The Stellar Population of the Orion A (L1640/L1641) Cloud

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Abstract.

We review recent progress toward understanding the stellar population and star formation history of Orion A. Key to our current knowledge is the combination of large–scale optical and near–IR imaging surveys with multi–fiber spectroscopic surveys, enabling a large fraction of the pre–main sequence population in the cloud to be placed in the HR diagram. We discuss the stellar mass and age distributions derived from the HR diagram, and compare star formation in different parts of Orion A, considering separately those stars which are "clustered" (the Orion Nebula cluster), "aggregated" (small groupings of 10–50 stars spread across the Lynds 1641 cloud south of the ONC) and "distributed" (found in L1641 but with no apparent group association). We summarize circumstellar disk statistics for both the ONC and L1641, and show that the fraction of stars with circumstellar disks depends on both stellar mass and stellar age. Finally, we discuss the stellar population of Orion A compared to that of Orion B, and the Taurus molecular cloud.

1. Introduction

As the nearest giant molecular cloud (GMC) complex, the Orion region offers a unique opportunity to study the star–forming history of a GMC. Its modest distance of only ∼500 parsec means that with small–aperture telescopes we are able to observe star formation over the full range of stellar masses, from the most massive O stars ($\sim 40\ M_\odot$) to late M stars at and beyond the hydrogen burning mass limit ($\sim 0.08\ M_\odot$). From the massive star population alone (see review by Brown *et al.*; this volume), we know that star formation in Orion occurred as long ago as 10^7 yr, based on the ages derived for the oldest subgroup of the Ori OB association. Massive stars have formed there very recently, as well; the famous Orion Nebula Cluster (ONC) with its luminous 1–2 Myr old Trapezium stars and embedded BN object, is the archetypal stellar nursery. The low–mass

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stellar population seems to have an even larger age spread (this paper; see also Brown *et al.*) with evidence across the association for stars as old as 30 Myr. At the same time, deeply embedded luminous sources, detectable only at infrared wavelengths and frequently associated with molecular outflows and optical jets, serve as signposts of current star formation across much of the cloud complex.

The stellar populations of the Orion A and Orion B clouds (the southern and northern "halves" of the GMC) have received much attention since the *Symposium on the Orion Nebula to Honor Henry Draper*, in which stars were virtually unmentioned. This review discusses stars in the Orion A cloud while that of Meyer & Lada (this volume) discusses stars in the Orion B cloud.

Orion A is comprised of L1640, L1641 and L1647. The apparent distinction between these three clouds on sky survey plates was not borne out by millimeter observations; maps of the molecular gas show them all to be connected, and part of a single GMC of total H_2 mass $\sim 10^5$ $M_\odot$ (Maddalena *et al.* 1986). The morphology of Orion A has been discussed by a number of investigators (*cf.* Maddalena *et al.* 1986, Bally *et al.* 1987, Tatematsu *et al.* 1993), who show that the molecular gas is filamentary, with the strongest emission concentrated along a ridge extending southeastward from the Trapezium (Figure 1). As discussed by Tatematsu & Wilson elsewhere in this volume, the dense molecular gas, or cloud cores, are distributed fairly uniformly along this main olecular ridge. Associated with several of these cores are young clusters or smaller groupings of stars, or "aggregates" (Chen & Tokunaga 1994; Strom, Strom & Merrill 1993).

Close physical association with molecular cloud cores of these just–emerging stellar groups means we are observing "initial" stellar populations. Questions such as the detailed shape of the stellar initial mass function and the time sequence of star formation with stellar mass immediately suggest themselves. This appealing situation has led a number of investigators to study the Orion Nebula Cluster (ONC), and more recently, the L1641 aggregates to the southeast of the ONC. Due to the large angular extent of the Orion A cloud on the sky (~ 30 deg^2), an important development in such studies was the advent of wide–field photometric capabilities – large–format optical and infrared detectors – and multi–object spectroscopic capabilities. Deep optical surveys (at I–band) have uncovered young stellar populations which are still partially embedded in molecular material. By combining photometry with spectroscopy, stars can be individually dereddened and located in conventional theoretical HR diagrams from which, *via* comparison to theoretical predictions of stellar evolution, stellar masses and ages (and thus mass and age distributions) can be derived. This traditionally optical technique has also been employed in regions where most of the stellar population is still fully embedded in molecular material, by combining near–infrared photometry (JHK) with near–infrared spectroscopy. We are thus able to derive stellar masses and ages for both the "surface" populations of clouds and for the presumably younger populations which are obscured by 10–50 magnitudes of interstellar and local circumstellar extinction. The goal of these investigations is to construct a complete picture of and quantify star formation, both spatially and temporally.

In this chapter we review the results of such investigations. We begin with a brief overview of the stellar surveys conducted in Orion A, followed by a more detailed discussion of work of the nature just described. After presenting

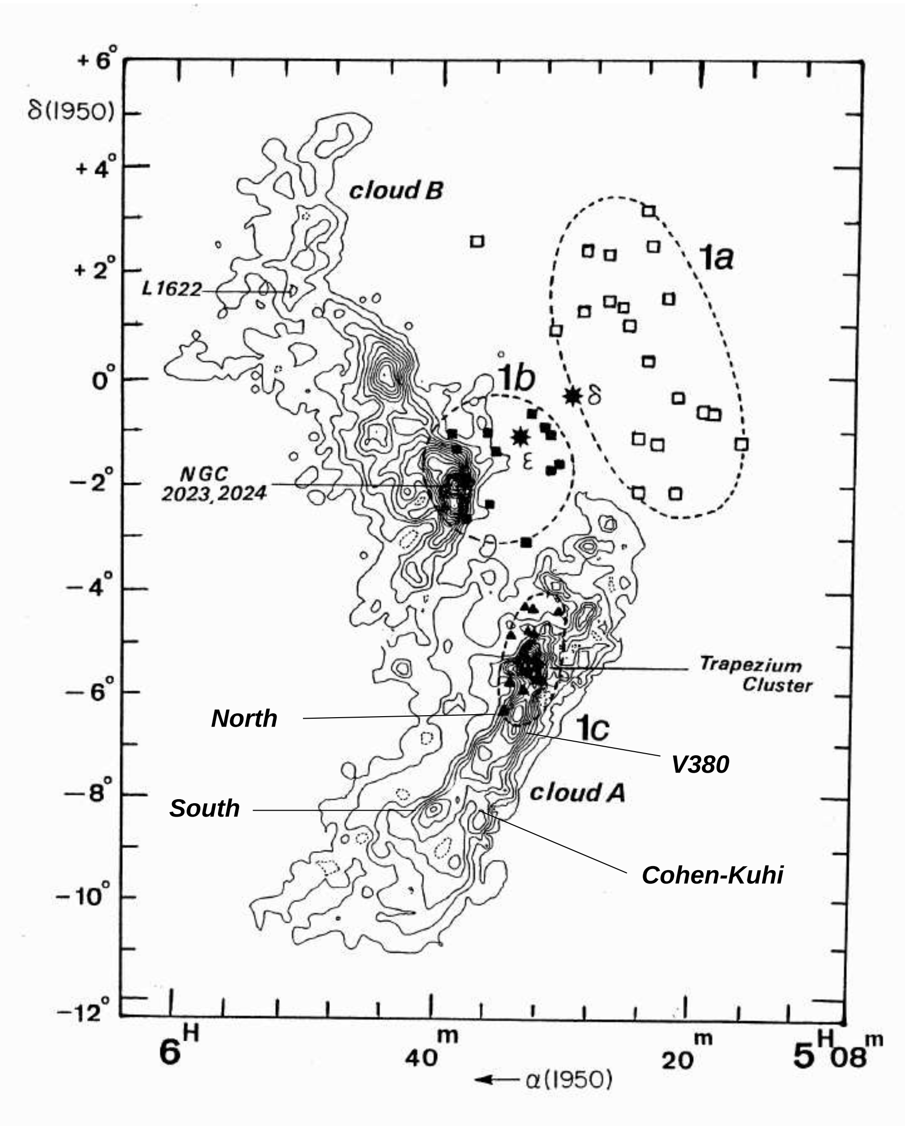

Figure 1. The Orion molecular cloud complex. Shown are contours of CO emission (Maddalena *et al.* 1986) for clouds A and B, in relation to the subgroups of the Ori OB1 association. Subgroup 1d surrounds the Trapezium. Also denoted are other regions of interest. (After Blaauw 1991).

mass and age distributions for five stellar clusters in Orion A, we discuss the near–infrared characteristics of the stars comprising these clusters with the goal of identifying those with circumstellar dust. We then discuss the differences between the clustered and the distributed populations of Orion A. Finally, we discuss the global star–forming properties of the cloud and how they might differ from other well–studied regions of star formation.

2. Surveys of the Stellar Population in Orion A

It is interesting to note that the only discussion of the Orion stellar population in the "Draper Symposium" book (1982) was by Herbig, who focussed primarily on the issue of the existence of a stellar cluster associated with the Trapezium stars. At that time, the extreme youth of this apparent stellar cluster was suspected based on the observation of photometric variability, optical emission–lines, and near–infrared continuum excesses, and the location of stars above the ZAMS in color–magnitude diagrams (Walker, 1969; Cohen & Kuhi, 1979; Herbig, 1950; Haro, 1953; Ney *et al.*, 1973; Penston, 1973; Penston *et al.*, 1975). These are the same criteria used today to signal stellar youth. However, none of these studies was deep enough to have revealed the true richness of the ONC or the more general L1641 stellar population. Herbig was to publish the first unbiased, flux–limited photometric (red CCD) survey of the ONC region a few years later (Herbig & Terndrup, 1986), and thus initiated its modern study.

Since the late 1980's numerous surveys of the stellar populations in Orion A (encompassing both the ONC and the L1641 cloud) have been completed, spanning ranges in wavelength, spatial resolution and areal coverage. Here we briefly summarize the most recent surveys, noting that this is not meant to be an inclusive review of all relevant work. We also note that only the IRAS infrared, KISO $\mathrm{H}\alpha$, and ROSAT all–sky X–ray surveys have covered the entirety of the Orion A cloud. None of the more sensitive infrared, optical, or X–ray studies discussed below have achieved full cloud coverage.

The traditional means of searching for young pre–main sequence stars has been through $\mathrm{H}\alpha$ surveys. These techniques are sensitive to $\mathrm{H}\alpha$ equivalent widths larger than 3–5 Å, and provide a lower limit to the number of PMS stars since large fractions of cloud populations may remain embedded in molecular material for 1 Myr or more. In addition, PMS stars can vary in their $\mathrm{H}\alpha$ emission, by as much as a factor of two or three. Nevertheless, objective prism surveys have been effective in identifying large numbers of PMS stars. The most comprehensive of these studies in Orion was the KISO $\mathrm{H}\alpha$ survey, which covered an area of 300 deg^2 to a limiting magnitude of $V = 17.5$ (Nakano *et al.* 1995; Kogure *et al.* 1989; Wiramihardja *et al.* 1989, 1991, 1993). A total of 1179 Hα emission stars were detected. In Figure 2 are plotted all stars from the KISO survey having emission–line strengths 3–5[2], superposed on a grayscale image of ^{13}CO integrated intensity (Bally *et al.* 1987). While the highest density of Hα–emitting stars is found in the ONC region, it appears that many of the Hα sources in L1641 are unassociated with any known clusters.

[2]The KISO by–eye estimate of the strength of $\mathrm{H}\alpha$ emission relative to continuum emission ranges from 0 (absent or doubtful) to 5 (very strong) (Wiramihardja *et al.* 1989).

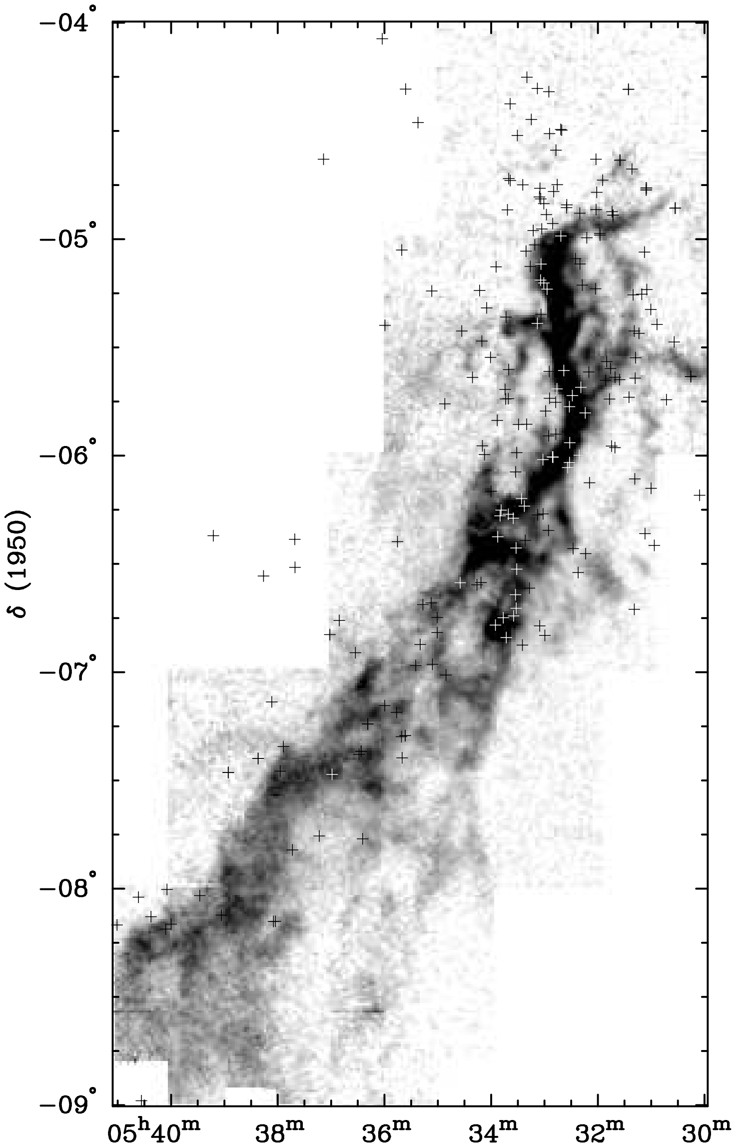

Figure 2. Hα emission–line stars from the KISO survey. Plotted are stars of strength 3–5, superposed on Bally's ^{13}CO map of Orion A.

Unlike H α line emission searches, X–ray surveys are sensitive to the detection of both "classical" T–Tauri stars "weak–line" T–Tauri stars. Results from 710 deg^2 of the ROSAT All–Sky Survey (RASS), centered on but exceeding the area of the Orion molecular clouds, are reported by Sterzik *et al.* 1995 (see also Sterzik *et al.*, this volume). RASS detected over 2000 X–ray sources, $\sim$1/2 of which were interpreted to be 10^7-10^8 yr old pre–main sequence stars. These stars may be associated with the Orion clouds but could also be young stars somewhat in the foreground. More sensitive, but spatially less extensive X–ray studies of the on–cloud regions were conducted by Strom *et al.* (1990), in L1641 using data from the Einstein Observatory, and by Gagne *et al.* (1994, 1995), in the ONC region using Einstein and ROSAT. In L1641, four overlapping IPC frames covering an area $\sim$2.5 deg^2 and centered on V380 Ori contained 65 X–ray sources. Comparison with Hα emission line surveys led Strom *et al.* to conclude that the ratio of all PMS stars (as detected *via* X–rays) to those detectable by their Hα emission is $\sim$3:1, yielding a density of young stars in L1641 of $\sim$32 deg^{-2}. In the ONC, $\sim$ 400 X–ray sources were found in 0.8 deg^2, nearly all of which can be associated with known optical/infrared stars. However, only $\sim$1/4 of the known optical stars and <1/8 of the infrared stars have X–ray counterparts (Gagne & Tsuboi, this volume), suggesting that even the X–ray surveys are still incomplete.

Near–infrared surveys have added much to our knowledge of the young embedded stellar populations in Orion A. Chen & Tokunaga (1994) surveyed 59 IRAS sources associated with dense molecular gas in L1641, and found that $\sim$1/4 of them are associated with small groupings of bright near–infrared sources. They showed that the surface densities of these groupings were significantly higher than that of background fields. Strom, Strom & Merrill (1993) surveyed 0.77 deg^2 (49 pc^2 for d=480 pc), to limiting magnitudes (5σ) of 16.8, 15.8, and 14.7 mag at J, H, and K. They identified a population of $\sim$1500 candidate pre–main sequence stars spread throughout the cloud, a cluster ($\sim$150 stars), and seven small aggregates comprised of 10–50 stars and having enhanced surface densities over the distributed population, by factors ranging from 4 to 10. Comparing extinction–corrected J–band luminosity functions with theoretical models, they derived an age for the aggregates of $\sim$1 Myr, and for the distributed population of 5–7 Myr. Hodapp and Deane (1993) had previously imaged a $30'$x $10'$ region centered on L1641 North at K', following with K–band spectra of selected stars as well as I–band polarimetry of stars near the North cluster and K' polarimetry of stars near the L1641 North molecular outflow. Based on a comparison of their observed K' luminosity functions with theoretical models and on their HR diagram (for 12 stars), they derived an age for the North cluster of $\sim$0.5 Myr. In the ONC region, McCaughrean & Stauffer (1994) used high resolution K–band imaging to catalog 123 stars in a 1.9 arcmin^2 area while Ali and Depoy (1995) found $\sim$3500 unique stellar sources over 1472 arcmin^2. Approximately 1/2–2/3 of these infrared sources have optical counterparts to a limit of $I_C \sim 18$ mag.

Following on the near–infrared surveys, and the discoveries of both young stellar aggregates and young isolated stars, the need for deep optical photometric and spectroscopic study was apparent. Next we describe the details and results of these surveys.

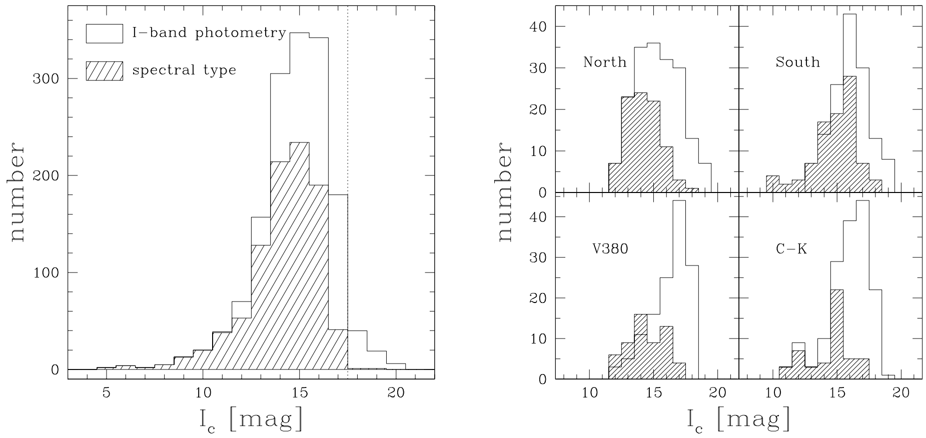

Figure 3. Histograms showing stars observed at I, in the ONC (left) and in the four regions studied in L1641 (right). Stars for which spectral types have been obtained are shown as shaded regions. Vertical dotted line in the ONC plot indicates the completeness of the I–band survey.

3. Quantifying Stellar and Circumstellar Properties

Recent optical photometric and spectroscopic surveys of various portions of the Orion A cloud have been reported by Allen (1996) and by Hillenbrand (1997). The Allen survey targetted four regions each $\sim 20 \times 20$ arcmin^2 in size and associated with a CS core. The Hillenbrand survey covered an area $\sim 30 \times 34$ arcmin^2 centered on the Trapezium stars in the core of the Orion Nebula Cluster. These surveys were conducted using nearly identical techniques, optical (VRI) + near–infrared (JHK) imaging and multi–object spectroscopy ($\sim 5500-9000$ Å), and the same instruments. They thus provide an opportunity to inter–compare the stellar populations in the clusters and aggregates forming across the face of the Orion A cloud. In particular, the combination of photometric and spectroscopic information allows us to construct theoretical HR diagrams (log $(L_*/L_\odot)$ *vs.* log T_{eff}) and thereby derive masses and ages for individual stars. The addition of infrared photometry allows us to investigate evidence from near–infrared excesses for the presence of circumstellar (accretion) disks.

The data acquisition, reduction, and analysis techniques for these surveys are described in Allen (1996) and Hillenbrand (1997, *et al.* 1998). The photometric completeness limits (R=20.2, I=19.3, J=16.8, H=15.8, K=14.8 for the L1641 survey and 1–2 mag less for the ONC survey, due to the increased nebular background) correspond to physical completeness to a mass of 0.1 $M_\odot$ at an age of 1 Myr for a star seen through $\sim$ 5 mag of visual extinction in L1641 and $\sim$ 2.5 mag of visual extinction in the ONC. Shown in Figures 3 and 4 are the distribution of I–band and K–band magnitudes for these surveys. Approximately 50% of the stars identified in the JHK surveys are also seen in the VRI surveys, and 50–70% of those have optical spectra. The newly acquired spectra are of resolution R≈1200 and signal–to–noise $\sim$ 20–100. We supplemented the spec-

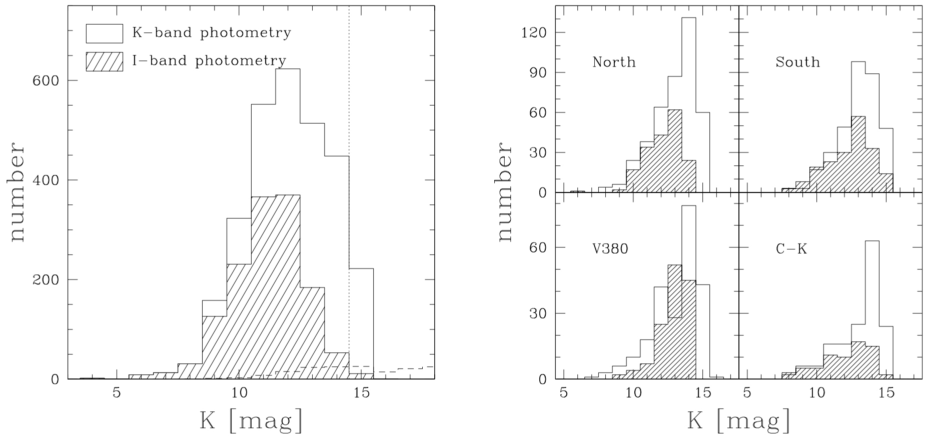

Figure 4. Histogram of K magnitudes observed in the ONC (left) and in L1641 (right). Shading indicates source for which I_C magnitudes were obtained. Dashed line on the ONC plot indicates the (nearly negligible) level of foreground field star contamination based on the Bahcall–Soneira Galactic model.

tral types derived from our spectroscopic surveys with previously determined spectral types located in the literature.

3.1. Stellar Parameters

Construction of HR Diagrams In order to construct an HR diagram, spectral types were translated to effective temperatures and bolometric corrections were applied to reddening–corrected photometry (J–band in the case of L1641 and I–band in the case of the ONC) to derive stellar luminosities. The uncertainties in the temperatures are ± 0.03 dex in log T_{eff} , assuming errors in spectral classification of 1 subclass for stars K7 and later and 3 subclasses for stars in the F–G range. The uncertainties in the luminosities are ± 0.3 dex in log $(L_*/L_\odot)$, assuming the propogation of spectral classification and photometric errors, and estimating the effects of unresolved binaries, excess flux due to circumstellar processes, and photometric variability. We show in Figures 5 and 6 the HR diagrams for the five regions studied in comparison to the pre–main sequence evolutionary tracks and age isochrones of D'Antona and Mazzitelli (1994, model 1).

While the ONC region is relatively well–shielded from background contamination, with extinction through the molecular cloud estimated at $A_V \approx 50 - 100$ for the inner portions of the ONC, total line–of–sight extinction estimates for L1641 range from just $A_V \approx 1$ up to $A_V \lesssim 20$ in the dense cores associated with the aggregates. Several background stars were identified from the spectroscopic surveys, a few giants in L1641 and a probable supergiant in the ONC. At a galactic latitude of ~ -20 deg and distance of ~ 470 pc, contamination in optical surveys by stars foreground to Orion A is more likely. Galactic models suggest contamination at the level of $\sim 3\%$, or 10–20 stars per L1641 field and ~ 50 stars for the inner few pc of the ONC. Although we have not accounted for the

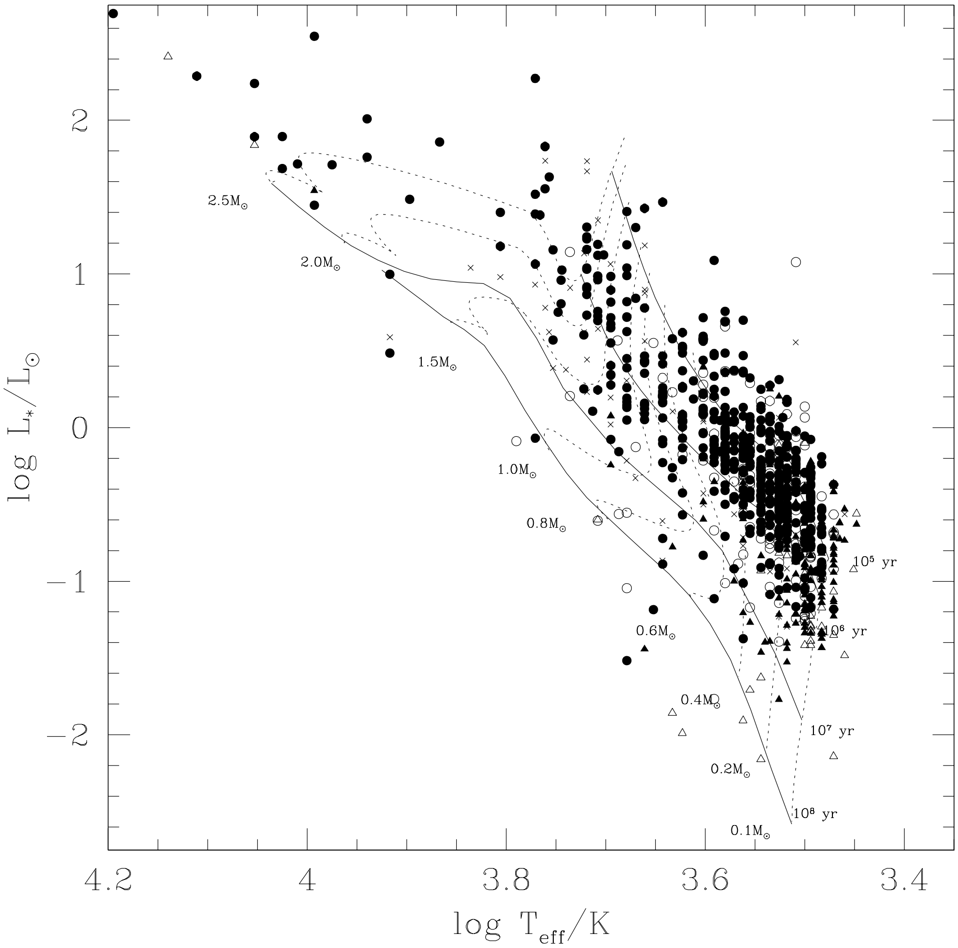

Figure 5. HR diagram for the Orion Nebula cluster. Evolutionary tracks and isochrones are from D'Antona and Mazzitelli (1994, model 1). Filled symbols represent proper motion cluster members; crosses represent proper motion nonmembers; open symbols represent stars without membership probabilities from proper motion studies. Triangles represent lower limits to luminosities.

possible presence of forground stars in the HR diagrams, proper motion studies of the ONC region reveal that foreground contamination is fractionally highest in the F–G spectral range with simulations showing luminosities (assuming the stars are located at the distance of Orion A cloud) corresponding to ages older than 3 Myr in the HR diagram. Thus any statements about older populations, particularly above 1–2 $M_\odot$, should be treated with caution.

To derive stellar masses and ages we interpolate between the theoretical pre–main sequence tracks and isochrones in the HR diagram. The stellar parameters given by this method are thus model–dependent, and we emphasize

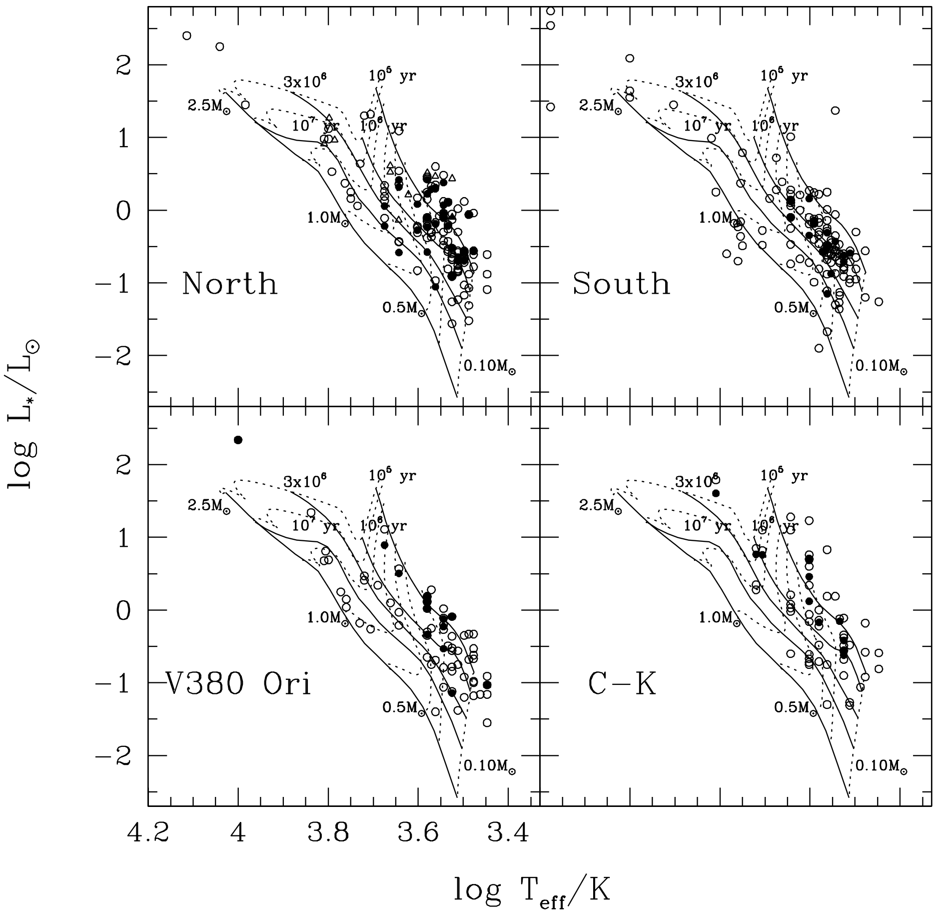

Figure 6. HR diagrams for L1641 North, South, C–K, and V380. Filled symbols are represent stars with infrared excess emission characteristic of circumstellar accretion disks. Triangular points (North) represent stars whose spectral types determined from K'–band spectra (Hodapp & Deane 1993). Tracks and isochrones are as in previous figure.

that all of the results presented here on stellar masses and stellar ages are uncertain in their absolute calibration due to uncertainties in the correctness of any particular set of theoretical models. However, the use of similar techniques for all stars projected on the Orion A cloud allows us to make comparisons between the stellar populations forming in various regions and environments of the cloud. Given the formal errors in locating a star in the HR diagram, the resulting errors in stellar masses are estimated at ±0.1 $M_{\odot}$ and the errors in stellar ages at ±0.8 dex, for a low–mass pre–main sequence star. These errors are in addition to any systematic errors in the theoretical tracks/isochrones them-

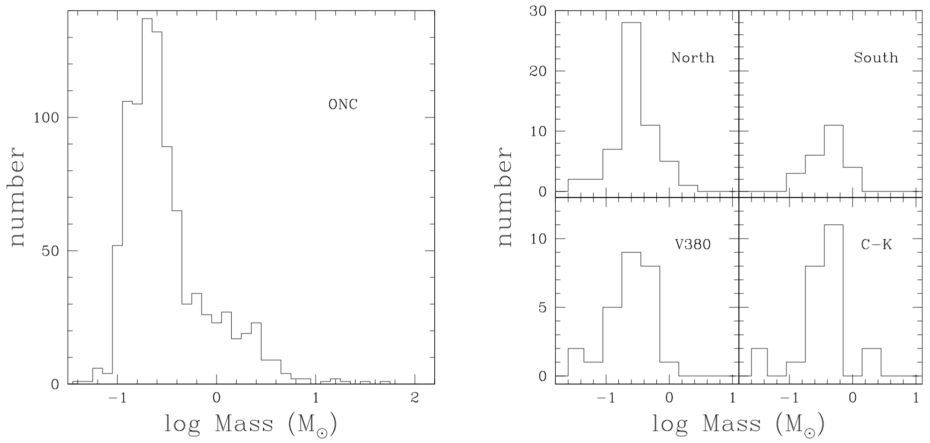

Figure 7. Mass distributions, for stars younger than 1 Myr.

selves. Again, the *relative differences* between the various clusters/aggregates, and between the aggregated and the distributed populations are independent of these uncertainties.

Stellar Mass Distributions Survey completeness limits combined with the probable location of any contaminating foreground stars in the HR diagram means that we must restrict our discussion of the mass distribution in Orion A to stars which are both younger than 1 Myr and more massive than 0.1 $M_\odot$. We show the so–derived mass distributions in Figure 7. In the ONC, where the statistics are better and the data more complete in mass, the mass distribution can be described as rising with decreasing mass from its maximum mass of ≈ 50 $M_\odot$ down to a few $M_\odot$, then flattening down to just below 1 $M_\odot$, and rising again to a peak at ~ 0.2 $M_\odot$ with strong evidence for a turnover (decreasing numbers of stars towards lower masses) below this. The evidence from the optical spectroscopy and photometry for a turnover in the ONC mass distribution at the low–mass end is confirmed by analysis of an infrared photometric dataset, which shows that significant numbers of stellar objects less massive than 0.1 $M_\odot$ simply do not exist in the region. The infrared stars appear to represent a more–extincted population, not an intrinsically redder, lower mass population. Although the ONC does not seem to have produced enough extremely low–mass objects for a flat or rising mass distribution, several tens of candidate young brown dwarfs are present. In the L1641 aggregates there are some, but not enough, intermediate– and high–mass stars to discuss the mass distribution above 1 $M_\odot$. Below 1 $M_\odot$ there is a general rise in the mass distributions for all four regions studied, to a peak which roughly coincides with the peak in the ONC mass distribution. However, the fractional completeness of the L1641 spectroscopic sample (with resect to the photometric sample) decreases towards fainter (and presumably lower mass) stars, so any indication of a turnover in the mass function can not be considered firm.

Are there differences in the mass spectra between the various clusters? A plot of the cumulative mass spectra from $0.2 - 1.0$ $M_\odot$ for each of the 5 regions,

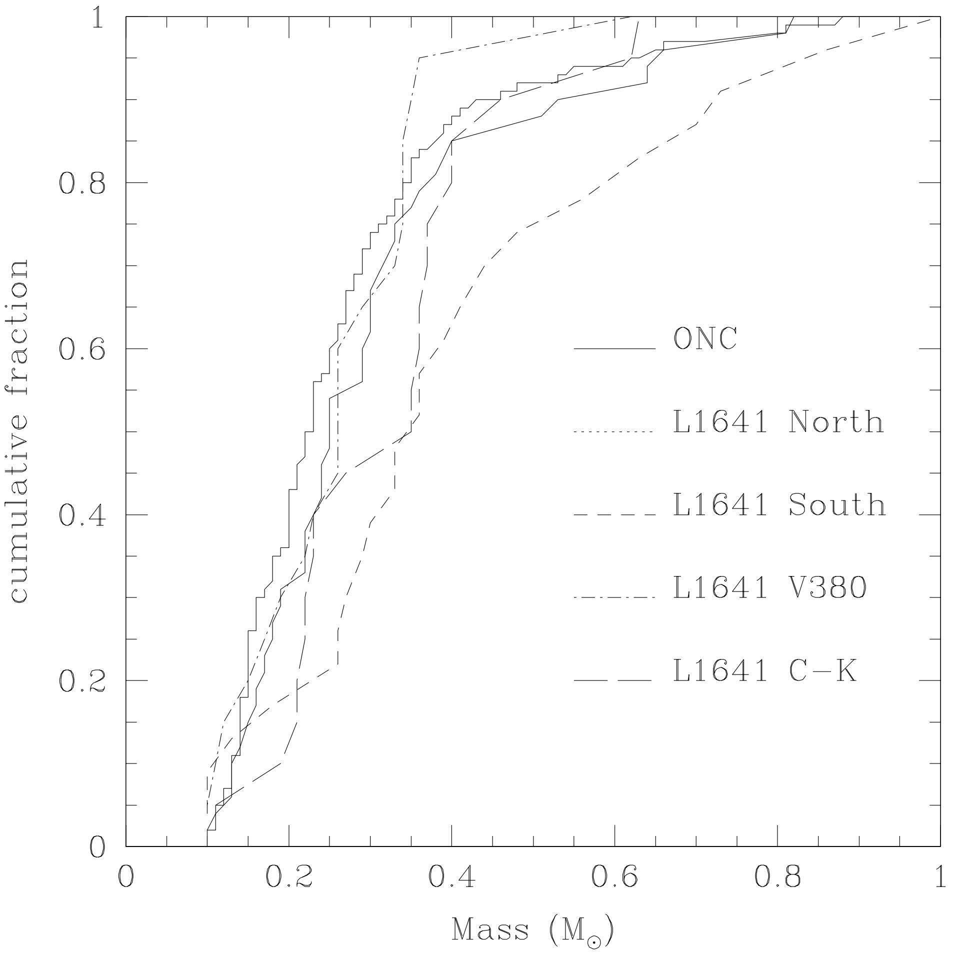

Figure 8. Cumulative mass distributions, from $0.2 - 1$ $M_\odot$, for the ONC, and the four groups in L1641. Though there is some scatter in the distributions, only V380 and South are statistically distinguishable from one another, given the errors in mass of ± 0.1 $M_\odot$.

is shown in Figure 8. The mass distributions are seen to have roughly the same form. Although L1641 South's distribution is steeper than the others', it is not significantly so, given the uncertainties in the masses.

Stellar Age Distributions We restrict our discussion of stellar ages to stars less massive than 1 $M_\odot$, since for higher mass stars both empirical and theoretical evidence suggests that currently available evolutionary calculations measure only upper limits to stellar ages due to the effects of "stellar birthline" in the HR diagram (see Palla & Stahler, 1993). We show in Figure 9 the distributions of stellar ages, derived from interpolation between the pre–main sequence isochrones. The ONC is the youngest region, with relatively few stars ($< 20\%$)

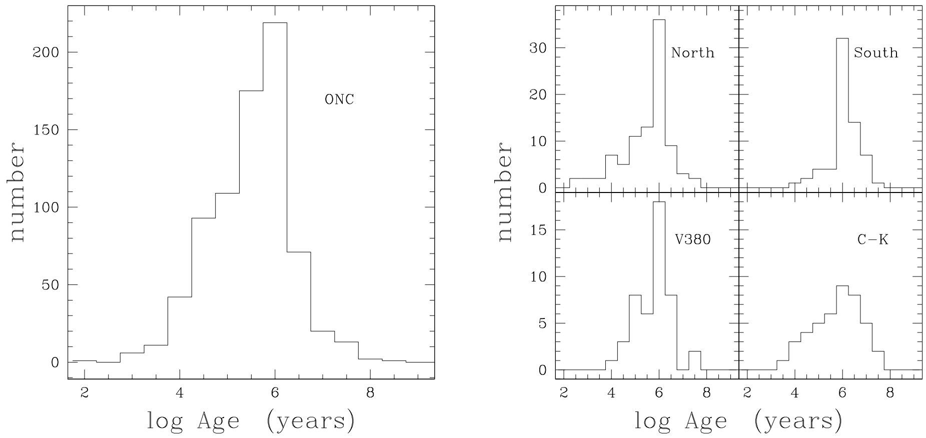

Figure 9. Age distributions, for all stars with $M < 1$ $M_\odot$.

older than 1 Myr. The mean age for the low–mass populations in most of the L1641 groups is about 1 Myr, with some indication that the L1641 South area may be slightly older, perhaps 2–3 Myr. Beyond the age of $\sim$3 Myr, all of the samples become seriously incomplete; however up to that age, a comparison of age distributions may be made. It is clear from Figure 10 that L1641 South has a paucity of stars younger than 1 Myr, relative to the other regions, and is therefore of a older mean age.

3.2. Circumstellar Disks

In this section we consider the evidence for circumstellar disks and their associated activity, in the Orion A cloud. Our observational diagnostics for disks are near–infrared photometric excesses (at J,H,K) and optical emission lines (*e.g.* Hα, CaII). Near–infrared continuum excesses are thought to be produced by heated dust in the inner 0.1 AU of a star/disk system. Optical emission lines are thought to be produced by heated gas in the inner accretion disk, in accretion columns and/or spots, and in accretion–driven winds. At present the evolution of such observational signatures for accretion disks surrounding stars of different mass is poorly known. The general expectation, however, is that the fraction of stars with disks should decrease with age. The wide range in stellar mass (<0.1-50 $M_\odot$) and stellar age (<0.1-30 Myr) represented by the L1641 and ONC populations allows us to address the issue of disk evolution empirically. Due to the effects of changing contrast between the flux expected from a circumstellar disk relative to that expected from the parent star, for disks surrounding stars of different mass and age, we can not be certain that objects without either of our diagnostics do not have disks. Disk detectability, particularly in the near–infrared, is further inhibited by the effects of source inclination and inner disk holes. However, from the data in hand we can at least place lower limits on the fraction of stars with circumstellar, probably accretion, disks, as a function of stellar mass and age.

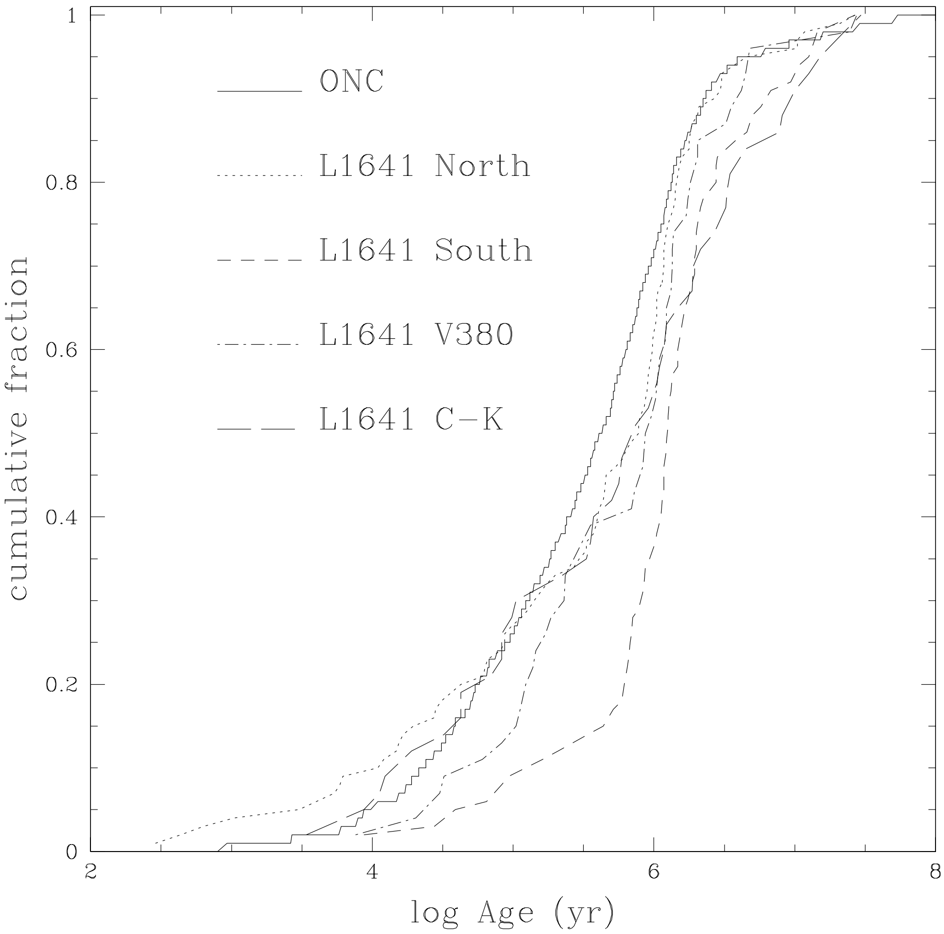

Figure 10. Cumulative age plots of the five regions, for comparison. L1641 South has the smallest relative fraction of young stars, suggesting an older age for this group, while the ONC appears to be the youngest.

Near–infrared Excesses We have chosen fairly conservative thresholds for the detection of a disk *via* the presence of near–infrared excess. In L1641, Allen (1996) defined stars with infrared excesses to have de–reddened (H–K) colors larger than (0.05 mag + 3× the photometric error) above the stellar photosphere. In the ONC, Hillenbrand *et al.* (1998) used de–reddened (I–K) colors to quantify infrared excesses; for the current discussion we set a limit of 0.3 mag in de–reddened (I–K) color above the stellar photosphere in order for an object to have an infrared excess. Given the behavior with wavelength of the excesses expected from circumstellar accretion disks (Calvet, private communication), these thresholds for disk detection between (H–K) and (I–K) are roughly comparable.

In Table 1 we show the trends in the observed disk frequency (not corrected for the effects of inclination or of relative star/disk contrast with mass) with stellar mass for the various L1641 clusters and the ONC. Examination of the location in the HR diagram of stars with and without disks, shows a relative paucity in the L1641 clusters of stars $M > 1\ M_{\odot}$ with disks. In the ONC, the fraction of stars in the same mass range with disks is apparently higher, consistent with the suggestion that the ONC may be slightly younger on average than the L1641 clusters. In both L1641 and the ONC, the disk fraction appears to increase towards lower masses. However, we note that the quoted disk fractions are necessarily lower limits for the latest type stars in these samples, since these low–mass stars typically have larger photometric errors in addition to smaller intrinsic excesses expected to be produced by disks. Because the ONC sample includes many more stars of lower mass than the L1641 sample (completeness to $0.1\ M_{\odot}$ instead of $0.2\ M_{\odot}$), this may explain the less dramatic increase in the ONC of the disk fraction with decreasing stellar mass.

TABLE 1

Disk Statistics with Mass in the L1641 Clusters and the Orion Nebula Cluster

Mass Range	North	V380	CK	South	L1641	ONC	ONC
[$M_{\odot}$]	[#]	[#]	[#]	[#]	[%]	[#]	[%]
$M < 0.5$	13/32	8/21	6/13	8/18	42%	302/624	48%
$0.5 \leq M \leq 1.0$	3/7	1/2	0/2	1/10	24%	45/85	53%
$1 < M$	2/15	1/6	2/4	0/10	14%	36/104	35%

In Table 2 we show the trends in disk frequency with stellar age (not corrected for the effects of inclination or of relative star/disk contrast with age) for the various L1641 clusters and the ONC. Although there is some general evidence that the disk fraction is lower for older stars, stars apparently have a wide range in disk dissipation timescales. In both L1641 and the ONC we find some young stars, aged 0.1 Myr or less, which have already lost their disks (presuming they were born with disks). In L1641, which has a larger age spread than the ONC, as was apparent from the HR diagrams (Figure 6) some stars as old as 10 Myr still have their disks. Similar results are obtained from a study of the much less populous Taurus–Auriga dark cloud (*i. e.*, Skrutskie *et al.*, 1990). Any acceptable theoretical model of disk dissipation (due, *e. g.*, to accretion onto the central star, outflow in a wind, or planet–building) must account for the range between objects born in the same dark cloud, in the timescales over which dissipation processes act.

TABLE 2

Disk Statistics with Age in the L1641 Clusters and the Orion Nebula Cluster

Age Range	North	V380	CK	South	L1641	ONC	ONC
[Myr]	[#]	[#]	[#]	[#]	[%]	[#]	[%]
$\tau < 1$	27/52	11/32	9/23	9/29	41%	79/108	73%
$1 \leq \tau \leq 3$	6/20	0/10	3/7	7/31	23%	42/61	69%
$3 \leq \tau \leq 10$	3/11	1/11	1/6	2/13	17%	.....	...
$10 < \tau$	1/5	0/9	1/3	1/4	14%	.....	...

Emission–line Properties We turn now to a discussion of spectrosopic signatures for circumstellar accretion disks. In the well–studied young pre–main sequence stars of the Taurus–Auriga dark cloud, there is a well–established correlation between the amount of optical spectroscopic veiling, a direct measure of accretion luminosity generated as infalling material crashes into the central star, and Hα, CaII (the "triplet" lines at 8498, 8542, and 8662$\AA$), and forbidden–line luminosities (Edwards *et al.*, 1998; Hartigan *et al.*, 1990; Bathala *et al.*, 1996; Hartigan, Edwards, & Ghandour, 1995). There is also a correlation between the luminosity of the infared excess and emission–line luminosities (Hamann & Persson, 1992; Cabrit *et al.* 1990). Although there is no standard model for the formation mechanisms producing these various lines, they are most likely associated with processes occurring in the inner part of the accretion disk, either in accretion columns reaching from the disk to the star or at the base of accretion–driven winds.

A relative measure, then, of the accretion activity in a stellar population is the fraction of late–type stars with significant Hα equivalent widths (W(Hα) $\geq$ 10) or with CaII emission. In L1641, the fraction of stars of spectral type K5 or later with W(Hα) $\geq$ 10 is 46%. In L1641 South and the Cohen–Kuhi group the fractions are 23% and 19%, respectively. The fraction of late–type stars with CaII emission is 6% in both L1641 North and South, and 9% in the C–K group. These numbers include both the aggregate and distributed populations in the three named regions, and are somewhat higher for the aggregates alone.

In the ONC, due to heavy contamination by the Orion Nebula itself, we can not consider the near–ubiquitous Hα emission in our spectra as an accretion indicator. However, approximately 20% of the ONC sample clearly have the CaII triplet in emission. Another 50% of the sample have these lines filled in to the level of the continuum when in fact absorption features should be present based on the spectral type of the star. This implies that at least 70% of the stars have some form of emission–line activity in the CaII lines.

4. Comparison of Clustered and Distributed Populations

An unanswered question in our understanding of the processes by which a molecular cloud turns itself into stars, is whether so–called "cluster–mode" star formation produces fundamentally different stellar products from "isolated–mode" star formation. We can use the distributions in age and mass, and the circumstellar disk characteristics of the L1641 and ONC regions, to look for differences between the populations forming in and out of the clusters/aggregates by studying their mass and age distributions and their circumstellar disk characteristics. In particular, we can ask where the youngest stars are located and where the most massive stars are located.

The most massive stars of the Orion A cloud are all located towards its northwestern edge. This region includes the ONC with its Trapezium stars as well as two aggregates of massive stars located ∼3.5 pc due north of and due south of the Trapezium region. The most massive stars, therefore, are always associated with clusters. This is consistent with what is known from studies of the dense clusters associated with Herbig Ae/Be stars (Hillenbrand, 1995), O and B IRAS sources (Carpenter *et al.* 1993), and the intermediate/high mass stars in the Orion B cloud (Lada *et al.* 1991). However, not all clusters/aggregates contain massive stars, as evidenced by the general clustering properties of L1641 and of the Taurus cloud.

What about stellar ages? As shown by Allen (1996), the L1641 aggregates contain a higher fraction of younger stars relative to the distributed populations. Similarly, Hillenbrand (1997) found a smooth gradient with projected cluster radius in the ONC, of decreasing stellar ages towards the cluster center. It seems that while stars of the youngest ages may be found anywhere across the Orion A cloud, in at least five instances of clustering, a higher fraction of the youngest stars are found in the aggregates/clusters. The question then arises, "do *all* stars form in aggregates/clusters?". For L1641, Strom, Strom, & Merrill (1993) defined aggregate sizes based on eyeball estimates, and Allen (1996) analyzed the stellar surface density to find that the radial extents of aggregates are $\sim$1/3 pc. The dispersal time for a small unbound aggregate can be estimated from its size and an assumed velocity dispersion (taken to be that typical of a molecular cloud), $2r/\sigma = 2 \times 0.33pc/1kms^{-1} < 1$ Myr. The aggregates thus are expected to be short–lived, though they may remain bound as long as there is a significant amount of molecular gas in the vicinity. It comes as no surprise, therefore, that the aggregates may represent a characteristically younger population than the distributed population. However, only 25–50% of the stars $\lesssim$1 Myr of age across the L1641 region are found in the aggregates, implying 50–75% of the stars $\lesssim$1 Myr of age are found outside of the aggregates. The answer to whether *all* stars form in aggregates/clusters appears, therefore to be "no." These distributed stars could have been associated with aggregates that dispersed on shorter timescales than the ones we see today, or they could have formed in relative isolation. The latter possibility implies that "cluster–mode" and "isolated–mode" star formation can occur in different regions of the same molecular cloud. This is also true of the Taurus cloud (Gomez *et al.*, 1993).

Are there differences in the disk properties in clusters/aggregates and the distributed population ? In L1641, the fraction of infrared excess stars is higher in the aggregates (60%) than in the distributed stars (30%) Strom, Strom & Merrill (1993). This is consistent with the interpretation presented above; that the aggregates represent a characteristically younger population. For the ONC, in Hillenbrand *et al.* (1998) it is argued that there is a smooth gradient with projected cluster radius in the fraction of stars surrounded by disks. This is consistent with a similar finding of an age gradient with projected cluster radius, but also with a decrease in the mean disk accretion rates with cluster radius.

5. Global Star–Forming Properties of the Orion A Cloud

Having derived masses and ages for some portion of the Orion A stellar population, we are in a position to discuss the total mass present in stars, the recent star formation rate, and the star formation history of the cloud. Orion A is a clumpy, fragmented cloud with multiple, well–separated, sites of recent star formation distributed across its face. The cloud has been forming stars for at least 30 Myr, as evidenced by the oldest stellar ages, and has formed stars most vigorously quite recently, as evidenced by the youth and compactness of the dense Orion Nebula Cluster. In Table 3 we compare the properties of the

ONC, representing "clustered" star formation with those of the L1641 regions, representing "aggregate" and "distributed" star formation.

TABLE 3
Comparison Between Stellar Populations in the Orion A Cloud

Parameter	ONC	L1641
survey area (pc^2)	20	49
number of stars[a]	3500–5000	1500
mass in stars ($M_\odot$)	2000–4000	500
mean mass per star ($M_\odot$)	0.8	0.4
mean mass over 0.1–2.5 $M_\odot$ ($M_\odot$)	0.5	0.3
most massive star ($M_\odot$)	50	4
fraction < 1 Myr (%)	80	47
fraction < 3 Myr (%)	> 99	84
fraction < 10 Myr (%)	100	99
mean age (Myr)	0.8	1–3
maximum age (Myr)	3	30
recent star formation rate ($M_\odot$ yr^{-1})	$\sim 10^{-3}$	$\sim 10^{-4}$

[a] based on near–IR surveys covering the areas indicated.

The *current* star formation rate in L1641 is given by the youngest observed stars (∼200 stars with ages younger than 1 Myr), and the mass consumed in the production of stars in a 1 Myr period is ~ 65 $M_\odot$, within a surveyed area of $\sim 3 \times (2.5\,pc)^2$. The total molecular mass of L1641, excluding the Orion Nebula region, is $\sim 4\times10^4\,M_\odot$ (Bally *et al.* 1987), and its total area is $\sim 130\,pc^2$. Scaling by these quantities, and assuming that L1641 continues to form only low– and intermediate–mass stars at the present rate, the gas depletion timescale of the cloud is quite long, $\sim 9\times10^7$ yr. In the ONC, the recent rate of gas consumption appears to be about an order of magnitude higher than in the rest of Orion A with several thousand stars forming within the past 1 Myr. The molecular mass of the Orion Nebula region is $\sim 4 \times 10^3\,M_\odot$ (Bally *et al.* 1987). These numbers suggest a gas depletion timescale of less than 10 Myr for the ONC region.

The idea that the Ori OB association subgroups form a temporal sequence was first discussed by Blaauw (1964). Although the most recently determined ages for the subgroups indicate that a–d are not temporally sequential (Brown etal and this volume), it is clear that the 1d subgroup, which includes the ONC, is the youngest part of the association, and the 1a subgroup, to the west of Orion B, the oldest. Blaauw (1991) and others have remarked on the apparent interaction between the 1a subgroup and Ori B, suggesting that it is responsible for the sharp molecular ridge on the western side of cloud B. Blaauw (1991) has also suggested that the 1b subgroup, so near in proximity to the young star forming region NGC 2024, is responsible for that cluster's formation.

The distribution of molecular gas in Orion A does not show any such obvious relation to possible winds from OB1 subgroups. However, since both 1b and 1c are older (Brown etal) than most of the Orion A population, it is conceivable that either (or both) subgroup has played a role in triggering star formation within the cloud. The OB 1c subgroup is centered on the ONC, and extends far enough southward to overlap, along the line of sight, with L1641 North. Thus it is possible that the L1641 North aggregate was triggered by the same theoretical shock wave from 1c that may have influenced the ONC's formation. However, it is unlikely that star formation in the southern extent of L1641 is related to the 1c subgroup, since (1) the projected separation is large (15 parsecs), and (2) the L1641 South cluster is older than the aggregates in the northern part of the cloud, and (3) the South cluster and the Cohen–Kuhi group are at approximately the same distance from 1c, as seen in projection, but are not the same age. Thus, the age distributions of stars in L1641 favor neither the sequential propagation of star formation from the northern end to the southern end of the cloud, nor a single cloud–wide triggered event.

6. Orion A in context

6.1. Comparison with Orion B

The discovery by Strom, Strom & Merrill (1993) of a significant distributed population in L1641 came just a few years after Lada *et al.* found that virtually all young stars in L1630 are in rich clusters. Both results have since been confirmed, by Allen (1996) for L1641 and by Li *et al.* (1997) for L1630. The conclusion is that different parts of the GMC are forming stars differently.

The differences between the two clouds in the spatial distribution of stars (see Meyer and Lada, this volume, for more detail) may be due to differences in the molecular cloud cores. Tatematsu & Wilson (this volume) report that cloud cores (as measured by CS (1–0) and (2–1)) in Orion A are distributed throughout the cloud, while those in B are concentrated in only a few places, where the clusters are found.

6.2. Comparison with the Taurus–Auriga Dark Cloud

Finally, how does star formation in the Orion GMC compare with that in another cloud ? The most extensively studied dark cloud is the Taurus–Auriga molecular cloud. Several optical and infrared photometric and spectroscopic surveys of Taurus–Auriga were synthesized recently by Kenyon & Hartmann (1995). They concluded that the distribution in stellar ages is consistent with a constant star formation rate over the past few Myr. The young stars are distributed individually or in small associations throughout a filamentary cloud (Gomez *et al.* 1993), with visual extinctions A_v = 5–10. In L1640 and L1641, star formation appears to have occured most vigorously more recently, with 40–80% of the stellar population less than 1 Myr in age. The location of young stars both in compact groups and distributed throughout the cloud suggests a similarity between the L1641 and Taurus regions.

However, the optically visible, spectroscopically observed populations in the two clouds have somewhat different mass distributions. In Figure 11 we plot the distribution of spectral types for Taurus–Auriga, as compiled from Kenyon & Hartmann (1995), Briceno *et al.* (1998), Strom & Strom (1994), and Luhman & Rieke (1998), against those for the ONC and L1641, restricted to the age and mass ranges for which our spectroscopic samples are representative of the cloud population. The most obvious differences in the mass distributions in Taurus

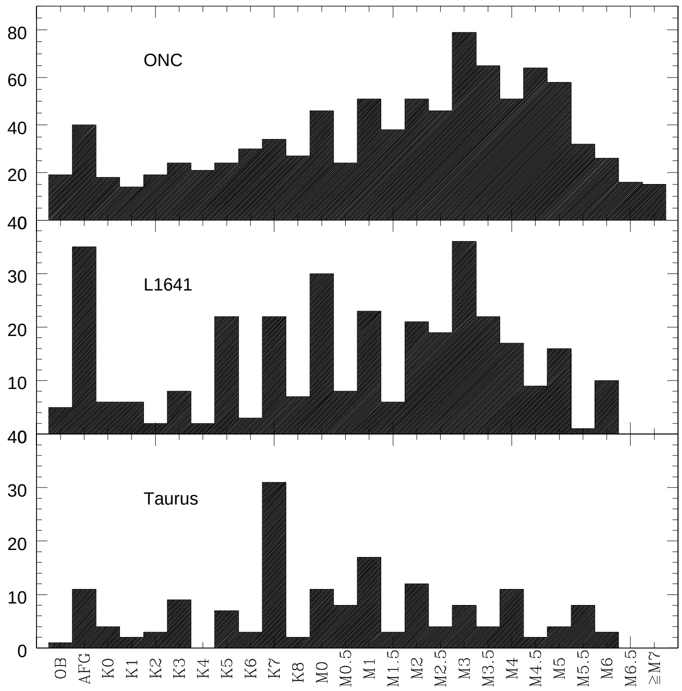

Figure 11. Comparison of spectral types in ONC, L1641 and Taurus.

and L1641 is that Taurus lacks the proportion of mid–M type stars found in Orion A.

7. Summary and Future Work

Since the 1982 publication of the Draper Symposium on Orion, extensive progress has been made toward understanding the stellar population of Orion A. In this contribution we have attempted to summarize results from photometric and spectroscopic surveys in the optical and near–IR. The main findings are:

1. Both "cluster–mode" and "isolated–mode" star formation has occurred within Orion A.

2. The mass distributions of the ONC and the L1641 aggregates are similar. In the ONC, where the statistics are sufficient and the data more complete in mass, there is strong evidence for a turnover in the mass function below $\sim 0.2\ M_\odot$. The most massive stars in Orion A are associated with clusters.

3. The mean age for stars less massive than 1 $M_\odot$ in most of the groups is ∼1 Myr. The ONC is the youngest with few stars (<20%) older than 1 Myr. L1641 South is the oldest group, at 2–3 Myr. The distributed population in L1641 is, on average, 2–3 Myr older than the groups, but does contain some very young stars (< 1 Myr) as well.

4. The fraction of stars with infrared continuum excess characteristic of circumstellar disks in both the ONC region and the L1641

groups increases with decreasing stellar mass. There is some evidence that, within a given mass range, the disk fraction is lower for older stars. However, stars apparently have a wide range in disk dissipation timescales, from a few to 10 Myr.

5. The “current” star formation rate in the ONC is $\sim 10^{-3}$ $M_\odot$ yr^{-1}; in L1641 it is $> 2 \times 10^{-4}$ $M_\odot$ yr^{-1}. At the current rate, the gas depletion timescales are <10 Myr and ~90 Myr for the ONC region and L1641, respectively.

Although we now know much more about the stellar population in Orion A than was known 15 years ago, there is still much to learn. Some of the results presented here, particularly those concerning distributed stars in L1641, would be greatly improved by increasing statistics. Near–IR surveys on still larger scales are wanted, and will be provided by the 2MASS and DENIS projects. Large–scale optical surveys are also underway, using a new generation of multiple–CCD cameras. Combined with multi–fiber spectroscopy, these tools provide the means of completely characterizing the surface and partially embedded stellar populations in Orion. More deeply embedded stars will be catalogued with mid–IR instruments like WIRE, and will continue to be explored by means of ground–based deep near–IR imaging and near–IR spectroscopy. Detailed studies of specific clusters or regions in Orion will have to be synthesized with the larger survey results to form a complete picture of the star forming properties and star formation history of the GMC.

Acknowledgments. We would like to thank M. Meyer, S. Strom, and K. Strom for enlightening discussions. Thanks to M. Meyer for help preparing Figure 2. LAH acknowledges travel support for attendance at this meeting from a NASA grant, administered by the AAS. LEA receives support from the Australian Research Council.

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