Abstract:

Stellar aggregates associated with isolated molecular cloud cores containing Herbig Ae/Be stars are not uncommon. These recently discovered clusters are small (0.1-0.3 pc in size), dense (0.3-3 $\times 10^3$ stars pc^{-3}), and young (0.3-2.0 Myr in age). They thus appear to represent a short-lived snapshot in cloud core evolution during which star formation *has* been initiated, but cloud dispersal *has not* yet been completed. We would like to use the Ae/Be aggregates to answer the following question: **do stars form sequentially in mass within isolated, individual star-forming episodes?** Operationally, therefore, we need to know whether star formation is ongoing in these groups or if gravitational collapse is no longer possible. If the former, it supports the interpretation that the high-mass Ae/Be stars might have formed first, and possibly even triggered the subsequent formation of the accompanying lower-mass stars. If the latter, it is more likely that the Ae/Be stars formed last and concluded, or perhaps actually prevented, further star formation in these cores. Our approach is to combine high-resolution molecular observations of the clouds with near infrared imaging, optical imaging, and optical spectroscopy of the stellar populations, in order to determine how the core and its stellar products might be related. In this presentation we compare new results in the MWC 1080 region to those already published for the BD+40 4124 region.

Introduction

To date, almost all *theoretical* studies of the star formation process have concentrated on the production of single and (recently) binary stars. However, *observational* studies of the youngest stellar populations (enabled by the increased size and sensitivity of near-infrared array cameras) have shown that single / binary star formation, may not be the dominant mode by which stars are born in the Galaxy. Instead of the canonical picture of "*isolated*" collapse – occurring in relatively low stellar density environments – "*clustered*" fragmentation / coagulation – occurring in high stellar density environments – appears to be a common, if not governing, process.

One important example of this phenomenon is that small clusters of partially embedded lower-mass stars often form within the same isolated molecular cloud cores as do young ($\tau < 1$ Myr) intermediate- and high-mass ($M > 3M_\odot$) Herbig Ae/Be stars. In Figure 1 we show representative Ae/Be regions to illustrate the prevalence of these aggregates.

Preliminary analysis has shown the Ae/Be clusters to have the following properties:

- small – 0.1-0.3 pc in size
- dense – 0.3-3 $\times 10^3$ stars pc^{-3}
- apparently spherical in geometry
- comprised of young stellar populations – 0.3-2.0 Myr in age
- span a range of masses down to the hydrogen burning limit.

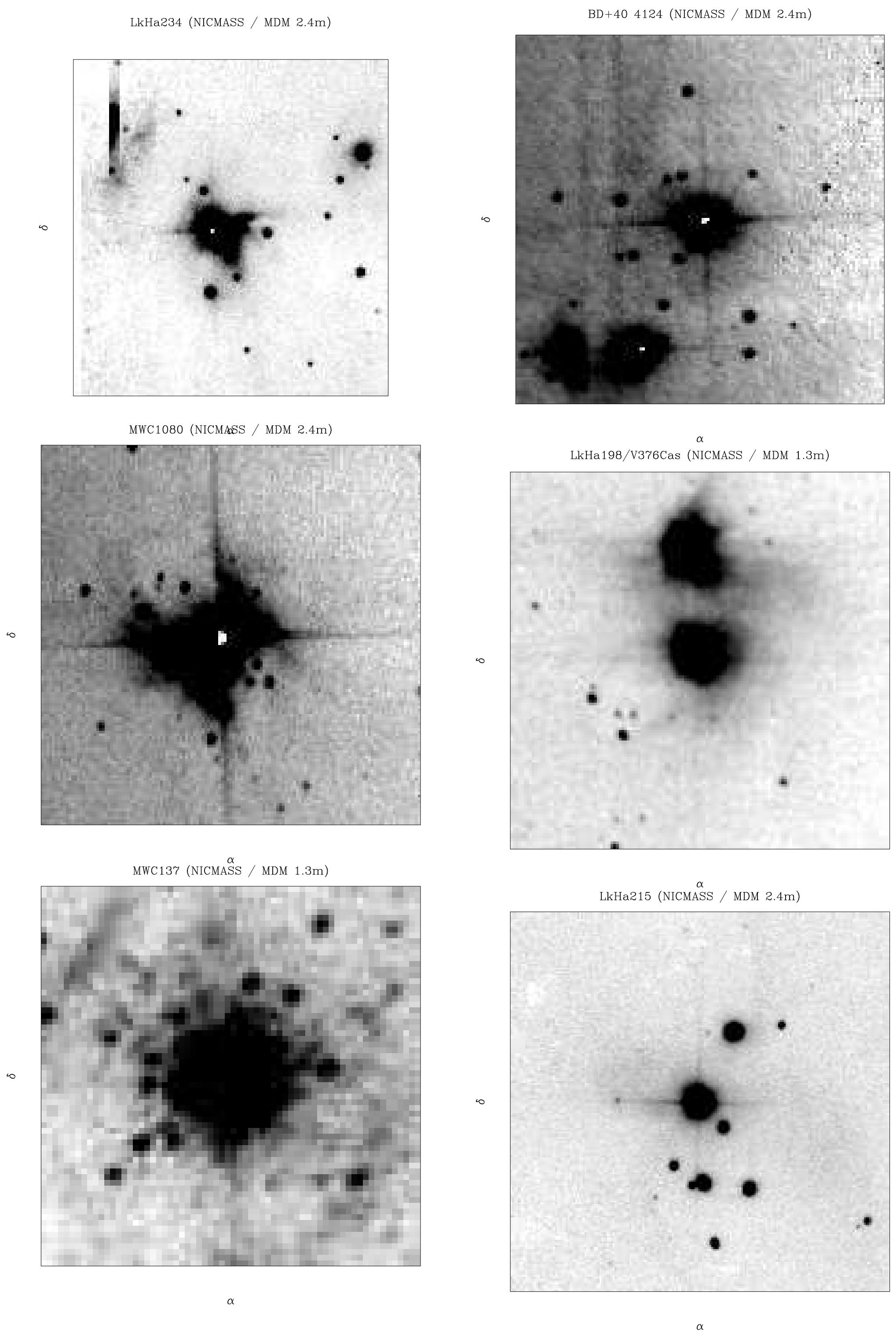

Figure 1. *K-band (2.2 μm) images of several Ae/Be regions.* In each case, the image is centered on the Ae/Be star itself and has been adjusted for source distance to cover an area 1/3pc × 1/3pc in size. The data were obtained with the University of Massachusetts NICMASS camera mounted on the Michigan-Dartmouth-MIT 2.4m and 1.3m telescopes on Kitt Peak.

Why are these clusters important?

Once OB stars form, they disperse any ambient molecular gas on a rather short timescale. An accompanying stellar cluster will quickly become unbound if the velocity dispersion of the gas is less than the cluster escape velocity, or if

$$\sqrt{\frac{G(M_{gas}+M_{stars})}{r}} < \sqrt{\frac{2GM_{stars}}{r}}$$

which can be simplified to

$$M_{stars} << M_{gas}.$$

Yet, we have identified a group of isolated, young OB stars which define both dense stellar clusters, and significant density enhancements in ambient molecular gas. The Ae/Be stars studied herein therefore represent a rarely observed, short-lived era in the cloud core evolutionary process during which

- star formation *has* been initiated,

but

- cloud dispersal *has not* yet been completed.

Figure 1..

Table 5.1. Summary of Cluster Parameters at $r < 0.167$ pc

Name	Mass $M_\odot$	Relative Distance	Rel. Inst. Sensitivity	IR Stars Detected	Opt. Stars Detected	# with Spectra	Comment on Spectra
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
MWC 297	26.5	0.45	1.0	41	9	4	1 Be, 2 GK, 1 cont+e star
MWC 1080	20.6	1.00	0.5	30	8	5	1 Be, 1 K, 2 Me, 1 M
MWC 137	18.9	1.30	0.7	26	12	9	1 Be, 1 F, 5 GK(e?), 2 M(e?)
BD +40° 4124	12.6	1.00	1.0	22	10	10	2 Be, 2 AFe, 1F, 2 Ke, 3Me
Lk Hα 198	9.6	0.60	0.4	19	14	2	2 Ae
Lk Hα 215	9.5	0.80	1.0	15	11	11	1 Be, 8 Me , 2 M
HD 259431	8.9	0.80	>0.3	3	3	3	1 Be, 2 M
Lk Hα 234	8.5	1.00	1.1	20	7	5	1 Be, 1 B, 2 K, 1 Me
RR Tau	8.4	0.80	0.5	5	5	0	–
VV Ser	7.5	0.44	1.0	30	25	15	1 Be and mostly K stars
BD +46° 3471	7.3	0.90	1.0	11	9	9	1 Ae, 1 G, 3 K, 2 M, 2 Me
HD 200775	7.2	0.60	1.0	7	4	4	1 Be, 1 Fe, 1 Ke, 1 Me
BD +61° 154	5.1	0.65	1.0	12	10	5	1 Be, 4 K
Lk Hα 208	4.1	1.00	0.7	6	3	0	–
HD 250550	3.9	0.70	0.7	7	5	2	1 Be, 1 early K
Lk Hα 218	3.8	1.15	0.5	5	3	0	–
Lk Hα 233	2.6	0.88	>0.6	2	2	2	1 Ae, 1 Me

Column (2): Stellar mass repeated from Table 1.1.
Column (3): Relative source distance normalized to 1 kpc.
Column (4): Relative instrumental sensitivity computed from $\sqrt{(exposure\ time/144\ s)} \times (telescope\ diameter/2.4m)$; HD 259431 and Lk H$\alpha$ 233 are given as lower limits due to relatively lower throughput infrared images.
Column (5): Number of K-band sources detected over 1/3 pc $\times$ 1/3 pc area; estimated error is $\sqrt{N}$.
Column (6): Number of detected infrared sources in (5) with optical counterparts.
Column (7): Number of optical counterparts in (6) with classification spectra.
Column (8): Comment on spectral types of cluster members, where available.

These young stellar *systems* may, therefore, provide important clues to the physical processes associated with forming high-mass stars. In order to understand the formation of these groups, we must solve two theoretical problems:

- the production of high-mass stars
- the production of small clusters.

These "problems" appear, however, to be linked in a non-intuitive way. In Figure 2 we show an apparent correlation between cluster density and the mass of the most massive star in the group, that of the Ae/Be star.

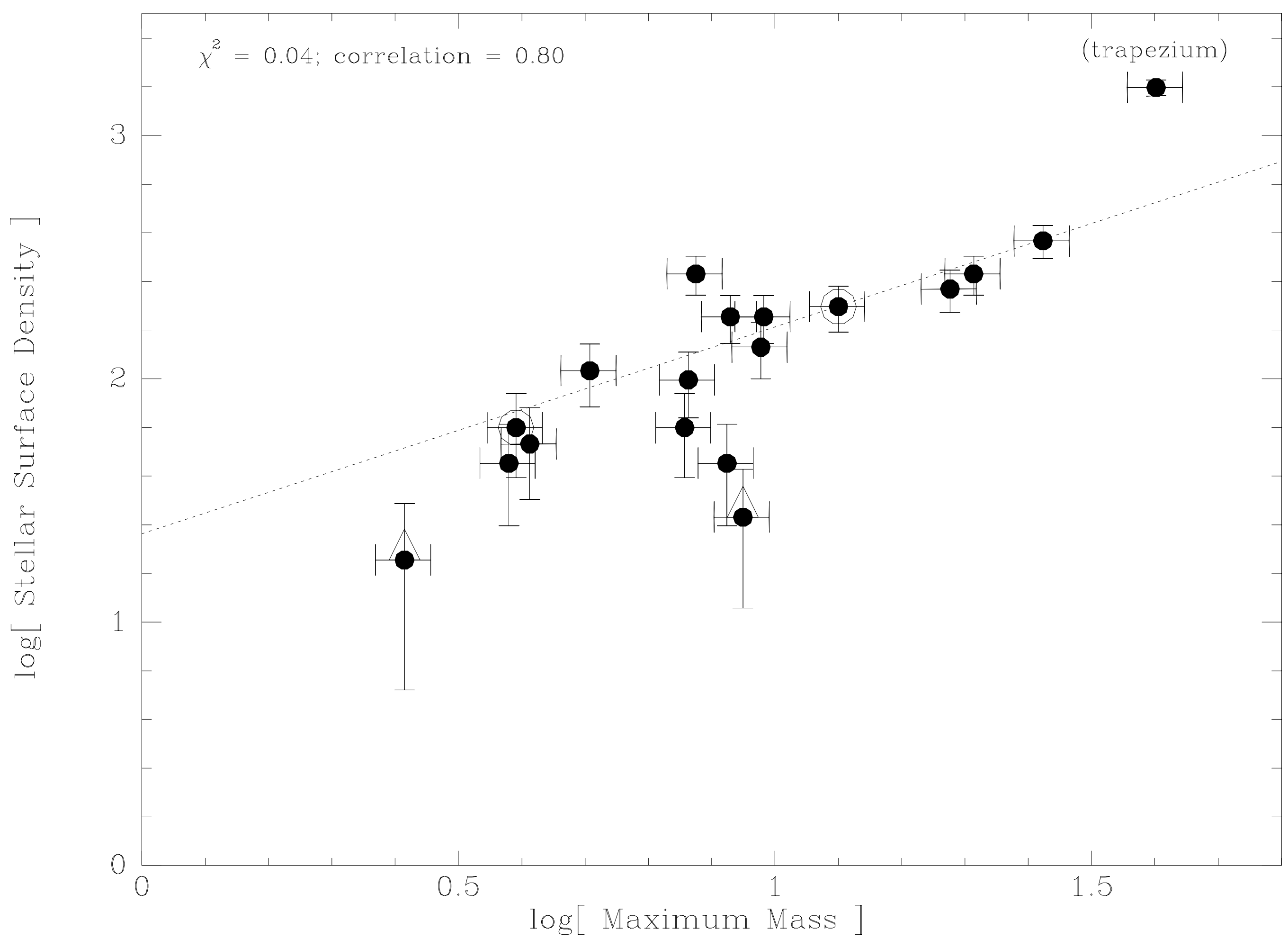

Figure 2. *Stellar surface density versus maximum mass for clusters associated with Ae/Be stars.* Random errors of 10% in the stellar masses and $\sqrt{N}$ in the cluster census counts are shown. Triangles represent lower limits in two cases where the infrared images are significantly less sensitive. The inner 0.167 pc of the Trapezium Cluster, for which the stellar density was computed in the same manner as for the Ae/Be regions, is also shown, for reference only. A line which accounts for the errors in both axes has been fit to the data distribution (not including the Trapezium or the lower limits) and produces a correlation coefficient of 0.8.

Approach to Analysis

We would like to decipher the star formation histories of these clusters and, in particular, to relate the properties of the output stellar products to those of the input cloud core environment.

This is a two-part process involving

- the combination of optical and infrared spectroscopic and photometric information, in order to characterize the properties (stellar ages and masses, disk accretion rates, *etc.*) of individual aggregate members
- the synthesis of low- and high-resolution molecular line and dust continuum observations, in order to characterize the properties (geometry, density structure) of the remnant cloud cores.

From observations of the stars, we can address the issue of the time sequence of star formation as a function of stellar mass. Did the Herbig Ae/Be star which defines the group form 1) first, 2) last, or 3) somewhere in the middle, of the star formation episode?

From observations of the cloud cores, we can address

- whether star formation is ongoing in these groups (consistent with the Ae/Be stars having formed first and possibly even triggered the subsequent formation of lower-mass stars.

or

- if gravitational collapse is no longer possible. (consistent with the Ae/Be stars having concluded star formation in these cores)

Comparison Between Two Ae/Be Regions

Analysis of several Ae/Be star-forming environments suggests that not all such star-forming "events" have similar histories. We summarize these findings for two regions in the Table below.

The BD+40 4124 Region

PICTURES

The MWC 1080 Region

PICTURES

Property	BD+40 4124 Region	MWC 1080 Region
Low-Resolution Cloud Morphology	cometary, with Hα-bright rim	spherical
Interpretation of Cloud Morphology	externally triggered?	undisturbed
Dust Continuum Morphology	multiple peaks over cloud core	??
Is the Optically Visible Ae/Be Star the Regional Center of Action?	no; source $\sim$0.1pc away is	yes
Fraction of Infrared Excess Objects	$>$ 50-80%; typical	<50%; low
Stellar Age Distribution	0.1-3 Myr	0.1-10 Myr
Stellar Mass Distribution	biased towards high-mass stars	consistent with Miller-Scalo
Interpretation Cluster History	star formation is ongoing; BD+40 4124 formed early but did not prevent further star formation activity	star formation has concluded; MWC 1080 formed last and did prevent further star formation activity

Figure 3. .

The Role of Interferometry

In order to clarify the relationships of newly formed stellar populations with their parent molecular environments, higher resolution observations of the cloud cores are necessary.

To date, all millimeter wavelength interferometric observations of star-forming environments have concentrated on single objects which are forming in relative isolation, and have been searches for either:

- evidence of infall or outflow

or

- evidence of rotating circumstellar disks.

However, a heretofore unexploited use of interferometric investigations, is in probing the structure of molecular cloud cores at sub- 0.1pc resolution or better. Dust continuum and molecular line emission maps are critical, for example, to determining whether the massive Ae/Be stars in our sample, have concluded the star formation histories of their respective clusters, or whether star formation is ongoing.

A few of these regions *have* been observed at high (> 15 arcsec) resolution.

- Dust continuum maps (IRAM 2.7mm, DiFrancesco *et al.*) have shown different dust morphologies in different regions, suggesting a lack of ongoing star formation in some cases but clear evidence for potentially protostellar dust condensations in other cases.
- Molecular line maps (OVRO 1.3mm, Hillenbrand & Sargent; BIMA 2.7mm, Hillenbrand & Wilner) have shown clumpy ^{13}CO structures in two regions. These observations are suggestive of either stochastic cloud core fragmentation, or perhaps of destructive interaction of the forming massive Ae/Be star with its molecular environment.

Analysis of these maps is ongoing, and further interferometric study of Ae/Be regions is encouraged.

Summary