram from the locations predicted by theoretical models for a given age and mass. Low-mass PMS stars exhibit variability ranging from a few tenths in the WTTS up to several magnitudes in the CTTS (*Herbst et al.*, 1994). Furthermore, binarity can add a factor of 2 (~ 0.75 mag) spread to the CMD. For regions spanning large areas on the sky there will be an additional spread caused by the distribution of distances along the line of sight among individual stars. Another source of uncertainty are the calibrations used to derive bolometric luminosities and effective temperatures, and finally, the choice of evolutionary tracks used, that in some cases yield different ages for intermediate ($\sim 2-5$ $\mathrm{M}_\odot$) and low-mass stars located in the same region (e.g., the ONC; *Hillenbrand*, 1997; see also *Hartmann*, 2001). Therefore, any age estimates in young star forming regions must account for the significant spread that a coeval population will necessarily have on the CMD, which translates into a spread on the H-R diagram.

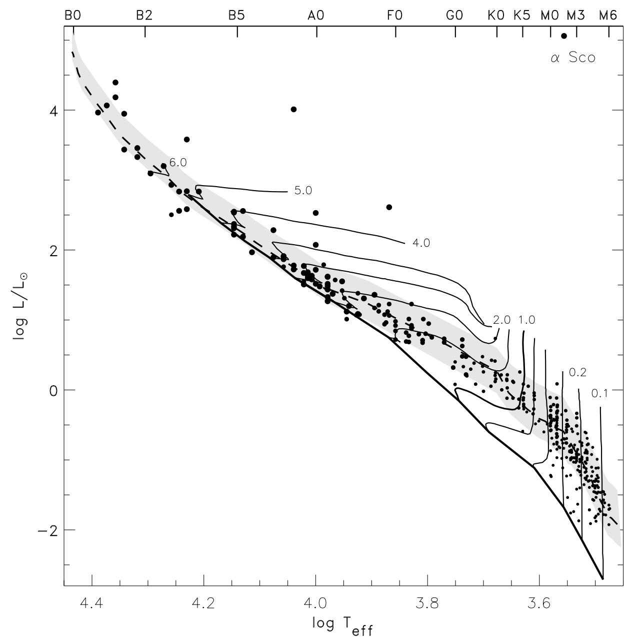

Fig. 2.— HR diagram for the Upper Sco association members from the study of *Preibisch et al.* (2002). The lines show the evolutionary tracks from the *Palla and Stahler* (1999) PMS models, some labeled by their masses in solar units. The thick solid line shows the main sequence. The 5 Myr isochrone is shown as the dashed line; it was composed from the high-mass isochrone from *Bertelli et al.* (1994) for masses $6-30\,M_\odot$, the *Palla and Stahler* (1999) PMS models for masses $1-6\,M_\odot$, and the *Baraffe et al.* (1998) PMS models for masses $0.02-1\,M_\odot$. The grey shaded band shows the region in which one expects 90% of the member stars to lie, based on the assumption of a common age of 5 Myr for all stars and taking proper account of the uncertainties and the effects of unresolved binaries (for details see text).

As an example, Fig. 2 shows the HR diagram containing all Upper Sco association members from *Preibisch et al.* (2002); the diagram also shows the main sequence and a 5 Myr isochrone. Not only the majority of the low-mass stars, but also most of the intermediate- and high-mass stars lie close to or on the 5 Myr isochrone. There clearly is a considerable scatter that may seem to suggest a spread in stellar ages. In the particular case of Upper Sco shown here, in addition to the other effects mentioned above, the most important factor for the apparent scatter is the relatively large spread of individual stellar distances ($\sim \pm 20$ pc around the mean value of 145 pc; *de Bruijne*, 1999 and priv. comm.) in this very nearby and extended region, which causes the luminosities to be either over or under estimated when a single distance is adopted for all sources. A detailed discussion and statistical modeling of these effects is given in *Preibisch and Zinnecker* (1999) and *Preibisch et al.* (2002). In the later work these authors showed that the observed HR diagram for the low-mass stars in Upper Sco is consistent with the assumption of a *common stellar age of about 5 Myr; there is no evidence for an age dispersion, although small ages spreads of* $\sim 1-2$ *Myr cannot be ex-*

cluded by the data. *Preibisch et al.* (2002) showed that the derived age is also robust when taking into account the uncertainties of the theoretical PMS models. It is remarkable that the isochronal age derived for the low-mass stars is consistent with previous and independent age determinations based on the nuclear and kinematic ages of the massive stars (*de Zeeuw and Brand*, 1985; *de Geus et al.*, 1989), which also yielded 5 Myr. This very good agreement of the *independent* age determinations for the high-mass and the low-mass stellar population shows that *low- and high-mass stars are coeval* and thus have formed together. Furthermore, the absence of a significant age dispersion implies that all stars in the association have formed more or less simultaneously. Therefore, the star-formation process must have started rather suddenly and everywhere at the same time in the association, and also must have ended after at most a few Myr. The star formation process in Upper Sco can thus be considered as a *burst of star formation*.

Sherry (2003) compared the observed spread across the V vs. V$-$I$_C$ CMD of low-mass members of the σ Ori cluster to the spread that would be expected based upon the known variability of WTTS, the field binary fraction, the photometric errors of his survey, and a range of simple star formation histories. The observed spread was consistent with the predicted spread of an isochronal population. Sherry concluded that the bulk of the low-mass stars must have formed over a period of less than ~ 1 Myr. A population with a larger age spread would have been distributed over a larger region of the CMD than was observed.

Burningham et al. (2005) also examined the possibility of an age spread among members of the σ Ori cluster. They used two epoch R and i' observations of cluster members taken in 1999 and 2003 to estimate the variability of each cluster member. They then constructed a series of simple models with a varying fraction of equal mass binaries. They found that the observed spread on the CMD was too large to be fully accounted for by the combined effects of observational errors, variability (over 1-4 years), and binaries. They conclude that the larger spread on the CMD could be accounted for by either a longer period of accretion driven variability, an age spread of $\lesssim 2$ Myrs (using a distance of 440 pc or 4 Myrs using a distance of 350 pc), or a combination of long term variability and a smaller age spread. However, their result is not necessarily in contradiction with the findings of *Sherry* (2003), especially if the actual variability is larger than they estimate based on their two epoch observations.

In the Orion OB1 association, the V and I$_C$-band CMDs for spectroscopically confirmed TTS (*Briceño et al.*, 2005a, 2006), which mitigate the spread caused by the variability of individual sources by plotting their mean magnitudes and colors, provide evidence that the Ori OB 1b sub-association is older (~ 4 Myr) than the often quoted age of about 1.7 Myr (*Brown et al.*, 1994), with a rather narrow age distribution regardless of the tracks used (Fig. 3). The same dataset for the older OB 1a sub-association also shows a narrow range of ages, with a mean value of ~ 8 Myr.

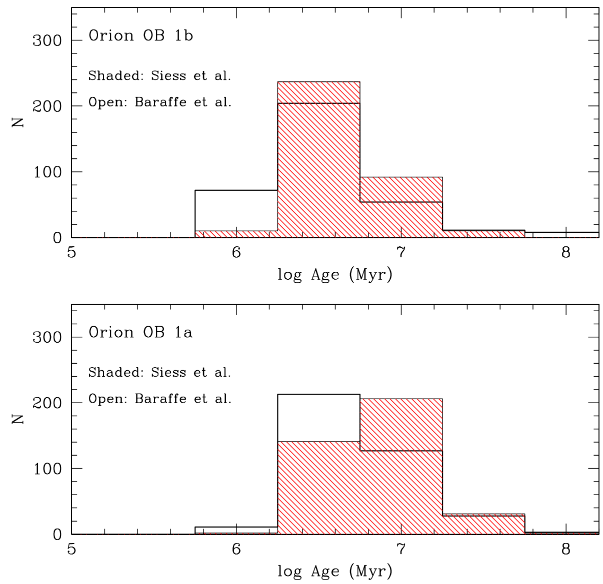

Fig. 3.— Distribution of ages of ~ 1000 newly identified TTS in a ~ 60 square degree area spanning the the Orion OB 1a and 1b sub-associations (*Briceño et al.*, in preparation). Ages were derived using the *Baraffe et al.* (1998) and *Siess et al.* (2000) evolutionary tracks and isochrones. The mean ages are ~ 4 Myr for Ori OB 1b and ~ 8 Myr for Ori OB 1a.

The λ Ori region also shows that the age distribution and star formation history is spatially dependent. *Dolan and Mathieu* (2001; see also *Lee et al.*, 2005) found that age distributions of high-mass and solar-type stars in the region show several critical features:

a) Both high- and low-mass star formation began concurrently in the center of the SFR roughly 6-8 Myr ago;

b) Low-mass star formation ended in the vicinity of λ Ori roughly 1 Myr ago;

c) Low-mass star formation rates near the B30 and B35 clouds reached their maxima later than did low-mass star formation in the vicinity of λ Ori;

d) Low-mass star formation continues today near the B30 and B35 clouds.

As with the Ori OB1 associations, this varied star-formation history reflects the rich interplay of the massive stars and the gas.

The accumulated evidence for little, if any, age spreads in various star forming regions provides a natural explanation for the "post-T Tauri problem" (the absence of "older" TTS in star forming regions like Taurus, assumed to have been forming stars for up to tens of Myrs, *Herbig*, [1978]), and at the same time implies relatively short lifetimes for molecular clouds. These observational arguments support the evolving picture of star formation as a fast and remarkably synchronized process in molecular clouds (Section 6).

4. THE IMF IN OB ASSOCIATIONS

The IMF is the utmost challenge for any theory of star formation. Some theories suggest that the IMF should vary systematically with the star formation environment (*Larson*, 1985), and for many years star formation was supposed to be a bimodal process (e.g., *Shu and Lizano*, 1988) according to which high- and low-mass stars should form in totally different sites. For example, is was suggested that increased heating due to the strong radiation from massive stars raises the Jeans mass, so that the bottom of the IMF would be truncated in regions of high-mass star formation. In contrast to the rather quiescent environment in small low-mass clusters and T associations (like the Taurus molecular clouds), forming stars in OB association are exposed to the strong winds and intense UV radiation of the massive stars, and, after a few Myr, also affected by supernova explosions. In such an environment, it may be harder to form low-mass stars, because, e.g., the lower-mass cloud cores may be completely dispersed before protostars can even begin to form.

Although it has been long established that low-mass stars can form alongside their high-mass siblings (e.g., *Herbig*, 1962) in nearby OB associations, until recently it was not well known what quantities of low-mass stars are produced in OB environments. If the IMF in OB associations is not truncated and similar to the field IMF, it would follow that most of their total stellar mass ($\gtrsim 60\%$) is found in low-mass ($< 2\,M_\odot$) stars. This would then imply that most of the current galactic star formation is taking place in OB associations. Therefore, the typical environment for forming stars (and planets) would be close to massive stars and not in isolated regions like Taurus.

In Fig. 4 we show the empirical mass function for Upper Sco as derived in *Preibisch et al.* (2002), for a total sample of 364 stars covering the mass range from $0.1\,M_\odot$ up to $20\,M_\odot$. The best-fit multi-part power law function for the probability density distribution is given by

$$\frac{\mathrm{d}N}{\mathrm{d}M} \propto \left\{ \begin{array}{llrl} M^{-0.9\pm0.2} & \text{for} & 0.1 & \leq M/M_\odot < \;\; 0.6 \\ M^{-2.8\pm0.5} & \text{for} & 0.6 & \leq M/M_\odot < \;\; 2 \\ M^{-2.6\pm0.5} & \text{for} & 2 & \leq M/M_\odot < \;\; 20 \end{array} \right. \tag{1}$$

or, in shorter notation, $\alpha[0.1-0.6] = -0.9 \pm 0.2$, $\alpha[0.6-2.0] = -2.8 \pm 0.5$, $\alpha[2.0-20] = -2.6 \pm 0.3$. For comparison, the plot also shows two different field IMF models, the *Scalo* (1998) model, which is given by $\alpha[0.1-1] = -1.2 \pm 0.3$, $\alpha[1-10] = -2.7 \pm 0.5$, $\alpha[10-100] = -2.3 \pm 0.5$, and the *Kroupa* (2002) model with $\alpha[0.02–0.08] = -0.3 \pm 0.7$, $\alpha[0.08-0.5] = -1.3 \pm 0.5$, $\alpha[0.5-100] = -2.3 \pm 0.3$.

While the slopes of the fit to the empirical mass function of Upper Sco are not identical to those of these models, they are well within the ranges of slopes derived for similar mass ranges in other young clusters or associations, as compiled in *Kroupa* (2002). Therefore, it can be concluded that, within the uncertainties, the general shape of the Upper Sco mass function is consistent with recent field star and cluster IMF determinations.

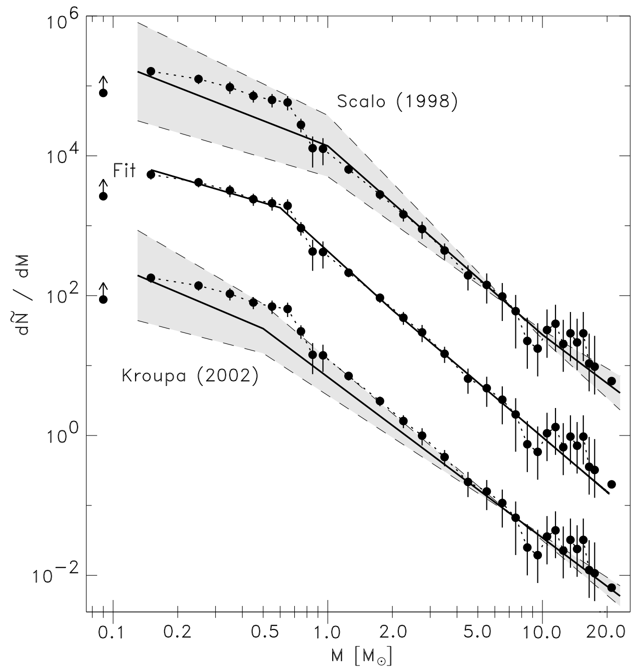

Fig. 4.— Comparison of the mass function derived for the Upper Sco association with different mass function measurements for the field (from *Preibisch et al.*, 2002). The Upper Sco mass function is shown three times by the solid dots connected with the dotted lines, multiplied by arbitrary factors. The middle curve shows the original mass function, the solid line is our multi-part power-law fit. The upper curve shows our mass function multiplied by a factor of 30 and compared to the *Scalo (1998)* IMF (solid line); the grey shaded area delimited by the dashed lines represents the range allowed by the errors of the model. The lower curve shows our mass function multiplied by a factor of 1/30 and compared to the *Kroupa* (2002) IMF (solid line).

In the Orion OB1 association *Sherry et al.* (2004) find that the mass function for the σ Ori cluster is consistent with the *Kroupa* (2002) IMF. In the immediate vicinity of λ Ori, *Barrado y Navascues et al.* (2004) combined their deep imaging data with the surveys of *Dolan and Mathieu* (1999, 2001; limited to the same area) to obtain an initial mass function from $0.02 - 1.2$ M$_\odot$. They find that the data indicate a power law index of $\alpha = -0.60 \pm 0.06$ across the stellar-substellar limit and a slightly steeper index of $\alpha = -0.86 \pm 0.05$ over the larger mass range of 0.024 M$_\odot$ to 0.86 M$_\odot$, much as is found in other young regions.

Over the entire λ Ori star-forming region, *Dolan and Mathieu* (2001) were able to clearly show that the IMF has a spatial dependence. *Dolan and Mathieu* (1999) had found that within the central ~ 3.5 pc around λ Ori the low-mass stars were deficient by a factor of 2 compared to the field IMF. Outside this central field, *Dolan and Mathieu* (2001) showed the low-mass stars to be overrepresented compared to the *Miller and Scalo* (1978) IMF by a factor of 3. A similar over-representation of low-mass stars is also found at significant confidence levels when considering only stars associated with B30 and B35.

Thus the global IMF of the λ Ori SFR resembles the field, while the local IMF appears to vary substantially across the region. No one place in the λ Ori SFR creates the field IMF by itself. Only the integration of the star-formation process over the entire region produces the field IMF.

5. DISK EVOLUTION

The presence of circumstellar disks around low-mass pre-main sequence stars appears to be a natural consequence of the star formation process; these disks play an important role both in determining the final mass of the star and as the potential sites for planet formation. Though we have a good general understanding of the overall processes involved, many important gaps still remain. For instance, the times scales for mass accretion and disk dissipation are still matters of debate. An example is the discovery of a seemingly long lived accreting disk around the ~ 25 Myr old, late type (M3) star *St 34* located in the general area of the Taurus dark clouds (*Hartmann et al.*, 2005a; *White and Hillenbrand*, 2005).

How circumstellar disks evolve and whether their evolution is affected by environmental conditions are questions that at present can only be investigated by looking to low-mass PMS stars, and in particular the best samples can now be drawn from the various nearby OB associations. First, low-mass young stars like T Tauri stars, in particular those with masses $\sim 1\,\mathrm{M}_\odot$ constitute good analogues of what the conditions may have been in the early Solar System. Second, as we have discussed in Section 3, OB associations can harbor many stellar aggregates, with distinct ages, such as in Orion OB1, possibly the result of of star-forming events (triggered or not) occurring at various times throughout the original GMC. Some events will have produced dense clusters while others are responsible for the more spread out population. The most recent events are easily recognizable by the very young ($\lesssim 1$ Myr) stars still embedded in their natal gas, while older ones may be traced by the ~ 10 Myr stars which have long dissipated their parent clouds. This is why these regions provide large numbers of PMS stars in different environments, but presumably sharing the same ”genetic pool”, that can allow us to build a *differential picture* of how disks evolve from one stage to the next.

Disks are related to many of the photometric and spectroscopic features observed in T Tauri stars. The IR emission originates by the contribution from warm dust in the disk, heated at a range of temperatures by irradiation from the star and viscous dissipation (e.g., *Meyer et al.*, 1997). The UV excesses, excess continuum emission (veiling), irregular photometric variability, broadened spectral line profiles (particularly in the hydrogen lines and others like Ca II), are explained as different manifestations of gas accretion from a circumstellar disk. In the standard magnetospheric model (*Königl*, 1991), the accretion disk is truncated at a few stellar radii by the magnetic field of the star, the disk material falls onto the photosphere along magnetic field lines at supersonic velocities, creating an accretion shock which is thought to be largely responsible for the excess UV and continuum emission (*Calvet and Gullbring*, 1998). The infalling material also produces the observed broadened and P Cygni profiles observed in hydrogen lines (*Muzerolle et al.*, 1998a,b, 2001). Disk accretion rates for most CTTS are of the order of $10^{-8}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ at ages of a 1-2 Myr (e.g., *Gullbring et al.*, 1998; *Hartmann*, 1998; *Johns-Krull and Valenti*, 2001).

Comparative studies of near-IR emission and accretion-related indicators (Hα and Ca II emission, UV excess emission) at ages $\sim 1-10$ Myr offer insight into how the innermost part of the disk evolves. One way to derive the fraction of stellar systems with inner disks is counting the number of objects showing excess emission in the JHKL near-IR bands. The availability of 2MASS has made JHK studies of young populations over wide spatial scales feasible. More recently, the emission of T Tauri stars in the Spitzer IRAC and MIPS bands has been characterized by *Allen et al.* (2004) and *Hartmann et al.* (2005b). Another approach is determining the number of objects that exhibit strong Hα and Ca II emission (CTTS), or UV excesses; these figures provide an indication of how many systems are actively accreting from their disks.

So far, the most extensive studies of how disk fractions change with time have been conducted in the Orion OB1 association. *Hillenbrand et al.* (1998) used the $I_c - K$ color to derive a disk fraction of 61%-88% in the ONC, and the Ca II lines in emission, or ”filled-in”, as a proxy for determining an accretion disk frequency of ~ 70%. *Rebull et al.* (2000) studied a region on both sides of the ONC and determined a disk accretion fraction in excess of 40%. *Lada et al.* (2000) used the JHKL bands to derive a ONC disk fraction of 80%-85% in the low-mass PMS population. *Lada et al.* (2004) extended this study to the substellar candidate members and found a disk fraction of ~ 50%. In their ongoing large scale study of the Orion OB1 association, *Calvet et al.* (2005a) combined UV, optical, JHKL and 10 μm measurements in a sample of confirmed members of the 1a and 1b sub-associations to study dust emission and disk accretion. They showed evidence for an overall decrease in IR emission with age, interpreted as a sign of dust evolution between the disks in Ori OB 1b (age ~ 4 Myr), Ori OB 1a (age ~ 8 Myr), and those of younger populations like Taurus (age ~ 2 Myr). *Briceño et al.* (2005b) used IRAC and MIPS on Spitzer to look for dusty disks in Ori OB 1a and 1b. They confirm a decline in IR emission by the age of Orion OB 1b, and find a number of ”transition” disk systems (~ 14% in 1b and ~ 6% in 1a), objects with essentially photospheric fluxes at wavelengths $\leq 4.5\ \mu$m and excess emission at longer wavelengths. These systems are interpreted as showing signatures of inner disk clearing, with optically thin inner regions stretching out to one or a few AU (*Calvet et al.*, 2002; *Uchida et al.*, 2004; *Calvet* *et al.*, 2005b; *D'Alessio et al.*, 2005); the fraction of these transition disks that are still accreting is low ($\sim 5-10\%$), hinting at a rapid shut off of the accretion phase in these systems (similar results have been obtained by *Sicilia-Aguilar et al.*, 2006 in Cep OB2, see below). *Haisch et al.* (2000) derived an IR-excess fraction of $\sim$ 86% in the $\lesssim$ 1 Myr old NGC 2024 embedded cluster. Their findings indicate that the majority of the sources that formed in NGC 2024 are presently surrounded by, and were likely formed with, circumstellar disks.

One of the more surprising findings in the λ Ori region was that, despite the discovery of 72 low-mass PMS stars within $0.5°$ (~ 3.5 pc) of λ Ori, only two of them showed strong Hα emission indicative of accretion disks (*Dolan and Mathieu*, 1999). *Dolan and Mathieu* (2001) expanded on this result by examining the distribution of Hα emission along an axis from B35 through λ Ori to B30. The paucity of Hα emission-line stars continues from λ Ori out to the two dark clouds, at which point the surface density of Hα emission-line stars increases dramatically. Even so, many of the Hα stars associated with B30 and B35 have ages similar to PMS stars found in the cluster near λ Ori. Yet almost none of the latter show Hα emission. This strongly suggests that the absence of Hα emission from the central PMS stars is the result of an environmental influence linked to the luminous OB stars.

The nearby Scorpius-Centaurus OB association (d $\sim$ 130 pc, *de Zeeuw et al.*, 1999) has been a natural place to search for circumstellar disks, especially at somewhat older ages (up to $\sim$ 10 Myr). *Moneti et al.* (1999) detected excess emission at the ISOCAM 6.7 and 15 μm bands in 10 X-ray selected WTTS belonging to the more widely spread population of Sco-Cen, albeit at levels significantly lower than in the much younger (age $\sim$ 1 Myr) Chamaeleon I T association. In a sample of X-ray and proper motion-selected late-type stars in the Lower Centaurus Crux (LCC, age $\sim$ 17 Myr) and Upper Centaurus Lupus (UCL, age ~ 15 Myr) in Sco-Cen, *Mamajek et al.* (2002) find that only 1 out of 110 PMS solar-type stars shows both enhanced Hα emission and a K-band excess indicative of active accretion from a truncated circumstellar disk, suggesting time scales of ~ 10 Myr for halting most of the disk accretion. *Chen et al.* (2005) obtained Spitzer Space Telescope MIPS observations of 40 F- and G-type common proper motion members of the Sco-Cen OB association with ages between 5 and 20 Myr. They detected 24 μm excess emission in 14 objects, corresponding to a disk fraction of $\geq 35\%$.

In Perseus, *Haisch et al.* (2001) used JHKL observations to estimate a disk fraction of $\sim 65\%$ in the 2-3 Myr old (*Luhman et al.*, 1998) IC 348 cluster, a value lower than in the younger NGC 2024 and ONC clusters in Orion, suggestive of a timescale of 2-3 Myr for the disappearance of $\sim 1/3$ of the inner disks in IC 348. The ~ 4 Myr old Tr 37 and the ~ 10 Myr old NGC 7160 clusters in Cep OB2 have been studied by *Sicilia-Aguilar et al.* (2005), who derive an accreting fraction of $\sim 40\%$ for Tr 37, and 2-5% (1 object) for NGC 7160. *Sicilia-Aguilar et al.* (2006) used

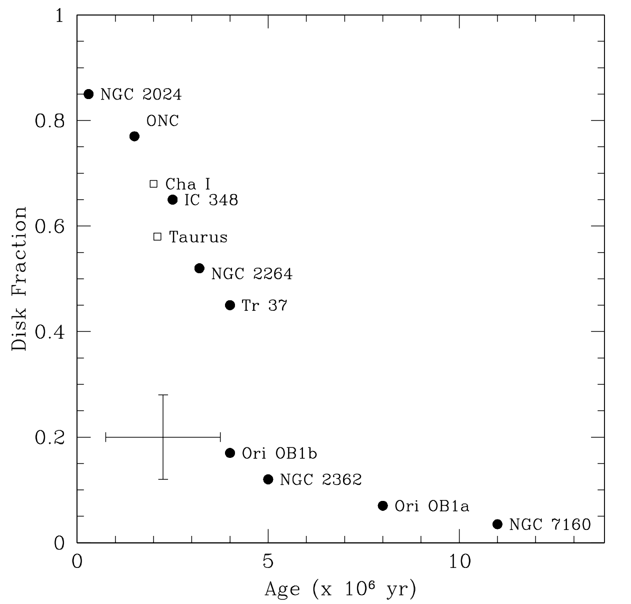

Fig. 5.— Inner disk fraction around low-mass young stars ($0.2 \lesssim M \lesssim 1$ M$_\odot$) as a function of age in various nearby OB associations (solid dots). The ONC point is an average from estimates by *Hillenbrand et al.* (1998), *Lada et al.* (2000), *Haisch et al.* (2001). Data in the JHKL bands from *Haisch et al.* (2001) were used for IC 348, NGC 2264, NGC 2362. Note that for the more distant regions like NGC 2362 and NGC 2264, the mass completeness limit is ~ 1 M$_\odot$. Results for Orion OB 1a and 1b are from JHK data in *Briceño et al.* (2005a). In Tr 37 and NGC 7160 we used values by *Sicilia-Aguilar et al.* (2005, 2006) from accretion indicators and JHK[3.6 μm] measurements. In As a comparison, we also plot disk fractions (open squares) derived in Taurus (from data in *Kenyon and Hartmann*, 1995) and for Chamaeleon I from *Gómez and Kenyon* (2001). A conservative errorbar is indicated at the lower left corner.

Spitzer IRAC and MIPS observations to further investigate disk properties in Cep OB2. About 48% of the members exhibit IR excesses in the IRAC bands, consistent with their inferred accreting disk fraction. They also find a number of "transition" objects (10%) in Tr 37. They interpret their results as evidence for differential evolution in optically thick disks as a function of age, with faster decreases in the IR emission at shorter wavelengths, suggestive of a more rapid evolution in the inner disks.

All these studies agree on a general trend towards rapid inner disk evolution (Fig. 5); it looks like the disappearance of the dust in the innermost parts of the disk, either due to grain growth and settling or to photo-evaporation (*Clarke et al.*, 2001), is followed by a rapid shut off of accretion. However, both these investigations and newer findings also reveal exceptions that lead to a more complex picture. *Muzerolle et al.* (2005) find that 5-10% of all disk sources in the ~ 1 Myr old NGC 2068 and 2071 clusters in Orion show evidence of significant grain growth, suggesting a wide variation in timescales for the onset of primordial disk evolution and dissipation. This could also be related to the existence of CTTS and WTTS in many regions at very young ages, the WTTS showing no signatures of inner, optically thick disks. Did some particular initial conditions favor very fast disk evolution in these WTTS (binarity)? Finally, the detection of long-lived disks implies that dust dissipation and the halting of accretion do not necessarily follow a universal trend. This may have implications for the formation of planetary systems; if slow accretion processes are the dominant formation mechanism for Jovian planets then long-lived disks may be ideal sites to search for evidence for protoplanets.

6. THE ORIGIN OF OB ASSOCIATIONS: BOUND VS. UNBOUND STELLAR GROUPS

Blauuw (1964) in his masterly review first provided some clues as to the origin of OB associations, alluding to two ideas: "originally small, compact bodies with dimensions of several parsec or less" or "regional star formation, more or less simultaneous, but scattered over different parts of a large cloud complex". Similarly, there are at present two (competing) models that attempt to explain the origin of OB associations:

A) origin as expanding dense embedded clusters

B) origin in unbound turbulent giant molecular clouds

We will label Model A as the KLL-model (*Kroupa et al.*, 2001; *Lada and Lada*, 2003), while Model B will be named the BBC-model (for Bonnell, Bate and Clark, see also *Clark et al.*, 2005).

The jury is still out on which model fits the observations better. It may be that both models contain elements of truth and thus are not mutually exclusive. Future astrometric surveys, $Gaia$ in particular, will provide constraints to perform sensitive tests on these models, but that will not happen for about another decade. We refer the reader to the review of *Brown et al.* (1999), who also points out the problems involved in the definition of an OB association and the division of these vast stellar aggregates into subgroups (see *Brown et al.*, 1997).

We now discuss both models in turn. The KLL model proposes that ultimately the star formation efficiency in most embedded, incipient star clusters is too low ($\lesssim 5$ percent) for these clusters to remain bound (see references in *Elmegreen et al.*, 2000; *Lada and Lada*, 2003) after the massive stars have expelled the bulk of the lower density, left-over cluster gas that was not turned into stars, or did not get accreted. Therefore the cluster will find itself globally unbound, although the cluster *core* may remain bound (*Kroupa et al.*, 2001) and survive. Such an originally compact but expanding cluster could evolve into an extended subgroup of an OB association after a few Myr. Essentially, the KLL model describes how the dense gas in a bound and virialized GMC is partly converted into stars, most of which are born in dense embedded clusters, the majority of which disperse quickly (so-called cluster "infant mortality").

The BBC model supposes that GMCs need not be regarded as objects in virial equilibrium, or even bound, for them to be sites of star formation. Globally unbound or marginally bound GMC can form stellar groups or clusters very quickly, over roughly their crossing time (cf. *Elmegreen et al.*, 2000; recent simulations also show that GMC themselves can form very quickly from atomic gas, in 1-2 Myr (see chapter by *Ballesteros-Paredes et al.*). The unbound state of the GMC ensures that the whole region is dispersing while it is forming stars or star clusters in locally compressed sheets and filaments, due to the compressive nature of supersonic turbulence ("converging flows"). The mass fraction of compressed cloud gas is low, affecting only ~ 10% of the GMC. In this model, the spacing of the OB stars that define an OB association would be initially large (larger than a few pc), rather than compact ($\lesssim 1$ pc) as in the KLL model. Furthermore, no sequential star formation triggered by the thermal pressure of expanding HII regions "a la *Elmegreen and Lada* (1977)" may be needed to create OB subgroups, unlike in the KLL model. Delayed SN-triggered star formation in adjacent transient clouds at some distance may still occur and add to the geometric complexity of the spatial and temporal distribution of stars in giant OB associations (e.g., NGC 206 in M31 and NGC 604 in M33; *Maíz-Apellániz et al.*, 2004).

A problem common to both models is that neither one explains very well the spatial and temporal structure of OB associations, i.e. the fact that the subgroups seem to form an age sequence (well known in Orion OB1 and Sco OB2). One way out would be to argue that the subgroups are not always causally connected and did not originate by sequential star formation as in the *Elmegreen and Lada* (1977) paradigm. Star formation in clouds with supersonic turbulence occurring in convergent flows, may be of a more random nature and only mimic a causal sequence of triggering events (e.g., in Sco OB2, the UCL and LCC subgroups, with ages of ~ 15 and $\sim$ 17 Myr from the *D'Antona and Mazzitelli* [1994] tracks, have hardly an age difference at all). This is a problem for the KLL model, as sequential star formation can hardly generate two adjacent clusters (subgroups) within such a short time span. It is also a problem for the BBC model, but for a different reason. The fact that star formation must be rapid in unbound transient molecular clouds is in conflict with the ages of the Sco OB2 subgroups (1, 5, 15 and 17 Myr), if all subgroups formed from a single coherent (long-lived) GMC. Still, the observational evidence suggesting that Upper Sco can be understood in the context of triggered star formation (see Section 7.2), can be reconciled with these models if we consider a scenario with multiple star formation sites in a turbulent large GMC, in which triggering may easily take place. It remains to be seen if subgroups of OB associations had some elongated minimum size configuration, as *Blaauw* (1991) surmised, of the order of 20 pc x 40 pc. If so, OB associations are then something fundamentally different from embedded clusters, which would have many ramifications for the origin of OB stars (However, a caveat with tracing back minimum size configurations [*Brown et al.*, 1997] is that, even using modern *Hipparcos* proper motions, there is a tendency to obtain overestimated dimensions because present proper motions cannot resolve the small velocity dispersion. This situation should improve with $Gaia$, and with the newer census of low-mass stars, that can potentially provide statistically robust samples to trace the past kinematics of these regions).

7. CONSTRAINTS ON RAPID AND TRIGGERED/SEQUENTIAL STAR FORMATION

7.1 The duration of star formation

One of the problems directly related to the properties of the stellar populations in OB associations are the lifetimes of molecular clouds. Age estimates for GMCs can be very discordant, ranging from $\sim 10^8$ years (*Solomon et al.*, 1979; *Scoville and Hersh*, 1979) to just a few 10^6 years (e.g., *Elmegreen et al.*, 2000; *Hartmann et al.*, 2001; *Clark et al.*, 2005). Molecular clouds lifetimes bear importantly on the picture we have of the process of star formation. Two main views have been contending among the scientific community during the past few years. In the standard picture of star formation magnetic fields are a major support mechanism for clouds (*Shu et al.*, 1987). Because of this, the cloud must somehow reduce its magnetic flux per unit mass if it is to attain the critical value for collapse. One way to do this is through ambipolar diffusion, in which the gravitational force pulls mass through the resisting magnetic field, effectively concentrating the cloud and slowly "leaving the magnetic field behind". ¿From these arguments it follows that timescale for star formation should be of the order of the diffusion time of the magnetic field, $t_D \sim 5 \times 10^{13} (n_i/n_{H2})$ yr (*Hartmann*, 1998), which will be important only if the ionization inside the cloud is low ($n_i/n_{H2} \lesssim 10^{-7}$), in which case $t_D \sim 10^7$ yr; therefore, the so called "standard" picture depicts star formation as a "slow" process. This leads to relevant observational consequences. If molecular clouds live for long periods before the onset of star formation, then we should expect to find a majority of starless dark clouds; however, the observational evidence points to quite the contrary. Almost all cloud complexes within ~ 500 pc exhibit active star formation, harboring stellar populations with ages $\sim 1 - 10$ Myr. Another implication of "slow" star formation is that of *age spreads* in star-forming regions. If clouds such as Taurus last for tens of Myr there should exist a population of PMS sequence stars with comparable ages (the "post-T Tauri problem"). Many searches for such "missing population" were conducted in the optical and in X-rays, in Taurus and in other regions (see *Neuhäuser* 1997). The early claims by these studies of the detection of large numbers of older T Tauri stars widely spread across several nearby star forming regions, were countered by *Briceño et al.* (1997), who showed that these samples were composed of an admixture of young, x-ray active ZAMS field stars and some true PMS sequence members of these regions. Subsequent high-resolution spectroscopy confirmed this idea. As discussed in Section 4, presently there is little evidence for the presence of substantial numbers of older PMS stars in and around molecular clouds.

Recent wide-field optical studies in OB associations like Sco-Cen (*Preibisch et al.*, 2002), Orion (*Dolan and Mathieu*, 2001; *Briceño et al.*, 2001, 2005, 2006), and Cepheus (*Sicilia-Aguilar et al.*, 2005), show that the groupings of stars with ages $\gtrsim 4 - 5$ Myr have mostly lost their natal gas. The growing notion is that not only do molecular clouds form stars rapidly, but that they are transient structures, dissipating quickly after the onset of star formation. This dispersal seems to be effective in both low-mass regions as well as in GMC complexes that give birth to OB associations. The problem of accumulating and then dissipating the gas quickly in molecular clouds has been addressed by *Hartmann et al.* (2001). The energy input from stellar winds of massive stars, or more easily from SN shocks, seems to be able to account for the dispersal of the gas on short timescales in the high density regions typical of GMC complexes, as well as in low-density regions, like Taurus or Lupus; if enough stellar energy is input into the gas such that the column density is reduced by factors of only 2-3, the shielding could be reduced enough to allow dissociation of much of the gas into atomic phase, effectively "dissipating" the molecular cloud.

7.2 Sequential and triggered star formation

Preibisch et al. (2002) investigated the star formation history in Upper Scorpius. A very important aspect in this context is the spatial extent of the association and the corresponding crossing time. The bulk (70%) of the *Hipparcos* members (and thus also the low-mass stars) lie within an area of 11 degrees diameter on the sky, which implies a characteristic size of the association of 28 pc. They estimated that the original size of the association was probably about 25 pc. *de Bruijne* (1999) showed that the internal velocity dispersion of the *Hipparcos* members of Upper Sco is only 1.3 $\mathrm{km\,s^{-1}}$. This implies a lateral crossing time of 25 pc / 1.3 $\mathrm{km\,s^{-1}} \sim 20$ Myr. It is obvious that the lateral crossing time is much (about an order of magnitude) larger than the age spread of the association members (which is < 2 Myr as derived by *Preibisch and Zinnecker*, 1999). This finding clearly shows that some external agent is required to have coordinated the onset of the star formation process over the full spatial extent of the association. In order to account for the small spread of stellar ages, the triggering agent must have crossed the initial cloud with a velocity of at least $\sim 15 - 25\ \mathrm{km\,s^{-1}}$. Finally, some mechanism must have terminated the star formation process at most about 1 Myr after it started. Both effects can be attributed to the influence of massive stars.

In their immediate surroundings, massive stars generally have a destructive effect on their environment; they can disrupt molecular clouds very quickly and therefore prevent further star formation. At somewhat larger distances, however, the wind- and supernova-driven shock waves originating from massive stars can have a constructive rather than destructive effect by driving molecular cloud cores into collapse. Several numerical studies (e.g., *Boss*, 1995; *Foster and Boss*, 1996; *Vanhala and Cameron*, 1998; *Fukuda and Hanawa*, 2000) have found that the outcome of the impact of a shock wave on a cloud core mainly depends on the type of the shock and its velocity: In its initial, adiabatic phase, the shock wave is likely to destroy ambient clouds; the later, isothermal phase, however, is capable of triggering cloud collapse if the velocity is in the right range. Shocks traveling faster than about 50 $\mathrm{km\,s^{-1}}$ shred cloud cores to pieces, while shocks with velocities slower than about 15 $\mathrm{km\,s^{-1}}$ usually cause only a slight temporary compression of cloud cores. Shock waves with velocities in the range of $\sim 15-45\ \mathrm{km\,s^{-1}}$, however, are able to induce collapse of molecular cloud cores. A good source of shock waves with velocities in that range are supernova explosions at a distance between ~ 10 pc and ~ 100 pc. Other potential sources of such shock waves include wind-blown bubbles and expanding HII regions. Observational evidence for star forming events triggered by shock waves from massive stars has for example been discussed in *Carpenter et al.* (2000), *Walborn et al.* (1999), *Yamaguchi et al.* (2001), *Efremov and Elmegreen* (1998), *Oey and Massey* (1995), and *Oey et al.* (2005).

For the star burst in Upper Sco, a very suitable trigger is a supernova explosion in the Upper Centaurus-Lupus association that happened about 12 Myr ago. The structure and kinematics of the large H I loops surrounding the Scorpius-Centaurus association suggest that this shock wave passed through the former Upper Sco molecular cloud just about 5–6 Myr ago (*de Geus*, 1992). This point in time agrees very well with the ages found for the low-mass stars as well as the high-mass stars in Upper Sco, which have been determined above in an absolutely independent way. Furthermore, since the distance from Upper Centaurus-Lupus to Upper Sco is about 60 pc, this shock wave probably had precisely the properties ($v \sim 20-25\ \mathrm{km\,s^{-1}}$) that are required to induce star formation according to the modeling results mentioned above. Thus, the assumption that this supernova shock wave triggered the star formation process in Upper Sco provides a self-consistent explanation of all observational data.

The shock-wave crossing Upper Sco initiated the formation of some 2500 stars, including 10 massive stars upwards of $10\,M_\odot$. When the new-born massive stars 'turned on', they immediately started to destroy the cloud from inside by their ionizing radiation and their strong winds. This affected the cloud so strongly that after a period of $\lesssim 1$ Myr the star formation process was terminated, probably simply because all the remaining dense cloud material was disrupted. This explains the narrow age distribution and why only about 2% of the original cloud mass was transformed into stars. About 1.5 Myr ago the most massive star in Upper Sco, probably the progenitor of the pulsar PSR J1932+1059, exploded as a supernova. This explosion created a strong shock wave, which fully dispersed the Upper Sco molecular cloud and removed basically all the remaining diffuse material.

It is interesting to note that this shock wave must have crossed the ρ Oph cloud within the last 1 Myr (*de Geus*, 1992). The strong star formation activity we witness right now in the ρ Oph cloud might therefore be triggered by this shock wave (see *Motte et al.*, 1998) and would represent the third generation of sequential triggered star formation in the Scorpius-Centaurus-Ophiuchus complex.

Other relatively nearby regions have also been suggested as scenarios for triggered star formation. In Cepheus, a large scale ring-like feature with a diameter of 120 pc has been known since the time of the Hα photographic atlases of HII regions (*Sivan*, 1974). *Kun et al.*, (1987) first identified the infrared emission of this structure in $IRAS$ 60 and 100 μm sky flux maps. The Cepheus bubble includes the Cepheus OB2 association (Cep OB2), which is partly made up of the Tr 37 and NGC 7160 open clusters, and includes the HII region IC 1396. *Patel et al.* (1995, 1998) mapped $\sim 100\ \mathrm{deg}^2$ in Cepheus in the $J = 1-0$ transition of CO and $^{13}\mathrm{CO}$. Their observations reveal that the molecular clouds are undergoing an asymmetrical expansion away from the Galactic plane. They propose a scenario in which the large scale bubble was blown away by stellar winds and photoionization from the first generation of OB stars, which are no longer present (having exploded as supernovae). The ~ 10 Myr old (*Sicilia-Aguilar et al.*, 2004) NGC 7160 cluster and evolved stars such as μ Cephei, VV Cephei and ν Cephei are the present day companions of those first OB stars. *Patel et al.* (1998) show that the expanding shell becomes unstable at $\sim$ 7 Myr after the birth of the first OB stars. The estimated radius of the shell at that time (~ 30 pc) is consistent with the present radius of the ring of O and B-type stars which constitute Cep OB2. Within a factor of $\lesssim 2$, this age is also consistent with the estimated age for the Tr 37 cluster (~ 4 Myr; *Sicilia-Aguilar et al.*, 2004). Once the second generation of massive stars formed, they started affecting the dense gas in the remaining parent shell. The gas around these O stars expanded in rings like the one seen in IC 1396. The dynamical timescale for this expansion is of the order of 1-3 Myr, consistent with the very young ages ($\sim 1-2$ Myr) of the low-mass stars in the vicinity of IC 1396 (*Sicilia-Aguilar et al.*, 2004). This HII region is interpreted as the most recent generation of stars in Cep OB2.

In the Orion OB1 association *Blaauw* (1964) proposed that the ONC is the most recent event in a series of star-forming episodes within this association. The increasing ages between the ONC, Ori OB1b and Ori OB1a have been suggested to be a case for sequential star formation (*Blaauw*, 1991). However, until now it has been difficult to investigate triggered star formation in Ori OB1 because of the lack of an unbiased census of the low-mass stars over the entire region. This situation is changing with the new large scale surveys (e.g., *Briceño et al.*, 2005) that are are mapping the low-mass population of Ori OB1 over tens of square degrees; we may soon be able to test if Orion can also be interpreted as a case of induced, sequential star formation.

8. CONCLUDING REMARKS

Low-mass stars ($0.1 \lesssim \mathrm{M} \lesssim 1\ \mathrm{M}_\odot$) in OB associations are essential for understanding many of the most fundamental problems in star formation, and important progress has been made during the past years by mapping and characterizing these objects. The newer large scale surveys reveal that low-mass stars exist wherever high mass stars are found, not only in the dense clusters, but also in a much more widely distributed population. As ever increasing numbers of low-mass stars are identified over large areas in older regions like Orion OB1a, their spatial distribution shows substructure suggestive of a far more complex history than would be inferred from the massive stars.

The low-mass stellar populations in OB associations provide a snapshot of the IMF just after the completion of star formation, and before stars diffuse into the field population. The IMF derived from OB associations is consistent with the field IMF. The large majority of the low-mass PMS stars in the solar vicinity are in OB associations, therefore this agrees with early suggestions (*Miller and Scalo*, 1978) that the majority of stars in the Galaxy were born in OB associations.

Since PPIV, the recent large surveys for low-mass members in several OB associations have allowed important progress on studies of early circumstellar disk evolution. With large scale surveys like 2MASS, large IR imagers and now the Spitzer Space Telescope, we have unprecedented amounts of data sensitive to dusty disks in many regions. Overall disks largely dissipate over timescales of a few Myr, either by dust evaporation, or settling and growth into larger bodies like planetesimals and planets; exactly which mechanisms participate in this evolution may depend on initial conditions and even on the environment. The actual picture seems more complex, current evidence supports a wide range of disk properties even at ages of $\sim$ 1 Myr, and in some regions disks somehow manage to extend their lifetimes, surviving for up to $\sim 10 - 20$ Myr.

As the census of low-mass stars in nearby OB associations are extended in the coming years, our overall picture of star formation promises to grow even more complex and challenging.

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