Star formation in unbound giant molecular clouds: the origin of OB associations?

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10 September 2018

ABSTRACT

We investigate the formation of star clusters in an unbound GMC, where the supporting kinetic energy is twice as large as the cloud’s self-gravity. This cloud manages to form a series of star clusters and disperse, all within roughly 2 crossing times (10 Myr), supporting recent claims that star formation is a rapid process. Simple assumptions about the nature of the star formation occurring in the clusters allows us to place an estimate for the star formation efficiency at about 5 to 10%, consistent with observations. We also propose that unbound clouds can act as a mechanism for forming OB associations. The clusters that form in the cloud behave as OB subgroups. These clusters are naturally expanding from one another due to unbound nature of the flows that create them. The properties of the cloud we present here are are consistent with those of classic OB associations.

Key words: Molecular clouds, turbulence, IMF

1 INTRODUCTION

Practically all star formation is thought to occur in clusters that are embedded in giant molecular clouds (GMCs) [Lada & Lada 2003]. This suggests that a clustering environment, where multiple objects compete for a common gas reservoir [Zinnecker 1982; Larson 1992], plays an important role in early stages of protostellar evolution, such as dictating the form of the stellar initial mass function (IMF) [Bonnell et al. 1997; Bonnell et al. 2001]. Furthermore, Elmegreen (2000) has collected observational evidence suggesting that star formation is a rapid process, occurring on roughly the crossing time of the region at a variety of scales. Not only does he propose that the star formation in a typical GMC occurs within ~ 4 Myr (approximately the crossing time for standard GMC) but that the cloud’s dispersal occurs within a few crossing times, or < 10 Myr.

The combined implication of these observations is that star formation occurs quickly and in groups and that the sites of star formation disperse quickly. Our proposal in this paper is that this is possible if GMCs are dynamically unbound objects, with the internal turbulent energy greater than that of the cloud’s self-gravity. This follows from the work of Vázquez-Semadeni, Passot & Pouquet (1995) who showed that transient (unbound) GMC sized objects can be formed from flows in the ISM. We also find that unbound GMCs may provide a natural mechanism for the creation of OB associations, a notion first suggested by Ambartsumian (1958).

In the rest of this first section we discuss the ideas behind rapid star formation and the dynamical state of GMCs. We also include in this section a discussion of OB associations. In section 2 we describe the details of the simulation and section 3 follows the general evolution of the GMC. In section 4 we give estimates of the star formation efficiency in the GMC based on some simple assumptions. In section 5 we highlight the similarities between the simulation and the general structure in an OB associations. A summary of the paper’s main conclusions can be found in section 6.

1.1 GMC Lifetimes and Rapid Star Formation

Until the last decade or so GMCs were generally believed to be long-lived structures, with some estimates of ages reaching as high as 10⁸ Myr [Solomon, Sanders & Scoville 1979; Scoville, Solomon & Sanders 1979; Scoville & Hersh 1979]. It was generally believed that the chemistry of turning atomic species into molecules would require millions of years before an object of a GMC would be detectable via its CO abundance [Jura 1975]. One also had the problem that the CO mass in the galaxy, coupled with estimates of the star formation rate, suggested that GMCs had to live for tens of millions of years if the star formation efficiency was to remain at the observed level of a few percent [Zuckerman & Evans 1974; Zuckerman & Palmed 1974].

Recent observations of embedded clusters tend to suggest that the whole process of star formation, including GMC formation...
and dispersal, occurs on roughly the crossing time for the region
(\text{Elmegreen} 2004). Not only do most molecular clouds in the so-
nearby contain signs of star formation in the form of clus-
ters, but the age determination of these clusters suggests they
are very young, typically less than 10 Myr \cite{Hartmann2004}. This
suggests that star formation occurs quickly in GMCs after their for-
mation. The fact that clusters with ages greater than \sim 5 Myr are
seldom associated with molecular gas, suggests that clouds disperse
quickly \cite{Leisawitz1989}.

In the original cloud lifetime proposition, it was assumed that
all of the CO observed in the galaxy was associated with molec-
ular hydrogen involved in star formation. We now realise that the
vast majority of the gas that comprises a GMC is never involved
in the star formation process. In fact the star formation efficiency
in GMCs is only a few percent. The reason behind this lies with
the fact that little of the cloud is actually dense and bound enough
to turn into stars in the cloud’s lifetime \cite{Padovani1995, Hartmann1998,Zinnecker2002}. Also, if GMCs are short-lived features then
there is little time for the more tenuous parts of the cloud to get in-
volved in the star formation via accretion.

The old GMC model also required the cloud to be supported
and in virial equilibrium, since that would permit them to remain as
coherent structures for as long as was necessary. This support pres-
sure had to be in the form of non-thermal kinetic energy, such as
turbulence \cite{Larson1981}, since the thermal energy component of
these clouds is typically very small. To counteract the gravity on
the large scales however requires motions which are supersonic, and
it is known that these quickly damp in shocks \cite{MacLow1998,Stone1998,Stone1998}. Even in the presence of magnetic
fields. Thus the bound GMC model requires some method of con-
 tinuously driving the turbulence on the large scale. These driving
mechanisms are not necessary in the short cloud lifetime model,
and there also is no need to assume that the clouds are in virial
equilibrium. GMCs can therefore exist in a variety of dynamical
states.

\cite{Heyer2001} have examined the stability of molecular clouds in
the outer galaxy and come to the conclusion that most clouds are indeed globally unbound by their internal
motions. They also point out the difficulty in producing mass es-
timates (which a great number of papers on the subject of GMCs
pass over) and note that even mass estimates determined via CO
measurements (both $^{12}$CO and $^{13}$CO) assume at some stage the
cloud is bound. Although they do find the clouds approach dynam-
ical stability at large masses ($> 10^3 M_\odot$), there is still considerable
scatter in the data, suggesting that there is no typical dynamic state
for GMCs.

\cite{Pringle2001} have shown that it might also be possible to build GMCs by accumulating very low density hy-
drogen gas, already in a molecular state. Their study came in re-
sponse to the ideas presented by \cite{Elmegreen2000}, in an attempt to
provide a new mechanism for GMC formation that can occur
quickly. They point out that it is quite possible that a large fraction of
the interstellar medium may be in molecular form, but either sim-
ply too low a density to be detectable by current methods or too far
away from illuminating sources. The GMCs are then formed from
large scale shocks, from spiral arm passage or feedback from high
mass stars, such as winds and supernovae. This cloud formation can
occur within a few million years. \cite{Pringle2001} also point out
that GMCs are probably not in virial equilibrium, and note that their
wind-swept appearance suggests that they are anything but.

The simulation that we present here draws on the above stud-
ies for motivation. We assume that large scale flows are able to
create an unbound GMC in a few millions years. Instead of be-
ing contained by external forces \cite{Heyer2001}, we assume that the cloud is free to expand into the ISM. Thus the
flows that created the cloud are assumed to have been used up
in its formation. Since the cloud is assumed to be short lived and
not quasi-static, there is no need for the internal turbulent
energy, which will dissipate on the crossing time, to be replen-
ished \cite{Ballesteros2003, Elmegreen2000}.

### 1.2 The Origin of OB Associations

OB associations are historically identified simply as extended
groups of OB stars, having diameters of tens of parsecs
\cite{Ambartsumian1958}. Furthermore they are rather more diffuse
than open clusters, with the mass density of OB type stars at \sim
0.1 M_\odot pc$^{-3}$ \cite{Blaauw1964, Ambartsumian1958, Garman1994,Lada2003}. It was found that these associations contain
considerable substructure which are referred to as ‘OB subgroups’
\cite{Blaauw1964}. These subgroups are unbound from one another
as was deduced from their expansion about the centre of the region
\cite{Blaauw1955}. Some regions or ‘subgroups’ are shown to be asso-
ciated with molecular gas. In general these regions are not coeval
but can exhibit a spread of ages between the subgroup population
as large as 10 Myr \cite{Blaauw1964}. The fact that OB associations
are very young, with some of the subgroups possessing ages of the
order of a millions years, suggests that unbound nature of the sub-
groups from one another is primordial.

The relationship between OB associations and other types of
clusters found in the galactic disc, such as open clusters
and embedded clusters, is still rather unclear. The OB associa-
tions do however have a classic theory regarding their formation.

\cite{Elmegreen1977} proposed that OB associations form via
triggering, prompted by the ionised regions produced by previous
generations of OB stars. In this manner, the star formation is self
propagating, with one generations of OB stars triggering the for-
mation of the next. Since the shocked layer in which the new group
of OB stars forms is moving away from the older OB stars, at a
few kms$^{-1}$, the new group is unbound from its parent group. The
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aries of molecular clouds and HII, such as NGC7538, M17 and M8
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initially supported against collapse by a turbulent velocity field. It was found that the dissipation of the large scale supersonic flows produced a number of distinct subclusters. Each subcluster contains at the core a massive star. The subclusters were mass segregated and each had a protostellar population consistent with that of the observed field star IMF, both of which are the result of competitive accretion. Since the cloud was initially bound, even more so after the dissipation of the turbulent energy, the whole system of subclusters is themselves bound to one another. They quickly merge within roughly 0.5 Myr (roughly twice the free-fall time for the original cloud). If this merging process was to occur on large scales, such as a whole GMC, one would never be able to form OB associations. The massive stars at the centres of the subclusters would find themselves in one large cluster.

Our proposal in this paper is that OB associations are just a series of clusters that form in unbound GMCs. The expanding cloud produces a series of clusters that are unbound from one another due to the fact that the flows that form them are also unbound from one another. The clusters, which become OB subgroups, then simply expand away from their mutual centre of mass along with the gas from the cloud, rather than merge into a single cluster. Thus only one star formation mechanism is at play here: clustered formation. The OB association therefore will have the universally observed IMF.

2 DETAILS OF THE GMC SIMULATION

The fluid was modelled using the Lagrangian particle method of smoothed particle hydrodynamics, or SPH (Lucy 1977; Gingold & Monaghan 1977). The smoothing lengths are variable in both time and space, with the constraint that there must be roughly constant number of neighbours for each particle, which is chosen to be roughly 50 (with a fluctuation from 30 to 70 neighbours). We use the standard artificial viscosity suggested by Gingold & Monaghan (1982) with $\alpha = 1$ and $\beta = 2$. Gravitational forces are calculated using dipole and quadrupole moments obtained via a tree structure (Benz et al. 1990), which is also used to construct particle neighbour lists. The code has been parallelised by Bate using OpenMP and the simulation presented here was performed on the UK Astrophysical Fluids Facility (UKAFF).

Our simulation starts with a uniform density sphere of molecular hydrogen of radius 20pc with a mass of $1 \times 10^5 M_\odot$. The gas is isothermal and has a temperature of 10K. These numbers (mass, size and temperature) are typical of those reported for GMCs in the solar neighbourhood (Blitz 1991). We model the gas with 500,000 SPH particles and are thus able to accurately follow the formation of self-gravitating regions down to a mass of $20 M_\odot$ (Bate & Burkert 1997; Whitworth 1998). The free fall time associated with this cloud, the time taken for the unsuppressed gas to collapse under gravity to a central point, is roughly 4.7 Myr. The cloud has an initial Jeans mass of 30.4$M_\odot$. We do not include any feedback processes, such as stellar winds and jets or the effects of massive stars such as ionisation fronts and supernovae.

To model the turbulence, we support the cloud with a Gaussian random velocity field with a power spectrum of $P(k) \propto k^{-4}$ which is consistent with a velocity field with a Larson-type relation of $\sigma \propto L^{0.5}$ where $\sigma$ is the velocity dispersion and $L$ is the length scale of the region (Myers & Gammel 1999). At the beginning of the calculation the ratio of gravitational to kinetic energy is 0.5 ($E_{\text{kin}} = 2E_{\text{grav}}$). We stress that the turbulent kinetic energy is able to decay freely in this simulation since we include no driving mechanism. The timescale for the energy decay is the crossing time of the initial velocity field $t_{cross} = 4.2$ Myr, slightly less than the free fall time.

The SPH code includes the modification by Bate et al. (1995), which replaces dense, self-gravitating, regions of the gas with point masses, or 'sink particles'. These sinks allow the code to model the dynamical evolution of accreting protostars, without integration time steps becoming prohibitively small. We set the sink particles to form at a density of 1000 times the initial density, with a subsequent accretion radius of 0.17pc. When a particle finds itself at the centre of a dense, bound and collapsing region it is turned into a sink particle and its 50 to 100 neighbours are accreted onto it. With the resolution used for this simulation the sink particles start with a mass of at least 15$M_\odot$ before further accretion. Therefore we cannot think of these point mass objects as 'protostars', as was the case in Bate, Bonnell & Bromm (2003), but instead assume that they represent 'proto-clusters'. To prevent the ‘sink particles’ behaving as point masses in gravitational interactions, we smooth the sink-sink gravitational forces to a distance of $r_{\text{min}} = 0.2$ pc in the form $F_{ij} = -Gm_im_j/(r_{ij} + r_{\text{min}})^2$ between particles $i$ and $j$.

In the analysis that follows, we discuss the properties of star formation centres, or 'SFCs'. These can either comprise of a single protocluster (or sink particle) or a coherent group of protoclusters. To identify SFCs where more than one sink particle is involved, we make use of the mass segregation that occurs naturally when the protoclusters interact in self gravitating groups (see for example Bonnell et al. 2004). First we sort all the protoclusters by mass. We then take the most massive protocluster and tag it and its fellow protocluster neighbours within 0.5pc to be a members of ‘SFC 1’. We then go down the mass sorted list of protoclusters until we arrive at the next most massive protocluster that has not been associated with SFC 1. It becomes tagged as being a member of ‘SFC 2’. All the protoclusters within 0.5pc of this protocluster are now tagged as being members of SFC 2, unless they are already members of SFC 1. This process continues down the list of protoclusters until all have been assigned membership to a SFC. There is thus a resolution of 0.5pc which distinguishes one SFC from another. We find that the choice of 0.5 pc used in attributing memberships does not significantly affect the SFC population, since the protoclusters formed in the simulation are either well separated (and thus in isolation) or exist in dense groups. The radius of the SFC is given by the radius of the furthest protocluster from the centre of mass. If there is only one protocluster then the radius is simply the accretion radius, which is 0.17pc.

One problem with trying to model turbulence in a numerical simulation of this type is that it is not always possible to resolve the velocity structure at all scales. Turbulence is assumed to be hierarchical, following a Larson-type relation of $\sigma \propto L^{0.5}$ (Larson 1981). In SPH, while a particle can have a kinetic energy based on its velocity, it can have no internal velocity structure. As a result, the kinetic energy below a certain mass scale ( actually the mass of an SPH particle and its neighbours) is not included in the calculation. We therefore stress that our simulation is lacking the kinetic energy that should be present at scales of less than $\sim 20 M_\odot$. The details of how individual stars form are thus not available from this simulation, and we must restrict ourselves to the large scale properties of star formation and the formation of clusters.
Figure 1. The panels show column density images from different points during the simulation and allows us to see clearly the evolution of the gas and regions of star formation. We see from the figure that the structure of the cloud changes remarkably quickly. It starts as a churning network of gaseous filaments and within 10Myr (when the simulation was terminated) evolves into an ensemble of distinct clusters, by which time the gas has lost much of its early character. The fact that an unbound GMC can form stars and star clusters reinforces the predictions made in Clark & Bonnell (2004).

Rather than simply discuss the individual protoclusters that form (the sink particles) it makes sense here to discuss the bound groups of these protoclusters as well, which we will simply refer to here as ‘star formation centres’ or SFCs. The formation of the SFCs actually occurs very rapidly. The mass of the 16 most massive of these centres is shown as a function of time in figure 2. Within 5Myr (or \( \sim 2.5 \) Myr after the onset of star formation) the 15 most massive SFCs all have masses greater than about 100 \( M_\odot \), and are beginning to get to a size where there is good possibility of them forming massive stars (this will be discussed in section 4).

A desirable feature of an initially unbound GMC is that cloud dispersal and star formation are occurring simultaneously. This removes the necessity for feedback mechanisms to disperse the cloud, or at the very least makes their task much easier. The timescale for star formation is thus comparable to the timescale for the cloud's dispersal and the formation of a turbulently dominated density structure (Padoan et al. 2001).

References: Clark & Bonnell (2004), Mac Low et al. (1998), Stone et al. (1998)
The dynamics of an unbound cloud is therefore naturally in keeping with the recent observations that star formation and cloud dispersal occur in a few crossing times. There is also the added bonus that star formation efficiencies will be kept low, since most of the gas around a protocluster clump will be unbound to it and moving away. This prevents the material getting involved in the accretion once a SFC starts to form.

Figure 3 shows the density distribution of the gas at three points in the simulation. The vertical dot-dashed line marks the original density of the cloud. Just before the first protocluster forms at 2.4 Myr we see that the most common density is roughly $7 \times 10^{-22}$ g cm$^{-3}$ (the solid line curve), an order of magnitude higher than at the start of the simulation. Note however that very little material at this point is as dense as $7 \times 10^{-21}$ g cm$^{-3}$, showing that the turbulence does not allow much material to get up to typical star forming densities (Falgarone, Phillips & Walker 1991; Padoan 1995; Zinnecker 2002).

After 7 Myr the peak in the distribution falls back to roughly the starting density, however there is much more spread in the distribution. This spread is controlled by two mechanisms. The high density tail increases as the SFCs grow by accretion and the subsequent rise in the potential energy. This causes yet more material to be dispersed. Instead, we realise that turbulence can mimic these effects. Furthermore the cavities in the simulation would be easily ionised by any high mass stars that form in the SFCs (Dale et al. 2004). We would then have a series of SFCs separated by a region of HII gas, just as is found in the classic picture of triggered star formation.

4 THE FORMATION OF STARS AND EXPECTED EFFICIENCY

In this section we use some simple assumptions about the star formation that occurs in the SFCs to determine the numbers of high mass stars and the star formation efficiency that one might expect from the simulation. It is still beyond the capabilities of current computational resources to model the details of how individual stars form in a body of gas as large as a GMC. In the simulation presented here we cannot model any gas dynamics below the 20M_☉ scale. We can however give the reader a feel for the star formation that is present by using the results of previous simulations, along with some assumptions about the star formation efficiency and the form of the IMF.

It has been shown from numerical simulations that star formation occurs on roughly the local crossing time for the turbulence when the region is dynamically bound (Bate et al. 2003; Klessen 2001). On the small scales such as those represented by our protoclusters, ~ 0.1pc, the crossing time is of the order $10^5$ years. We can therefore assume that all of our protoclusters form stars and that the star formation in our protoclusters takes place quickly, rapidly enough to be regarded here as instantaneous compared to the evolution of the whole GMC.

The simulation presented also has no method of incorporating...
feedback into the GMC model. As is shown in figure 2, in the right hand plot, the mass accreted into the SFCs gradually increases as the simulation progresses. At the point where the simulation is terminated, 30% of the GMC has been accreted by the protoclusters. It is unlikely that this value is representative of how much mass would be available for accretion into the SFCs. What is needed is an estimate of when one would expect the star formation process to be halted by feedback mechanisms. This requires some knowledge of the star formation taking place within the SFCs.

We have already pointed out that the protoclusters in the simulation group into large SFCs. From now on in the paper we will use the details of these regions, rather than the individual protoclusters, to assess the nature of the star formation in the GMC. Table I gives the details of the SFCs after 9 Myr. The masses quoted for the SFCs in table I includes all particles (SPH and protoclusters) that fall within the radius of the region. The gas particle component is however quite small, generally less than 20%.

Although the star formation efficiency of GMCs is thought to be in the range of 1 to 10%, at the cluster level it is thought to be about 20 to 50% depending on the region (for a discussion we point the reader to Lada & Lada 2003 and Kroupa 2001). In this paper we assume that the star formation efficiency in our SFCs is 50%, but will include a discussion about the case in which 100% of the mass is turned into stars. The assumed efficiency here is high but this is deliberate since it actually assumes as little as possible about the effect that the feedback mechanisms from the young stars are having on the accretion processes in the SFC. We will also assume that the IMF of the stellar population in the SFCs follow a two step power law form, \( dN \propto m^{-\alpha} dm \), with \( \alpha = 1.5 \) for \( 0.8 < m/M_{\odot} \leq 0.5 \) and \( \alpha = 2.35 \) for \( 0.5 < m/M_{\odot} \leq 100 \). This IMF, in conjunction with our assumption that 50% of the mass of the SFCs is turned into stars, allows us to estimate the stellar population produced by the simulation.

As already mentioned in the previous section, figure 2 shows in the left hand plot how the mass of the 15 largest SFCs evolves with time. The horizontal lines mark the point at which high mass stars can form. From our IMF model, 15% of the mass should be contained in stars with masses greater than 10M_{\odot}. Thus a 10M_{\odot} star will be present provided that there is 10/0.15 = 67M_{\odot} in the stellar population. Applying our assumed star formation efficiency of 50%, the SFCs must therefore have a mass of 134M_{\odot} if they are to harbour a 10M_{\odot} star. The horizontal long-dashed line in the figure denotes the point at which the SFCs achieve this mass. Doing the same for 25M_{\odot} stars, which should comprise 7.7% of the stellar mass in our chosen IMF, we find that the SFCs need to contain 25/(0.077 x 0.5) = 650M_{\odot} if they are to contain a 25M_{\odot} star. This is represented by the horizontal short-dashed line in the figure.

From our simple assumptions about the small scale efficiency and the form of the IMF, we can estimate at what point in the simulation the star formation process will be disrupted by feedback mechanisms. From figure 2 we can estimate that the formation of 10M_{\odot} stars would occur at about 0.8t_{ff} (or at \( \sim 4 \) Myr). A star of mass 25M_{\odot} would form after \( \sim 1.1t_{ff} \) (or \( \sim 5 \) Myr). Since the mass of the SFCs is increasing fairly rapidly at this point, stars with even higher masses would be expected to be present shortly after this, within 0.5 Myr or so. It would thus appear that the GMC is able to get enough mass into the SFCs for them to be able to form a full stellar population within about 1 Myr. This is consistent with the observations of the small age spread in the stellar population of the Orion cluster (Hillenbrand et al. 2001).

Very rapidly after the first stars form we see that 10M_{\odot} objects will be present. This means that shortly after their formation, SFCs are going to contain ionising sources. Such stars are commonly suggested to be responsible for controlling the star formation efficiency by expelling the gas from the cluster in which they form (such as our SFCs), thus preventing the protostellar population from accreting or preventing new stars from forming. However Dale et al. (2004) have noted that the ionisation from these stars does not appear to significantly affect the accretion rate in the clusters. The clumpy/fractal nature of the gas at the centre of the cluster where the OB type stars are situated acts to shield vast regions of the cluster from ionisation. Rather than pushing through the dense material, the ionising photons just find the path with the least resistance out of the cluster. This is low density gas which would not normally be associated with protostellar accretion in the first place. Similarly, the gas structure may also prevent the winds from OB stars expelling gas from the cluster. It has been suggested that winds are able to escape via the fractal holes, without imparting much momentum to the dense regions (Henning 1989).

It is therefore not clear if ionisation or winds will be able to expel the gas from cluster, thus halting the star formation process. One mechanism that certainly will produce the desired effect is a supernova explosion. In fact it has been estimated that these events will not only remove the gas from a cluster, but also be able to disperse the natal GMC. Thus a high mass star’s death will definitely mark the end of the star formation period in our cloud. Stars with masses greater than 25M_{\odot} have very short main-sequence lifetimes, of about 3-5 Myr, and we see from the figure that they form at about \( \sim 5 \) Myr after GMC formation. If we assume that a supernova event will occur at about \( \sim 4 \) Myr after the formation of the very high mass stars, then we estimate the first supernova event to occur at about 9 Myr or when the OB stars are \( \sim 4 \) Myr old.
5 Dynamical Evolution of the Clusters and Their Relation to OB Associations

As already discussed, the simulation produces a series of star formation centres (SFCs). Of these regions, 16 of them (see table) are massive enough to contain a star of greater than 10 M☉ by the time at which we estimate a SN explosion will destroy the GMC. From figure we see that these SFCs are expanding as a group away from one another (in fact this is true of the GMC structure in general). Furthermore, the distance between SFCs is roughly 10pc after about 13Myr. Thus the group of clusters have the appearance of an OB association, with the individual SFCs being OB subgroups that are expanding about some common point. In this section we examine the properties of the SFCs and compare them to the observations of OB associations.

Assuming the supernova event will halt the star formation, we can now get an estimate of the star formation efficiency in the GMC. The vertical dashed line in figure denotes the point at which we might see the first SN event. At this time, ∼ 0.1 to 0.2 of the GMC’s mass is contained in the SFCs. However we have assumed up until now that the efficiency in the SFCs is not 100% but 50%, therefore our estimate of the star formation efficiency in the GMC is roughly 5 to 10%. This is easily comparable to the expected efficiencies in GMCs by Elmegreen’s (2000) rapid cloud formation/dispersal model.

The above analysis relied on a lot of assumptions about the nature of the star formation in the SFCs. In particular, it is guilty of invoking a star formation efficiency in the SFCs in order to determine the star formation efficiency of the cloud: one could argue that this is not entirely self-consistent. Here we redo the above analysis but without the SFC efficiency assumption. If all the mass in the SFCs is used in forming a stellar population, then the mass required by a SFC before a 25M☉ star forms is 25/0.077 = 325M☉. The first SFC to achieve this mass does so at about 4 Myr, only 1 Myr less than our previous estimate. Thus we can predict the supernova to occur at ∼ 8 Myr. At this point in the simulation there is about 7 - 8% of the cloud incorporated in the SFCs. Thus the expected star formation efficiency is still less than 10%, suggesting that our analysis is not heavily dependent on the assumptions.
In figure 4, the left hand panel shows the positions of the SFCs that are large enough to contain stars greater than 10$M_\odot$ at $t = 9$ Myr, assuming a star formation efficiency of 50% and the IMF presented in section 4. Their positions are plotted at the time we estimate the SN event to start expelling gas from the cloud. We now assume that the SN event removes the gas from the GMC quickly enough such that the motions of objects have no time to adjust to the change in potential. We assume that this is true both at the scale of the SFC motions and at the smaller scale of the stellar motions inside the SFCs. The right hand panel shows the positions of the SFCs after a further 4 Myr, i.e. at $t = 13$ Myr, assuming that they continue on the path they had before the gas expulsion. The circles denote the size of the SFCs at $t = 13$ Myr, which have been evaluated from $r = r_{SN} + \Delta V \times 4$ Myr, where $\Delta V$ is the region’s internal velocity dispersion and $r_{SN}$ is the radius of the SFCs at the point when the SN event occurs (i.e. at $\sim 9$ Myr). This assumes that the star forming regions will disperse at roughly their internal velocity dispersion once the gas has been expelled.

Figure 4 clearly shows that the SFCs are expanding away from one another. By determining the average radius of the SFCs from their common centre of mass, both at $t = 9$ Myr and at $t = 13$ Myr, we can get an estimate of their expansion velocity from their dynamical centre. At $t = 9$ Myr the average distance of the SFCs from their centre of mass is 18.4 pc, while after 13 Myr it is 25 pc. This corresponds to an expansion velocity (that is a 3-dimensional velocity) for the SFCs of 1.5 km s$^{-1}$. We compare this, for example, with the ages determined by Elmegreen & Lada (1977), which is in turn motivated by the observations of Blaauw (1964). However, we note here that the Orion OB association exhibits no discernible age progression in the subgroups (Brown et al. 1999).

Does our simulation show a convincing age spread between the subgroups/SFCs? In figure 5 we plot the age of the protoclusters (the sink particles that group together to form the SFCs) and their position from their common centre of mass. All the points are plotted at $t = 13$ Myr, with the positions being the y-direction in the simulation, since the SFCs are more spaced out in this direction. The ages are determined in two ways. The crosses denote the ages determined by when the protocluster first forms. The filled hexagons are determined by the time when the protoclusters reach a mass of 134$M_\odot$, the point at which a 10$M_\odot$ star can form. Note that in the previous sections we determined when 10$M_\odot$ stars could form based on the mass contained in an SFC, rather than its constituent protoclusters and gas. We are forced to use the individual protoclusters here since the SFCs are not coherent objects throughout the entire evolution of the simulation.

We see clearly from figure 5 that while a large range of ages exist at any particular distance from the centre of mass, no trend is present in the ages with distance. Thus our simulation predicts that the OB association would be essentially coeval. However this is just a symptom of our idealised initial conditions. The initial uniform density sphere, with multiple Jeans masses, allows the entire cloud to proceed directly to star formation, via the dissipation of kinetic energy. Since the turbulence is the same throughout the cloud, star formation occurs simultaneously in quite separate locations. If on the other hand our GMC needs to accumulated in a large scale shock, as suggested by Pringle et al. (2001), then there would naturally be an age spread as the layer in which the GMC forms starts to grow. The most important point in this picture is that the whole

### Table 1

The table gives the properties of all the star formation centres (SFCs) that would be expected to contain massive stars by $t = 9$ Myr (see section 4 for a discussion of this). $\Delta V$ is the internal SFC velocity dispersion and assumes the region is in virial equilibrium such that $\Delta V = (GM_{SFC}/R)^{1/2}$. Cross sections are then calculated from $t_{cr} = 2R/\Delta V$. Note that $M_{SFC}$ is the total (gas + stars) mass enclosed within $R$.

| SFC No. | $M_{SFC}$ ($M_\odot$) | $\Delta V$ (km s$^{-1}$) | $R$ (pc) | $t_{cr}$ (Myr) |
|---------|----------------------|--------------------------|--------|-----------|
| 1       | 1763                 | 3.27                     | 0.71   | 0.42      |
| 2       | 761                  | 2.68                     | 0.45   | 0.33      |
| 3       | 706                  | 3.24                     | 0.29   | 0.17      |
| 4       | 624                  | 2.24                     | 0.53   | 0.46      |
| 5       | 455                  | 2.37                     | 0.35   | 0.29      |
| 6       | 362                  | 1.77                     | 0.50   | 0.55      |
| 7       | 338                  | 1.77                     | 0.46   | 0.51      |
| 8       | 329                  | 2.88                     | 0.17   | 0.12      |
| 9       | 305                  | 1.68                     | 0.46   | 0.54      |
| 10      | 212                  | 2.31                     | 0.17   | 0.14      |
| 11      | 174                  | 1.37                     | 0.39   | 0.56      |
| 12      | 151                  | 1.95                     | 0.17   | 0.17      |
| 13      | 150                  | 1.95                     | 0.17   | 0.17      |
| 14      | 144                  | 1.91                     | 0.17   | 0.17      |
| 15      | 141                  | 1.63                     | 0.23   | 0.27      |
| 16      | 140                  | 1.39                     | 0.31   | 0.44      |

This is calculated by taking the total mass in the SFCs of stars of greater than the required mass type and dividing by the volume of region containing all the SFCs with these types of stars. After the system has had time to evolve for 4 Myr, the densities are 0.06 and 0.04$M_\odot$ pc$^{-3}$ for the OB type stars and those with masses $\geq 25M_\odot$ respectively. Note these figures are based on the SFCs having a star formation efficiency of 50% and containing the IMF of stellar objects that was presented in section 4.

The turbulent flows are thus able to create a series of star forming regions that have roughly the same properties as those found in OB associations. Since the regions (the SFCs) are formed within large flows, the stars that form will have roughly the same motion as the gas stream that formed them, potentially explaining why Blaauw (1991) finds that the gas surrounding OB subgroups is generally moving with the group.

Observations of some OB associations also indicate distinct age spreads between their subgroups. This generally takes the form of an age progression from one side of the association to the next. The ages are generally derived from where the very high mass stars turn off the main sequence, which is a much more reliable method than using pre-main-sequence (PMS) tracks of low mass objects. Also the high mass end is normally the only part of the mass spectrum that is well established in OB associations. This age spread has been the motivation behind the triggered sequential star formation model developed by Elmegreen & Lada (1977), which is in turn motivated by the observations of Blaauw (1964). However, we note here that the Orion OB association exhibits no discernible age progression in the subgroups (Brown et al. 1999).
region would not be at the same density, but instead would have to evolve to star forming densities as the GMC accumulates.

6 CONCLUSIONS

The simulation presented in this paper highlights that GMCs need not be regarded as objects in virial equilibrium, or even bound, for them to be sites of star formation. Globally unbound GMCs can form stellar clusters very quickly, on roughly their crossing time. Furthermore, the unbound state of the cloud ensures that whole region is also dispersing while it is forming stars. They are thus naturally transient features. This evolutionary picture of a cloud forming, producing a stellar population, and then dispersing has been shown by Elmegreen (2000) to be apparent in a number of independent observations.

Using some simple assumptions about the form of the star formation in the star formation centres (SFCs) of our simulation, we have provided an estimate of the star formation efficiency in the GMC. At the point one would expect the first supernova events, we find that the star formation efficiency is about 5 - 10%. This assumes that the SFC environment in the simulation yields an efficiency of ∼ 50%. Removing this assumption about the SFCs, and letting the SN event be the only control over the efficiency, we find that the cloud has a global star formation efficiency of ∼ 7-8% (for our assumed IMF).

We argue that unbound GMCs may provide a simple mechanism for forming OB associations, a concept that was touched upon by Ambartsumian [1958]. OB stars form at the centre of a population of SFCs. These SFCs, which condense out of the unbound flows in the GMC are naturally expanding away from one another, as the positive energy disperses the cloud’s gas. Not only does the mechanism explain the OB association dynamics but it also explains the observed substructure, generally referred to as OB subgroups. Since the OB association is just a series of independently formed clusters, one would also expect the association to have the field star IMF.

ACKNOWLEDGMENTS

The computations reported here were performed using the UK Astrophysical Fluids Facility (UKAFF). We also acknowledge the assistance of the EC-network grant EC-RTN1-1999-00436. The authors would like to dedicate this paper to Adriaan Blaauw, on the occasion of his 90th birthday.

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