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OB ASSOCIATIONS: NEW INSIGHTS FROM LARGE SCALE SURVEYS

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RESUMEN

Una de las preguntas fundamentales de la astronomía moderna es cómo se formó el Sistema Solar. Ahora reconocemos que la mayoría de las estrellas en la Galaxia se formaron en vastas regiones llamadas asociaciones OB, que exhiben todas las etapas del proceso de formación estelar, desde cúmulos embebidos muy jóvenes, hasta estrellas más viejas ya libres de su gas y polvo primigenios. Los sondeos a gran escala en estas regiones han revelado que las estrellas de baja masa existen dondequiera que se han formado estrellas de alta masa. La distribución espacial y edades de las estrellas jóvenes de baja masa apoyan la idea de que la nubes moleculares progenitoras son estructuras transitorias, con tiempos de vida de 10 Maños o menos, y que la formación estelar es un proceso rápido y a menudo inducido. Los estudios de los discos circunestelares en estas poblaciones jóvenes indican que la fase de formación de planetas dura en promedio 10 Maños o menos.

ABSTRACT

One of the fundamental questions in modern astronomy is how the Solar System formed. We now recognize that the majority of stars in the Galaxy formed in vast regions called OB associations, which exhibit all stages of the star formation process, from very young, embedded clusters, to older, fully exposed young stars. Large scale surveys in these regions have revealed that low-mass stars exist wherever high-mass stars have recently formed. The spatial distribution and ages of low-mass young stars provide support to the idea that the parent molecular clouds are transient structures, with lifetimes of 10 Myr or less, and that star formation is a rapid and often triggered process. Studies of circumstellar disks in these young populations indicate that the duration of the planet-forming phase is on average 10 Myr or less.

Key Words: open clusters and associations: general — stars: formation — stars: pre-main sequence

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). These are typically loose aggregates containing 10–100 massive stars of spectral class O and B. Because the stellar density is rather low, $\lesssim 1$ M$_\odot$ pc^{-3}, once the surrounding dust and gas are blown away by the powerful winds of the early type stars, or by shock waves when the most massive stars explode as supernovae, the remaining stars become unbound and begin to drift apart, under the combined effect of the internal velocity dispersion (of a few km/s) and galactic tidal forces. This means that OB associations cannot survive as coherent entities in space for much longer than 10–30 Myr; proper motion measurements in nearby OB associations show that members share a common space motion. This timescale of a few tens of Myr is also of the order of the main-sequence lifetimes of the massive stars (a B0 star has a main sequence lifetime of roughly 11 Myr). Thus, it follows from their definition that OB associations are regions harboring populations of very young stars, their low-mass members still on their pre-main sequence phase. The Hipparcos satellite provided measurements that located a dozen OB associations within 650 parsecs of the Sun (de Zeuuw et al. 1999). The nearest OB association is the Scorpius-Centaurus Association, located at ~ 160 pc (e.g. Preibisch & Mamajek 2008).

Since most stars probably originate within the environment of OB associations, it is important to study how the ambient conditions may affect the resulting young stars and their surrounding planetary systems. Possible effects can include the stellar winds & ionizing UV radiation from the massive O and early B-type stars, which can help disperse the molecular gas surrounding low-mass stars in their earliest formation stages (Hartmann et al. 2001); this could provide a mechanism to terminate star formation in the regions closest to the massive stars, or alternatively it could truncate the lower mass end of the Initial Mass Function (Whitworth et al. 2007). Photoevaporation from strong EUV and FUV radi-

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ation from massive stars can also destroy circumstellar disks, affecting planet formation (e.g. Adams et al. 2004; Robberto et al. 2008). At the same time, powerful stellar winds and SN shock waves can help trigger star formation in nearby dense molecular clouds, or even help compress lower density HI to create new molecular clouds (see Ballesteros-Paredes et al. 2007; Briceño et al. 2007a).

2. STELLAR POPULATIONS IN YOUNG ASSOCIATIONS

Recent studies made possible by the advent of panoramic CCD cameras installed on wide-field telescopes, are starting to produce our first significant view of the young, low-mass stellar populations in nearby OB associations. However, obtaining a complete census of the low-mass stars is not a simple task. Unlike partly embedded, 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 $\sim$ 4 Myr the stars are no longer associated with their parent molecular clouds (Briceño et al. 2007a), 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 pre-main sequence (PMS) stars.

2.1. *Finding young, low-mass stars*

Low-mass PMS stars, also known as T Tauri stars (TTS) are characterized by late spectral types (G-M), strong emission lines (especially Hα), photometric variability, uv excess emission, strong X-ray emission, and infrared excesses. Stars resembling the original variables first identified as TTS are currently called "strong emission" or Classical TTS (CTTS). The extreme emission 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.

Because of these observational characteristics, the main search strategies have been objective prism, X-ray, and proper motion surveys, single-epoch photometry, and more recently, variability surveys (see Briceño et al. 2007a, for a more extensive review). In particular, large scale photometric variability searches have proved to be an efficient means of selecting reliable candidate TTS samples over extended areas of the sky. In Figure 1 it is evident

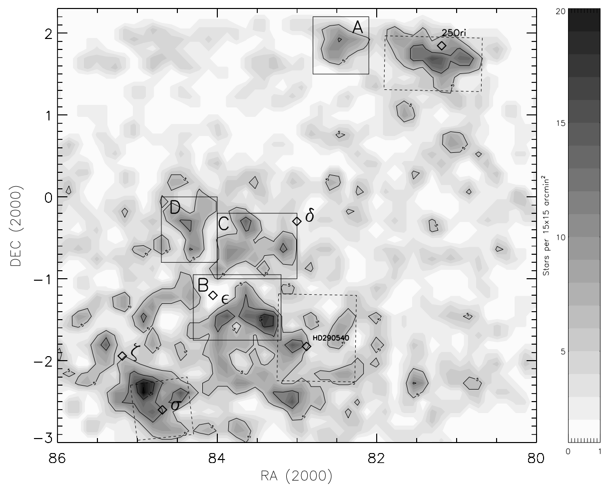

Fig. 1. Surface density of 2MASS sources, located above the ZAMS and flagged as variable, in part of Orion OB1 (Briceño et al. 2001, 2005). In the upper right is the $\sim$ 8 Myr old 25 Ori cluster (Briceño et al. 2007b); in the lower left the $\sim$ 3 Myr old σ Ori cluster (Hernández et al. 2007a). Rectangles indicate regions studied with Spitzer (see Hernández et al. 2007b). The three stars of the Orion belt are labeled.

that objects selected as variable stars located above the zero-age main sequence, trace well the actual distribution of young members in the Orion OB1 association.

However, any of the various search methods ultimately requires low to moderate resolution spectra to confirm membership of PMS stars. The presence of strong 6708 Å Li I absorption is one of the most commonly used spectroscopic diagnostics of youth (e.g., Briceño et al. 1993, 2001; Dolan & Mathieu 2001; Briceño et al. 2005). The advent of powerful multi-object spectrographs, such as Hydra on the WIYN 3.5 m and the CTIO 4 m telescopes, and Hectospec on the 6.5 m MMT, has now made feasible the necessary large scale followup spectroscopy, with enough sensitivity and resolving power to detect Li I in faint, low-mass candidate PMS stars.

3. WHAT WE HAVE LEARNED FROM YOUNG, LOW-MASS STELLAR POPULATIONS IN OB ASSOCIATIONS

3.1. *Short molecular cloud lifetimes — Rapid 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 (e.g., Scoville & 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 our picture 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, Adams, & Lizano 1987). In order for the cloud to attain the critical value for collapse, the magnetic flux per unit mass can be reduced 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". Therefore, the duration of star formation should be of the order of the magnetic diffusion timescale, $t_D \sim 5 \times 10^{13}(n_i/n_{H2})$ yr (Hartmann et al. 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. If molecular clouds do indeed 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.

Recent wide-field optical studies in OB associations like Sco-Cen (Preibisch et al. 2002), Orion (Dolan & Mathieu 2001; Briceño et al. 2001, 2005, 2007b; Briceño 2008), 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. 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; 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.

3.2. *Star formation is often triggered*

One of the best sample cases for triggered star formation in a nearby OB association is Upper Scorpius. Preibisch et al. (2002) investigated the star formation history in this region, and estimated that the original size of the association was probably about 25 pc. The internal velocity dispersion of the *Hipparcos* members of Upper Sco is only 1.3 km s^{-1} (de Bruijne 1999), implying a lateral crossing time of 25 pc/1.3 km s^{-1} $\sim$ 20 Myr. This crossing time is much larger (about an order of magnitude) than the age spread of the association members (which is $<$ 2 Myr as derived by Preibisch & Zinnecker 1999). This finding clearly shows that some external agent must 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 $\sim 15 - 25$ 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.

The scenario in Upper Sco is consistent with 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 Sco-Cen association suggest that this shock wave passed through the former Upper Sco molecular cloud just about 5–6 Myr ago (de Geus 1992), which agrees very well with the ages of the low and high mass stars. Furthermore, since the distance from Upper Cen-Lup to Upper Sco is about 60 pc, this shock wave probably had precisely the properties ($v \sim 20-25$ km s^{-1}) that are required to induce star formation according to various numerical studies (e.g., Boss 1995; Foster & Boss 1996; Vanhala & Cameron 1998; Fukuda & Hanawa 2000) that have modeled the outcome of the impact of a shock wave on a cloud core. 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.

Other relatively nearby regions have also been suggested as scenarios for triggered star formation. The Cepheus OB2 association (Cep OB2), located inside a 120 pc wide ring-like feature, also known as the Cepheus bubble, contains the Tr 37 and NGC 7160 open clusters, and the HII region IC 1396 (Figure 2). Patel et al. (1995, 1998) found that the molecular clouds are undergoing an asymmetrical expansion away from the Galactic plane, and proposed 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 $\sim$ 10 Myr old (Sicilia-Aguilar et al. 2004) NGC 7160 cluster and evolved stars such as μ Cephei, VV

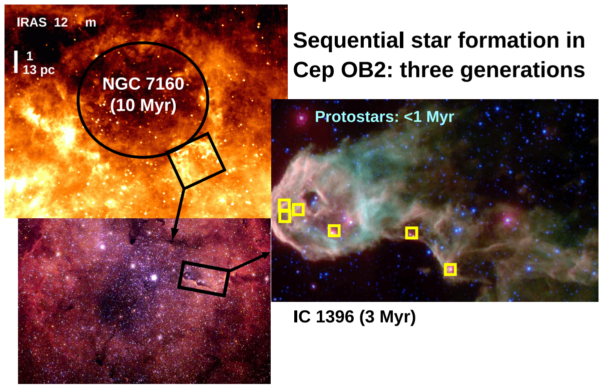

Fig. 2. Star formation in Cepheus. The oldest generation is marked by the NGC 7160 cluster. The $\sim$ 4 Myr old Tr 37 cluster is located on the lower right edge of the bubble. The O6 star HD 206267 is exciting the IC 1396 HII region, inside which Spitzer has revealed a series of embedded protostars (open squares; Reach et al. 2004), on the edge facing the massive star.

Cephei and ν Cephei are the present day companions of those first OB stars. Once the second generation of massive stars formed, they started affecting the dense gas in the remaining parent shell, which 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).

3.3. *Star Formation is a rapid process*

Another implication of "slow" star formation is that of *age spreads* in star-forming regions. If clouds did last for tens of Myr there should exist a population of PMS stars with comparable ages (the "post-T Tauri problem"). Many searches for such "missing population" were conducted in the optical and in X-rays (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 members of these regions. Subsequent high-resolution spectroscopy con-

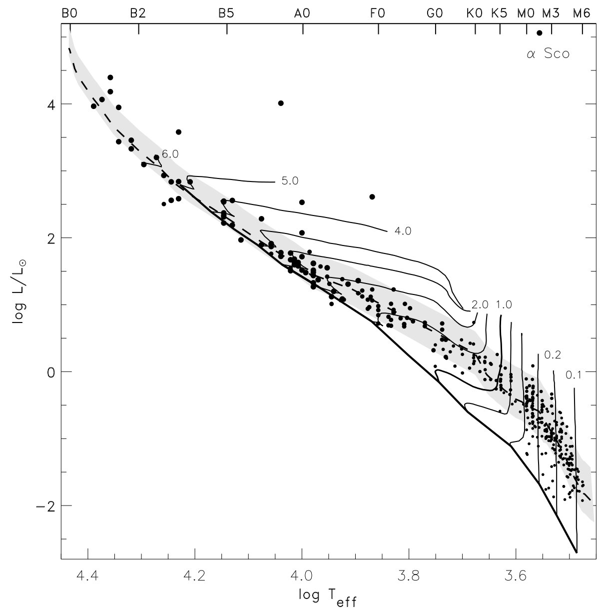

Fig. 3. HR diagram for the Upper Sco association members from the study of Preibisch et al. (2002). The lines show the evolutionary tracks from the Palla & Stahler (1999) PMS models, some labeled by their masses in solar units. The thick solid line shows the main sequence. The 5 Myr isochrone is shown 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 & 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.

firmed this idea. Presently, there is little evidence for the presence of substantial numbers of older PMS stars in and around molecular clouds.

Figure 3 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 effects like photometric errors, variability, and unresolved binaries, the most important factor for the apparent scatter is the relatively large spread of individual stellar distances ($\sim\pm20$ pc around the mean value of 145 pc; 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. Preibisch et al. (2002) 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 a small age spread of* $\sim 1-2$ *Myr cannot be excluded by the data.* The absence of a significant age dispersion implies that all stars in the association 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.

3.4. *The timescale for planetary formation*

Circumstellar disks around young stars play an important role in determining the final mass of the star and as potential sites for planet formation. We now recognize that dust particles suspended in the disk gas evolve, with solids coagulating and settling toward the midplane (Weidenschilling 1997); this dust growth and settling are thought to be the first stage in planetary accumulation (Pollack et al. 1996).

The presence of disks can be infered by optical signatures like strong emission in hydrogen Balmer lines like Hα, produced by hot (T $\sim 10^4$ K) gas flowing through a magnetosphere, and by excess IR emission from warm dust in the disk, heated by irradiation from the central star. By counting the number of disk-bearing stars at each age, under differing conditions, we can investigate how bulk disk properties evolve, what is the overall timescale for planetary formation and how ambient conditions may influence this evolution. So far, the most extensive studies of how circumstellar disk fractions change with time have been conducted in the Orion OB1 association.

Briceño et al. (2005, 2007b), used the strong Hα emission in CTTS as a proxy for disk accretion, and derived accretor fractions of 6–13% in Ori OB1a and in 12–23% Ori OB1b. McGehee (2006) found a similar CTTS fraction of $\sim 10\%$ in Ori OB1a. Within the uncertainties, there is a clear decline in the number of accreting stars between the ~ 4 Myr old OB1b and the 7–10 Myr old OB1a. Calvet et al. (2005) used UV excesses to derive mass accretion rates in a subset of Orion OB1 CTTS. They found a decrease of $\dot{M}$ with age, which qualitatively agrees with expectations from viscous disk evolution. However, viscous evolution alone cannot explain the decreasing fraction of accreting objects with age; other factors (e.g. inner disk clearing associated with planet formation Calvet et al. 2002; D'Alessio et al. 2005) must also play a role in slowing accretion onto the central star.

More recently, Hernández et al. (2007b) used IRAC and MIPS on Spitzer to look for dusty disks

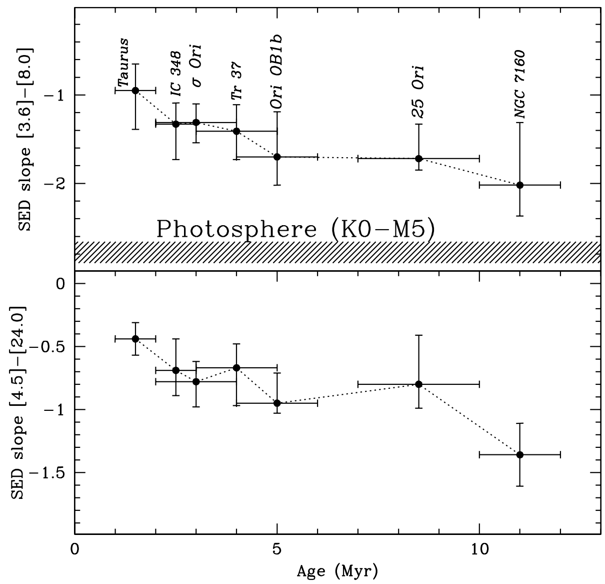

Fig. 4. Disk Evolution with Spitzer (from Hernández et al. 2007b). Upper panel: median slope of the spectral energy distributions between 3.6 μm and 8 μm for various stellar groups, including 25 Ori and σ Ori. "Error bars" are quartiles, i.e., 50% of the observations are within these bars. Lower panel: similar plot for the IRAC 3.6 μm and MIPS 24 μm bands.

in Ori OB1a and OB1b. They derived disk fractions of 6% in the 25 Ori cluster and 13% in Ori OB1b, similar to what Briceño et al. (2007b) found from accretion indicators. Hernández et al. (2007b) also showed that not only does inner disk emission decay with stellar age, but the inner disk dissipates more rapidly. In Figure 4 there is a clear decrease of the median slope of the IRAC spectral energy distribution with age. There is also a decrease in the slope of the spectral energy distribution in the IRAC-MIPS diagram (lower panel), but slower than in the IRAC-only plot; the IRAC-MIPS slope corresponds to regions further out in the disk. The faster decrease in the IR dust emission from the inner parts of the disk is indicative of an "inside-out" clearing. This study also found a number of "transition" disk systems, with essentially photospheric fluxes at $\lambda \leq 4.5$ μm and excess emission at longer wavelengths, interpreted as a signature of inner disk clearing, with optically thin inner regions stretching out to one or a few AU (e.g., Calvet et al. 2002; D'Alessio et al. 2005; Espaillat et al. 2007).

Therefore, the accumulating observational evidence suggests that the planet-forming material has largely dissipated in most young, solar-like stars by ages of ~ 10 Myr. This result constrains the planetary formation phase to timescales of several Myr, in agreement with the more recent theoretical models that allow for rapid growth of large rocky bodies in protoplanetry disks (e.g. Brauer, Dullemond, & Henning 2008).

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