THE LOW-MASS STELLAR POPULATION OF THE ORION OB1 ASSOCIATION AND IMPLICATIONS FOR THE FORMATION OF LOW-MASS STARS

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The OB associations, which are fossil star formation regions, retain the end-products of the star formation process in an open, unobscured environment. Observations of the low mass stars in OB associations provide a far clearer picture of the results of the star formation process than do observations of embedded, on-going star formation regions. We review the X–ray and optical surveys of the fossil star formation regions in the Orion OB1 association. Low mass pre-main sequence stars abound not only in the known regions of recent star formation, but are also distributed over a much larger volume. The pre-main sequence stars have a narrow age spread, and the mass function extends down to substellar masses. The clustering of pre-main sequence stars around σ Ori may represent an evolved version of the Orion Nebula Cluster. We speculate about the effect of the OB environment on the initial mass function and the formation of planetary systems like the Solar System.

I. Star Formation in T and OB Associations

A long time ago[1], in a part of the Galaxy far far away, our Sun was

[1] about 4.6 Gyr

born. The isotopic abundances in the chondrules and CaIs (chapter by Goswami and Vanhala, this volume), in particular the existence of very short-lived parent radionuclides, provide clues about the environment in which our Sun and its planets were born. Among the plausible sources for these short-lived nuclides are an AGB star, a supernova, a Wolf-Rayet star, or a combination thereof (Cameron 1993; but also see Lee et al. 1998 and the chapter by Glassgold et al., this volume). If the Sun formed in close proximity to a supernova or a W-R star, then the Sun most likely formed in an OB association, and not in the quieter confines of a T association.

The T associations[2] are young unbound groups of low mass stars with ages of a few million years (Myr), characterized by dust clouds and T Tauri stars. Most of what we know about the formation of low mass stars is based on observations of T associations, because they are closer than OB associations and the stars are easier to study. That only a few T Tauri stars were known to be associated with the nearby OB associations was taken to mean that low mass stars did not form in great numbers in the OB associations. However, we now know that only a small percentage of the low mass stars form in T associations: most form in the OB associations, which are striking concentrations of short-lived, bright, high mass stars.

The very different environments of OB and T associations will influence the formation of the low mass stars and subsequent evolution of their protoplanetary disks. To infer the general properties of low mass pre-main sequence (PMS) stars and their protoplanetary disks from observations of T associations alone may lead to biased conclusions. Our purpose in this review is to draw attention to the low mass star formation in OB associations.

We concentrate here on the low mass stars of the Orion OB1 association (Brown, Walter, and Blaauw 1998 review the high mass stars). Our focus is on the more exposed parts of the complex, the fossil star formation regions (SFRs) of the Ori OB1a and Ori OB1b subassociations. We will not discuss Ori OB1c, which surrounds the sword, or Ori OB1d, the Orion Nebula Cluster (ONC), a dynamically young, partially embedded, active SFR associated with the Orion A cloud (Hillenbrand 1997) .

We begin with a brief review of low mass PMS stars. In § II we review the techniques used to identify low mass PMS stars. We discuss the Orion OB1 association in § III and IV, and speculate about the implications for star and planet formation in § V.

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[2] Under T associations we include all star forming regions except those dominated by OB stars. This encompasses such regions as Taurus-Auriga, Chamaeleon I, and ρ Oph, which include B and Ae stars.

A. The Low Mass PMS Stars in T Associations

T Tauri and other stars of its class are characterized by strong Balmer emission lines, ultraviolet and infrared continuum excesses, and erratic variability. They are generally found near dark clouds. Joy (1945) first identified these stars as a distinct class of objects. Ambartsumian (1947) concluded that these T Tauri stars were recently formed stars, and introduced the term “T association” for their groupings. Herbig (1962) arrived at similar conclusions. Cohen and Kuhi (1979) created a spectral atlas of the then-known classical T Tauri stars (cTTS). Herbig and Bell (1988) have produced the most current catalog of low mass PMS stars. Recent reviews of the cTTS and their evolution include those by Basri and Bertout (1993) and Stahler and Walter (1993).

In the 20 years since the launch of the *EINSTEIN* Observatory, X–ray imaging observations provided a new view of SFRs. Not only were some cTTS found to be strong soft X–ray sources, but many other X–ray sources present in these SFRs were identified optically as low mass PMS stars. Most of these newly-identified PMS stars lacked the strong line emission and the UV and near-IR continuum excesses of the cTTS, and were thought to be post-T Tauri stars (Herbig 1978) – stars which have lost their circumstellar material and were evolving towards the zero-age main sequence (ZAMS). Placement on the Hertszprung-Russell diagram showed that many of these stars had ages of a few Myr, comparable to those of the cTTS. Walter (1986) called these the naked T Tauri stars (nTTS), stars that had become unveiled, but they are more commonly referred to as the weak T Tauri stars (wTTS)[3].

Spurred in part by the realization that X–ray surveys could reveal a more complete population of low mass PMS stars, much effort went into studying the nearby T associations (e.g., Taurus [Walter et al. 1988; Neuhäuser et al. 1995b]; Chamaeleon [Feigelson et al. 1993; Alcalá et al. 1995]; Corona Australis [Walter et al. 1997]; ρ Oph [Montmerle et al. 1983; Casanova et al. 1995]; Lupus [Wichmann et al. 1997; Krautter et al. 1997]). These studies have shown, among other things, that

- The low mass population is dominated, at least at ages of more than about 1 Myr, by stars which do not have circumstellar disks (Walter et al. 1988; Strom et al. 1989).
- Low mass stars can form either in small clumps (cluster mode) or individually (distributed mode) (Strom et al. 1990).
- Most stars form in multiple systems. The binary fraction in T associations seems to be twice that of the field (Leinert et al. 1993; Ghez et al. 1993; Simon et al. 1993; Kohler and Leinert 1998).

[3] The definition of the wTTS is that the Hα equivalent width is less than 10Å, while the nTTS lack evidence for circumstellar material. All nTTS are wTTS; the converse is not always true.

- Low mass stars may be found far from their natal clouds, or may not be associated with any recognizable cloud (Walter et al. 1988; Alcalá et al. 1995; Neuhäuser et al. 1995c; Kastner et al. 1997).
- The distribution of rotational periods is bi-modal, with both slow rotators, whose periods are set by disk-breaking, and a rapidly rotating population representing stars which have spun up as they contract along their Hayashi tracks (Edwards et al. 1993; Bouvier, Forestini, and Allain 1997).
- There is a large spread of stellar ages in T associations.

The large age spread suggests that the star-formation lifetime of a molecular cloud is related to the sound-crossing time-scale of the cloud (Herbig 1978), or to the ambi-polar diffusion timescales. Given the typical 1 to 2 km s^{-1} velocity dispersion within associations (Herbig 1977, Hartmann et al. 1986, Frink et al. 1997), one would expect the older population to have dispersed far from the cloud. The lack of these older stars gives rise to the post-T Tauri problem. Palla and Galli (1997), however, noted that star formation is not a steady process, but that it runs slowly and less efficiently in the first few million years of the cloud life-time. Hence, there should be only few post-TTS, but many coeval cTTS and nTTS.

B. The Low Mass PMS Stars in OB Associations

While the T associations produce perhaps a few thousand stars over their 10-30 Myr lifetimes, the OB associations are far more productive, though for a shorter interval. OB associations are loose, easily identifiable concentrations of bright high mass stars (see Humphries 1978; Blaauw 1964). Ambartsumian (1947) showed that their typical mass densities of <0.1 $M_\odot$ pc^{-3} are unstable to galactic tidal forces, and therefore they must be young. This conclusion is supported by the ages derived from the Hertzprung-Russell diagrams for these associations.

Blaauw (1991) reviewed the nearby OB associations and their relation to local star formation. The older OB associations retain a fossil record of star formation processes in a giant molecular cloud. The very process of formation of the massive stars disperses the giant molecular cloud and thereby disrupts further star formation.

One can estimate the importance of OB associations for low mass star formation. Within 500 pc of the Sun lie 3 OB associations (Ori OB1, Sco-Cen-Lup, and Per OB2) and a number of T associations (Tau-Aur, Cha, CrA, Lup, TW Hya). Assuming a Miller-Scalo mass function in the OB associations, and counting stars in the T associations, one can show that over 90% of the low mass stars with ages less than about 10 Myr are likely to be members of OB associations.

It had long been thought that star formation was bi-modal, in the sense that high mass stars did not form in T associations, and that low mass stars did not form in great numbers in OB associations (e.g., Larson 1986, Shu and Lizano 1988). We now know that the latter is not true. Hα surveys suggest that Hα-emitting stars are found not only in the actively star-forming parts of giant molecular clouds (e.g., Haro 1953; Duerr et al. 1982; Strom et al. 1990), but also abound in the fossil OB associations (e.g., Kogure et al. 1989; Nakano et al. 1995).

Walter et al. (1994) investigated the low mass population of the Upper Sco association (de Geus, de Zeeuw, and Lub 1989), a 5 Myr old association at a distance of $\sim$140 pc. Starting with EINSTEIN X–ray observations, they found a low mass PMS population, whose properties appear significantly different than those found in T associations.

- The space density of PMS stars is higher than that in Taurus by about a factor of 3.
- The low mass stars seem to be coeval, at an age of 1-2 Myr.
- The low mass PMS population is largely devoid of circumstellar material and near-IR excesses, even at this age.
- The distribution of rotational periods is not peaked, suggesting that the association is observed during an epoch when all the stars are spinning up (Adams et al. 1998).
- Between 10 and 0.3 $M_{\odot}$, the mass function $dlogN/dlogM$ is consistent with the field star initial mass function (Miller and Scalo 1979).

Sciortino et al. (1998) reached similar conclusions about the Upper Sco Association based on ROSAT observations. Brandner and Köhler (1998) suggested that the binary fraction of PMS stars in OB associations is about half that observed in the T associations, and is comparable to that of the field. They note that the binary fraction may be smaller yet near the OB stars.

The nearest giant molecular cloud complex and site of active star formation is in Orion – the Orion A and B clouds and the Orion OB1 association. All stages of the star formation process can be found here, from deeply embedded protoclusters to fully exposed OB associations. The different modes of star formation occurring in these clouds (clustered, distributed, isolated) allow us to learn more about the influence of the environment on the star formation process.

We study the Ori OB1a and OB1b fossil SFRs because in these regions star formation is complete, all the stars are visible (few embedded sources remain), and the stars are at their final masses. Yet these fossil SFRs are sufficiently young (2-10 Myr) that the full population remains cospatial, and that spatial substructure in the star formation process may still be detectable.

II. How to find low mass PMS stars in associations

To study the global processes of low mass star formation, one must identify and sample all the populations of low mass PMS stars. The embedded sources, the cTTS, and the nTTS may represent different populations, with different spatial and age distributions. All the populations, or their evolutionary descendents, are present (and none are hidden) in fossil SFRs. The cTTS tend to be readily identifiable either photometrically, because of their variability or their prominent near-IR continuum excesses, or spectroscopically, through their strong emission lines. However, the vast majority of the low mass PMS stars are not so easily discovered. Their coronal X–ray and chromospheric emission line fluxes are little stronger than those of active ZAMS stars, they have no continuum excesses, and they are no more variable than heavily spotted, active late-type stars. We review methods of searching for the nTTS and wTTS, and identifying the complete PMS population of an association.

A. X–Ray surveys

Low mass PMS stars have X–ray luminosities between 10^{29} and 10^{31} erg s^{-1}, reflecting the strong magnetic activity of these stars. The X–ray surface flux scales with the stellar mass (Walter 1996), which gives an apparent rotation-activity correlation because stellar rotation rates increase with increasing mass. There is no clear evidence that either the X–ray surface flux or the ratio of the X–ray-to-bolometric flux correlates with stellar rotation[4]. The surface flux of the PMS stars is somewhat lower than the "saturated" value seen in the rapidly rotating dwarfs in the Pleiades (Stauffer et al. 1994).

The high X–ray luminosities, at a characteristic temperature of about 1 keV, are easily detectable in short pointed X–ray imaging observations, or in flux-limited surveys like the ROSAT All-Sky Survey (RASS; eg. Voges et al. 1996). Although most cTTS have been detected as X–ray emitters, they tend to be fairly heavily absorbed, so their mean observed fluxes in soft X–rays are lower than those of the nTTS. Neuhäuser et al. (1995a) argue that the cTTS are also intrinsically less X–ray-luminous than the nTTS. The detection rate for cTTS in the RASS is only 15% (Neuhäuser et al. 1995a). The detection efficiency of unveiled stars is unknown, but deep pointings seem to recover 70-80% of the photometrically-identifiable PMS stars (Walter, Wolk, and Sherry 1998). These X–ray surveys complement optical Hα emission line surveys that mainly yield cTTS.

The complete sky coverage of the RASS to a flux-limit of $\approx 1-2\times10^{-13}$ erg cm^{-2} s^{-1} has permitted unbiased analyses of the spa-

[4] This is not surprising. Among the Pleiades G stars (Stauffer et al. 1994), a rotation-activity relation is seen only for v sin i <15 km s^{-1}. Nearly all PMS stars rotate more rapidly.

tial distribution of X–ray active stars, including low mass PMS stars. However, the complete identification and classification of all detected sources requires optical spectroscopy of each of the possible counterparts of an X–ray source. Neuhäuser et al. (1995b) and Sterzik et al. (1995) established a discrimination criterion, based on X–ray spectral appearance and f_x/f_v of known TTS, for selecting PMS candidates. Sterzik et al. (1995) applied it to map the large-scale spatial distribution of young stars in a 700 deg^2 field centered on the Orion SFR. The spatial distribution of the stellar X–ray sources selected in this way gives a qualitative idea of the general morphology of the SFR, by tracing the X–ray active young stellar population[5].

The $\sim 10^{-14}$ erg cm^{-2} s^{-1} limiting fluxes of existing X-ray observations, together with the $f_x/f_v \sim 10^{-3}$ typically seen in the PMS stars, means that the X-ray pointings can select optical counterparts down to about V=15. At the distance and age of Ori OB1, this corresponds to ≈ 0.5 $M_\odot$.

B. Spectroscopy

The most certain way to identify low mass PMS stars is by their optical spectra.

The principle spectroscopic characteristic of low mass PMS stars is the 6707Å line of Li I. This line is generally considered to be an indicator of youth because the depletion of Li in the outer layers of convective low mass stars is very rapid. Lithium is easily destroyed by convective mixing in the stellar interiors when the temperatures at the bottom of the convective layer reaches about 2.5×10^6 K (Bodenheimer 1965; D'Antona and Mazzitelli 1994). The surface Li abundance is indeed anticorrelated with the stellar age in convective stars (Duncan 1981). Among the G and K stars, there is no significant Li destruction on the convective track, so lithium can be used as a criterion to identify low mass PMS stars of G and K spectral types. Many PMS stars do exhibit abundances ($\log[n_{\rm Li}]=3$) consistent with undepleted cosmic material (e.g., Basri, Martin, and Bertout 1991).

PMS lithium burning is expected among the M stars (e.g., Pinsonneault, Kawaler, and Demarque 1990). Walter et al. (1997) observed this among the lowest mass PMS stars of the CrA association, but the depletion was greater than expected by the models. They noted that

[5] The main source of contamination of X–ray surveys is by active ZAMS stars that have X–ray colors and activity levels similar to those of the PMS stars, and that are expected to dominate among field star X–ray emitters (ages up to about 10^8 years; Briceño et al. 1997). Such stars are still young, but not necessarily PMS; their ages must still be determined from observations of the space motions and parallaxes. A second source of contamination is active binary stars and RS CVn systems, for which high levels of X–ray activity are maintained by tidal coupling of the close binary system.

this could be accounted for by the fact that the presence of an active chromosphere/transition region will over-ionize Li relative to LTE, giving an apparent underabundance (Houdebine and Doyle 1995). In the CrA association, the M stars with the largest Hα emission equivalent widths do exhibit the smallest apparent Li abundances.

The nTT stars exhibit strong chromospheric emission at Hα, Ca II K&H and Mg II k&h. The transition region emission lines are at saturated levels. The saturated chromospheric Hα emission surface flux of order 10^7 erg cm^{-2} s^{-1} (averaged over the star) is sufficient to cause an emission line above the photosphere only among the late K and M stars. While such activity appears commonplace among the PMS stars, it is not unique and cannot be used to identify a star as PMS. Walter and Barry (1991) discuss the timescales for the decay of the chromospheric and coronal emissions.

The cTTS show far stronger levels of chromospheric and transition region emission, including the hydrogen Balmer lines, the Ca II K&H resonance lines, the FeII λ 4924 Å and the fluorescence lines of FeI $\lambda\lambda$ 4063 and 4132 Å in emission (Herbig 1962). We now know that much of this flux arises, not in a compact solar-like chromosphere, but in an extended atmosphere and accretion flows (e.g., Hartmann, Hewett and Calvet 1994; Muzerolle, Hartmann, and Calvet 1998). Bastian et al. (1983) defined a phenomenological working definition for cTTS as having an Hα emission equivalent width of >5Å, to discriminate against dMe stars, and in general a 10Å Hα emission equivalent width is used to discriminate between the cTTS and the nTT or wTT stars. The emission line spectra of cTTS also often have forbidden lines of [S II] and [O I] that, together with a broad Hα emission line profile and P Cygni line profiles, are diagnostics of strong winds (e.g., Mundt 1984; Hartigan, Edwards, and Ghandour 1995).

Radial velocities are powerful tools for establishing membership in a particular cluster or association, because the dispersion in radial velocities of an association is 1-2 km s^{-1} (e.g., Hartmann et al. 1986). Proper motions (e.g., Jones and Herbig 1979; Frink et al. 1997) can also be used to establish likely membership.

Star formation regions are big: efficient searches must survey large solid angles. Traditionally, objective prism surveys with photographic plates have been used to survey for Hα emission-line objects. Most known cTTS have been discovered in such surveys. Herbig, Vrba, and Rydgren (1986) used objective prism techniques at Ca II K&H. They could identify emission from M stars, but the bright $\lambda\lambda$3900-4000Å continuua of the K stars greatly reduce sensitivity for hotter stars. Because of the generally low spectral resolution (>10Å), objective techniques are not suitable for measuring relatively weak absorption lines, like the important Li I line.

Once limited to single objects, high resolution spectroscopy is now commonly undertaken in survey mode, due to the maturation of optical fiber technology and multi-object spectroscopy. One can obtain high resolution spectra of hundreds of objects within a field as large as a square degree simultaneously. At these higher resolutions, weak absorption lines such as Li I λ6707Å can be resolved from the Ca I λ6717Å line, and radial velocities can be measured for all the objects in the field. Examples of such data are given by Walter, Wolk, and Sherry (1998).

C. Wide field imaging photometry

In an area with little interstellar and circumstellar reddening, optical color-magnitude diagrams (CMDs) are a powerful tool for selecting PMS stars. Large CCD arrays coupled with small (1-meter class) telescopes can map out large areas of the sky fairly efficiently. Star identification algorithms such as DAOPHOT are robust in rejecting objects with non–stellar point spread functions and provide very reliable photometric results at the mean stellar densities observed in the Orion OB1 association (about 2 stars brighter than V=18 per arcmin^2).

In practice, we use the known PMS stars to define the PMS locus in the V vs. V–R or V vs. V–I CMD. As the reddening vector is nearly parallel to the PMS locus in these CMDs, it is not important to know the reddening in order to identify the PMS candidates. While the X–ray sources calibrate the PMS locus to about V=15, the optical photometry extends to V$\sim$20 even in short exposures.

For example, we have obtained CCD photometry of a 2200 arcmin^2 region in Orion's belt (Ori OB1b), near σ Ori. Completeness of these images, as determined by number counts, was V=22, with some stars as faint as magnitude V=23 detected in at least three colors. The data (Fig. 1) bifurcate into two distinct groups: a group of stars, including most of the X–ray sources, which lies in a diagonal band across the diagram, and a set of background stars below the band. These data will be discussed in § IV.

III. LOW MASS STARS IN ORI OB1: LARGE SCALES

The Orion complex covers about 25° in declination (including the λ Ori region) and one hour in right ascension. Surveys for low mass stars over this entire area are important for studies of the subassociation boundaries, the history of star formation, and the kinematics of the association and its interactions with the molecular gas.

A. Hα Surveys

The Kiso objective prism survey in Orion (Wiramihardja et al. 1989; 1991; 1993; Kogure et al. 1989) revealed 1157 Hα emission line objects over an area of 150 deg^2 from 5.15^h to 5.85^h in right ascension and from -13.0° to +2.8° in declination, to a limiting magnitude of

V=17.5. The magnitude distribution, peaked around V=15, supports a classical T Tauri nature for these objects. Kogure et al. (1992) followed-up with low-dispersion spectroscopic observations of 34 emission line stars in Ori OB1b, and concluded that they were indeed T Tauri stars based on H-Balmer and CaII K emission lines. Nakano and McGregor (1995) obtained near-IR photometry for a number of these stars, and also concluded that they were mostly T Tauri stars.

The spatial distribution of the Kiso Hα emission-line objects is shown in the left panel of Figure 2. Concentrations of emission-line objects coincide with the general location of the NGC 2023 and NGC 2024 clusters, the OB1c, OB1b, and OB1a associations. Note that emission line objects are also found far outside the limits of the OB1 associations.

B. ROSAT Survey Results

The surface density distribution of X–ray-selected PMS star candidates in a 700 deg^2 field around the Orion molecular clouds (Sterzik et al. 1995) shows peaks associated with subgroup associations (OB1a, OB1b, OB1c, and λ Ori). The spatial extent of the density peaks is consistent with dispersal times between 2 and 10 Myrs, the ages of the stellar components in these regions. Surprisingly, the largest fraction of the PMS star candidates in this sample is not in this 'clustered' population but is distributed widely over an area many times greater than that of the molecular gas or the OB stars. A large number of sources are seemingly unrelated to any molecular clouds or fossil SFR. This distributed population has also been found around other nearby SFR's such as Taurus-Auriga (Wichmann et al. 1996), Lupus (Krautter et al. 1997), and Chameleon (Alcalá et al. 1995).

To explore the nature of these PMS candidates, Sterzik et al. (1997) extended their earlier analysis to a larger area around Orion. They interpreted the spatial distribution of PMS candidates (Fig. 3) in the framework of a stellar population model of the galaxy. The 6482 RASS sources in the $\sim$ 5000 deg^2 field include a subsample of 1467 PMS candidates. The densest regions (up to 10 stars/deg^2) coincide with centers of active star formation, e.g., in the Orion nebula region, near λ Ori, and in well-known star forming sites in the Taurus clouds. In all these cases, the expected sensitivity for selecting young stars is verified. In addition, other clusters (e.g., around NGC 1788 [§ IV.C]) which have not previously been recognized as prominent SFR's, are also detected with this method, and are likely to harbor a high fraction of PMS stars.

Figure 3 shows that the Orion and Taurus SFRs are projected against an $\sim$10° wide strip of apparently young stars (density <1 star/deg^2 above the RASS detection limit). Although Orion and Taurus are at different distances from the Sun, they seem to be connected by a broad lane that extends further southeastward. This contiguous structure is not symmetric about the galactic plane, but rather follows the mean location of the Gould Belt as defined by early type stars in this direction (Blaauw 1991). The surface density of young star candidates drops down to a background value of about 0.1 candidate stars/deg^2 near $b_{II} = 0°$, and below that value at high galactic latitudes.

Based on the morphology and surface density distribution of X–ray selected young star candidates, and detailed comparisons with the predictions of a galactic X–ray population model (Guillout et al. 1998), Sterzik et al. (1997) show that the X–ray population consists of a mixture of three distinct populations: (1) The *clustered population* comprises the dense regions associated with sites of active or recent star formation (e.g., OB1a, OB1b, OB1c, λ Ori, NGC 1788). (2) The strip connecting Orion and Taurus, which coincides with Gould's Belt. (3) The *background population* having a density ~ 0.1 stars/deg^2 near the galactic plane, which is likely dominated by ZAMS stars.

C. Optical followups to the ROSAT Survey

The spatial distribution of 671 PMS candidates in the RASS sample is shown in the right panel of Figure 2. There is an apparent spatial coincidence between those regions of high X–ray source density and those of high densities of Hα emission objects from the Kiso survey. An immediate conclusion would be that many of the emission-line objects are detected in X–rays, but this is not the case. Fewer than 5% of the Kiso emission line stars are coincident with RASS PMS candidate X–ray sources. Although the Kiso survey goes deeper than the expected optical magnitude of PMS stars detectable in the RASS, over 90% of the RASS X–ray sources are not coincident with an emission-line star. We note that only a handful of emission-line objects in the λ Ori region (Duerr et al. 1982) coincide with RASS sources.

The lack of coincidences between the RASS sources and the Hα emitters is a consequence of the fact that cTTS are more difficult to detect in soft X–rays than nTTS, perhaps because X–rays are efficiently absorbed in the dense circumstellar envelopes of cTTS (Walter and Kuhi 1981) or because nTTS rotate faster than cTTS (Bouvier et al. 1993; 1995). The important implication is that most of the PMS stars are not emission-line objects.

Alcalá et al. (1996) observed a spatially unbiased sample of 181 RASS sources, using intermediate resolution long slit spectroscopy and photoelectric photometry. They identified 112 stars which showed Li absorption and a late-type spectrum. These low mass PMS star candidates have a spatial distribution indistinguishable from that shown in the right panel of Figure 2.

More recently, Alcalá et al. (1998) placed a representative subsample of these stars in the HR diagram assuming a distance of 460 pc and found that they fall well above the main sequence with typical T Tauri masses and ages ($0.8 < M_{star}/M_{\odot} < 3.4$; $0.2 < \tau_{age}(\mathrm{Myr}) < 7$). They found that the stars with stronger Li I (λ 6707Å) line tend to concentrate toward the Orion molecular clouds, but they did not find any other correlations between the spatial location, age, or other stellar parameter. The lack of stars with masses less than $0.8 M_{\odot}$ in this sample is simply due to the flux limit of the RASS, and the approximately constant f_x/f_v of PMS stars.

To verify the Li measurements (which are blended at moderate resolution), and to obtain radial velocities, which can be used to distinguish association members from non-members, Alcalá et al. (1999) undertook high resolution (R=25,000) spectroscopic observations of many of the 112 stars in the Alcalá et al. (1996) sample.

The distribution of radial velocities of the RASS stars in Orion which have strong Li and appear to be PMS is shown in Figure 4. The radial velocity distribution is broad with a velocity dispersion of about 9 km s^{-1} and apparently shows a double peak, one at $\approx$18 km s^{-1} and the other at $\approx$25 km s^{-1}. The former coincides with the mean radial velocity for Orion, while the latter appears to coincide with the radial velocity of the Taurus clouds. This suggests that the RASS PMS sample in Orion is a juxtaposition of two distinct groups of stars, one associated with the Orion SFR. The relation of the other group to the Taurus SFR is unclear, as these stars would lie a minimum of 50-80 pc from the currently-active star formation in the Taurus clouds. This group might be related to the Gould's Belt population (§ III.B).

There is no statistical difference in the lithium strength between the two radial velocity groups: most of the stars have lithium abundances comparable to those of low mass PMS stars. We conclude that most of these stars in the RASS sample are indeed PMS, and that at least some are demonstrably members of the Orion association.

IV. LOW MASS STARS IN ORI OB1: SMALL SCALES

On scales of a few degrees or less, the Orion OB1 association breaks up into individual subassociations. Orion is sufficiently young that the subassociations retain their individual identities. One can investigate the timescales of the star formation process, and study the initial mass function and mass segregation. Aside from the obvious differences in age and total mass, just how similar are these subassociations?

A. The Belt

A series of ROSAT PSPC pointings (Walter 1994) in the belt of Orion revealed hundreds of X–ray sources, of which many are now confirmed low mass PMS stars, based on spectroscopic and photometric followups. We have concentrated our efforts on the region surrounding σ Ori (Walter, Wolk, and Sherry 1998). The ROSAT PSPC and HRI observations reveal over 100 X–ray point sources within 1° of σ Ori, a member of Ori OB1b and a Trapezium-like system.

Walter, Wolk, and Sherry (1998) obtained spectra of most of the optical counterparts of the X–ray sources near σ Ori, and of a randomly-selected sample of nearby stars. Among these ∼300 stars, they identified 104 likely PMS stars within 30 arcmin of σ Ori. Primary identification was made on the basis of a strong Li I λ6707Å absorption line. The Hα strengths range from an emission equivalent width of 77Å in a K1 star to normal photospheric absorption. The distribution of radial velocities is strongly peaked at the 25 km s^{-1} velocity of the OB association (Fig. 5).

The color-magnitude diagram (Fig. 1) for 0.6 deg^2 surrounding σ Ori shows a clear PMS locus, well separated from the background galactic stars. The narrowness of the PMS locus suggests coevality, but an age less than the 1.7 Myr age of the OB association.

The spectroscopic sample, which is spatially uniform and statistically complete to about V=15, has a surface density of 120 PMS stars/deg^2 (10$<$V$<$15), and shows evidence for clustering. The centroid of the PMS star distribution is centered on the position of σ Ori. Summation of the stars into radial bins centered on σ Ori shows that the distribution is flat for the non-PMS stars, but that the radial distribution of the PMS stars is peaked at σ Ori. The inferred cluster radius (where the density of PMS stars reaches zero) is about 0.5 deg (3.3 pc). If all the PMS stars are distributed in this way, then the space density, in the magnitude range $12< V <19$, is about 400 stars per deg^2 (or more, if many stars are multiple). The total inferred mass of this group of stars is about half that of the ONC. The σ Ori cluster is the *second youngest* cluster now known after the ONC, and may be an evolved analog of the ONC.

Wolk (1996) showed that about 30% of these stars are slow rotators and 70% are rapid rotators. Similarly, about 30% of the spectroscopically-identified PMS stars have strong Hα emission, and appear to be cTTS. This suggests that, at an age of about 2 Myr, 30% of the low mass stars near σ Ori retain their circumstellar disks. This is a higher fraction than seen in Upper Sco (Walter et al. 1994) at a similar age.

The existence of the σ Ori cluster implies that there is substructure in Ori OB1b. As there is no evidence for evolutionary differences between the early-type stars in Ori OB1b (Brown et al. 1994), it may be that Ori OB1b formed through the merging of several Trapezium-like clusters that formed at more or less the same time. Observations are underway to test this hypothesis.

B. Ori OB1a

Observations of five other regions in Ori OB1 reveal similar concentrations of PMS stars, with space densities (V$<$15) from about 40 to 150 stars/deg^2, comparable to that near σ Ori. We find the highest space density of PMS stars within the Ori OB1a association, near

$5^h\ 24^m\ +1°$. This sample of stars includes no slow rotators (rotation periods longer than 4 days; Wolk 1996), and only one classical T Tauri star, suggesting that essentially all circumstellar disks have dissipated by the ~10 Myr age of this association. The CMD is similar to that for the σ Ori region, except that the PMS stars appear older. For a 330 pc distance (Brown, Walter, and Blaauw 1998), the PMS stars lie above the 10 Myr locus expected from the age of the B stars. In general, the low mass stars in OB associations appear younger than the high mass stars. This effect is evident in σ Ori, in the λ Ori region (Dolan 1998), and in the Upper Sco association (Walter et al. 1994).

C. NGC 1788

A significant density enhancement of RASS PMS candidates is present near the reflection nebula NGC 1788, which coincides with the CO-clump #13 of Maddalena et al. (1986) at $\alpha \approx 76°$ and $\delta \approx$ -3.5°. This reflection nebula is centered on a cluster of stars and illuminated by the B9V star HD 293815 (Witt and Schild 1986). The cluster seems heavily obscured by foreground material, consistent with gas column densities $> 5 \times 10^{22}$ N_{H_2} derived from $^{12}CO/^{13}CO$ line ratio observations (Knapp et al. 1977). This high column density is likely to hide most X–ray sources in the cloud itself. One cTTS, LkHα 333, is known in its vicinity. A surface density of $\approx$ 4 sources/deg^2 in an elongated structure of 3° length and 1.5° width is detected in the RASS. A preliminary analysis of the recent HRI pointing resulted in the discovery of more than 50 additional X–ray sources, probably embedded in the molecular cloud. The relatively small width of the density enhancement would indicate a diffusion age of less than 5 Myr, if these stars have formed in a central cluster with a dispersion velocity of 2 km s^{-1}. More support for the existence of a young cluster near NGC 1788 follows from recent near-infrared imaging by Dougados et al. (in preparation).

Unlike the fossil SFRs, NGC 1788 appears to be a region of ongoing star formation far from the Orion A and B clouds. Its relation to the Orion complex is not known.

D. Run-Away T Tauri Stars and the Distributed Population

Not all PMS stars are found in or near molecular clouds: RASS observations have shown that a distributed population of PMS stars appears to be a common characteristic of SFRs. While such a distributed population may have formed locally (e.g., Feigelson 1996), Sterzik et al. (1995) suggested that the PMS stars in the distributed population were ejected from their birth clouds with high velocities. They called such stars "run-away TTS" (raTTS). Few-body encounters can happen early in the lifetime of a multiple protostellar system, so that they are also of relevance in establishing the fraction of binary (and triple) PMS stars. Many on-cloud PMS stars are multiples, so the multiplicity must be established very early in the PMS phase (e.g., Leinert et al. 1993, Ghez et al. 1993, Mathieu 1994 and chapter by Mathieu et al., this volume). In star-star or star-cloud encounters such as those studied by Sterzik and Durisen (1995), ejected raTTS are either single stars or close binaries, and should be on average less massive than average TTS. Gorti and Bhatt (1996) modeled the ejection of protostars in encounters of protostars with clouds, and found that some protostars can be ejected in such a way. Kroupa (1995) showed that several percent of the members of a cluster as rich as the Trapezium can be ejected by close encounters with velocities exceeding 5 km s^{-1}.

The characterization of any individual star as an raTTS requires detailed knowledge of their space motions and ages. There are a few well-studied stars in Orion whose space motions, locations, and ages indicate that they may well be raTTS. These include: Par 1540 (Marschall and Mathieu 1988) which may have been ejected from the ONC $\sim 10^5$ years ago; Par 1724 (V1321 Ori; Neuhäuser et al. 1998), which is moving north at about 10 km s^{-1}, and may also have been ejected from the ONC $\approx 10^5$ yrs ago; and RXJ0511.2+1031 (Magazzù et al. 1997; Neuhäuser et al. 1997) which may have originated in the λ Ori region.

These examples show that there are indeed very young stars far away from star forming clouds, whose space motions point back to those clouds. RaTTS certainly do exist, and if they are numerous the RaTTS may be the bridge between the star formation, occurring on small scales, and the observed large scale distribution of PMS stars observed after a few million years.

V. APPLICATIONS AND IMPLICATIONS

A. The Low End of the Mass Function

Very low mass (VLM) objects – the lowest mass stars as well as substellar mass objects – are quite bright when young. A 2 Myr old star at the hydrogen burning limit (0.08 $M_\odot$) is only about 10 times less luminous than the Sun (Burrows et al. 1997). At the distance of Orion, such stars will have V$\approx$19, which is easily observable with small telescopes. By the age of the Pleiades, VLM stars have faded by about 3 magnitudes at V, and are some 200-400K cooler. So while IR studies and large telescopes (e.g., Stauffer, Hamilton, and Probst 1994; Zapatero Osorio, Rebolo, and Martin 1996) are required to detect VLM objects in clusters like α Persei and the Pleiades, a more modest approach will yield similar results in nearby SFRs.

At the 2 Myr age of Ori OB1, a star near the H-burning limit will have V–R$\sim$1.2 (Baraffe et al. 1998). Our deep photometry of the σ Ori field (Fig. 1) shows that the empirical PMS locus seems to continue into the brown dwarf regime. To determine whether the red colors are intrinsic, or are due to extreme reddening, Wolk (in preparation) has obtained low resolution spectra of several of these objects. The filled circle in Figure 1 redward of the theoretical brown dwarf limit is of spectral type M6 with minimal reddening. M6 is the spectral type of the Pleiades brown dwarfs PPl15 and Teide 1, confirmed by the "Lithium test" (Basri, Marcy, and Graham 1996). Since a younger object of the same spectral type must be less massive, it is highly likely that our object is of substellar mass. It is unlikely that all the other very red objects are subject to extreme reddening. The 2200 arcmin^2 area included in Figure 1 contains 8 additional brown dwarf candidates both fainter and redder than the candidate discussed above.

Color-magnitude diagrams of 2200 arcmin^2 around δ Ori and of 1100 arcmin^2 around ϵ Ori reveal 9 photometric brown dwarf candidates. This is a density of about 12 brown dwarfs per deg^2, and suggests that there may be an abundance of substellar mass objects in OB associations.

B. The Initial Mass Function

The easiest time to determine the initial mass function (IMF), the relative numbers of stars as a function of mass, is early in the life of an association or a cluster, before high mass stars burn out, and before dynamical friction segregates the masses and ejects the lower mass systems. Studies of unobscured fossil SFRs – the OB associations – afford all of the advantages of studying the IMF in embedded clusters (chapter by Meyer et al., this volume), and none of the disadvantages encountered in highly obscured regions where the stars may not yet have reached their final masses. At ages of a few Myr, one can readily see to – and below – the hydrogen-burning limit. The ability to identify PMS stars independent of their activity levels gives the opportunity to identify a (statistically) complete population of PMS stars. In OB associations we can directly observe and measure the IMF from O stars through substellar mass objects.

The published data suggest that there is a universal slope to the mass function in associations, and that it is similar to the field star mass function (Miller and Scalo 1979). Walter and Boyd (1981) found that the mass function in Taurus approximated the field star mass function from a few solar masses to about 0.3 $M_\odot$; Walter et al. (1994) found the same in Upper Sco. Hillenbrand (1997) found the mass function in the ONC to agree overall with the Miller and Scalo IMF, though with some differences in detail. This universality should not be surprising, because most stars are born in associations, which disperse to populate the field. However, the question of whether there are small differences in the mass function between associations remains open.

One place where differences may exist is at the low mass end of the mass function. Brown dwarfs appear to be rare in T associations (e.g., Stauffer et al. 1991), although recently Luhman et al. (1997) and

Neuhäuser and Comerón (1998) reported finding brown dwarfs in the ρ Oph and Cha I SFRs, respectively. But there appears to be a high density of VLM objects in Ori OB1b. This may be a simple consequence of the differences between the T and OB association environments. A low mass protostar in a T association is able to accrete mass for a time set by the accretion process and the local environment. However, in an OB association, the mass accretion can be terminated abruptly as the local cloud is disrupted by nearby massive stars (see Walter et al. 1994), either due to winds or supernovae. So while in a T association a protostar may accumulate a significant fraction of the mass within its original Jean's radius, a low mass protostar in an OB association may never accrete that last fraction of a solar mass, and VLM stars may end up with substellar masses. OB associations may be the place to search for brown dwarfs.

There is some evidence that this may indeed be the case. In the Taurus T association, the typical PMS star is spectral type K7-M0, suggesting a mass function peaking near 0.3-0.4 $M_\odot$. Walter et al. (1994) found the typical low mass PMS star in Upper Sco to be early M, and found that the mass function extended to 0.2 $M_\odot$. Hillenbrand (1997) finds a mass function peaking at 0.2 $M_\odot$ in the ONC. If the mass functions are different in OB and T associations, it will have profound consequences for where one looks for brown dwarfs, or perhaps for large planets.

C. Disk survival times and implications for planets

We cannot yet directly detect planets orbiting PMS stars in Orion, or in any SFR. We cannot yet detect terrestrial-size planets anywhere. We can detect circumstellar disks, which are likely to be a necessary ingredient for planet formation, but we do not know how the disk turns into planets. Models which qualitatively explain the distribution of planets in our solar system fail to predict the existence of giant planets close to their stars (but see chapter by Lin et al., this volume). An observer of stars and disks can only speculate about how planets might fare in an OB environment, but can describe those conditions under which planet formation must proceed.

Elsewhere in this volume, Hollenbach et al. discuss the evaporating disks seen in HST images of the Orion Nebula. In a simple picture, longer-lived disks provide more time for planets to form, and disks in T associations may survive longer than disks in OB associations. One needs about a million years to form a Jupiter (see review by Wuchterl et al. in this volume). In the ONC, with a nominal age of about 0.5 Myr, about half the low mass PMS stars seem to have disks (Hillenbrand 1997). In the older σ Ori cluster (nominal age 1.7 Myr), about 30% seem to retain disks, based on using rotation periods and Hα emission as disk proxies, while by the age of Ori OB1a there is little evidence for disk survival. The disk survival times do appear to be short in OB associations.

Short disk survival times may not impede the formation of terrestrial planets: small bodies can form very quickly, and need not accumulate in the presence of gas (Weidenschilling and Cuzzi 1993; Lissauer and Stewart 1993). Indeed, short disk survival times may be advantageous for terrestrial-sized planets. Lin, Bodenheimer, and Richardson (1996) suggest that giant planets tend to migrate inwards in the presence of a disk, sweeping ahead of them all planetesimals which may have formed in the inner planetary system (see also the reviews in this volume by Lin et al. and by Ward and Hahn). Short disk survival times may prevent such orbital migration, and protect small inner planets. Thus one could make a case that planetary systems like our own may be most likely to form in environments like OB associations.

D. Summary

There is a wealth of knowledge to be gained about the global processes of star formation from studying the low mass population of OB associations. The IMF is best determined in fossil star formation regions, because all the stars are readily countable, and have reached their final masses. The ages of the low mass stars can be estimated more accurately (subject to systematic uncertainties in the evolutionary models) than can the ages of massive stars already on the main sequence, permitting studies of the coevality of star formation across the association. The apparent difference in ages between the high- and low-mass stars may provide information about the triggers and timescales of low mass star formation. The radial velocities of the low mass stars can often be measured more precisely than can those of the rapidly rotating O and B stars, and can provide more definitive measures of the kinematics of OB associations. The spatial distribution of the numerous low mass stars can yield insights into the substructuring of the associations.

Low mass stars, revealed by X–ray and Hα surveys, abound in the fossil SFRs of Orion OB1. The PMS stars not only concentrate in the known subassociations, but are also distributed over a much larger volume than are the OB stars. Optical photometry shows that the PMS stars have a narrow age spread, and extend down to substellar masses. The high density of brown dwarf candidates in Ori OB1b may be a consequence of star formation in the OB environment. The ONC is not the only young cluster in Orion; σ Ori has its own cluster. Subclustering may be common: the belt of Orion may be the amalgamation of ONC-like systems which formed at about the same time.

Most low mass stars in our galaxy likely formed in large OB associations like the Orion OB1 association. There is circumstantial evidence that our Sun may have formed in an OB association 4.6 Gyr ago. If so, then star formation in the OB environment does not preclude the formation of planetary systems, and we can be optimistic that planetary systems like our own are common in the galaxy.

FIGURE CAPTIONS

Figure 1. The color–magnitude diagram for all stars (dots) in the 2200 square arcminute region centered on σ Ori. Effective temperatures are derived from Bessell (1995). The dashed lines trace the expected pre-main sequence locus. The vertical dotted line indicates the brown dwarf cut–off derived in Baraffe et al. (1998) with corrections for "missing opacity" and mean reddening. The "X's" indicate X–ray sources confirmed to be PMS by their spectra. Filled circles are photometrically–selected and spectroscopically–confirmed PMS candidates. "T's" indicate classical T Tauri stars among these confirmed candidates. Open circles are photometric candidate PMS stars whose V–R and R–I colors are consistent with PMS nature (uncircled dots within the PMS locus have discrepant R–I colors), but for which we have no spectra. The A_V=1 reddening vector is indicated. The clear separation of the PMS stars from the general distribution of background stars: demonstrates the efficacy of using wide-field optical photometry to identify low mass PMS stars in OB associations.

Figure 2. Spatial distribution of the Hα emission line objects found in the Kiso survey (left panel) and of the ROSAT all-sky survey X–ray sources in Orion (right panel). The position of the OB1 associations as well as the NGC 2023 and NGC 2024 clusters (Zinnecker et al. 1993) are indicated in the left panel. The outlines of the CO survey by Maddalena et al. (1986) are also show. The dashed square in each panel indicates the extents of the Kiso survey. While the strongest density enhancements in both the Hα and X–ray source densities are associated with the Orion A cloud, significant numbers of sources extend out beyond the molecular cloud.

Figure 3. Large-scale spatial distribution of candidate young stars in Orion and Taurus-Auriga. The X–ray sources (dots) have been selected from the ROSAT All-Sky Survey. Their space density is color-coded, in units of X–ray sources per square degree. Contours of molecular clouds (Maddalena et al. 1986) are overlayed. The dashed lines show the galactic plane and galactic longitude=180°. The regions of enhanced young star candidate density south of the galactic plane coincide with Gould's Belt.

The Orion Nebula Cluster is the strongest enhancement at the center of the image. The enhancements immediately to the north of the ONC are Ori OB1b and Ori OB1a. NGC 1788 is west of Ori OB1b. The Pleiades cluster is visible at the northwestern edge of the field.

Figure 4. Radial velocity distribution of the RASS PMS candidates observed with high-resolution. The radial velocity of the Orion association is about 25 km s^{-1}; the peak near 18 km s^{-1} is consistent with the radial velocity of the nearby Taurus SFR (Hartmann et al. 1986). This suggests that the RASS survey has detected two discrete populations of low mass PMS stars.

Figure 5. The radial velocity distribution of stars within 30 arcmin of σ Ori. We determined radial velocities by cross-correlating the spectra with those of the dusk or dawn sky. Uncertainties are about $\pm$5 km s^{-1} for spectra with high S/N. The spectroscopically-identified PMS stars (solid histogram) are well-fit as a Gaussian distribution of mean 25 km s^{-1} with σ=5 km s^{-1}. The secondary peak at 12 km s^{-1} is due to a systematic

shift of M star velocities, and may be an artifact of using a sky spectrum as a velocity template. The radial velocities of the other stars in the sample (dotted histogram) have a mean of 31 km s^{-1} with σ=37 km s^{-1}. It is clear from the radial velocities that the PMS stars in this field are all members of the same association.

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