THE DYNAMICAL EVOLUTION OF YOUNG CLUSTERS AND ASSOCIATIONS

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A young cluster or association bears the imprint of the conditions at its birth for perhaps ten million years, after which the initial conditions are lost to either dilution in the galactic field or erasure by orbital mixing and stellar encounters. In its youngest years, however, the dynamical state of the system can provide valuable information concerning the structure and energetics of the parent gas, the star-formation efficiency and the star-formation process itself. This short review discusses recent theoretical and observational progress in the study of the very youngest of stellar systems.

Much recent theoretical work has concentrated on the dynamical evolution of young stellar systems. The essential finding of several recent studies can be summarized in the statement that inefficient star-formation during the lifetime of a molecular cloud (i.e., $M_*/(M_*+M_{gas}) << 1$) produces unbound stellar systems (Hills 1980, Duerr, Imhoff and Lada 1982, Mathieu 1983a, Elmegreen 1983, Wilking and Lada 1983, Lada, Margulis and Dearborn 1984). The line of argument is as follows. Most stars form in gravitationally bound molecular clouds. While the initial velocity distribution of newly formed stars is not known, it is reasonable to assume that the stars form with a velocity distribution similar to that of the parental gas. In particular, observations of molecular clouds show the internal gas motions to be comparable to those expected in virial equilibrium. Indeed, even if the stars do not form with these velocities, within a crossing time ($\sim 10^6$ yr for dynamically isolated regions $<$ 10 pc in size, e.g. a molecular cloud core) the stellar system will relax into an equilibrium velocity distribution with the gravitational potential in which it finds itself. Thus we envision a stellar system embedded in a molecular cloud having a stellar velocity distribution in equilibrium with the gravitational potential of the gas and stars.

However, the star formation process is inherently destructive to the parent cloud. Energetic phenomena associated with the formation of massive stars, such as HII regions, stellar winds and supernovae, act

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to disperse the gas from which these stars formed. Indeed it is possible that massive stars are not necessary for this gas dispersal; outflows from low-mass stars may suffice to at least locally remove the gas. The essential point is that the gas in a star-forming region is inevitably removed from the region. Unless a substantial fraction of the gas has been converted into stars by that time, the removal of the gas represents a substantial loss of the binding mass of the system. In the case of rapid mass loss, the stellar kinetic energy remains unchanged during the process. Consequently the energy of the stellar system becomes positive and the stellar system is unbound.

Observations indicate that in general star-formation is in fact an inefficient process over size scales of a few parsecs or greater. The conclusion then is that the formation of unbound stellar systems, or associations, is the rule, not the exception. These associations will expand, initially with velocities comparable to the stellar velocities prior to gas dispersal, and mix with the field population. A point worth stressing is that in this picture the expansion of the stellar system is not due to any acceleration mechanism, e.g. star formation in an expanding shell driven by a supernova (Opik 1953) or an HII region (Oort 1954); the expansion is simply a consequence of the loss of binding mass. Thus an observational test is the magnitude of the expansion velocities in young associations; this picture suggests that the expansion velocities should be comparable to the internal motions of molecular clouds, on the order of a few km/sec.

As a concrete example of this theoretical scenario, let us now examine one association in some detail, the group of young stars surrounding and including λ Orionis. Attention has most recently been drawn to the λ Orionis region by Duerr, Imhoff and Lada (1982; hereinafter DIL), who completed an extensive Hα survey of the region. Figure 1 is taken directly from their paper and shows the essential morphology of the region. Centered in the complex is the λ Orionis OB-association, consisting of an O8III star (λ Ori) and several B stars. A large spherical HII region surrounds λ Ori, at the edge of which lies an HI shell coincident with a ring of dark clouds. Within the HII region lie a large number of Hα stars, presumably very young low-mass stars. The highest concentrations are found on the inside edges (i.e., toward the OB stars) of the clouds B30 and B35; the remainder are scattered in a more or less linear fashion between the two clouds. DIL noted that the linear spatial distribution and the extent of the Hα stars is very much like the gas distributions found in giant molecular clouds (GMCs), and that the amount of material in the HI shell ($\sim 10^5$ $M_\odot$) is comparable to the amount of molecular gas found in a GMC. They thus proposed that the λ Orionis region is essentially a well-preserved "fossil" GMC, recently exposed by the action of λ Ori. They find a star-formation efficiency in the region of only 0.2-0.3%.

DIL point out that if the material in the HI shell was originally molecular gas distributed in the volume delineated by the Hα stars, then the cloud would have had an escape velocity at its surface on the

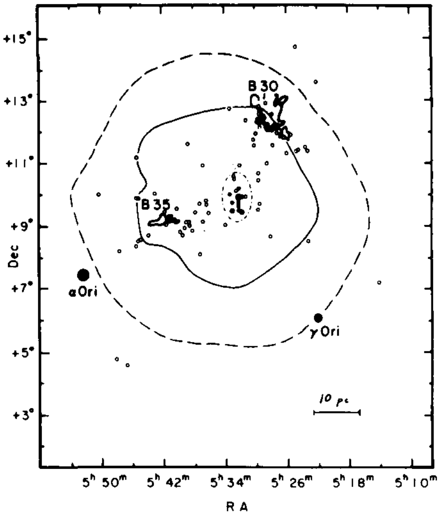

Fig. 1. Morphology of the λ Orionis region. Open circles are Hα stars, the solid line is the extent of the HII region and the outer dashed line delimits the surrounding dark cloud material. The inner oval encompasses the OB association (filled circles).

order of 5 km/sec and would be stable with respect to galactic tides. However presently, after removal of that molecular gas, the escape velocity is but 0.2 km/sec and the global stellar system is unstable to galactic tides. In the immediate vicinity of the clouds B30 and B35 the local escape velocities are higher, on the order of 5 km/sec. However, the local escape velocities due only to the stellar mass about B30 and B35 are also small as is the local escape velocity from the OB association, all being roughly 0.2-0.5 km/sec.

Mathieu and Latham (in preparation) have recently completed a radial velocity study of ~ 30 Hα stars in the region, using the MMT/echelle spectrograph and cross-correlation techniques (Latham 1985). Typical errors are 1 km/sec for a single measurement; multiple measurements over several years have been obtained for each star. The observed velocity distribution is roughly gaussian. The velocity dispersion of the stellar system is small; globally we measure a dispersion of 2 km/sec. (All quoted velocity dispersions are one dimensional.) This is comparable to typical velocity dispersions in GMCs. There is some structure in the velocity field which matches that in the molecular gas; the mean stellar velocities about B30 and B35 differ by 2 km/sec and are consistent with the molecular line velocities of each cloud. Locally about each dark cloud the velocity dispersion is smaller, on the order of 1 km/sec. This is again essentially the same as the CO line widths in each cloud (Maddalena _et al._ 1985). Thus our first conclusion is that the stellar velocity distribution is indeed similar to that of the gas out of which the stars formed. The peak-to-peak velocity range is only 8 km/sec, so the stars were bound to the original molecular cloud, just as the stars in the vicinity of B30 and B35 remain bound to those clouds today. However, the stellar velocities are significantly larger than the present escape velocity of the global system. With the removal of the gas the stellar system has become unbound and will ultimately disperse.

The measurement of the internal motions of the OB association itself is technically difficult due to the presence of only a few lines in the spectra of such hot stars and their large rotation velocities. However, indirect morphological arguments are enlightening. The OB system has a radius of 4 pc and an age of $2\text{-}6\times10^6$ yr. Thus an upper limit on the internal motions of the stars is on the order of 1-2 km/sec, similar to the motions of the late-type stars.

Given the discussion so far, it is clear that the fact that bound open clusters do exist presents a particularly interesting problem for the study of star formation. The arguments presented above can easily be reversed to argue that if a cloud is to form a bound stellar system, the star-formation efficiency must be high. The actual lower-limit on the efficiency is somewhat dependent on the details of the gas removal, in particular whether the gas is removed rapidly or slowly with respect to the crossing time of the system (Mathieu 1983a, Elmegreen 1983), and the cluster structure. Using virial arguments, Mathieu (1983a) compared the initial and final states of open clusters and concluded that star-formation efficiencies at least as high as 30% were required to produce open clusters as observed today. Lada, Margulis and Dearborn (1984), using numerical techniques, added the important insight that a system can be globally unbound and still have a substantial bound core. This allows the lower limit on the star formation efficiency to be somewhat lessened. Nonetheless, it seems clear that high star-formation efficiencies are required to form bound stellar systems.

With this in mind, the remainder of this discussion will concern the search for sites of forming or very recently formed open clusters. The theory tells us that if one wants to find a forming open cluster one does not look for young stellar systems that have the structure and kinematics of an old open cluster such as the Plieades, with half-mass radii of a few parsecs and internal velocity dispersions on the order of 1 km/sec. Rather one must search for more compact systems with higher densities and velocity dispersions, which, with the removal of the parent gas, will expand into a Pleiades-like open cluster.

Let us first consider the classic young star-forming region NGC 2264. In Figure 2, we show the distribution of Hα stars in the NGC 2264 region (Herbig 1954), superimposed on the ^{12}CO and ^{13}CO maps of the region by Crutcher, Hartkopf and Giguere (1978). The spatial distribution of the Hα stars has none of the symmetry or central concentration of an older open cluster. Indeed if there is any significant structure in the spatial distribution of the stars it is

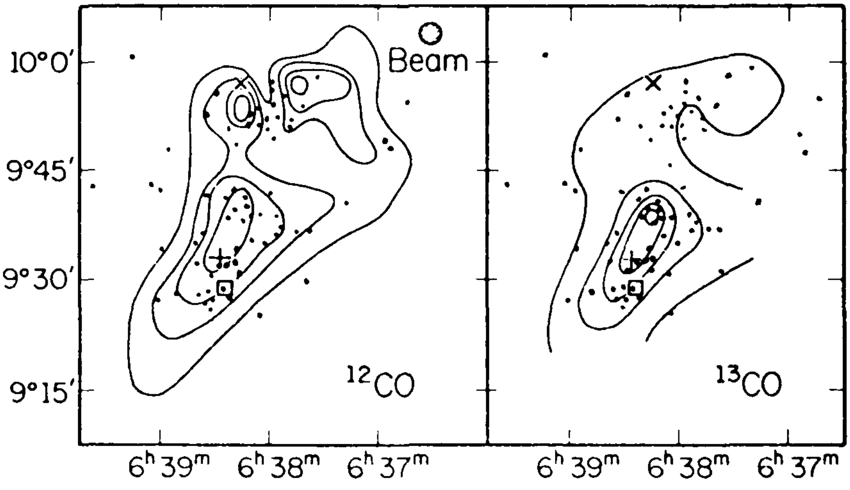

Fig. 2. Morphology of the NGC 2264 region. Dots are Hα stars.

the similarity of the stellar and gas distributions, both having two centers of concentration. The earlier spectral-type stars are also notably clumped at the two sites. The crossing time of the system (see below) is ~2×10^6 yr. The ages of many of the Hα stars are comparable or older (Iben and Talbot 1966), so it might at first seem surprising that the system is not well mixed. However, the youngest stars in the region are less than 10^6 yr old, indicating that the gas was only recently removed from the region by the O8 star S Mon. This suggests that in fact the older stars may have dynamically relaxed, but in a gravitational potential that until very recently was dominated by clumped molecular gas. There has not been sufficient time for the stars to respond to the removal of that gas, so that the present configuration reflects the configuration of the embedded stellar system. On the other hand, Adams, Strom and Strom (1983) find that even lower mass stars in the region are distributed uniformly, regardless of stellar age, so the picture may not be so simple.

Radial velocities are being obtained with the MMT and Whipple Observatory 1.5m echelle spectrographs, as described above. Data have now been obtained over two years. A preliminary velocity distribution is given in Fig. 3. The distribution is notable in that the observed velocity dispersion is ~2.5 km/sec. Typical open cluster velocity dispersions are 1 km/sec or less. This point is made dramatically by the comparison in Fig. 3 with the velocity distribution of M11 (Mathieu 1983b), one of the most massive open clusters known. The point here is clear: NGC 2264 is of comparable size to M11, less concentrated and less massive, yet has a notably larger velocity dispersion. Clearly the stellar system is not in virial equilibrium. In fact, most of the stars observed have velocities greater than or comparable to the escape velocity due to the stellar mass alone, of order 2 km/sec. We thus suggest the possibility that NGC 2264 is not in fact a young open

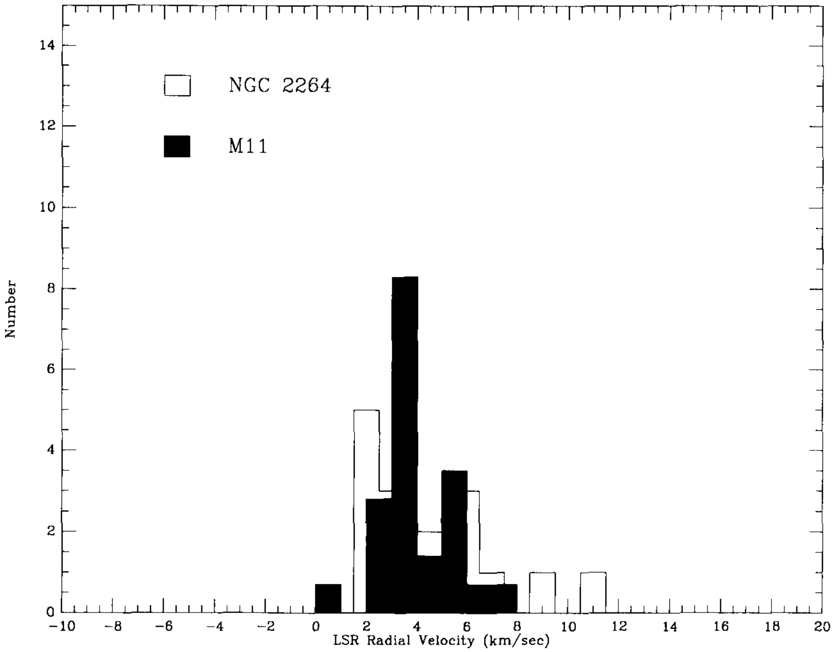

Fig. 3. Stellar radial-velocity distributions of NGC 2264 and M11 (the latter scaled in number and shifted in velocity).

cluster but rather an unbound association. We note that the velocity dispersion of NGC 2264 is entirely consistent with the system having been in equilibrium with the gas out of which it formed. Indeed the velocity field of the stars is quite comparable to that of the background gas.

We turn next to the Trapezium Cluster, a dense clustering of stars within a parsec of the Trapezium. This system has been discussed in detail by Herbig (1982) and Herbig and Terndrup (1986); the latter suggest a stellar density of at least 2000 stars pc^{-3} and a minimum mass density of order 3000 $M_\odot$ pc^{-3}, to be compared with typical open cluster mass densities of 1-10 $M_\odot$ pc^{-3}. Several groups have succeeded in measuring the internal motions of the stellar system (van Altena and collaborators and Jones and Walker independently with proper motions and Marschall, Mathieu and Latham with radial velocities, all in preparation). All agree that the motions are large relative to typical open clusters, with a velocity dispersion on the order of 2 km/sec. Using the physical parameters given by Herbig and Terndrup one finds a minimum escape velocity from the stellar system to be of order 2-3 km/sec. Thus the Trapezium cluster is somewhat more tightly bound than NGC 2264; nonetheless, many of the stars will ultimately escape. The core of the cluster may remain bound and evolve into an open cluster, albeit one of low total mass which may not survive long due to external dynamical effects.

An excellent candidate for an open cluster still in the process of formation has been found in the ρ Oph cloud by Wilking and Lada (1983). They did a near-IR survey around a dense molecular ridge in the cloud and found numerous sources concentrated within a 1 pc diameter area. They determine a stellar density of 250 $M_\odot$ pc^{-3}, again markedly higher than typical open clusters. Because the parent gas is as yet substantially undisturbed, Wilking and Lada were able to directly estimate the star-formation efficiency in the region. They estimate a value on the order of 30%; thus the high efficiencies indicated by the dynamical arguments as necessary to form bound clusters do indeed exist in nature.

Perhaps the most massive candidate for a forming cluster has been found at millimeter wavelengths. Vogel and Welch (1983) have done an HCO^+ aperture synthesis maps of the compact HII region K3-50. Previous far-infrared measurements had indicated a stellar population of several thousand solar masses in addition to K3-50 itself (Thronson and Harper 1979). Vogel and Welch find a warm dense cloud of about 2000 $M_\odot$ within a 1 pc diameter. The mean density within a 0.5 pc radius is 4000 $M_\odot$ pc^{-3}. Interestingly, the cloud is rotating with a rotational velocity of 4 km/sec at a radius of 0.5 pc and is somewhat flattened. Thus the present system differs markedly from known open clusters. However, as Vogel and Welch discuss, adopting a star-formation efficiency of 25% and removing the remaining gas slowly, perhaps with OB stellar winds, one predicts a final stellar system with a radius of 2 pc, a density of 15 $M_\odot$, a rotational velocity of 1 km/sec at 2 pc and a total stellar mass of 500 $M_\odot$. Except for perhaps the rotational velocity, these are compatible with the core of a massive open cluster.

We find then that the theoretical picture and the observations of young star-forming regions are in reasonable accord, although we still do not have a certain example of a very young, bound cluster. However, substantial issues remain for both the theory and the observations. In particular, we have not yet begun to address the questions of 1) the initial spatial and velocity distributions of a young stellar system (ultimately as a function of mass) and 2) the dynamical evolution of a stellar system while embedded in the parent gas cloud. With regard to the latter, it has often been suggested that the stars in clusters do not form coevally and in fact may have an age spread of as much as 10 million years. This is ample time for substantial dynamical evolution before the cluster is ever revealed for optical study. It is interesting that several very young clusters already seem to show mass segregation (e.g., NGC 6530 (McNamara, priv. comm.)). We must better understand the evolution of embedded systems before we can ascertain whether this is the consequence of formation or dynamical processes. And, observationally, we need better infra-red and radio studies of star-forming regions in order to directly study the spatial and velocity distributions of embedded systems.

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