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Star Formation in the Galaxy*

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Abstract

Star formation in the Galaxy occurs on different spatial scales from single star formation events in Bok Globules to the formation of OB associations and star clusters. We review recent observations of Bok Globules and relate them to the dense NH_3 cores observed in dark clouds. Recent work on the Chamaeleon I dark cloud supports quasi-static subcritical collapse models for low mass star formation. This cloud is a typical region of low mass star formation similar to the Taurus–Auriga clouds; star formation has continued in the cloud for $\sim 10^7$ yr, the most massive embedded stars have masses of $\sim 2M_\odot$, and the cloud appears to be magnetically supported in its long dimension.

Supercritical collapse theories for star formation in giant molecular clouds are less certain and make few specific predictions. Accretion processes may be needed to form supercritical cores and star clusters, and would produce the power law form of the initial mass function at the high mass end.

Recent observations of the Orion A giant molecular cloud are summarised. The helical magnetic field around L1641, the filamentary structure of the cloud, and the collapsed and fragmented nature of the massive Orion molecular ridge bear directly on the processes of cloud collapse. The star formation history of the cloud provides another record of the cloud collapse. Low mass star formation has occurred in the L1641 cloud for $\sim 10^7$ yr, and differs from Chamaeleon and Taurus–Auriga in forming slightly higher mass stars and in forming an embedded star cluster. Low mass star formation in the Orion Nebula region has paralleled that in L1641, but higher mass OB stars have formed as well. A more detailed investigation of the stellar populations around the Orion Nebula might better elucidate the cloud collapse history.

The Trapezium Cluster is younger than $\sim 10^6$ yr and contains many low mass stars. A turn-over in the K luminosity function at $K \sim 13$ mag may be due to truncation of the initial mass function at $M \leq 1M_\odot$, possibly through competition for available gas in the extremely close protostellar environment.

1. Introduction

The study of star formation in the Galaxy has attracted intense effort. Twenty years ago, infrared astronomers were finding the first high mass protostars. These are point sources with colour temperatures of $\sim$500 K, and were identified with the cocoon stars postulated earlier by Davidson and Harwitt (1967). Just ten years ago, Lada and others were recognising the role in the star formation

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process of energetic outflow phenomena, both as bipolar CO flows and as optical jets. Five years ago, the presence of circumstellar accretion disks around low mass pre-main sequence stars was being defined. As a result, we now have a workable, although undoubtedly sketchy, model of the early evolution of a star after the time that its parent cloud decides to collapse. However, our knowledge of what triggers this collapse and what factors influence the resultant stellar mass function, with the associated question of whether the star formation process is intrinsically bimodal, remains very uncertain areas indeed. It is this aspect of Galactic star formation on which I would like to concentrate in this presentation. I will mainly use the Chamaeleon I dark cloud and the Orion A giant molecular cloud as examples of regions undergoing star formation. In keeping with the theme of stimulating exchange between theoreticians and observers, I will try to present the current state of observational knowledge about these regions and only briefly outline some possible mechanisms by which these regions may have reached their current states.

Star formation in the Galaxy occurs on a variety of spatial scales from the small Bok Globules forming single stars to the formation of OB associations and dense star clusters from giant molecular clouds (GMCs). I will discuss these in the following order:

- Bok Globules including all small dark clouds.
- Dark cloud complexes such as the Taurus–Auriga and Chamaeleon dark clouds.
- Giant molecular cloud complexes such as Orion A.

2. Star Formation in Bok Globules

The Bok Globules form a heterogeneous group of small dark clouds. In principle, they provide the simplest laboratory in which to study the star formation process. Leung (1985) distinguished four classes of these globules based on their optical morphologies: (*a*) elephant-trunk and speck globules, (*b*) cometary globules, (*c*) globular filaments, and (*d*) isolated dark globules. Studies based on the *IRAS* Point Source Catalog have shown that star formation is commonly occurring in these globules. The various Bok Globules generally have sizes in the range $\sim 0 \cdot 1$–$1 \cdot 0$ pc, masses in the range ~ 1–$100 M_{\odot}$, and densities of $\geq 10^4$ cm^{-3}. The total number of Bok Globules in the Galaxy is estimated to be $\sim 3 \times 10^5$, and accounts for a gas mass $\sim 4 \times 10^6 M_{\odot}$ or $\sim 0 \cdot 1\%$ of the Galactic molecular mass (Clemens *et al.* 1991).

(2a) Elephant-trunk and Speck Globules

The elephant-trunk and speck globules are associated with H II regions and often show bright rims which are photoionised by the adjacent OB stars (Fig. 1). These globules may be formed by instabilities in shells of material swept up by the stellar winds from the central OB stars or the expanding H II region. Sugitani *et al.* (1991) have recently presented evidence for recent star formation in ~ 50 bright-rimmed globules associated with *IRAS* point sources. The *IRAS* luminosities of the embedded stars (~ 10–$10^3 L_{\odot}$) are larger by on average two orders of magnitude than those of the young stars embedded in isolated dark globules and the molecular cores of dark cloud complexes. This luminosity range

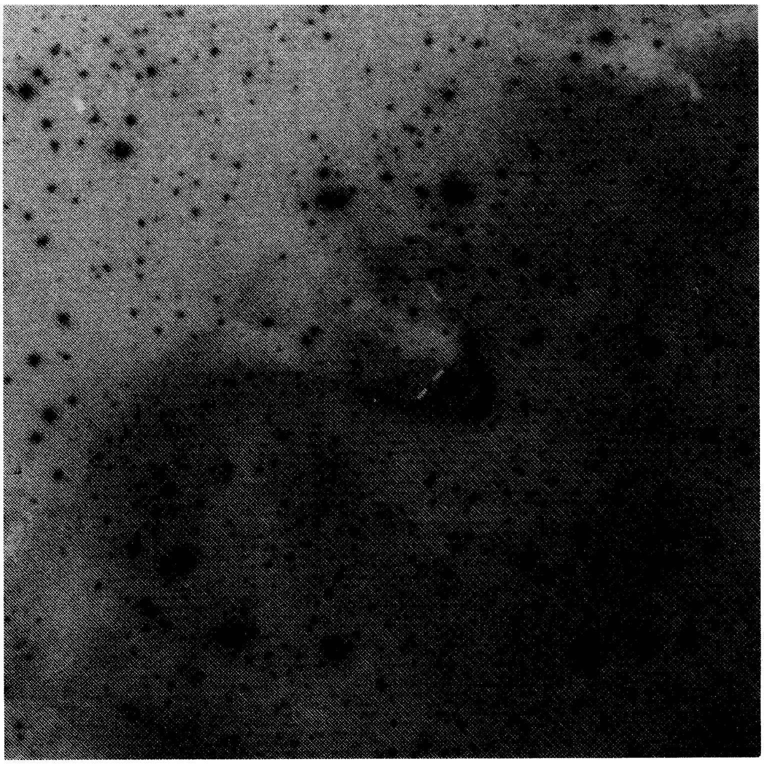

Fig. 1. Bright-rimmed globule associated with the H II region IC 1848 and containing the embedded *IRAS* source 02570+6028 (from Sugitani *et al.* 1991).

is typical of intermediate mass stars ($\sim 2-6M_{\odot}$) and suggests that the stars forming in bright-rimmed globules may be up to a factor of ~ 4 more massive than the stars forming in isolated dark globules. Radiation-induced implosion is a possible mechanism for triggering star formation in such clouds (Bertoldi 1989; Bertoldi and McKee 1990; and references therein), and may enhance cloud collapse sufficiently to result in the formation of more massive stars. However, the association of these globules with H II regions already suggests an association with more massive stars so the real importance of this trigger, relative to the cloud collapse mechanisms operating in other molecular cores, remains unclear.

(2b) Cometary Globules

Cometary globules are isolated clouds, not physically attached to any neighbouring bright rims or nebulosity, and have compact dusty heads with long faint one-sided tails extending from the head (Hawarden and Brand 1976). Typical examples are those associated with the Gum Nebula (Zealey *et al.* 1983; Reipurth 1983; see Fig. 2). In the favoured scenario for their formation (Reipurth 1983), they are cloud cores still surviving from the main star formation era of a dark cloud complex or GMC. UV photons from the central OB stars weakly photoionise their outer layers; the ionised layer is ablated to form the tail and shocks associated

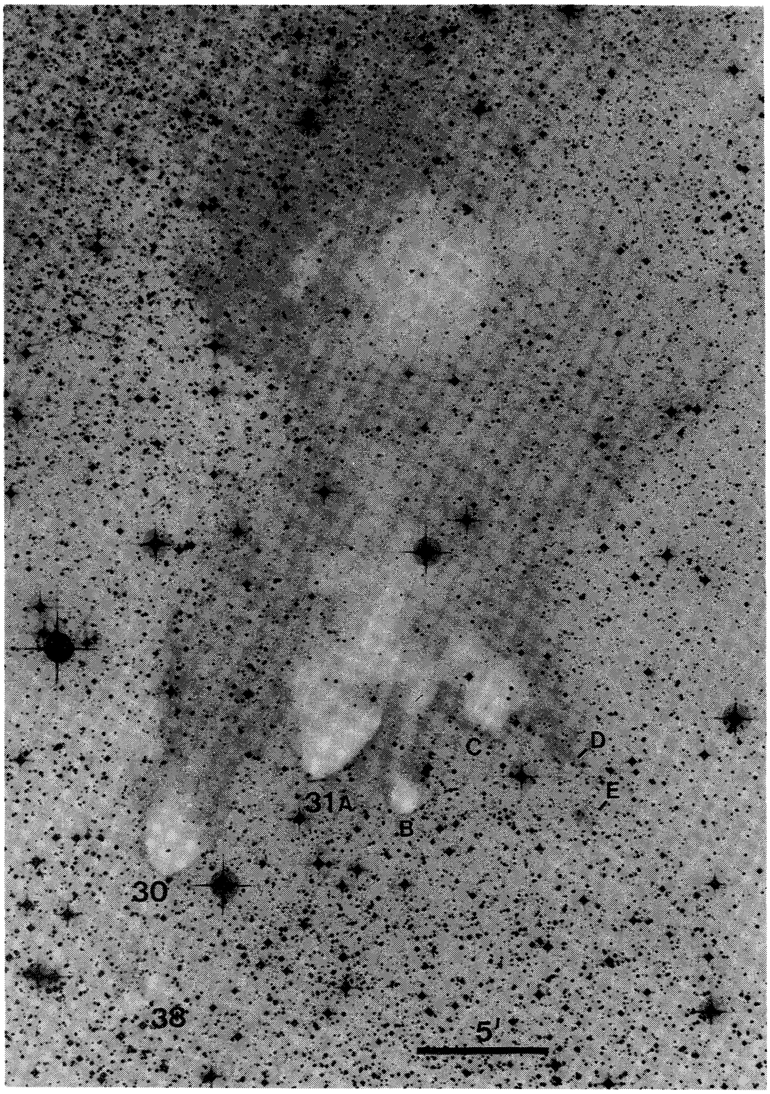

Fig. 2. Cometary globules CG30, CG31ABCDE, and CG38 in the Gum Nebula (from Reipurth 1983).

with the ionisation front may compress the head. There is, therefore, limited evidence for an evolutionary connection between the elephant-trunk and speck globules and the potentially older cometary globules. After the OB stars have expired, cometary globules which have not evaporated or been disrupted by star formation may take on the appearance of isolated dark globules. However, this connection is far less certain. Radiation-induced implosion is likely to be less

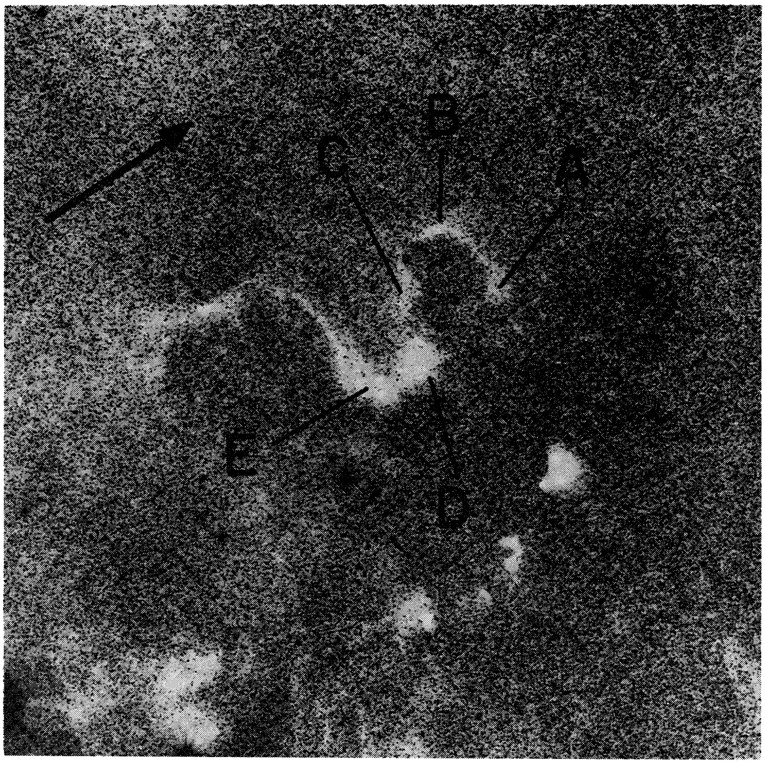

Fig. 3. Globular filament B72, also known as the Snake, in Ophiuchus (from Schneider and Elmegreen 1979).

important in cometary globules than in the bright-rimmed globules which are more intimately associated with H II regions and have more prominent rims.

(2c) Globular Filaments

The globular filaments are elongated dark clouds having a filamentary appearance and often containing a number of condensations or cores spaced along the filaments (Schneider and Elmegreen 1979; see Fig. 3). Their tenuous nature and locations in the outer parts of dark cloud complexes suggest an origin related to the formation of larger dark cloud complexes. They may be the result of the gravitational collapse and fragmentation of an initially uniform filament with an axial magnetic field (Schneider and Elmegreen 1979). Optical polarisation data support this interpretation in at least one case (McDavid 1984). The star forming properties of these filaments are uncertain.

(2d) Isolated Dark Globules

The isolated dark globules are the simplest of the Bok Globules. They are typified by objects such as B335 and B68 (Fig. 4) which resemble the individual molecular cores in dark cloud complexes. In fact, the isolated dark globules appear to have similar sizes, masses, densities, temperatures, velocity dispersion,

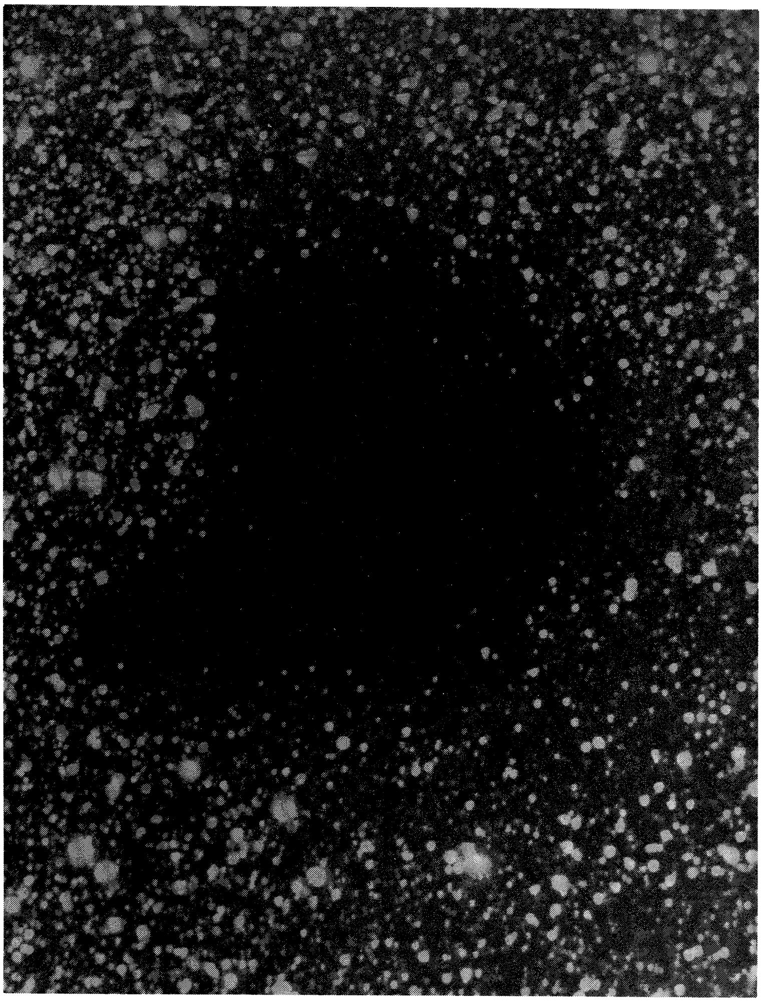

Fig. 4. The isolated dark globule B68 in Ophiuchus (from Bok 1977).

and star forming properties to the molecular cores in dark cloud complexes (Benson and Myers 1989). The physical parameters of isolated globules have been comprehensively summarised by Leung (1985). It is not yet clear whether these are the remnants of earlier cometary globules no longer excited by OB stars, or whether they represent an early phase in the formation of dark cloud complexes. Early molecular line work suggested that many of these clouds are in virial equilibrium (Leung *et al.* 1982; Dickman and Clemens 1983), raising questions of their role in the formation of stars. Recent studies using the *IRAS* database (Yun and Clemens 1990; Clemens *et al.* 1991) have found that one in four dark globules contain an embedded star more massive than $\sim 0 \cdot 7 M_{\odot}$, and this fraction may be as high as 100% if the Miller–Scalo (1979) initial mass function is applicable at lower masses. The star formation efficiency in these dark globules is between $\sim$3% and $\sim$6%.

The role of magnetic fields in the support of isolated dark globules remains uncertain. Dickman and Clemens (1983) satisfactorily explained the observed properties of an isolated dark globule without considering magnetic support. Jones *et al.* (1984) presented weak evidence for a pinching in the magnetic field structure of Coalsack Globule 2 based on the near-infrared polarisation vectors for background stars. However, Klebe and Jones (1990) have recently studied three more isolated dark globules in this way and failed to find similar evidence for dynamically important magnetic fields. They speculate that significant ambipolar diffusion may have already taken place in these globules (and so reduced the role of magnetic support) since ambipolar diffusion is predicted to be most efficient in clouds of this size and density (Myers and Goodman 1988; see below). On the other hand, Frerking *et al.* (1987) noted that the inclusion of a magnetic field with $B \sim 25$ μG in their model for B335 would help explain the observed shape and orientation of the cloud, the near stability of the core, the low observed angular momentum of the core, and the observed expansion of the outer envelope. Further studies of the magnetic properties of isolated dark clouds, especially direct magnetic field strength measurements, are required to address this question.

3. Star Formation in Dark Cloud Complexes

Star formation in dark cloud complexes such as the Taurus–Auriga dark cloud occurs in the vicinity of dense ($n \geq 10^4$ cm^{-3}) molecular cores (Benson *et al.* 1984; Benson and Myers 1989). Approximately half of these molecular cores have formed low mass stars (Beichman *et al.* 1986). Cores forming low mass stars are characterised by thermal velocities while cores forming more massive stars are characterised by non-thermal velocities, with the division occurring in the luminosity range 7–22$L_\odot$ (Myers *et al.* 1991). The physical basis for these non-thermal, i.e. supersonic, motions in regions of high mass star formation is poorly understood, but may be due to mechanical turbulence or hydromagnetic waves propagating at near the Alfvén speed.

Shu *et al.* (1987) proposed that clouds forming low mass stars are initially magnetically supported and that subsequent evolution occurs in a quasi-static fashion at a rate determined by the ambipolar diffusion timescale. As the core contracts slowly under the influence of ambipolar diffusion, the gravitational and thermal energy densities increase, but the magnetic energy density remains constant. Under such conditions, the Alfvén speed would decrease and allow thermal motions to dominate. In this model, mass accretion is stopped when the star produces a stellar wind capable of first halting, and then dissipating, the accretion flow. More recently, Mouschovias (1991; see also Carlberg and Pudritz 1990) has shown that sub-regions, or cores, within clouds can contract due to ambipolar diffusion while the bulk of the cloud remains magnetically supported. In this more attractive model, the stellar mass spectrum is determined by the mass sizes of cloud cores (the *Alfvén length scale* in the notation of Mouschovias 1991), and does not require a stellar wind to terminate the accretion flow. The observed characteristic stellar mass is then a consequence of the nature of core formation in molecular clouds. This naturally accounts for the apparent universality of the stellar initial mass function. Mouschovias (1991) estimates typical masses of $\sim 1 M_\odot$ for the contracting cloud cores. Since core formation is magnetically controlled, magnetic braking will reduce the core angular momentum at early times. The formation of low mass stars with low rotational velocities is therefore a prediction of the model. This is supported by observations of T Tauri stars (Vogel and Kuhi 1981). The star formation efficiency should also be low, as is observed.

Myers and Goodman (1988) provided further evidence in support of these ideas using a uniform self-gravitating spherical cloud model which is based on the simple assumption that the non-thermal kinetic energy density equals the magnetic energy density. They fitted the well known observed relations of non-thermal velocity dispersion versus radius ($\sigma_{NT} \propto R^{1/2}$) and volume density versus radius ($n \propto R^{-1}$) for molecular cores with reasonable magnetic field strengths using this model. For typical core magnetic fields of $\sim$30 μG, they showed that the timescale for ambipolar diffusion is a minimum for clouds with sizes of $\sim$0·1 pc, typical of low mass cores. The low mass cores in dark clouds and the isolated dark globules of this size may therefore have undergone, or currently be undergoing, significant ambipolar diffusion. This may account for the predominantly thermal line widths seen in low mass cores, and for the relatively large numbers of low mass stars formed in molecular clouds. Ambipolar diffusion in such clouds should occur on a timescale of $\geq 2 \times 10^7$ yr.

Harrison *et al.* (1992) have studied the stellar populations in the Chamaeleon I dark cloud complex. The full $\sim 35' \times 45'$ extent of the western region of the cloud has been scanned at 2 μm to $K \sim 12$ mag on the AAT, and follow-up JHK measurements of 212 stars made on the ANU 2·3 m telescope. From these data and *IRAS* ADDSCAN data, we have identified 112 cloud members. *H* band polarimetry has also been obtained for 29 member stars and 37 reddened background stars (McGregor *et al.* 1992).

The near-infrared photometry allows us to place these stars in the infrared colour–magnitude diagram (Fig. 5). The majority of cloud members are low mass pre-main sequence stars with masses $\leq 2M_\odot$, as is found for the Taurus–Auriga dark cloud. The slope of the initial stellar mass function in Chamaeleon is consistent with the Salpeter (1955) mass function. The youngest stars are still heavily embedded and have ages of $\sim 10^5$ yr. A significant population of member stars have low reddenings and $M_K \geq 5 \cdot 0$ mag, which corresponds to main sequence M dwarfs at the distance of Chamaeleon. If these stars are near the main sequence, they have ages $\geq 2 \times 10^7$ yr and masses $\leq 0 \cdot 5M_\odot$. If they have not yet reached the main sequence, they may be slightly younger but must be of even lower mass and later spectral type. Any correspondingly old population of high mass stars would be on the main sequence and most likely have been classified as background stars. HD 97300 lies near the main sequence and has an age $\geq 4 \times 10^6$ yr. Based on these results, we conclude that low mass star formation began in the Chamaeleon I dark cloud at least $\sim 10^7$ yr ago and has continued until the present. This timescale is of interest because it is comparable to the ambipolar diffusion timescale in low mass cores (Myers and Goodman 1988). A similar age is found for the oldest stars in the Taurus–Auriga dark cloud complex (Cohen and Kuhi 1979; Walter 1987). The star formation histories of both these clouds therefore appear to be at least in qualitative, and possibly in quantitative, agreement with models of the quasi-static contraction of magnetised cloud cores.

Light from background stars observed through a dark cloud is polarised due to the presence of magnetically aligned dust grains within the cloud. In this

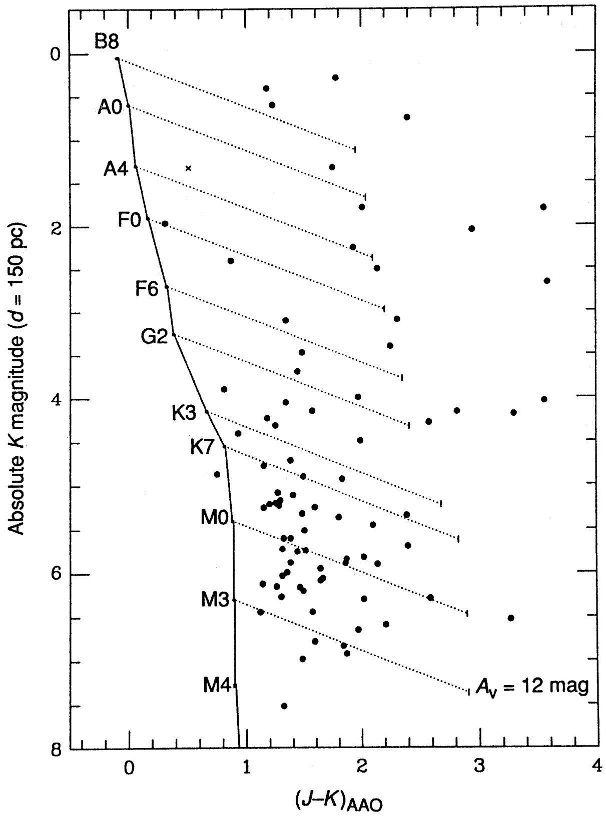

Fig. 5. Infrared colour–magnitude diagram for member stars in the Chamaeleon dark cloud (from Harrison *et al.* 1992). No reddening correction has been applied to the data, but the effect of 12 mag of visual extinction is indicated. The zero age main sequence is represented by a solid line and the luminosities of various main sequence spectral types are marked. The most luminous stars correspond to late-B main sequence spectral types. The faintest stars correspond to early-M main sequence spectral types, with masses of $\sim 0 \cdot 5 M_{\odot}$ and ages of $\sim 2 \times 10^7$ yr.

situation, the polarisation vectors for background stars indicate the magnetic field direction. The polarisation vectors for stars behind the Chamaeleon dark cloud (Fig. 6*a*) clearly reveal a uniform global magnetic field structure crossing the cloud in its short dimension. The N–S elongation of the cloud is perpendicular to the magnetic field lines, suggesting that the cloud has collapsed preferentially in the direction of the magnetic field. It appears that magnetic pressure continues to support the cloud in the direction of the elongation, even though active low mass star formation is occurring within the cloud. This result is consistent with Mouschovias' model for low mass star formation where the cloud can remain magnetically supported while sub-regions contract quasi-statically via ambipolar diffusion to form stars.

The polarisation directions for cloud members show a significantly larger scatter around the global magnetic field direction than for background stars (Fig. 6*b*). The light from young member stars is polarised by anisotropic scattering from

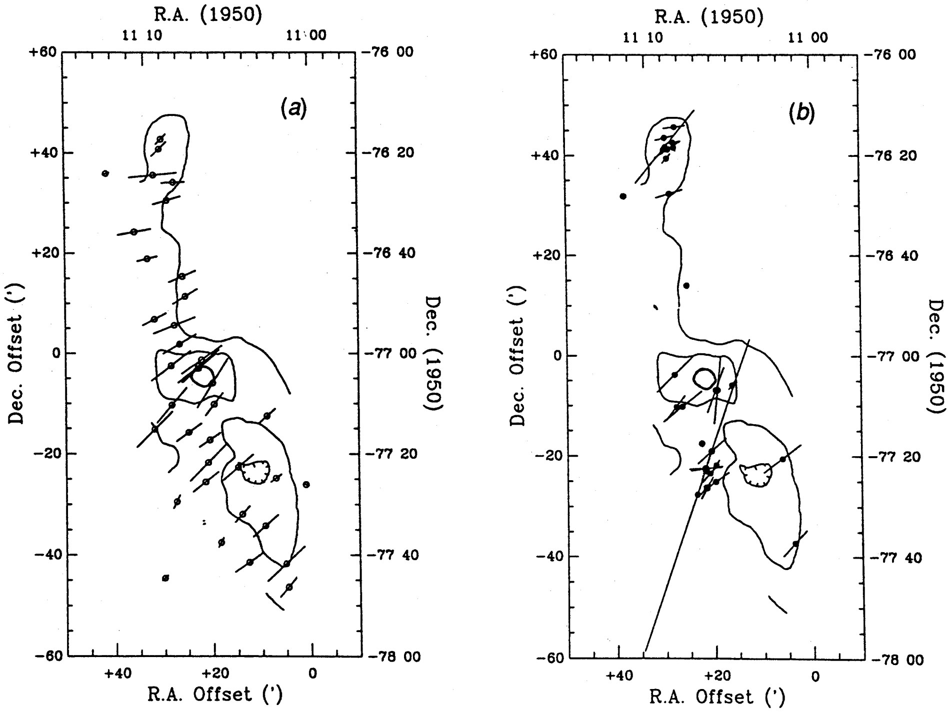

Fig. 6. *H* band linear polarisation vectors for (*a*) stars behind the Chamaeleon dark cloud and (*b*) member stars embedded in the cloud (from McGregor *et al.* 1992). The background star vectors show the large-scale magnetic field structure within the cloud. The member stars show a larger range in position angle due to polarisation by anisotropic scattering in their envelopes. The solid lines are $C^{18}O$ contours.

Fig. 7. Optical linear polarisation map of the ρ Ophiuchi dark cloud (from Vrba *et al.* 1976). Note how the magnetic field appears to be aligned with the long dimensions of two filamentary 'streamers'.

dust in the immediate vicinity of the star. The range of polarisation directions reflects a significant range in scattering orientations. In addition, the outflow axis of *IRAS* 11054–7706C, a bipolar CO outflow source, makes an angle of $>60°$ to the large-scale magnetic field, and the axis of the Infrared Nebula, a bipolar reflection nebula around a very young embedded star, makes an angle of $\sim 50°$ to the large-scale magnetic field. This scatter suggests that the local magnetic field does not play a strong role in defining the orientations of the outflow axes of stars formed recently in the cloud. This can again be understood within the framework of the Mouschovias (1991) model; ambipolar diffusion acts to reduce the importance of magnetic fields relative to gravitational and thermal pressures within the mass element which contracts to form a star. The orientation of the outflow axis may therefore evolve away from the large-scale magnetic field direction as the core contacts.

Polarisation vectors for stars behind the Taurus–Auriga and Lupus dark cloud complexes are generally also consistent with the above model (Tamura and Sato 1989, and references therein; Strom *et al.* 1988). However, several elongated clouds within the Taurus–Auriga complex are oriented at significant angles to the magnetic field direction suggesting that their structure on scales ≥ 1 pc is not strongly influenced by the large-scale magnetic field (Goodman *et al.* 1990). The magnetic field geometry in the ρ Ophiuchi dark cloud (Vrba *et al.* 1976; Sato *et al.* 1988) and in the R Corona Australis dark cloud is more complicated and does not simply fit within the above model. The elongation of the dense core region of ρ Ophiuchi is perpendicular to the local magnetic field, as expected for magnetically controlled collapse, but the magnetic field appears to run along the long dimension of filaments in the outer parts of both dark clouds (Fig. 7). Uchida *et al.* (1990) found evidence that a streamer in ρ Ophiuchi is rotating about its long dimension and interpreted this as an 'angular momentum drain' which may provide a mechanism by which the core can collapse more efficiently. The ρ Ophiuchi dark cloud is more massive, and forming more massive stars, than the Chamaeleon, Taurus–Auriga, and Lupus dark clouds. We will return to this 'angular momentum drain' model below in discussing massive star formation in the Orion A GMC. However, we note that the rotation period of the ρ Ophiuchi streamer is $\sim 2 \times 10^7$ yr, based on the observed velocity gradient across the streamer of $\sim 1\,\mathrm{km\,s^{-1}}$ and width of ~ 3 pc. Consequently, the streamer cannot have made more than a few rotations during the entire star forming lifetime of the ρ Ophiuchi dark cloud.

4. Star Formation in Giant Molecular Clouds

High mass stars form in OB associations (Blaauw 1964) which evolve from dense gas in GMCs. Star clusters are common constituents of OB associations and these clusters often contain multiple-star systems similar to the Trapezium system in the Orion Nebula (Sharpless 1954). The conditions under which star clusters form are likely to be quite different from those appropriate to the isolated low mass stars in the cores of dark cloud complexes; star formation efficiencies in excess of $\sim 30\%$ are required to form bound star clusters (Lada *et al.* 1984), and interactions between the various protostars in the protocluster environment may significantly alter the initial mass function which results. Low mass stars have long been known to form in GMCs as well, and it remains to be determined

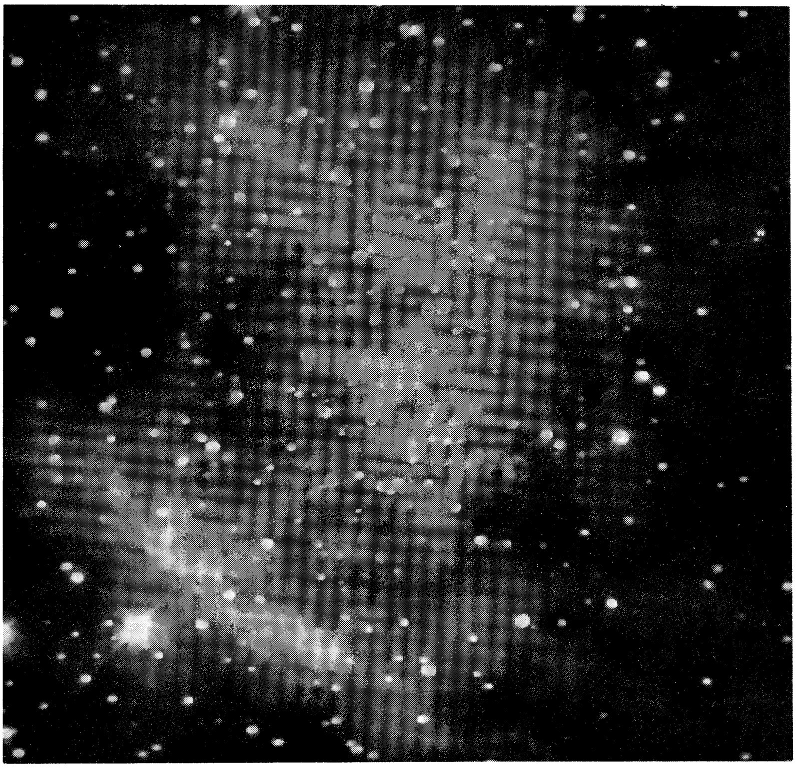

Fig. 8. Near-infrared image of the Trapezium Cluster at the centre of the Orion Nebula (from McCaughrean 1989).

whether these low mass stars form through the quasi-static collapse of molecular cores as appears likely in dark cloud complexes. Recent infrared array images have shown that many more low mass stars in GMCs form in clusters associated with embedded high mass stars (McCaughrean 1988; DePoy *et al.* 1990; C. Lada *et al.* 1991; E. Lada *et al.* 1991; Hodapp and Rayner 1991; see Fig. 8). The molecular cores in GMCs differ from those in dark cloud complexes; their masses are larger by factors of $10-10^3$ than in dark cloud complexes, their temperatures are higher by factors of $3-10$, their velocity dispersions are larger by factors of $3-10$, they are physically bigger by factors of $1-30$, and they tend to form more massive stars (Myers 1985; Harju *et al.* 1990). We would like to know how both high and low mass stars form in GMCs, and what conditions result in the formation of star clusters. It is especially important to identify differences in the star formation processes between GMCs and dark cloud complexes because these will allow us to decide whether or not star formation is fundamentally a bimodal process.

Theories of star formation in regions forming high mass stars ($M \geq 2M_{\odot}$) are less developed than for clouds forming only low mass stars, and consequently make fewer specific predictions. In the model of Shu *et al.* (1987), molecular cores forming high mass stars are assumed to be supercritical in the sense that they are sufficiently massive for gravity to overwhelm their magnetic and thermal support. As these clouds collapse, the magnetic field remains coupled to the matter and the magnetic, kinetic, and gravitational energy densities increase together, increasing the Alfvén speed and allowing non-thermal hydromagnetic motions to dominate thermal motions. Thus, in this model massive stars should be characterised by rapid rotation (since magnetic braking is less efficient) and strong magnetic fields (because of magnetic flux trapping), as is observed.

A possible difficulty with this model is that supercritical cloud cores may collapse on short timescales. If all GMCs were supercritical and collapsed on short timescales the star formation rate in the Galaxy would be prohibitively high (Zuckerman and Palmer 1974), and such clouds would be rare. How then do supercritical cores form? A possible solution to this problem arises if massive molecular cores in regions of high mass star formation are built up by agglomeration of material (Lizano and Shu 1987). Although far from proven, this possibility is appealing because it permits subcritical collapse, and low mass star formation, to proceed in GMCs before high mass star formation has begun. Certainly, further star formation is unlikely in a massive molecular core once H II regions have developed around the first OB stars. The notion that molecular cores continue to accrete material from their surroundings after low mass star formation has begun is also a convenient one when attempting to understand the formation of star clusters in GMCs (Larson 1982). The masses of cores associated with star clusters appear to increase with the mass of the star cluster and with proximity to the cluster (Myers 1991), and the most massive stars in a cluster are often located at its centre. This can be understood if the masses of GMCs increase during their lifetimes, and the most massive cores and star clusters form at the bottom of the gravitational potential well of the complex by accretion of peripheral gas into this well. A power law form for the initial mass function is also a natural result of massive star formation by accretion (Larson 1991).

Mouschovias (1991) has suggested an alternative solution which is that high mass star formation is triggered by external factors such as supernovae, H II regions, or stellar winds which increase the ambient pressure on the core. This allows a subcritical core to collapse under the combined inward pressures of gravity and the external trigger. An example may be the radiation-induced implosion discussed above.

(4a) Molecular Gas in the Orion A Giant Molecular Cloud

We take as an example of a giant molecular cloud the Orion A GMC which includes the Orion Nebula in its northern region and the dark cloud L1641 to the south. Identifying the mechanisms responsible for cloud collapse and star formation in this region is central to our understanding of high mass star formation. Bally *et al.* (1991) have shown that the main body of the Orion A and B molecular clouds and at least 16 smaller clouds in the larger Orion star forming region ($\sim$100 pc extent) have a cometary appearance with their 'tails' oriented radially away from the oldest OB association Orion Ia (Fig. 9). They speculate that the morphologies of these clouds on scales >1 pc are determined by supernovae, stellar winds, and radiation processes from massive stars in the OB association. As with the Gum Nebula cometary globules, it is not yet clear whether radiation-induced implosion is a significant star formation trigger in these clouds, although several cometary clouds have formed low mass stars in

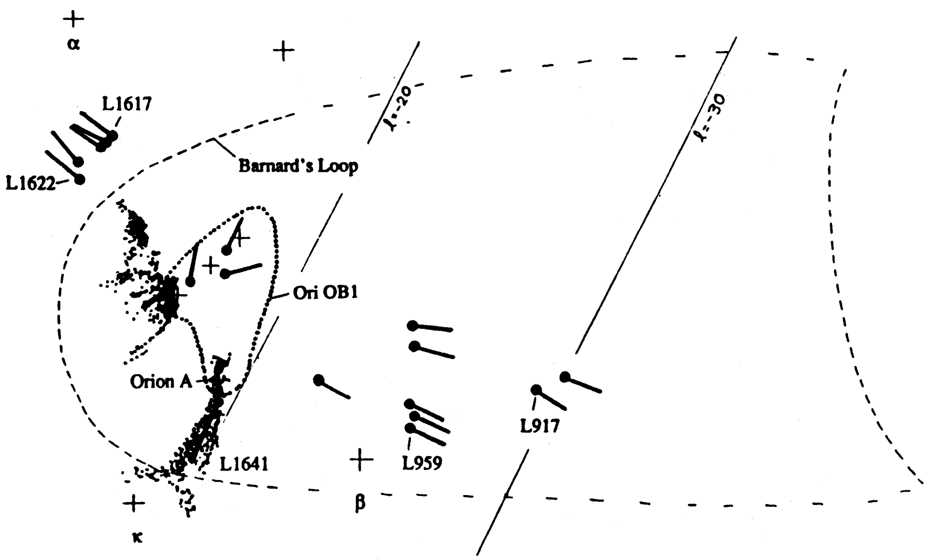

Fig. 9. Large-scale schematic of the Orion complex showing the locations and orientations of 16 cometary molecular clouds (from Bally *et al.* 1991). The location of the Orion I OB association is shown by the dotted region.

their 'heads' (e.g. L1617 and L1622). The possibility exists that such factors also played a role in triggering star formation in the Orion A cloud.

The Orion A GMC is embedded in a large H I cloud with a mass of $\sim 10^5 M_\odot$ (Chromey *et al.* 1989). The molecular cloud itself has a filamentary structure in ^{13}CO (Bally *et al.* 1987; see Fig. 10) with aspect ratios larger than 30 : 1 (length : width) being common. Bally *et al.* (1991) speculate that these filaments may be threaded with magnetic fields. Heiles (1987) has measured the magnetic field structure near the cloud using 21 cm H I Zeeman splitting and found that $B_\|$ is oriented towards us on the western side of the cloud and away from us on the eastern side, and has a magnitude of $\sim 10\,\mu$G (Fig. 11). He interprets this as a helical magnetic field wrapped around the molecular cloud in its long dimension. Optical polarisation measurements of background stars (Appenzeller 1974; Vrba *et al.* 1988) show that $B_\perp$ crosses the cloud at an angle of $\sim 20°$ to its long dimension (Fig. 11). Bally (1989) has combined these results to produce a consistent picture of the cloud magnetic field (Fig. 12) which demonstrates the close connection between the cloud structure and the magnetic field geometry. OH Zeeman splitting measurements show that the magnetic field in the Orion A core has a strength of $125 \pm 20\,\mu$G (Troland *et al.* 1986).

Uchida *et al.* (1991) used additional ^{13}CO data to claim that the molecular filaments also have a helical structure, and that they are spinning about the long axis of the cloud in the same sense as the gas in the Orion A core region (Fig. 13; Fukui and Mizuno 1991). They suggest that these 'streamers', which extend to the south of the Orion Nebula, may act as an 'angular momentum drain' for the Orion A core. The same model was used by Uchida *et al.* (1990) to explain the existence of rotating filamentary streamers associated with the ρ Ophiuchi dark cloud complex. In this model, the streamer (L1641 in the case

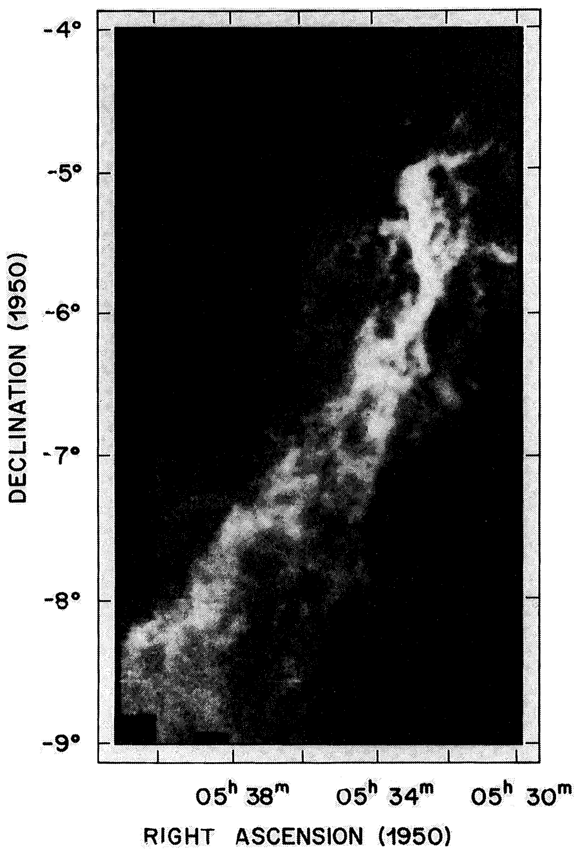

Fig. 10. Integrated ^{13}CO map of the Orion A giant molecular cloud showing its complex filamentary structure (from Bally *et al.* 1987). The Orion Nebula is near the top at R.A. $\sim 5^h\ 33^m$, Dec. $\sim -5^\circ\ 25'$. The L1641 dark cloud forms the southern portion of the cloud.

of the Orion complex) is spun up by a magnetic field originating in the massive molecular core. The spiralling magnetic fields carry angular momentum away from the core, and allow it to contract more readily and ultimately form stars with greater efficiency. We note that the rotational period of L1641 around its long dimension is $\sim 10^7$ yr, based on the observed velocity gradient across L1641 of $\sim 2\,\mathrm{km\,s^{-1}}$ and a width of ~ 3 pc. As with the ρ Ophiuchi streamer, L1641 cannot have made more than a few rotations around its long dimension during its star forming lifetime of $\sim 10^7$ yr (see below). The efficiency of the Uchida *et al.* (1990) model therefore should be investigated in this light.

The molecular gas in the Orion A core behind the Orion Nebula forms a narrow N–S ridge of $\sim 1^\circ$ extent. The molecular ridge has a mass of $\sim 5 \times 10^3 M_\odot$, which constitutes $\sim 25\%$ of the total cloud mass, and a similar mass per unit length to the more diffuse L1641 region which suggests that the ridge has been compressed (Bally *et al.* 1987). The molecular ridge is aligned closely with the Orion sword region, with the groups of OB stars defining the sword to the north and south

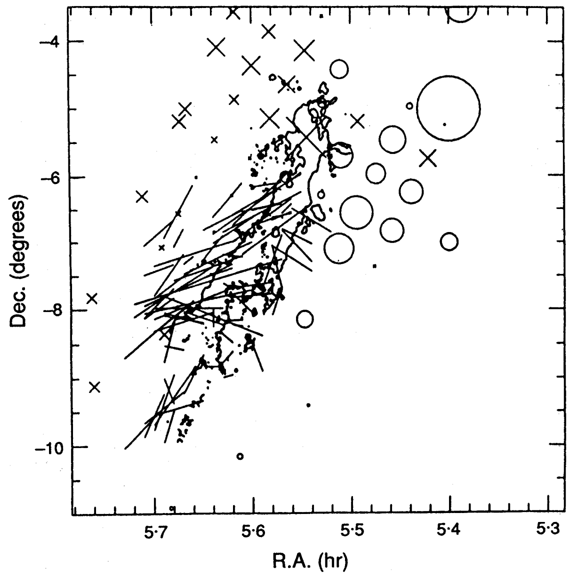

Fig. 11. Magnetic field measurements in the Orion A GMC (from Bally 1989) showing orientations of optical linear polarisation vectors (Vrba *et al.* 1988) and 21 cm HI Zeeman splitting measurements (Heiles 1987; circles for B coming out of page, crosses for B going into page) on the outline of the L1641 ^{13}CO cloud.

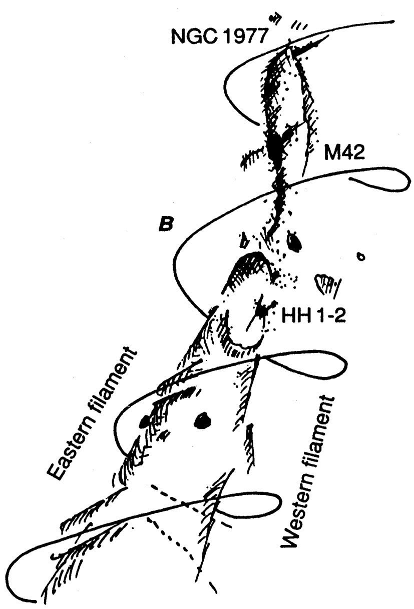

Fig. 12. Schematic magnetic field structure in the Orion A GMC superposed on the outline of ^{13}CO intensity, showing the spiralling magnetic field enveloping the L1641 cloud (from Bally 1989).

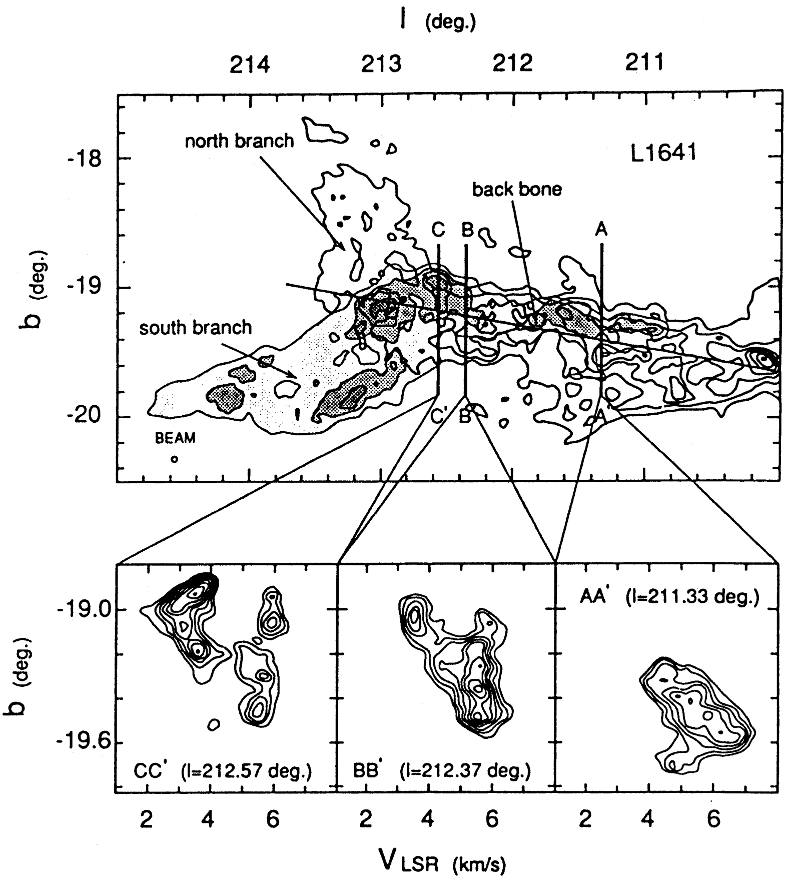

Fig. 13. Distribution of two ^{13}CO velocity components in the southern 'tail' of L1641 (from Fukui and Mizuno 1991). The velocity contours show that L1641 is rotating about its long dimension with a velocity gradient of $\sim 2\ \mathrm{km\,s^{-1}}$.

of the Orion Nebula being located near its ends where the molecular ridge bends and merges with the larger L1641 filaments. Recent C^{18}O maps show the gas in this region to be fragmented into several clumps periodically spaced along the ridge with a separation of ~ 1 pc (Dutrey *et al.* 1991; see Fig. 14). The C^{18}O linewidths are $\sim 1{\cdot}0\ \mathrm{km\,s^{-1}}$, the densities in the fragments are $\geq 5 \times 10^3\ \mathrm{cm^{-3}}$, and their masses range from $\sim 70 M_\odot$ to $\sim 150 M_\odot$. The appearance of these fragments qualitatively resembles the globular filaments associated with small dark clouds, and suggests a similar origin of fragmentation along a magnetic flux tube. However, the magnetic field in the core either crosses the N–S elongation of the molecular ridge or continues the helical structure seen further south (Gonatas *et al.* 1990; Leach *et al.* 1991). Dutrey *et al.* (1991) presented arguments for the support of these fragments by hydromagnetic waves.

The nature of the spiralling magnetic field around L1641 and the periodically spaced molecular clumps along the Orion molecular ridge suggest to us a picture

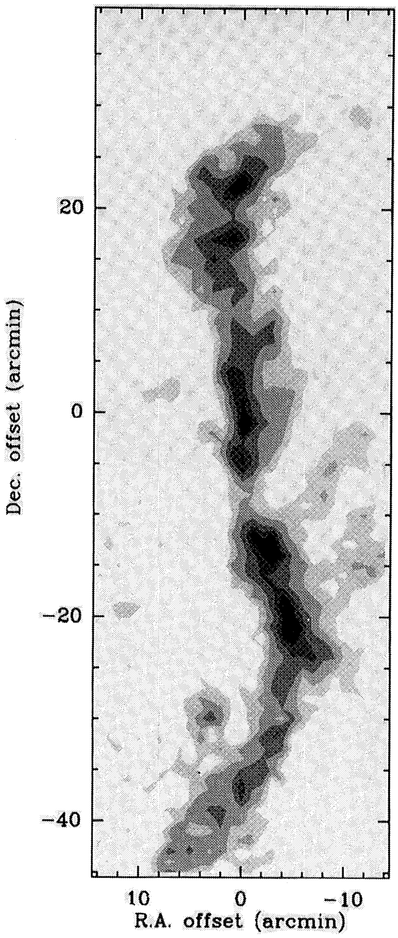

Fig. 14. $C^{18}O$ map of the Orion molecular ridge showing the fragmentation of the ridge into a number of approximately evenly spaced cores (from Dutrey *et al.* 1991). The molecular ridge corresponds closely with the Orion sword region, with groups of OB stars formed at its ends where the molecular ridge bends and merges with the larger L1641 filaments.

for the collapse of the Orion A core which more closely follows the Shu *et al.* (1987) scenario than that of Uchida *et al.* (1990). We suggest that the Orion A core once occupied a larger volume and had a small rotational velocity. The molecular cloud accreted material from the surrounding massive H I cloud and eventually became supercritical, in the sense of Shu *et al.* (1987), and collapsed to form the Orion A core. As it did so, the magnetic field was frozen to the matter and collapsed with the molecular gas, becoming twisted around L1641 due to the rotation of the molecular core. Thus the twisted field is a fossil record of the collapse process, rather than a controlling factor in it. The collapsed material fragmented to form the string of dense cores along the Orion molecular ridge. Each molecular core generated a local minimum in the gravitational potential and grew as surrounding material was accreted into its potential well. Ultimately, the most massive stars formed in the most massive core where the Trapezium Cluster is located.

(4b) Star Formation in the L1641 Dark Cloud

We now consider the young stellar populations in the Orion A molecular cloud in order to define its star formation history. L1641 in the southern part of the

Orion A cloud is a well known site of active low mass star formation. Strom *et al.* (1989*b*) have conducted an extensive study of *IRAS* point sources in L1641. These stars generally have luminosities in the range 1–250 $L_\odot$, suggesting that predominantly low mass stars ($M \leq 3M_\odot$) are forming in this part of the cloud. This has been confirmed by radio continuum measurements in the cloud (Morgan *et al.* 1990) which failed to detect any more luminous embedded sources. L1641 contains a larger percentage of class I (steep far-infrared spectrum) sources than the Taurus–Auriga dark cloud. This fact is attributed to their location in higher optical depth molecular cores (Harju *et al.* 1990). The visible *IRAS* sources have ages less than $\sim 3 \times 10^6$ yr, but X-ray measurements in the cloud reveal the presence of a pre-main sequence stellar population with ages up to $\sim 10^7$ yr (Strom *et al.* 1990). Thus low mass star formation has been occurring in the L1641 cloud for at least 10^7 yr, a time comparable to the age of the whole Ori OB I association (Blaauw 1964; Warren and Hesser 1978).

Strom *et al.* (1989*a*) have identified an embedded star cluster of low mass stars in L1641, $\sim 1°$ south of the Trapezium cluster. This new cluster, associated with *IRAS* 05338–0624, contains ~ 20 young stars with an estimated stellar density of $\sim 6800\,\mathrm{pc}^{-3}$, even greater than the star density in the Trapezium Cluster ($\sim 2000\,\mathrm{pc}^{-3}$). Several star clusters have also been identified in the Orion B GMC (E. Lada *et al.* 1991). Any comprehensive theory for star formation in GMCs therefore must be able to explain the formation of multiple star clusters within a single GMC.

At least ten molecular outflows are known within the L1641 cloud (Fukui *et al.* 1986; Levreault 1988; Morgan and Bally 1991; Morgan *et al.* 1991), as well as numerous Herbig–Haro objects. Strom *et al.* (1986) originally suggested that the molecular outflows known then, and the identified Herbig–Haro objects, aligned with the cloud magnetic field and the long dimension of the cloud. The discovery of further molecular outflows (Morgan and Bally 1991; Morgan *et al.* 1991) and the clearer understanding of the magnetic field geometry in the cloud (discussed above) negate this result. It is now apparent that outflow phenomena in the L1641 cloud are not directed along a preferred direction. The ambient molecular gas distribution may play the dominant role in directing molecular outflows (Morgan *et al.* 1991).

The star formation history of the L1641 dark cloud appears to have been similar to that of the Taurus–Auriga dark cloud and the Chamaeleon dark cloud, with the possible exception of the following two factors. First, the molecular cores which are currently present in L1641 are more massive than those in Taurus–Auriga, and presumably Chamaeleon. We obviously have no information on the mass range of molecular cores in the cloud 10^7 yr ago. However, if the molecular core masses have not changed significantly, the main effect of these larger core masses appears to be a slight increase in the maximum stellar mass formed ($\sim 3M_\odot$ in L1641 compared with $\sim 2M_\odot$ in Taurus–Auriga and Chamaeleon) and a shift to higher masses in the median stellar mass formed. The second difference with the Taurus–Auriga and Chamaeleon dark clouds is that L1641 has formed a dense star cluster in its northern region (in addition to the Trapezium Cluster which we treat separately below). There is no evidence for cluster formation in the Taurus–Auriga or Chamaeleon dark clouds.

(4c) Star Formation in the Orion Nebula Cluster

The above picture of star formation in the L1641 cloud suggests that low mass star formation also may have occurred in a large region around the Orion Nebula for a significant fraction of the lifetime of the Orion A molecular cloud. The Orion A GMC probably had a much larger E–W extent before the present massive and very compact molecular ridge formed. Indeed, it is well known that the Ori Ic OB association, which has an extent of $\sim$10 pc centred on the Orion Nebula, is older ($\sim 4\times10^6$ yr) than the smaller ($\sim$1 pc) and younger ($\sim 1\times10^6$ yr) Ori Id subgroup which includes the Trapezium stars (Blaauw 1964; Warren and Hesser 1978). A detailed investigation of the stellar populations in and around the Orion Nebula (i.e. the Orion Nebula Cluster within $\sim 0\cdot5^\circ$ of θ^1C Orionis) should therefore help elucidate the collapse history of this molecular core.

This has not been done in a sufficiently complete fashion as yet. However, the early work of Larson (1982) is suggestive. Larson (1982) compared the spatial distributions of Hα emission line stars in the Orion Nebula Cluster using age and mass estimates from Cohen and Kuhi (1979). The Hα emission line stars are T Tauri stars with masses $\leq 3M_\odot$. Cohen and Kuhi (1979) showed that star formation has been occurring in the Orion Nebula Cluster region for $\sim 10^7$ yr, and has continued to the present. Both the timescale and the mass range are the same as in the L1641 cloud, although this probably only reflects the lifetime of the T Tauri phenomenon since we know that more massive stars of the Ori Ic subgroup are present in the same region. Larson (1982) found that the youngest T Tauri stars (age $<10^6$ yr) form a more compact group than the full sample, and that their spatial distribution is elongated in a N–S direction in the same sense as the more compact N–S molecular ridge (Fig. 15). There is also weak evidence that these youngest T Tauri stars may be more massive on average than for the full sample. The same results are probably also true for the OB stars. Larson (1982) offers further evidence for this contraction from the $\sim$35 pc spatial distribution of older flare stars in Orion (Gurzadyan 1980).

The results from these limited data suggest that the northern region of the Orion A GMC has been forming low mass stars for as long as the L1641 region, and probably since or before the formation of the first massive stars in the Orion OB I association. Star formation in the region appears to have become more localised to the Trapezium region over the last $\sim 10^6$ yr, as it would in response to the collapse of the Orion A core. As the core collapsed, conditions under which stars were forming changed, with the result that higher mass stars were probably formed. The presence of OB stars in the Orion Nebula Cluster demonstrates clear differences in the mode of star formation occurring here and in the L1641 region.

(4d) Star Formation in the Trapezium Cluster

The Trapezium Cluster is located at the centre of the Orion Nebula and is generally regarded as having an extent of $\sim 2'$ (Herbig and Terndrup 1986). It merges smoothly with the Orion Nebula Cluster and forms the central core of that larger star cluster. Star formation in the Trapezium Cluster has been studied recently by Herbig and Terndrup (1986), Jones and Walker (1988), McCaughrean (1988), and Samuel (1991, unpublished paper at this workshop), among others.

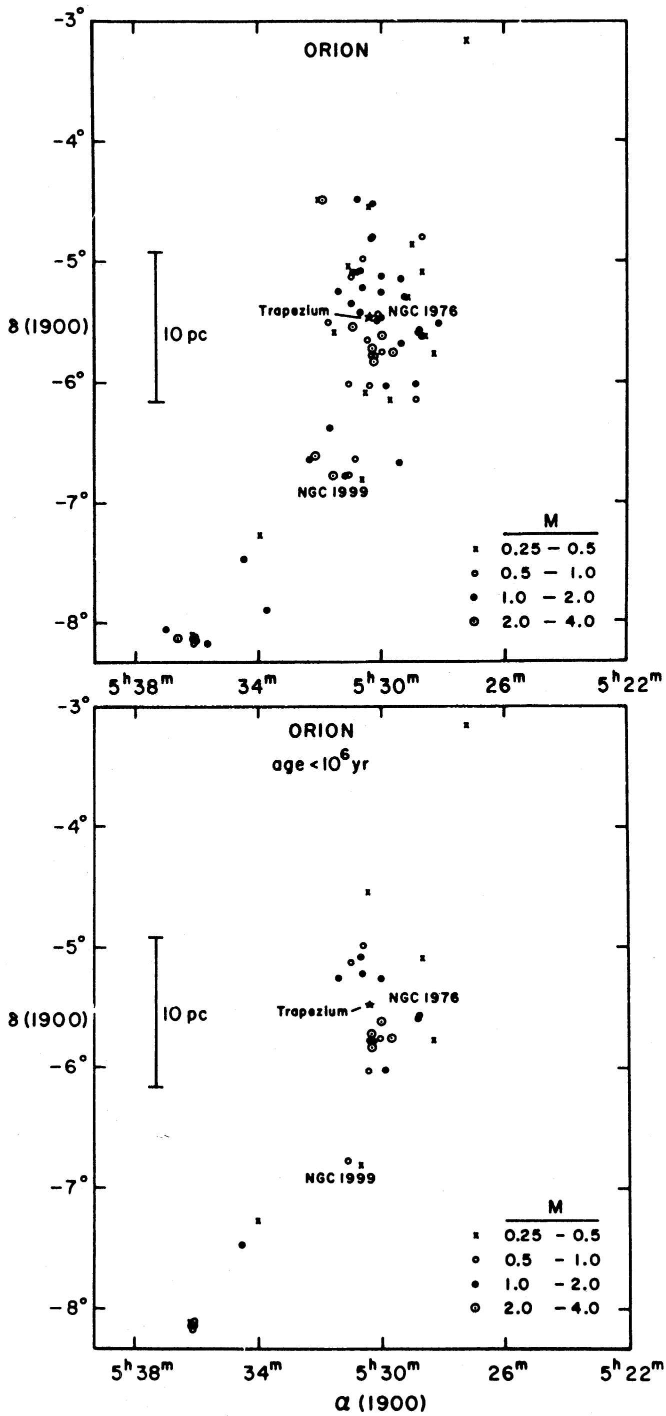

Fig. 15. Spatial distribution of T Tauri stars in the Orion Nebula Cluster region (from Larson 1982). The top panel shows all stars from the Cohen and Kuhi (1979) sample, while the bottom panel shows only stars $<10^6$ yr old.

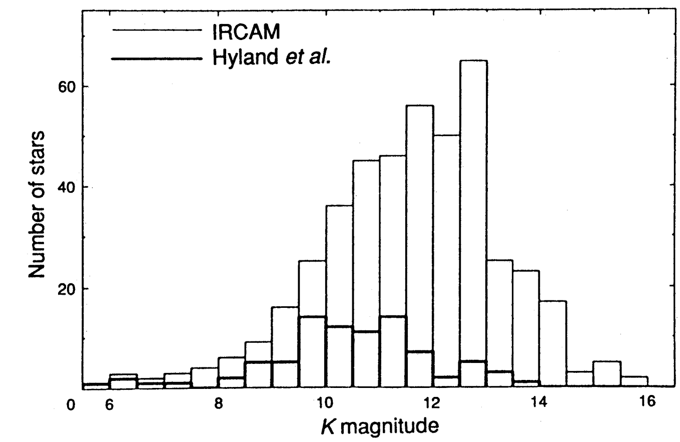

Fig. 16. The K luminosity function for the Trapezium Cluster stars (from McCaughrean 1988). The narrow line is for infrared array data from McCaughrean (1988) and the thick line is for AAT raster scan data from Hyland *et al.* (1984).

Herbig and Terndrup (1986) used optical photometry and a mean reddening estimate to derive an H–R diagram for the cluster. They found that the cluster stars were $\lesssim 10^6$ yr old and ranged in mass up to $\sim 3M_\odot$. The stellar density for the Trapezium Cluster was estimated to be $\sim 1800 M_\odot$ pc^{-3}, and $\sim 3000 M_\odot$ pc^{-3} if the θ^1 Ori stars are included. The stellar mass in the cluster corresponds to an equivalent gas density of $\sim 6\times 10^4$ cm^{-3} within the same volume (with no account taken for star formation efficiency). The Trapezium Cluster therefore must have formed from a high mass, high density molecular core. Near-infrared images of the Trapezium Cluster (McCaughrean 1988; Fig. 8) reveal a large number of embedded faint stars in the cluster and clearly show the concentrated cluster structure. Samuel (1991) confirms the young age of the Trapezium Cluster stars and finds a mean stellar mass of $\lesssim 1\cdot 5M_\odot$. A variety of evidence suggests that the Trapezium OB stars are $\sim 10^6$ yr old (Warren and Hesser 1978). In addition, two of the brightest stars have proper motions which will take them out of the Orion Nebula Cluster in $\lesssim 10^6$ yr (van Altena *et al.* 1988), suggesting that their ages are unlikely to be much in excess of this figure. This evidence reinforces earlier impressions that star formation in the Orion region has become progressively more concentrated around the most massive star θ^1C Orionis.

The K magnitude luminosity function for the Trapezium Cluster (McCaughrean 1988; see Fig. 16) appears to turn over at $K \sim 13$ mag. Although the reality of this turnover needs confirmation, if it is real it reveals much about the competitive nature of star formation in a cluster environment. The turnover can be interpreted as being due to a truncation in the mass function for the cluster with few stars less massive than $\sim 0\cdot 7M_\odot$ having formed. The stellar density within the cluster may have been sufficiently high that lower mass protostars either did not form, or merged with other protostars to form more massive end products. Evidence for similar mass truncation has been found in the young cluster associated with NGC 2023 (DePoy *et al.* 1990), the older star clusters

NGC 3923 (Herbst and Miller 1982), and NGC 2362 (van den Bergh and Sher 1960; Wilner and Lada 1991).

5. Conclusions and Future Work

The foregoing has drawn together a variety of observational and theoretical evidence in an attempt to identify the processes responsible for star formation in different galactic environments. Current theories for the quasi-static subcritical collapse of magnetically supported molecular cores in Bok Globules and dark cloud complexes through ambipolar diffusion appear satisfactory. There is good observational evidence that isolated low mass stars may form in this way. Low mass stars may also form in this way in the more massive molecular cores present in GMCs, but few observations exist which directly address the nature of low mass star formation in these regions. The mechanisms responsible for high mass star formation in GMCs are less well defined. Considerable observational data are available which suggest that the collapse of the Orion A GMC has been more complex than present theories for supercritical collapse suggest.

On the theoretical side, there is a need for a more detailed theory of the formation and supercritical collapse of massive magnetised molecular cores. Why are the cores in GMCs more massive than in dark cloud complexes? Do they form by accretion of surrounding material? Do dark cloud complexes naturally evolve into GMCs by this process? What produced the twisted magnetic field in L1641, and in other cloud 'streamers'? Are they related to the formation of the Orion molecular ridge?

On the observational side, several specific pieces of evidence are needed: A clearer census of molecular core sizes and masses in regions of high mass star formation; a better knowledge of the mass function of stars formed in such regions; and a more detailed study of the spatial and temporal distributions of past star formation in the Orion Nebula Cluster region to help define the collapse history of the Orion molecular ridge.

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