THE EVOLUTION OF GIANT MOLECULAR CLOUDS

Colin Norman
Huygens Laboratory, University of Leiden
and
Joseph Silk
Department of Astronomy, University of California, Berkeley

ABSTRACT

We discuss the origin, lifetime, destruction, spatial distribution and relation to star formation of giant molecular clouds. A coagulation model including the effects of spiral density wave shocks is described. We explore implications for CO observations of external galaxies. The collective effects of OB star winds and supernova remnants in disrupting clouds are considered.

I. INTRODUCTION

Our galaxy contains $\sim 2 \times 10^9$ $M_\odot$ in molecular clouds that have been found in recent CO surveys. Many of these clouds are associated with large molecular complexes and OB associations. A considerable fraction of molecular gas appears to be in complexes with masses of 10^5 - 10^6 $M_\odot$ (Burton and Gordon 1978; Solomon, Sanders and Scoville 1979). Currently unresolved issues are the lifetimes of these giant molecular complexes, their origin, and destruction, and their relation to ongoing star formation.

In an earlier paper, we have discussed the stability, structure and disruption of molecular clouds in relation to low mass star formation (Norman and Silk 1980). Our goal here is to examine the formation and evolution of the giant molecular complexes or clouds (denoted by GMC) in an attempt to understand many of their physical characteristics and their relation to OB associations.

Strong arguments have recently been presented by Kwan (1979) and Scoville and Hersh (1979) that GMC are built up by the coagulation of many smaller clouds. Further, Solomon and co-workers (Solomon et al. 1979, Solomon and Sanders 1979) have shown that GMC particularly within 4 - 8 kpc of the galactic centre cannot have formed by sweeping up diffuse H I material. This conclusion rests on the value of H_2/H I in this region that is inferred from ^{12}CO and ^{13}CO surveys. A major source of uncertainty in this result lies in the adopted $^{13}CO/H_2$ ratio of 1×10^{-6}. CO appears to become depleted in cloud cores, the correlation

B. H. Andrew (ed.), Interstellar Molecules, 137–149.

between A_V and ^{13}CO breaking down at $A_V > 5$. This means that Dickman's (1978) value of $^{13}CO/H_2 = 2 \times 10^{-6}$ will underestimate the H_2 mass by a factor $\gtrsim 2$. We therefore assume that the molecular mass estimated by Solomon et al. (1979) is reliable to within a factor ~ 2.

The coagulation models for GMC indicate long formation times ($\gtrsim 2 \times 10^8$ yr). This is comparable to the rotation time, and the effects of density wave shocks should therefore be included. We show below that inclusion of spiral density wave shocks significantly modifies coagulation models of GMC, and leads to a shorter time scale for GMC formation. The basis of our model is that the ambient interstellar medium can be treated as a fluid on scales greater than or of the order of the mean free path for cloud-cloud collisions, and the existence of a shock is therefore independent of the current controversy about the existence of a hot phase in the interstellar medium.

We argue that the GMC formation rate may be boosted by the magnetic Rayleigh-Taylor instability by a factor ~ 3 (Mouschovias, Shu, and Woodward 1975). Large scale gravitational instability may also play a role in enhancing the GMC formation rate. However, we emphasize that the *coagulation process is inevitable* and suffices to account for the observed properties of GMC whether or not these mechanisms are operative. We point out an observational test of the role of the magnetic Rayleigh Taylor instability in forming GMC.

We present arguments that indicate GMC lifetimes of $\sim 4 \times 10^7$ yr or at least $\leq 10^8$ yr. The mean lifetime of H I at 4 kpc must also be of order $\sim 10^8$ yr, implying that GMC disruption occurs with $\sim 90\%$ of the matter remaining in molecular form. It must however be dispersed into small molecular clouds, which are the building blocks for future GMC upon passage through the spiral arms.

The distribution of OB stars in our Galaxy and other spirals can now be explained if we assume that GMC disruption is triggered by the formation of a giant OB association over the indicated time scale of $\lesssim 4 \times 10^7$ yr (Bash 1979). The long cloud lifetimes of $\sim 10^8$ yr can be explained if continuing non-disruptive star formation is occurring. For cloud masses of $\sim 10^3 - 10^4\ M_\odot$ we might expect predominantly less massive O and B stars to be produced. Thus a key feature of our model is the formation of small OB associations throughout the arm and interarm regions, with giant OB associations forming predominantly near the arms.

It is the collective effect of simultaneous formation and evolution of several massive stars that results in GMC disruption.

In the solar vicinity, a substantial fraction of the molecular cloud material will be in small clouds, and we are therefore able to reconcile our star formation model with the observed widespread distribution of OB stars in arm and interarm regions (Mezger 1978).

II. OBSERVATIONAL CHARACTERISTICS

A typical GMC has mass $\sim 2 \times 10^5\ M_\odot$, maximum dimension ~ 100 pc, projected surface area ~ 2000 pc^2, volume $\sim 10^5$ pc^3 and mean density $\sim 50 - 100$ cm^3 (Blitz 1978). The mass of the molecular material appears to be the largest fraction of mass present, exceeding the H I mass and

https://doi.org/10.1017/S0074180900072417 Published online by Cambridge University Press

greatly exceeding the mass in stars and ionized gas. The CO appears to be a good tracer of the sites of active star formation, and there are some 4,000 molecular complexes and OB associations in the Galaxy according to Blitz (1978).

Scoville (1979) has argued that the GMC populate both arm and interarm regions, and Burton and Gordon (1978) estimate that typical cloud sizes lie between 3 and 30 pc. In general, these clouds appear to be grouped into molecular complexes, which show considerable structure, characteristic clump scales being $\sim$ 10 pc with masses $\sim 10^3\ M_\odot$ (Blitz 1978).

The association of many GMC with OB associations suggests that their lifetimes may not exceed those of the OB associations. Bash (1979) has developed a kinematical model for the CO distribution which indicates a lifetime of $\sim 4 \times 10^7$ yr on the assumption that the molecular clouds acquire a significant non-circular velocity component in the spiral density wave shock and subsequently move in ballistic orbits. This only constrains the post-shock lifetime of the clouds which could have existed prior to entering the shock.

General constraints on the lifetimes of complexes and clouds come from consideration of star formation efficiency. The present mean rate of star formation is about 3 $M_\odot\ yr^{-1}$ (Tinsley 1976). Studies of cold molecular clouds indicate a star formation efficiency $\xi \sim 10\%$ (Cohen and Kuhi 1979), implying that molecular clouds must be formed and disrupted at an overall rate of 30 $(0.1/\xi)\ M_\odot\ yr^{-1}$. If the total mass of molecular clouds is $\sim 2 \times 10^9\ M_\odot$ with an additional $\sim 2 \times 10^9\ M_\odot$ in more diffuse gas, then the mean lifetime of these clouds must be $\lesssim 10^8(\xi/0.1)$ yr.

Let us assume that GMC disruption produces predominantly small molecular clouds with a fraction η of the gas dispersed into H I. Within 4 - 6 kpc the ratio of H_2 to H I mass is $\sim$ 10 to 1; a lower bound may be taken to be 5 to 1 (§ I). In a steady state, the mean lifetime for the H I gas must therefore be $\lesssim 2 \times 10^7\ \eta^{-1}\ (\xi/0.1)$ yr. The most plausible mechanism for converting H I to H_2 is associated with passage through the spiral arm, which occurs every $\sim 5 \times 10^7$ yr (at 4 kpc). This therefore provides an estimate of the H I lifetime, and we find $\eta \lesssim 0.4\ (\xi/0.1)$. We discuss in § IV a more detailed model for GMC disruption.

III. FORMATION OF MOLECULAR CLOUD COMPLEXES

Oort (1954) originally suggested that cloud growth by coalescence led to gravitational instability and ensuing star formation, and subsequent papers examined this idea in considerable detail (Field and Saslaw 1965, Penston et al. 1969, Field and Hutchins 1968, Taff and Savedoff 1972, 1973). These studies were all of interstellar H I clouds. Formation of giant molecular cloud complexes by a similar aggregation mechanism has been proposed by Kwan (1979) and by Scoville and Hersh (1979). In what follows, we shall describe a simplified model for massive cloud coagulation in which the role of spiral density waves is explored.

a) Kinetic Equation For Cloud Growth

To illustrate the physics of massive cloud growth, we assume that most of the molecular cloud material is in small molecular clouds with mean mass density ρ_{cl}, and that more massive clouds grow predominantly by coalescing with the smaller clouds. We wish to explore the effect of the spiral density wave on cloud growth. In the case of a shocked diffuse intercloud medium, (Shu et al. 1972) find that the density increase amounts to a factor ~ 10. This model may not be relevant if the intercloud medium is pervaded by the hot interiors of old supernova remnants (Cox and Smith 1974; McKee and Ostriker 1977), and a shock will not develop in the hot ($\sim 10^6$ K) component. However, provided that the mean free path for cloud-cloud collisions is sufficiently short, the clouds will simulate the behaviour of a fluid and experience a similar increase in overall density and in collision rate (Shu 1978). Observational evidence for a density enhancement in the H I distribution amounting to a factor ~ 10 in the spiral density wave shock has been found in studies of external galaxies (van der Kruit and Allen 1978). The mean free path for cloud collisions, ℓ, can be inferred from the observed frequency of H I clouds of about 4 per kpc, and consequently $\ell \sim 250$ pc. We can therefore consider the molecular cloud complexes (mean mass M_g and cross-section σ_g) to be dynamically coupled in the spiral density wave via interactions with smaller clouds (mean mass M_s, and cross section σ_s) provided that the spiral density shock width exceeds

$$\left(\frac{\sigma_s}{\sigma_g}\right)\left(\frac{M_g}{M_s}\right)\left(\frac{\ell}{\zeta}\right) = 600\left(\frac{10}{\zeta}\right)\left(\frac{1600\ \mathrm{pc}^2}{\sigma_g}\right)\left(\frac{\sigma_s}{75\ \mathrm{pc}^2}\right)\left(\frac{400\ M_\odot}{M_s}\right)\left(\frac{M_g}{2\times10^5 M_\odot}\right)\mathrm{pc}$$

where ζ is the density contrast in cloud material between arm and interarm regions.

If the dominant growth mechanism of molecular cloud complexes is by coagulation with smaller clouds of mean density $\rho_{cl}(t)$, where the time dependence is determined by the dissipative hydrodynamics of spiral density wave theory, the kinetic equation for growth of massive clouds with number density $N(m,t)$ in the mass range $(m, m + dm)$ can be written in the form

$$\frac{\partial N(m,t)}{\partial t} = -\rho_{cl}(t)\frac{\partial}{\partial m}\{N(m,t)\ \sigma(m)\ v_{cl}(m)\} \qquad (1)$$

where $\sigma(m)$ is the cross section of a cloud of mass m, and $v_{cl}(m)$ is the mean collision velocity between low mass clouds and clouds of mass m. Note that we have not included a destruction term in (1) since we shall argue later that the destruction mechanism is triggered by an external effect, namely the influence of density waves. The solution of equation (1) is, with subscript o denoting reference quantities,

$$N(m,t) = \int_{-\infty}^{\infty} ds\ A(s)\left(\frac{\sigma_o v_o}{\sigma v}\right)\exp\{s\{\int^t \sigma_o v_o \rho_{cl}(t)dt - \int^m\left(\frac{\sigma_o v_o}{\sigma v}\right)dm\}\} \qquad (2)$$

where A(s) is chosen to fit suitable initial conditions, namely

https://doi.org/10.1017/S0074180900072417 Published online by Cambridge University Press

$$N(m,o) = \int_{-\infty}^{\infty} ds\ A(s)\left(\frac{\sigma_o v_o}{\sigma\ v}\right) \exp\{\ s \int^{m} \frac{\sigma_o v_o}{\sigma\ v}\ dm\ \} .$$

Molecular clouds complexes will build up by coagulation of smaller clouds over a time scale $\sim 2 \times 10^8 - 10^9$ yr (Kwan 1979; Scoville and Hersh 1979). We introduce an additional simplification by assuming that the massive clouds move either in a uniform density interarm region or a uniform density arm region. Then, in the interarm region, denoted by subscript i, we have

$$N(m,t) \sim \exp\ (\beta\ \rho_{cl,i}\ \sigma\ v_{cl,i}\ t/\bar{m}) ,$$

and in the arm region, denoted by subscript a,

$$N(m,t) \sim \exp\ (\beta\ \rho_{cl,a}\ \sigma\ v_{cl,a}\ t/\bar{m})$$

where β is a coefficient of order unity which can be determined by the complete solution to (2), and $\bar{m}$ is the mean mass of a small cloud.

b) Cloud Coalescence in Arm and Interarm Regions

The ratio of growth rates in arm and interarm regions is $\sim (\rho_{cl,a}/\rho_{cl,i})(v_{cl,a}/v_{cl,i})$. In order for greater growth to be achieved in arms where the cloud spends only ~ 0.1 of a rotation period, we evidently require that the shock strength

$$\frac{\rho_{cl,a}}{\rho_{cl,i}} \gtrsim 10\ \left(\frac{v_{cl,i}}{v_{cl,a}}\right)\left(\frac{t_i/t_a}{10}\right) \qquad (3)$$

where t_i and t_a are the times spent by a cloud in the interarm and arm regions respectively. It appears from equation (3) that the density increase in the arms may only be marginally greater than the total growth in the interarm region in our galaxy, where clouds will experience comparable amounts of growth. Thus coalescence in our galaxy may give only weak correlation of GMC with spiral arms. However, because the relative growth in the arm region is sensitive to shock strength, it is clear that CO observations of external galaxies may give rather different structures. For example M81 and M31 are good candidates for a strong shock, so we expect the GMC distribution to be in the arms. NGC 157 with its weaker and more open arms may have a less marked concentration of GMC in the arms. For filamentary-armed galaxies such as NGC 2841, we expect the GMC distribution to be spread over the entire face of the galaxy disk. An important consideration in selecting galaxies for CO study may be the manner in which the spiral structure is generated (Kormendy and Norman 1979). In particular, theoretical models of barred galaxies give rather strong shock strengths, ~ 20, and thus we may expect a good GMC correlation with the arms.

c) Parker Instability

The magnetic Rayleigh-Taylor instability in the interstellar medium originally proposed by Parker (1967) may lead to a significant enhancement

https://doi.org/10.1017/S0074180900072417 Published online by Cambridge University Press

of the cloud coalescence rate as a consequence of the passage of the spiral density wave shock. This instability in a uniform medium produces a density contrast of about a factor of three (Mouschovias 1974), and may enhance the growth rates (3) by this factor. This could lead to a significant enhancement of cloud coalescence, and formation of GMC preferentially in the spiral arms (Mouschovias et al. 1974).

We note here one unique characteristic of cloud coalescence enhanced by the Parker stability. One would expect both odd and even modes to develop, leading to a significant velocity dispersion and greater scale height for the GMC before final equilibrium is attained. Since the time scale to attain an equilibrium state is comparable to the lifetime of the complexes after passage through a shock, we would expect many observed complexes to exhibit a significant center-of-mass velocity dispersion. In the absence of significant cloud acceleration, both by shocks and Parker instability, the GMC that form by coagulation of smaller clouds attain approximate equipartition of random kinetic energy of their center-of-mass motions (Penston et al. 1969). The resulting scale height for the complexes would therefore be relatively small. However acceleration in spiral shocks is inevitable, and will lead to an enhanced velocity dispersion.

d) Triggering of Star Formation

A key unsolved problem in theories of GMC is the triggering mechanism by which star formation is initiated in the spiral density wave. We have argued that cloud collisions and coalescence, possibly coupled to the Parker instability, could lead to the formation of GMC preferentially in the spiral arms. However in galaxies with weak spiral shocks only a moderate contrast in cloud masses can be attained between arm and interarm regions, and initiation of gravitational instability will probably not provide an adequate trigger for star formation. In such systems, a more plausible trigger could be a pressure increase in diffuse H I clouds in the spiral density wave, initiated either by the passage of a shock through a warm intercloud medium or by repeated collisions with other diffuse H I clouds (Shu 1978). This could lead to the initiation of gravitational instability, fragmentation, and ensuing OB star formation.

e) Cloud Orbits

If a cloud on entering the spiral density wave sweeps up its own mass either from the ambient medium or by collisions with other clouds, it will be strongly momentum-coupled to the swept-up material. Consequently the velocity field inferred from gas dynamical calculations also applies to clouds in the shocked region. If the cloud is self-gravitating, it will leave the spiral density wave on a ballistic trajectory, having acquired a significant non-circular component of velocity. In this manner the initial conditions required in the model of Bash (1979) can readily be understood, and it follows that the cloud subsequently survives for $\sim 4 \times 10^7$ yr before being disrupted by OB star formation (§ IV).

IV. DISRUPTION OF CLOUD COMPLEXES

The correlation of molecular cloud complexes with OB associations, coupled with the kinematical arguments of Bash (1979), strongly suggests that the lifetimes of cloud complexes are determined by the ages of their OB associations. We emphasize again that molecular clouds may exist in the interarm regions for substantially longer periods; however once prolific massive star formation is triggered, the complexes must be disrupted within $\sim 4 \times 10^7$ yr.

We now consider possible mechanisms for disruption of GMC. These are formations of H II regions by massive stars, supernova explosions, and OB star winds. The energy output in each of these modes is comparable over the lifetime of an OB association, but each possibility must be considered in detail in order to evaluate its overall efficiency for potential disruption.

a) H II Regions

Compact H II regions tend to form preferentially near the outer edges of molecular clouds, leading to a blister-type structure (Habing and Israel 1979). A massive young star is embedded in an open cavity at the edge of the molecular cloud, and ionized gas flows out of the cavity. Whitworth (1979) has studied the erosion and dispersal of massive molecular clouds by this process, and argues that a few O stars can effectively destroy a massive molecular cloud.

However the success of the blister model relies on the maintenance of an extensive ($\sim$ 25 pc) low density cavity around a massive star. Now the Stromgren radius for an O6 star is only 1.7 $n_3^{-2/3}$ pc, where $n_3 \equiv 10^3$ cm^3. It seems clear that a realistic model of a molecular cloud complex, which consists of many bound clumps of mass $\sim 10^3$ $M_\odot$ and size $\sim$ 10 pc moving with random velocities $\sim$ 5 km s^{-1} (Blitz 1978), will rapidly fill in any extended cavities generated by the blistering process. Thus the Stromgren radius gives an effective measure of the disruption by O stars. Because only early type O stars can play a role, and OB associations are localized within a few pc^3 at formation, we conclude that blistering cannot be a significant erosion mechanism as long as only a small fraction of the surface of the cloud is ionized by O stars. Blistering is ineffective at disruption, and the total volume ionized by an OB association containing, say, 10 O5 stars, will be $\lesssim$ 150 pc^3, or less than 0.2 percent of the volume of a typical molecular cloud complex. Note that stars of type later than O5 only contribute $\sim$ 35 percent of the total number of ionizing photons if a Salpeter initial mass function is adopted.

b) Supernovae

A single supernova is incapable of disrupting a molecular cloud complex. To demonstrate this, we note that the maximum radius of the remnant is

$$R_{max} = 4.6\ E_{51}^{\ 0.23}\ n_3^{\ -0.36}\ T_4^{\ -0.20}\ \text{pc}.$$

https://doi.org/10.1017/S0074180900072417 Published online by Cambridge University Press

However, it is possible that multiple supernovae may occur, reinforcing one another and thereby disrupting the complex. The relevant criterion for this to occur is similar to that given by Cox and Smith (1974) and McKee and Ostriker (1977) in their studies of the interaction of supernova remnants with the interstellar medium, namely

$$Q_{SNR} = 10^{-4.61} E_{51}^{1.28} \left(\frac{S}{10^{-13} pc^{-3} yr^{-1}}\right) n_3^{-1.44} T_4^{-1.30}$$

where Q_{SNR} is the filling factor of the region with supernova remnants, $E_{51} = E/10^{51}$ ergs, S is the supernova rate per unit volume per unit time, and the effective temperature (including random supersonic velocities) of the ambient medium $T_4 = T/10^4$K. We have assumed that star formation continues for 10^7 yr. Within this time, $\sim$ 30 massive stars (of spectral type earlier than B1) per OB association of mass $M_* \approx 3 \times 10^3 M_\odot$ have evolved and become potential supernovae (Reeves 1978). In a cloud of mass M_{cl} and volume V_{cl}, we obtain a supernova rate per unit volume per unit time

$$S = 3 \times 10^{-10} \left(\frac{\xi}{0.1}\right)\left(\frac{M_{cl}}{3\times10^5 M_\odot}\right)\left(\frac{3\times10^3 M_\odot}{M_*}\right)\left(\frac{10^5 pc^3}{V_{cloud}}\right) pc^{-3} yr^{-1} .$$

This condition demonstrates that supernovae can sweep out a medium of density

$$n = 10^{2.22} Q_{SNR}^{-0.69} \left(\frac{\xi}{0.1}\right)^{0.69} \left(\frac{M_{cl}}{3\times10^5 M_\odot}\right)^{0.69} \left(\frac{3\times10^3 M_\odot}{M_*}\right)^{0.69} \times$$

$$\left(\frac{10^5 pc^3}{V_{cl}}\right)^{0.69} E_{51}^{0.88} T_4^{-0.90} \ cm^{-3} .$$

We conclude that supernovae are probably capable of disrupting molecular cloud complexes. Note that $M_*/M_{cl} \sim 0.01$ is only a lower limit to the mass fraction in stars, since no account is taken here of low mass star formation.

c) OB Stellar Winds

The discovery that stars of spectral type earlier than B1 (Snow and Morton 1976) undergo extensive high velocity mass outflows provides a significant mode of energy input into the interstellar medium, and in particular into molecular cloud complexes, as we now demonstrate. A theoretical model for the evolution of wind-driven bubbles around massive young stars has been developed by Weaver et al. (1977), who show that the bubble radius at time t is given by

$$R_{bubble} = 6.8 \ n_3^{-1/5} L_{36}^{1/5} t_6^{3/5} \ pc$$

where $L \equiv \dot{M} V_w^2$, $\dot{M}$ is the mass loss, V_w is the wind velocity, $L_{36} = L/10^{36}$erg s^{-1} and $t_6 = t/10^6$ yr. The bubble interior is filled with shocked wind gas at $T \sim 10^6$ K, and the wind is separated by a contact discontinuity from the shell formed by the swept-up ambient medium. It is immediately apparent, because of the weak sensitivity to the ambient density and stellar luminosity, that stellar winds provide a potentially more potent mechanism for cloud disruption than do H II regions. Moreover, since the wind activity is initiated continuously once star formation begins, it can provide the primary mechanism for cloud disruption. To demonstrate that winds are indeed effective in dispersing a molecular cloud complex, we must show that the bubbles can intersect and act coherently in molecular cloud complexes. Following the previous section, we find that, for disruption, the rate of formation of OB star bubbles per unit volume must be

$$S_{OB} = 10^{-8.1} \left(\frac{\bar{v}_{cl}}{5 \text{ km s}^{-1}}\right) n_3^2 \, L_{36}^{-2} \text{ pc}^{-3} \text{ yr}^{-1}$$

where $\bar{v}_{cl}$ is the internal random velocity dispersion inferred from molecular line widths. Therefore choosing $S_{OB} \sim S$, we find that bubbles can disrupt a cloud of density

$$n \simeq 10^2 \left(\frac{S_{OB}}{10^{-10} \text{pc}^{-3} \text{yr}^{-1}}\right) \bar{v}_{cl}^{-1/2} \; L_{36} \text{ cm}^{-3}.$$

We conclude that OB winds and supernova remnants are likely to play comparable roles in the disruption of molecular cloud complexes over a period of $\sim 10^7$ years.

d) Survival of Molecular Clouds

The efficiency arguments of § I indicate that GMC disruption results in the formation of a number of smaller molecular clouds (SMC) with a small fraction of H I produced near 4-6 kpc. In the solar neighbourhood the dominance of H I suggests that molecular cloud disruption may be more complete. This could result because of the longer time spent in the interarm region. The SMC must definitely exist on time scales $\gtrsim 10^8$ yr. They are likely to be bound units and the most plausible stabilizing mechanism would seem to be star formation. A simple statistical model of star formation in which stars first form at low mass and the formation of massive stars is limited by the cloud mass suggests that the SMC will be deficient in their content of very massive stars. Thus, we speculate that the SMC are associated with predominantly low mass stars and occasional small OB associations that provide sufficient momentum and energy to support them in the form of stellar winds and ionizing radiation. This provides us with an interpretation of the hitherto puzzling result that up to $\sim 80\%$ of the Lyman continuum photons inferred from radio continuum studies are produced by OB stars from the interarm regions of the Galaxy. Star formation could also occur in a similar manner in the solar vicinity in the local interarm region where there is evidence for a wide-spread OB star population.

V. FURTHER IMPLICATIONS

We have found that GMC can form in both arm and interarm regions by coagulation of smaller clouds. In many galaxies with strong spiral shocks, GMC's will form preferentially in the spiral arms, and we emphasize that a study of CO in external galaxies of varying spiral structure with different shock strengths and different driving mechanisms (Kormendy and Norman 1979) may resolve many of the issues discussed here. The accumulation process may be further enhanced in the spiral arms by the Parker instability, and a possible observational test of this mechanism has been indicated. Disruption of these complexes preferentially occurs as a consequence of massive star formation after passage through the arms, resulting in coherently interacting stellar winds and supernova remnants. Our estimates of disruption by these mechanisms suggest that only when GMC develop masses of $\gtrsim 3 \times 10^5$ $M_\odot$ (assuming that a fraction $\xi \sim 0.1$ of the GMC has formed predominantly low mass stars with a single OB association) will disruption occur.

We note, finally, several further implications of this model for molecular cloud complexes. Once massive star formation is initiated, the studies of Bash (1979) indicate that disruption will occur on a time scale $\sim 4 \times 10^7$ yr corresponding to the lifetime of OB associations. The galactic rotation period is less than 10^8 yr at a distance $\lesssim 3$ kpc from the Galactic centre. Thus, within this distance it may be impossible for molecular clouds moving on predominantly circular orbits to build up into GMC's. Furthermore, the increase in mean gas density towards the inner regions of the Galaxy implies a coagulation rate that increases with decreasing galactocentric radius. In this manner one might hope to understand the concentration of molecular clouds between 4 - 8 kpc.

The viscosity associated with cloud-cloud collisions leads to an inward radial drift velocity $\sim \frac{1}{3}\, v_{cl}\, l/r \lesssim 0.1$ (10 kpc/r) km s^{-1}, at radius r. Radial inflow and mixing of gas could, in principle, lead to the development of abundance gradients in spiral disks. However, a radial velocity of several km s^{-1} is required to produce abundance gradients characteristic for disk galaxies (Tinsley and Larson 1978). Radial inflow induced by this mechanism is only significant within ~ 1 kpc of the galactic centre, where it could have interesting implications for feeding active galactic nuclei (cf. Lynden Bell and Pringle 1974) such as Seyfert galaxies.

Observed phenomena that may be related to the disruption of molecular cloud complexes are the large scale features in the H I distribution that have been found in our own Galaxy (Heiles 1977, 1979) in M101 (Allen and Goss 1979) and M31 (Brinks 1979). The large scale (~ 1 kpc) associated with these structures indicate that a coherent phenomenon, similar to that proposed for the disruption of molecular cloud complexes, must be operative.

In summary, we have argued that GMC could be coagulated predominantly in arms in our own Galaxy. The GMC distribution in external galaxies depends on the ratio of arm to interarm growth, and therefore depends on the specific shock strength and relative arm-interarm residence time. Finally we emphasize that only coherent massive star formation can disrupt GMC.

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DISCUSSION FOLLOWING NORMAN

Mouschovias: You made the very strong statement that "coagulation is inevitable." It seems to contain at least three implicit assumptions. First, that some mechanism other than coagulation has formed your building blocks, the $10^3 M_\odot$ self-gravitating clouds. I know of no such mechanism. Thermal instability will not do. (See Protostars and Planets, ed. T. Gehrels, Univ. of Ariz. Press, 1978, pp. 209-242.) Second, that the $10^3 M_\odot$ blobs move randomly with respect to one antoher. Is there any evidence for that, especially since we can only observe radial velocities? Third, that collision between two blobs leads to agglomeration rather than to disruption. The old calculation in 1.5 dimensions, by Stone, although not conclusive, suggests disruptions.

Norman: The calculations of cloud-cloud collisions by Stone were for HI clouds of densities ~ 1 cm^{-3}. I discussed densities $\gtrsim 100$ cm^{-3} Thus the condition for inelastic cloud-cloud collisions to result in sticking is well satisfied, namely, that the cooling time is very much shorter than the time taken to cross the cloud by the shock generated in the collision. Thus if these molecular clouds collide, they will certainly coagulate. Do they collide? The estimate of collision rate given by Solomon and co-workers has very little uncertainty since it is based on the observed number of clouds along the line of sight, their observed cross-section, and their observed velocity-dispersion. The velocity-dispersion used in Solomon's calculation is certainly in the range 5-10 km s^{-1}(Blitz, this volume). Thus there is no question that the observed clouds collide and stick and that *"coagulation is inevitable"* for the observed cloud distribution. To make this statement, it is not strictly necessary to discuss how the molecular clouds form, although both coagulation and compression in the density wave have been proposed as possible models.

Elmegreen: In models using collisions to build up giant molecular clouds the time-scales for forming clouds are 10 times longer than the duration of OB-star formation in any one cloud, so there must be 10 times as many quiescent massive clouds as active (OB-star forming) massive clouds. This inference strongly contradicts both the direct observations of giant clouds in the solar neighbourhood and the cloud count for the whole galaxy extrapolated from large surveys.

Norman: From the infrared survey data discussed by Rowan-Robinson (1979, Ap. J., in press), and from the CO survey data presented at this symposium, only $\sim 10\%$ of the giant molecular clouds have $T_{CO} > 20$ K. We associate this warming with the influence of more massive OB-star formation on the cloud. Furthermore, as discussed by Solomon, it is these warm clouds that seem to be associated with the arm region, in good agreement with the model given here.

Gold: What could cause star formation to be restricted to low-mass stars in these clouds? In the presence of turbulence a spectrum of star masses would always be expected. Why should there be a sharp cut-off in some cases?

Norman: That question concerns the details of star formation. Three IAU Symposia from now on this subject I may be able to give you an answer! The model demonstrates that in dark clouds, where there is clearly no OB-star formation occurring, low-mass pre-main-sequence stars provide via their winds sufficient energy to explain the supersonic line widths. Thus, implicit in our model is the assumption that dark clouds make predominantly low mass stars and infrequently some low mass OB-stars. We contend that formation of more massive OB-stars needs a trigger. This trigger seems to be associated with the arm region, since the giant HII regions, which are clearly tracers of the arm regions, are associated with the more massive OB stars. Possible candidates for the trigger are (1) rapid increase in cloud mass $M >> M_J$ through enhanced coagulation in the arms (although $M > M_J$ anyway, since these clouds appear to be bound), (2) an external trigger such as a nearby supernova explosion or OB-star wind, or (3) an increase in cloud-cloud collision velocity in the arm region, due to acceleration by interaction with the shock. Generally we speculate that OB stars are formed in the process of collision-coagulation. It could be that the mass of the most massive star is correlated with the velocity of collision.

Carruthers: Two of the mechanisms you mentioned, formation of HII regions and OB-star winds, are due to the same OB stars. How do you differentiate between these two effects? It would seem that HII-region formation would be a more important "trigger" mechanism, since it occurs earlier in the life of an OB star.

Norman: The distinction of the OB-star wind is that it can create a bubble structure over a time considerably longer than that of the conventional HII region, of which it is in fact, a modified form (Weaver et al. 1977, Ap. J. 218, 377). The increased time-scale makes it easier for bubbles to intersect, and it is only by coherent interactions of OB-star winds or supernova remnants that a giant molecular cloud can be disrupted.

Gillespie: My observations of large and giant molecular clouds in the southern hemisphere show that in almost all cases there are several sites of increased CO intensity, implying multiple sites of star formation, but not all sites are at the same stage of evolution. What would be the effect on the evolution of the clouds according to your model?

Norman: Different ages at different sites of star formation would be expected if star formation is triggered by cloud-cloud collision, or is triggered in bound smaller clouds before coagulation with the giant cloud. There might also be a sequential process in which the effects of a supernova or OB-star wind trigger star formation in a nearby clump. Detailed observations such as you described may allow us to differentiate between various triggering processes.