Chapter 5

Conclusions and Discussion

5.1 Introduction

The detailed analysis presented in the previous chapter suggests the following picture for the spatial distribution and the kinematics of the local dark clouds. Figure 5.1 shows the distribution of these clouds derived from Table 4.5 projected onto the plane of the Galaxy. As will be seen, the clouds are distributed in an "annulus" (the projection of a doughnut onto the plane) which is slightly elongated towards 225° longitude. The projected distance of the inner edge of this distribution from the Sun varies from $\sim$ 150 to 250 pc, and the distance to the outer edge varies from $\sim$ 400 to 600 pc, depending upon the longitude. In our opinion the depletion of clouds in the central region is statistically significant. A rough estimate suggests that the "morphological centre" of the population of these clouds is at a distance of $\sim$ 160 pc from the Sun towards 215° longitude. The mean radius of the doughnut from such an assumed morphological center is $\sim$ 400 pc.

In most of the directions the clouds are receding from the morphological centre, and the average expansion velocity with respect to us is $\sim$ 4 $\mathrm{kms^{-1}}$. This would correspond to an "expansion age" $\sim$ 100 Myr. There is also definite evidence for peculiar velocities whose dispersion varies from 2.5 to 5 $\mathrm{kms^{-1}}$ depending upon the longitude.

Having recalled our main conclusions regarding the distribution and kinematics of the local dark clouds, we next turn to a discussion of a possibe connection between this system of expanding clouds and the so called Gould's belt which is an expanding system of young O-B stars. In the next Section we shall briefly describe the only other study we are aware of dealing with the population of local dark clouds and inferences drawn regarding their association with Gould's belt. In Section 5.3 we shall summarize the optical studies pertaining to Gould's belt. Earlier studies have shown that a substantial amount of neutral hydrogen gas may also be associated with this expanding system of stars. The primary conclusions from the studies of HI are summarized in Section 5.4. The next Section is devoted to a comparative discussion between our findings with the conclusions arrived at earlier. In the final Section we shall comment upon some of the earlier speculations regarding the origin of this expanding system of stars and clouds.

5.2 An earlier study of the dark clouds

As mentioned in Chapter 1, the only earlier systematic study of the local dark clouds that we are aware of is that of Taylor et al. (1987). In view of growing evidence for an expanding system of HI clouds associated with the Gould's belt system of stars, Taylor et al. (1987) set out to determine whether a subset of the local dark clouds might be associated with the Gould's belt. With this in mind they obtained the radial velocities towards $\sim$ 650 northern dark clouds of high opacities using the $J = 1 \rightarrow 0$ transition of carbon monoxide. Their analysis differed from ours in the following essential way. They assumed that the population of clouds under study could be decomposed into two distinct distributions: a set of clouds confined to the so called "Gould's belt plane" inclined to the global galactic plane by about $18°$, and the rest confined to the local "galactic plane". Their procedure for separating clouds into two such distinct distributions may be summarized as follows: In a longitude vs. latitude plot each of the assumed distributions will correspond to a sinusoidal distribution since they are confined to planes (The local galactic plane also describes a sinusoid in the above plot due to its local tilt with respect to the global galactic plane). The amplitudes and phases of these two sinusoidal distributions will, of course, be different. By assigning a particular cloud to one or the other plane based upon a simple proximity criterion, and an iterative procedure, they separated the population of local dark clouds into two such groups. It is important to mention in this context that the population distributed around the inclined plane was fairly confined to a thickness of only $\sim$ 30pc (assuming a mean distance to these clouds $\sim$ 400 pc). Having thus separated the clouds into two populations, they arrived at the following conclusions:

1. Although a subset of clouds appear to be confined to a thin slab inclined with respect to the galactic plane, the *inclination did not correspond precisely to that defined by the O-B stars.* Whereas the latter plane is inclined at an angle of $18°$, the former was inclined at an angle of only $12°$.

2. As shown in Figure 5.2 reproduced from the paper of Taylor et al. (1987), the observed radial velocities of the Gould's plane clouds was not fit well by a simple model of galactic differential rotation for an assumed mean distance of 400 pc. From the excess of positive velocities as seen in the figure, *they concluded that the clouds in Gould's plane were in a state of expansion.* (We

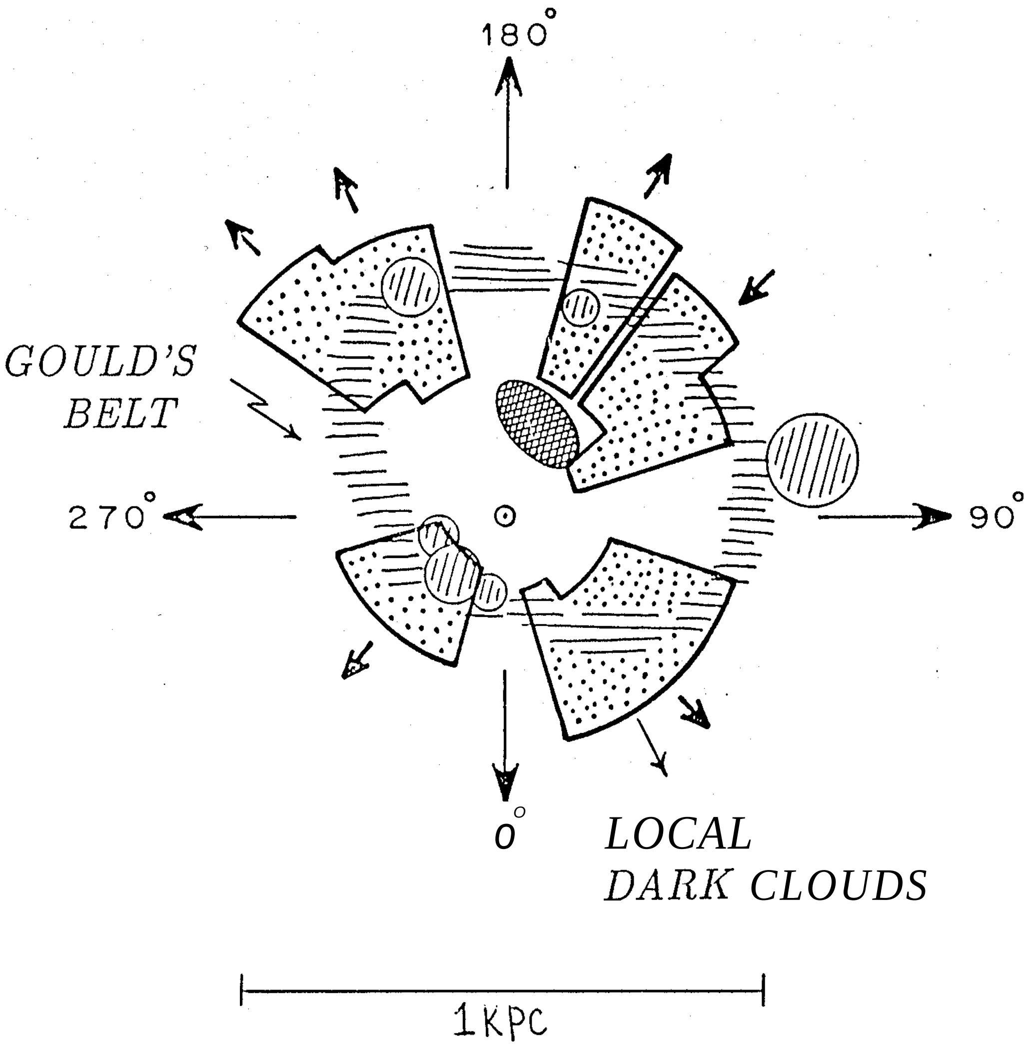


Fig 5.1 : A schematic diagram of the projected spatial distribution of the local dark clouds derived from Table 4.5. The position of the Sun is marked. We have not shown the clouds along the four "null directions" since the distance estimates to them as derived from the analysis described in Section 4.4 are unreliable. The clouds in the longitude range 235° –255'-are at a distance of ~ 1.4 kpc and are presumably unrelated to the local system of expanding clouds; hence they too are not shown. For comparison, Gould's belt has been shown by the hatched oval. Except for clouds in the longitude range 105° – 145° which have predominantly negative (inward) velocities, the rest of the clouds are all receding.

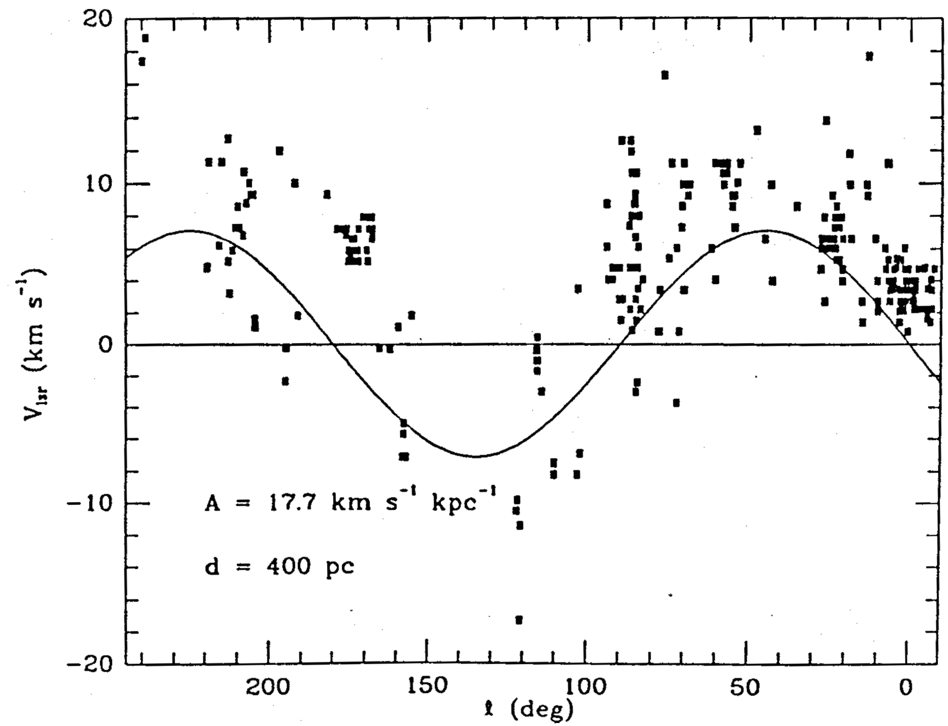


Fig.5.2 : A longitude-velocity plot of the northern dark clouds taken from Taylor et al. (1987). The curve is not a fit but represents the expected behaviour of clouds at 400 pc in pure differential rotation around the centre of the Galaxy. From the excess of positive velocities Taylor et al. concluded that this system of clouds must be expanding. Notice that their data is dominated by clouds in the I quadrant.

would like to remark at this stage that their data is dominated by clouds in the first quadrant.)

3. Taylor et al. (1987) attempted to fit a model of an expanding ring to this subset of clouds, but concluded that no satisfactory fit was possible.

In Section 5.5 we shall return to these tentative conclusions arrived at by them and shall comment upon them in the light of our findings.

5.3 Gould's Belt

As already explained in Chapter 1, Gould's belt is a local system of bright O-B stars that are apparently confined to a plane tilted with respect to the plane of the Galaxy. Oort (1927) while discussing the differential rotation of the Galaxy pointed out that the local system of bright B stars showed a small positive residual velocity of $\sim$ 5 kms^{-1} even after correcting for the effects of the differential rotation. The positive residual was significant even though peculiar velocities were also present. Further progress had to wait till Blaauw's pioneering work on expanding groups (Blaauw, 1956). Bonneau (1964) conclusively sh'owed that there **was** expansion in the local system of bright B stars and derived an expansion age of $\sim$ 40 Myr. From a study of a larger catalogue of the local group of stars which had by then become available, Lesh (1968) concluded that:

1. The system contains both an expanding and a differentially rotating component which are mixed in some unspecified way, and has an overall expansion age of 90 MYr, OR

2. The local associations define the expanding subset, consisting $\sim$ 30% of the local B star population and having an expansion age of 45 MYr. The rest of the sample follows the laws of pure differential rotation.

Subsequently, Stothers and Frogel (1974) demonstrated that the Gould's belt of stars is a statistically significant feature inclined to the galactic plane at an angle of $\sim 19^\circ$. From a larger and more reliable data set, Westin (1985) concluded that the local stars *younger than 20 Myr* define a plane inclined by 19° to the galactic plane, while stars older than 60 Myr were symmetrically distributed about the plane (see Figures 5.3 reproduced from Westin, 1985). He also found that both the *nearby older stars* ($>$ 60 Myr), as well as the young and old stars outside the limits of Gould's belt show the characteristics of pure circular rotation. But the local stars with ages $<$ 20 Myr showed clear expansion which however could not be explained by any simple model (Lindblad and Westin, 1985). The physical extent of the stellar distribution participating in the expansion is $\sim$ 250 pc towards Ophiuchus and $\sim$ 500 pc towards Orion. Along the longitudes 90° and 270° the spatial extent is $\sim$ 500 pc and $\sim$ 700 pc, respectively.

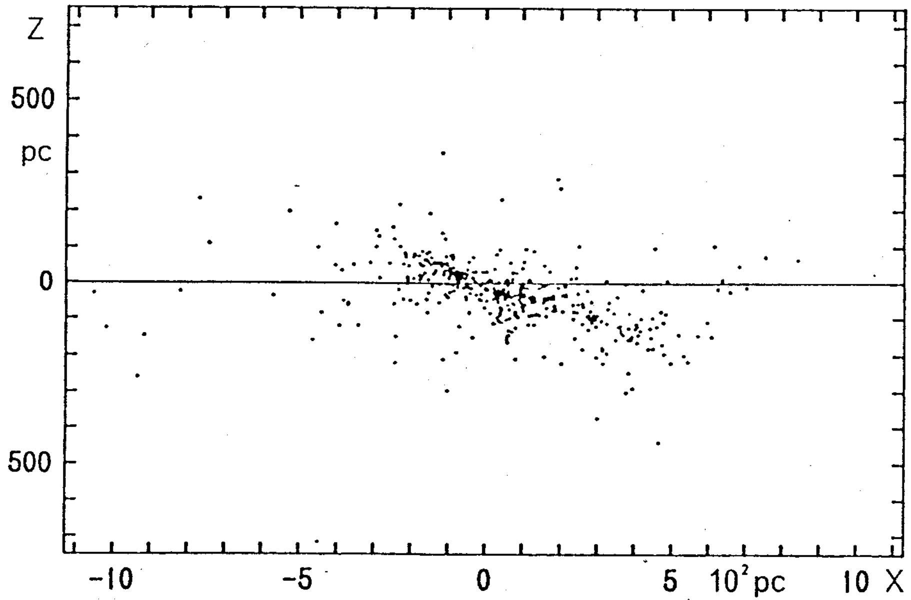


Fig.5.3 : The distribution of stars younger than 30 Myrs projected onto a plane through the galactic centre and the northern galactic pole (from Westin, 1985). There is a clear evidence for these young stars to be arranged in an inclined plane. In contract to this, the distribution of stars older than 60 Myrs does not show this trend but is isotropic.

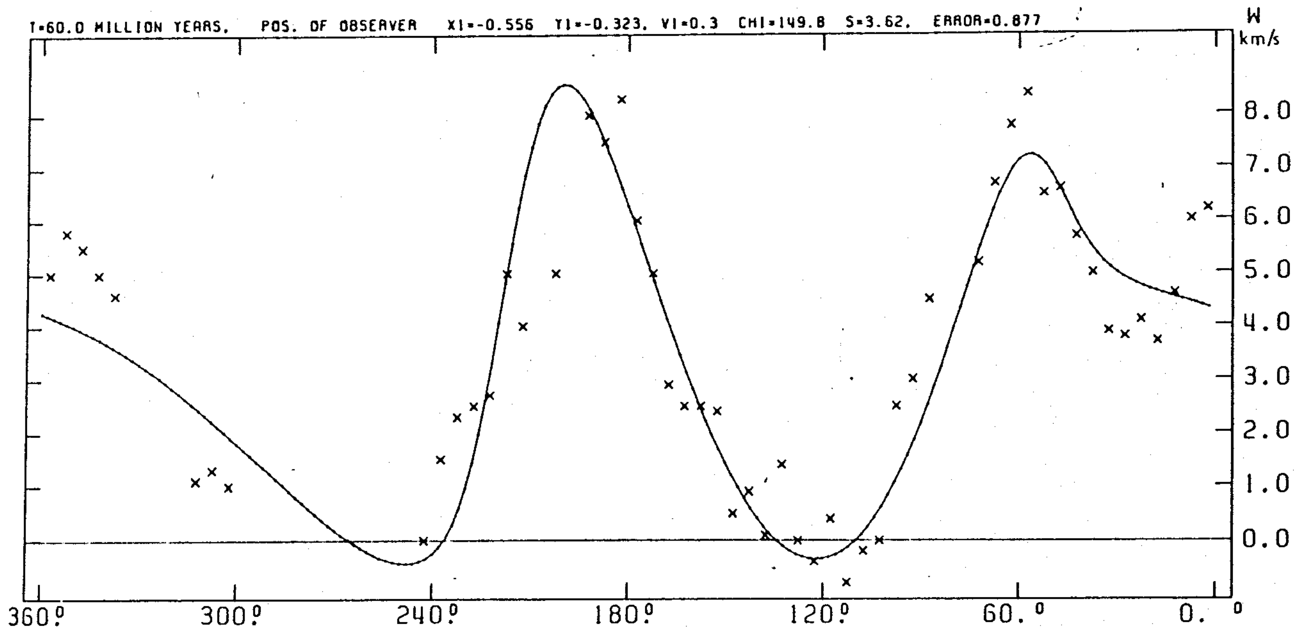


Fig.5.4 : This figure taken from Lindblad et al. (1973) shows the longitude-velocity plot for the local HI gas. The curve represents an expanding ring model advanced by them.

Westin (1985) also investigated the extinction in various longitudes and concluded that the extinction is relatively large in the first two quadrants (except between 60° and 80° longitude), while it is relatively small in the third quadrant particularly for $l > 200^\circ$. The extinction again increases in the fourth quadrant beyond $l > 280^\circ$.

In their recent study Cameron and Torra (1990) confirm the expansion of the local group of stars; their estimated expansion velocity is $\sim$ 5 kms^{-1} and age $\sim$ 70 Myr.

5.4 HI associated with Gould's Belt

The earliest kinematical study of the local HI gas was that of Lindblad (1967). By analysing the optical depth profiles in terms of Gaussian components he identified several "physically connected extended features". Lindblad et al. (1973) fitted a model of an expanding ring sheared and perturbed by the effects of galactic differential rotation to an improved set of HI observations. The parameters of their model were the following: The initial velocity of expansion of the ring, its age and size, the distance of the centre of expansion with respect to us and its longitude, and the components of the LSR velocities of the assumed centre of expansion. They found their model to fit the data quite well. The distance to the centre was $\sim$ 160 pc towards 150° longitude. The major and minor axes of the ring were 650 pc and 310 pc, respectively. An initial velocity of expansion of $\sim$ 3.5 kms^{-1} and an expansion age of $\sim$ 60 Myr were found to fit the data best. Figure 5.4 shows their data and their model fit.

In a later study Olano (1982) included the effects of deceleration of the expanding ring. It was found that the overall conclusions of Lindblad et al.(1973) were still valid with minor modifications. To illustrate the differences compared to the earlier work, Olano's estimate of the expansion age is $\sim$ 30 Myr and the initial expansion velocity could be anywhere from 5 to 20 kms^{-1} depending upon what one assumed for the initial radius of the ring.

5.5 Comparison with earlier studies

In this section we compare our conclusions summarised in section 5.1 with those arrived at by earlier workers and highlight the agreements and disgreements.

5.5.1 Expansion :

Our conclusion that the local population of dark clouds are expanding is in agreement with a similar result arrived at by Taylor et al. (1987) from an earlier but more limited study. These clouds are participating in the same kind of expansion

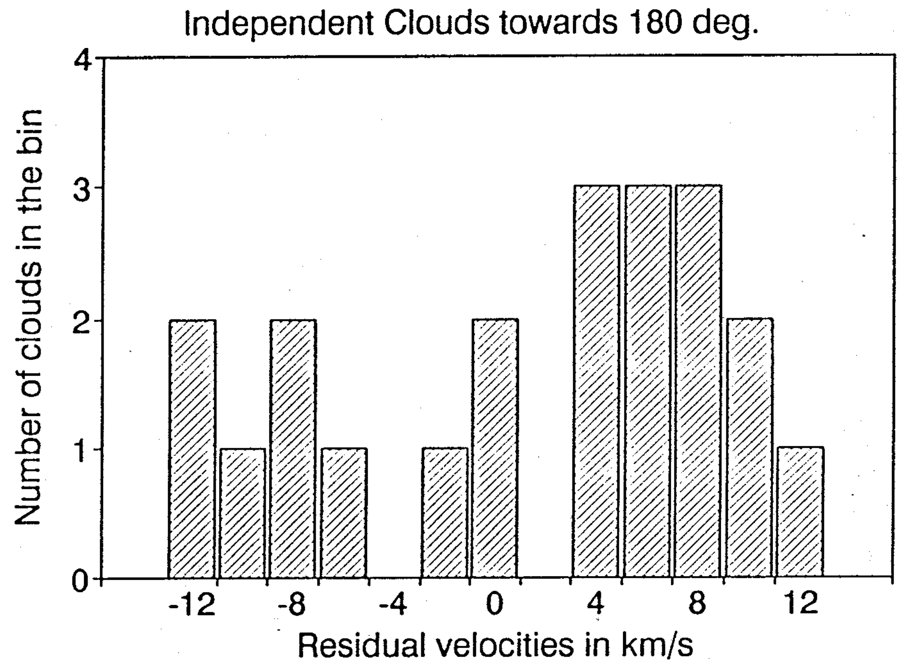


Fig.5.5 : The histogram shows the residual velocities of clouds towards the anticentre direction observed by Stark (1984) after correcting for multiple sampling of the clouds. This was done by requiring that only one cloud occupies a *cell* of dimension 1.5° in longitude as well as latitude, and 2 km/s in velocity. At first sight this histogram would suggest a very large velocity dipersion for the clouds, but in our opinion this distribution may consist of more than one group of clouds. Also, any systematic velocity has to be taken out before deducing the true velocity dispersion.

seen in the local population of O-B stars. The average expansion velocity of $\sim$ 4 kms^{-1} derived by us is also consistent with the estimates from optical studies. However there are some important differences. For example, as we mentioned earlier, optical studies suggest that even within 500 pc it is only stars with ages $<$ 30 Myr that show expansion; the older stars even within this volume appear to be kinematically inactive. *Our study shows that the local molecular clouds cannot be sub-divided into two groups: one of which is expanding and another which is kinematically inactive.* One of our important conclusions viz.that there is a depletion of molecular clouds within a distance of $\simeq$ 150 pc is consistent with this.

5.5.2 Peculiar velocities :

Although the local population of clouds is in a state of expansion, there is clear evidence for peculiar motions as well. The dispersion in the peculiar velocities is $\sim$ 2.5 to 5 kms^{-1}. This is consistent with the mean absolute deviation in the peculiar velocities of the nearby OB stars as derived by Blaauw (1956). He found this quantity to be $\sim$ 2 kms^{-1} perpendicular to the line of sight and $\sim$ 3 kms^{-1} along the radial direction. As we mentioned in the previous chapter, our values for the dispersion in different directions are likely to be a little higher because of contributions due to improper distance corrections.

The velocity dispersion of 2.5 to 5 kms^{-1} estimated by us is *smaller* than the value of 7 to 10 kms^{-1} as derived by Stark (1984) from a study of molecular clouds in the anti-centre direction. Note, however, that our value is based on a much larger sample and distributed in all directions. Also, we have removed systematic non-circular motions before calculating the dispersion. Stark himself has noted that his sample of clouds is likely to be affected by redundancies. Further, we feel that his sample may not be representative of the entire local population of clouds.

In Figure 5.5 we have plotted a histogram of the residual velocities of the clouds discussed by Stark (1984) after correcting for multiple sampling (which was not done in his paper). A glance at the distribution clearly shows that this is not a "randomised" distribution that one would expect for a population of clouds that have come to equilibrium via collisions. In our opinion this is more likely to be due to some systematic motions not removed. In principle this histogram could also be rationalised in terms of two distinct groups of clouds, although we have no way to prove this. At this stage we merely wish to point out that an estimate of "velocity dispersion" derived from this histogram is bound to be an overestimate. The kind of estimate made by Stark is, of course, the relevant one if one wishes to study the overall energy in non-circular cloud motions. Our estimate, by removing systematic motions as far as feasible, would correspond to a local dispersion which would be the relevant parameter for modelling the dynamics of a cloud complex i.e.estimating collisions between subclouds, the need for "heating" mechanisms, etc..

5.5.3 Distribution of the local dark clouds :

In figure 5.1 we have sketched the projected space distribution of the clouds as derived by us. It should be pointed out straight away that the molecular clouds have a much thicker distribution and corresponds more to a **doughnut** shaped distribution rather than a thin ring as conjectured by Lindblad et al., (1973). However, the mean distances to molecular clouds as derived by us is in general agreement with the dimensions as obtained from the HI studies. The "ring-like feature" delineated by the O-B associations is well within the doughnut distribution of molecular clouds as shown in figure 5.1.

The overall distribution given in this figure is also consistent with the extinction data along various longitudes in the solar neighbourhood. For example, it will be seen that between $235°$ and $255°$ longitude most of the dark clouds contained in our sample are at a much greater distance of $\sim$ 1.2 kpc (and therefore not shown in the figure). This is in agreement with the low extinction in this direction as found by Westin (1985) upto large distances (see Section 5.3). The rise of extinction to substantial values even at smaller distances in the first two quadrants is also consistent with smaller values for the inner radius of the doughnut in these quadrants.

While the overall distribution is in accord with the optical and the HI studies, there is an important difference. We do not find any evidence for this expanding system of clouds to define a distinct plane or a slab inclined to the galactic plane. In this regard we disagree with the conclusion drawn by Taylor et al. (1987) that only the clouds in the Gould's belt plane show significant evidence for expansion. As already explained in Section 5.2, they separated the population of the local dark clouds into two distinct groups and argued that the data suggests that it is only the clouds in the Gould's belt that show significant evidence for expansion. The local clouds in the galactic plane showed at best only marginal evidence for expansion. Even this, they felt might be due to a "contamination" of the galactic plane population by the clouds belonging to the Gould's belt in cross-over directions where the separation into two populations is rather difficult.

In our analysis so far we have made no attempt to separate the clouds in this manner. But in order to verify this conjecture by Taylor et al. (1987) we separated our sample of clouds (i.e. both the northern and southern clouds) into two distinct planes or slabs following their prescription. According to Taylor et al. (1987) the Gould's belt plane and the galactic plane as delineated by molecular clouds may be represented by the following latitude-longitude relations:

$$b(\mathrm{Gould}) = -3.5° + 12.5° \sin (l - 275°) \tag{5.1}$$

$$b(\mathrm{Gal}) = 4.5° \sin (l - 43°) \tag{5.2}$$

The longitude-latitude and longitude-velocity plots of clouds separated according to the above criteria are shown in Figure 5.6. Having thus separated the local population of clouds into two subgroups, it turns out that *there are only two sectors* (15" to 35" longitude and 55° to 75° longitude) *with statistically significant number of clouds belonging to each of the two subgroups* (see Table 5.1). We subjected the clouds in the two sectors mentioned above to the same type of analysis outlined in Section 4.4, *but this time keeping the two populations distinct.* The comparison of the simulated cumulative distributions with the observed ones is shown in Figure 5.7, and the resultant best fit parameters are given in Table 5.2. As can be clearly seen, **the two populations i.e. one belonging to Gould's belt plane and the other to the galactic plane show no significant differences in their kinematical behaviour or spatial distribution.** We thus conclude that the clouds in the various longitudes share similar motions regardless of which of the two hypothetical planes they are assigned to.

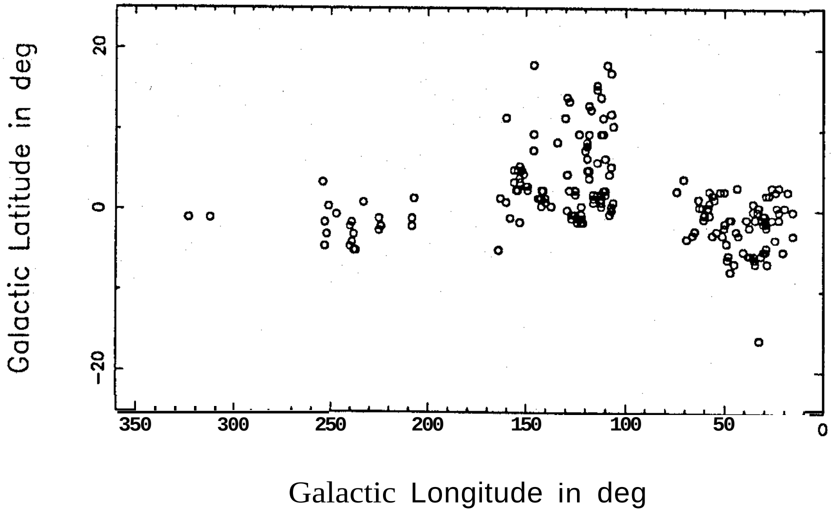
Table 5.1 : Longitude distribution of clouds after segregation into Galactic and Gould's belt populations.

Longitudebins	1	2	3	4	5	6	7	8	9	10
Galacticplane	33	27	19	61	25	33	4	6	16	2
Gould's plane	25	9	18	10	0	8	22	6	0	23

Table 5.2 : The best fit values of the four model parameters for the two directions with sufficently large number of clouds

	15" $\leq l \leq$ 35°				55° $\leq$ 1 $\leq$ 75°			
	V_{exp} kms^{-1}	σ kms^{-1}	R_L pc	R_H pc	V_{exp} kms^{-1}	σ kms^{-1}	R_L pc	R_H pc
Galactic Plane	5.5	2.5	150	350	4.0	4.0	150	400
Gould's Plane	4.0	2.5	200	400	3.5	4.0	200	400

We also wish to make the following additional remark: Even if a set of expanding clouds were initially confined to a thin planar ring inclined with respect to the galactic plane, with the passage of time this distribution will get smeared out and merge with the so called "galactic plane clouds" due to peculiar or random motions. Imagine a ring-like structure of radius ~ 400 pc inclined to the galactic plane at an angle of ~ 15°. For this geometry even the extremities of the ring will be only at ~ 100 pc above or below the plane. Given a random velocity dispersion of ~ 3 to 5 kms^{-1} and a lower limit to the age of the expanding system of ~ 30 Myr, the ring would have got sufficiently smeared out and some of these clouds would have merged with the disk population. In the discussion regarding the smearing out of the Gould's belt so far we have assumed that such a structure is physically realisable and stable. However, creation of such a structure would require a very contrived situation. For example, if it is created initially in the plane it would require the normal component of the mean velocity to have a very specific gradient with opposite polarities at the two extrema. Any deviation from



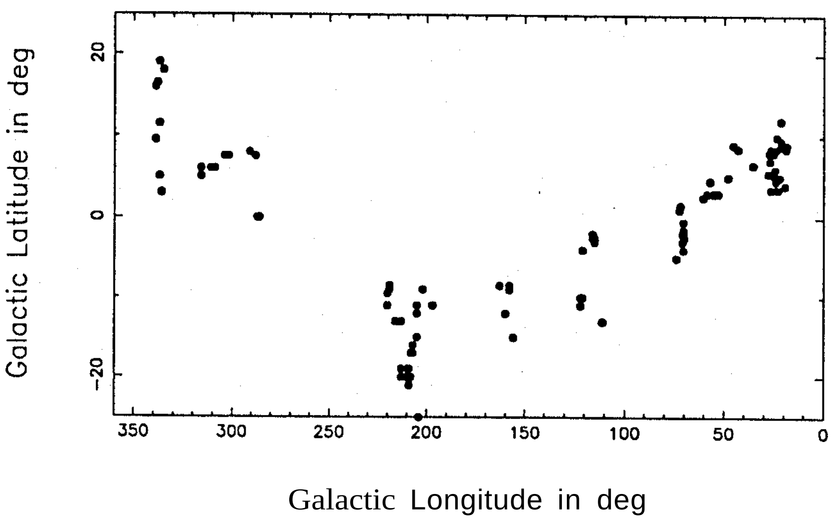
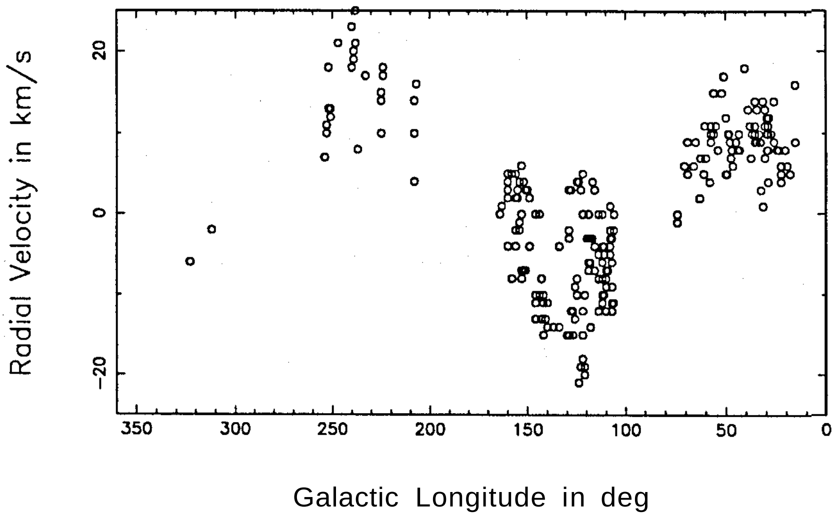
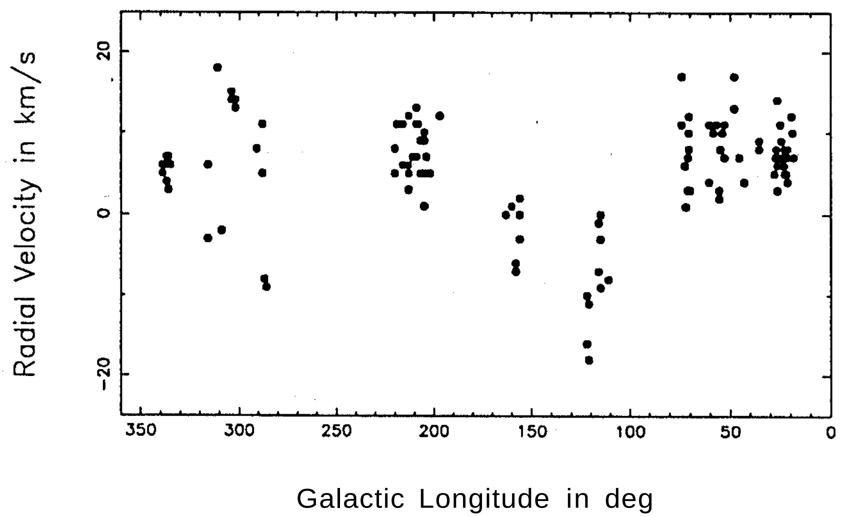


Fig.5.6: Sky distributions of the clouds belonging to the "galactic plane" and the "Gould's belt plane" are shown in (a) and (b) respectively. The population of local clouds have been separated into these two groups following the prescription of Taylor et al. (1987)





• Fig.5.6.c-d : Longitude-velocity plots for the "galactic plane" clouds and the "Gould's belt plane" clouds.

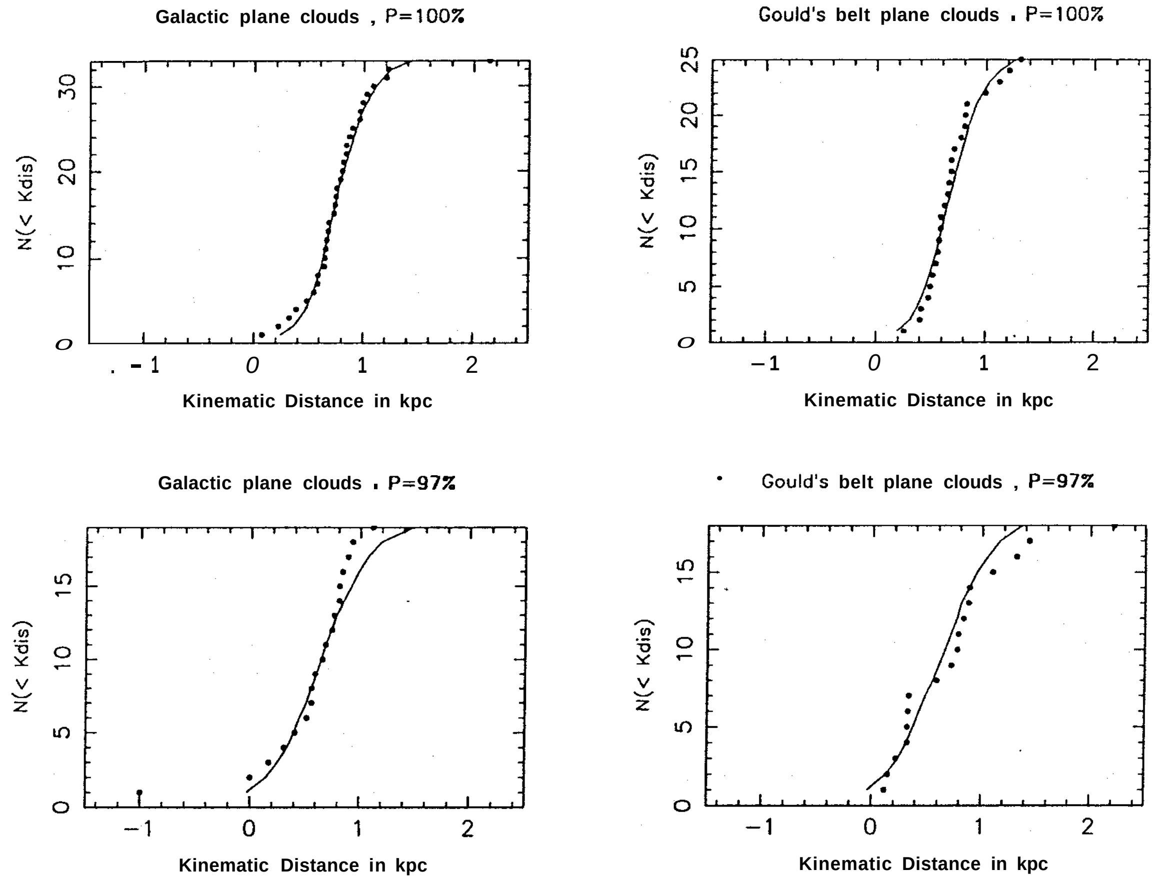


Fig.5.7 : The cumulative distribution of the kinematic distances of the clouds in the longitude ranges 15° – 35" and 55° – 75°. The panels on the left are for the "galactic plane" clouds while those on the right are for the "Gould's belt plane" clouds. Our main conclusion from this is that both the "galactic plane" clouds and the "Gould's belt plane" clouds show evidence for expansion.

this would produce warps and wriggles along the belt as it oscillates in the local galactic potential. This, given the age of 30-45 Myr, would help in obliterating its distinct identity from the disk population. Thus it appears that such a structure with age comparable to the local semi-oscillation period of 30 - 40 Myr, even if found to be present, is likely to be apparent rather than real.

5.5.4 Some dark clouds with "anomalous" motions :

As already mentioned, most of the clouds in the longitude range 100° to 145° are not receding *but coming* towards us. We have no plausible suggestions to make regarding such an apparent streaming motion. It would be worth exploring whether this is due to a velocity reversal induced by some recent stellar explosions or young associations in that region.

Another puzzling feature is the presence of the Taurus molecular clouds near the morphological centre of the expanding population of clouds that we have been considering. Although the radial component of their velocities are positive suggesting that they might be part of the expanding system, their location right near the centre would contradict such an association. A plausible resolution of this dilemma might be the following: The Taurus molecular clouds differ in an important way from the Ophiucus and Orion clouds in that they do not show evidence of one-sided compression such as one would expect from a set of clouds expanding due to a central energy-momentum source. Also, star formation in these clouds is more or less uniformly distributed, again suggesting a difference (Blaauw, 1991). For these reasons, earlier workers have suggested that the Taurus molecular clouds may have migrated to their present location and therefore are not part of the family of expanding clouds. It may also be that these clouds have formed more recently than the expanding system of clouds (Blauuw, 1991).

5.6 Concluding remarks

Having discussed the distribution and the kinematics of the local dark clouds as well as the Gould's belt system of stars, we now turn to a discussion of the possible origin of these systems and their interconnection. The two basic facts that need to be explained are the expansion of the system of stars as well as the clouds, and their presently observed morphology.

Energy, Momentum and the *Origin* of expansion: The suggestions that have been made in the literature regarding the source of the energy and momentum responsible for the expansion fall into two categories: according to one hypothesis (see Blaauw, 1991 for a review), the observed expansion could be understood in terms of the continued action of the ionising radiation, stellar wind and supernovae from massive stars belonging to the Cas – Tau association located close to the morphological centre of the system. The one-sided star formation in the three major nearby cloud complexes Orion, Sco-Cen and Perseus is consistent with this idea. But the "inclination" of the Gould belt system of bright B stars is harder to explain in this picture. An alternative hypothesis due to Franco et al. (1988) is that the observed ring-like structure might be understood in terms of the impact of a high-velocity cloud with the galactic disk and the resultant "splash" (Elmegreen, 1991). While such an exotic mechanism might explain the location of some of the nearby big molecular cloud complexes (such as Orion) at substantial distances from the galactic plane it is difficult to understand the observed expansion in this picture. In view of this, in the discussion to follow we will assume that the $Cas-Tau$ association is the more likely "central engine" which has powered the expansion. Similar expanding systems of clouds with young associations located in the interior – such as the systems of cometary globules and clouds found in Orion, Vela, and Rosette regions (Bally et al. 1991, T.K.Sridharan 1992, Patel et al. 1993) - lend credibility to this idea. We shall now make simple estimates for the energy and momentum that each of these processes can contribute to see if they can meet the requirements.

The local dark clouds are found to have an average ^{13}CO column density of $\sim$ 60 x 10^{14} cm^{-2} (Section 3.4). Using a $N_{13_{CO}}$ to N_{H_2} conversion factor of 5 x 10^5 (Dickman, 1978) and assuming a mean molecular hydrogen volume density of 500 cm^{-3} the estimated average sizes and masses of the clouds are $\sim$ 2 pc and $600M_\odot$, respectively. We estimate that there are $\sim$ 300 such clouds in the first two quadrants alone. Thus the total mass of these clouds would be $\geq 2 \times 10^5 M_\odot$. For an average expansion velocity of $\sim$ 4 kms^{-1} the total energy and momentum of the expanding system of molecular clouds would be $\sim 10^{50}$ ergs and 2 x 10^{44} gm cm/s, respectively. Blaauw (1991) has estimated that $\sim$ 15 OB stars would have evaporated from $Cas-Tau$ in its lifetime ($\sim$ 45 Myrs). The combined effect of 10-15 such early type stars for a period of $\sim$ 10 Myr can easily supply the required energy.

Accounting for the momentum appears to be more difficult. In principle, there are three mechanisms that can supply energy and momentum to the clouds: (1) supernovae, (2) stellar winds, and (3) the rocket effect (Oort and Spitzer, 1955). We shall now make simple estimates for the energy and momentum that each of these processes can contribute to see if they can meet the requirements. In the following estimates we assume that the initial solid angle Ω_c subtended by the clouds which were originally located close to the $Cas-Tau$ group and eventually pushed away was $\sim$ 1 steradian which is quite realistic.

Supernova explosions: If E_{SNE} is the mechanical energy released in a supernova and M_{ej} the ejected mass, then the energy and momentum intercepted by the clouds per supernova are given by

$$E = E_{SNE}\left(\frac{\Omega_c}{4\pi}\right) \sim 4 \times 10^{50}\left(\frac{4_{SNE}}{5 \times 10^{51}}\right)\Omega_c \text{ ergs}$$

$$P = \sqrt{2M_{ej}E_{SNE}} \left(\frac{\Omega_c}{4\pi}\right) \sim 10^{42} \left(\frac{E_{SNE}}{5\times 10^{51}}\right)^{0.5} \left(\frac{M_{ej}}{10M_\odot}\right)^{0.5} \Omega_c \text{ gm cms}^{-1}$$

Thus, although the required kinetic energy can be easily supplied by 10 supernovae, the intercepted momentum is only $\sim 10^{43}$ gm cms^{-1}, an order of magnitude smaller than that required (if our estimate of the total mass is correct).

Stellar winds: Stellar winds may also be unable to impart the required momentum. Let V_∞ and $\dot{M}$ be the mean terminal wind velocity and the mass loss rate, respectively, of the early type stars that have evaporated. The energy and momentum intercepted by the clouds from the wind from a single star over a period τ would be,

$$\begin{aligned} E &= \frac{1}{2}\dot{M}V_\infty^2\tau\left(\frac{\Omega_c}{4\pi}\right) \\ &\sim 1.6\times 10^{49}\left(\frac{\dot{M}}{5\times 10^{-6}M_\odot \text{ yr}^{-1}}\right)\left(\frac{V_\infty}{2000 \text{ kms}^{-1}}\right)^2\left(\frac{\tau}{10^6 \text{ yr}}\right)\Omega_c \text{ ergs} \\ P &= \dot{M}V_\infty\tau\left(\frac{\Omega_c}{4\pi}\right) \\ &\sim 1.6\times 10^{41}\left(\frac{\dot{M}}{5\times 10^{-6}M_\odot \text{ yr}^{-1}}\right)\left(\frac{V_\infty}{2000 \text{ kms}^{-1}}\right)\left(\frac{\tau}{10^6 \text{ yr}}\right)\Omega_c \text{ gm cms}^{-1} \end{aligned}$$

Thus, for the typical values (indicated in the denominators) and over a period of 10 Myrs, the net energy released by, say, 10 stars far exceeds the requirement, but one will still fall short of the momentum of the expanding clouds by roughly an order of magnitude.

The Rocket Effect: When a neutral gas cloud is exposed to the ionising radiation from a star, an ionisation front will be driven into the cloud. The ionised hydrogen produced on the side of the cloud facing the star is at a much higher pressure than the gas outside because of the higher density. Hence this gas expands producing a recoil on the cloud and thus accelerating it away from the star. This process known as the *rocket effect* (Oort and Spitzer, 1955) can accelerate interstellar clouds to high velocities. However in the process it leads to the ablation of a significant part of the cloud, as well. In fact, the sound velocity in the ionised expanding dense gas is ~ 15 kms^{-1}, and to accelerate a cloud to this velocity half of its initial mass has to be ionised and ablated. But this process can supply the required momentum. It is conceivable that this gas after recombination is now seen as the expanding HI ring.

To summarize, the combined effect of the three processes discussed above can, in principle, supply the required momenum with the *rocket effect* likely to be the most efficient.

Morphology and Kinematics: There have been two distinct suggestions regarding the origin of the observed clouds and the OB associations:

(a) The clouds were formed due to gravitational collapse of an expanding ring of gas set in motion by the central activity.

(b) The clouds existed close to the center of activity and they were pushed by an expanding ring of gas resulting from the activity at the center.

In both these scenarios the observed OB associations are to be understood in terms of induced star formation. But there are difficulties with both these scenarios. For example, scenario (b) is inconsistent with the fact that the molecular clouds and associations are located *outside* the expanding *HI* ring. One would have expected the clouds to have lagged behind the expanding ring which set them in motion. From a kinematical point of view neither of the scenarios mentioned above are able to provide a satisfactory explanation for the observed radial velocities. As already remarked, Taylor et al. (1987) had concluded from their analysis that an expanding ring model does not fit the observed radial velocities of the northern dark clouds. Our analysis of the combined data of both the northern and southern clouds confirms this. The longitude-radial velocity plot (Figure 4.1) clearly shows a double sinewave behaviour characteristic of galactic differential rotation. Of course, there is a scatter which we have attributed to the distribution of clouds having finite radial thickness and also peculiar velocities. That the local dark clouds may be expanding and that their motions may be dominated by galactic differential rotation was already pointed out by Frogel and Stothers (1977); they, too, had noticed a double sinewave signature in the radial velocities available in the literature. To summarize, although the local dark clouds clearly show an expansion of $\sim 4\ kms^{-1}$, galactic differential rotation effects seem to dominate. This is at variance with the conclusion arrived at by Lindblad et al. (1973). According to them, the HI data is reasonably well explained by an expanding ring of gas sheared by galactic rotation effects, i.e. galactic rotation does not dominate the kinematics. In the following we shall focus our attention on the conclusion drawn from our study of the dark clouds.

If we were to accept the conclusion that the galactic differential rotation effects dominate the kinematics of the local dark clouds, then it is quite clear that cloud-cloud encounters must be an important ingredient of any scenario. To conclude this chapter we wish to advance the following suggestion. Let us consider a giant molecular cloud in which the Cas $-$ *Tau* group of stars formed. Due to stellar winds and ultraviolet radiation from the massive stars as well as supernova activity, the parent cloud would have fragmented: the denser fragments would have been accelerated through, say, the *rocket effect* (Oort and Spitzer, 1955), and in the more diffuse regions the molecular gas would have been dissociated and perhaps even ionised. Due to the continuing action of the stellar winds from the association a large cavity would have been excavated with the more diffuse gas swept into an expanding shell. As the local dark clouds in the vicinity were overtaken by this expanding shell of swept up gas they too would have been set in motion due to the combined effect of the Cas – Tau group of stars and also possibly due to the interaction between the expanding shell of gas and the dark clouds. It is entirely conceivable that during the subsequent 30 to 40 Myr the systematic motions of these clouds could have been degraded through collisions with other clouds in the surrounding interstellar medium. Provided these collisions are sufficient in number, one would expect that the galactic differential rotational effects would eventually become more important than expansion.

We present a simple estimate to support this conjecture. Let us assume that due to the combined effects of ultraviolet radiation and stellar winds a certain number of clouds are accelerated to a velocity of, say, $\sim$ 20 kms^{-1} which is comparable to the sound speed in the ionised front of the clouds (Spitzer, 1978). Let M_1 be the combined mass of these clouds and M_2 be the total mass of the interstellar clouds to which they have imparted energy and momentum. Thus $M_1 + M_2$ will be the mass of the clouds in the doughnut shaped configuration expanding radially with a velocity of $\sim$ 4 kms^{-1}.

Momentum conservation requires $(M_1 + M_2)\ V_2 = M_1\ V_1$. For the assumed values of $V_1 \sim 20\ \mathrm{kms}^{-1}$, $V_2 \sim 4\ \mathrm{kms}^{-1}$, this implies that $M_2/M_1 \sim 4$. An inspection of Figure 5.1 displaying our derived distribution of the system of expanding clouds shows that the ratio of the projected area of the annulus to that of the centrally depleted region is $\sim$ 5 to 6. Thus the expectation that a certain number of clouds initially accelerated by the Cas – Tau group of stars could have imparted radial motions to the remaining clouds is consistent with our derived distribution. Or to put it differently it is not too difficult to account for the energy and momentum of the system of clouds.

A more arguable point is the following: Does one expect a sufficient number of cloud-cloud collisions to have taken place during the last 30 Myr or so to erase the initial signature of uniform expansion from a common centre? In order for this to be true the effective cross section for cloud-cloud collisions must be greater than a minimum value given by $\sigma_{min} \sim \frac{a^3}{Vt}$. Here a is the mean separation between the clouds, V the relative velocity and t the age of the system. From the geometry of the distribution of clouds given in Figure 5.1 and the total number of clouds in the sample we estimate the mean separation to be $\sim$ 60 pc. For an assumed value of V $\sim$ 20 kms^{-1} and t $\sim$ 30 Myr, the effective cross section must be $\geq$ 225 pc^2 in order for collisions to be important. In other words, the "effective sizes" of the clouds must be $\sim$ 15 pc. Interestingly this is only 3 to 5 times the mean sizes of the clouds. Thus the importance of cloud-cloud collisions cannot a *priori* be ruled out (see Elmegreen, 1987 for a relevant discussion). **A** detailed investigation of this important and interesting question may be very worthwhile but is beyond the scope of this thesis. We merely wish to point out the difficulty in understanding the kinematics of the local dark clouds without invoking cloud-cloud collision.

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Chapter 6

The Lynd's Cloud L1616

6.1 Introduction

In chapter 3 we presented some average physical properties of the local dark clouds and attributed the narrow structures seen in the longitude versus kinetic temperature plot to local heating by the OB associations such as *Orion* and *Sco* – *Cen*. In the subsequent two chapters we analysed in detail the kinematics of the local dark clouds and concluded that their non-circular motion may be due to the activity of massive stars associated with the *Cas* – *Tau* group in the past. In this scenario the young OB associations located along Gould's belt are to be understood as *secondary stars* formed due to external triggering. There are several examples of shells and supershells in our Galaxy, as well as in the Large Magellanic Cloud, which are low density regions surrounded by clouds in which there is active star formation. Massive stars also influence the structure and evolution of clouds in their neighbourhood. Globules and clouds with bright rims and cometary appearance are found in the vicinity of nearby OB associations: Vela (Gum nebula), Orion, Cepheus and Rosette. These stars also accelerate the globules, as well as induce low mass star formation in them (Bally 1991, Sridharan 1992, Indrani and Sridharan 1994, Patel 1993). et al.

There are many clouds in the Orion complex which show evidence of being affected by the nearby stars. Lynd's dark cloud L1616 is one such cloud. This cloud has an associated reflection nebula NGC 1788, also known as CED 040. This is the 1788th entry in the New General Catalog compiled by Dreyer (1888) who has described this nebula to be *"bright, considerably large, round, brighter in the middle excited by three stars with one of them having an apparent magnitude of* ~ 10." This is both a comprehensive and succinct description of the nebula. This nebula is also the 40th entry in the catalogue of Cederblad (1946). Visible reflection nebulae result from close spatial association of relatively dense interstellar clouds

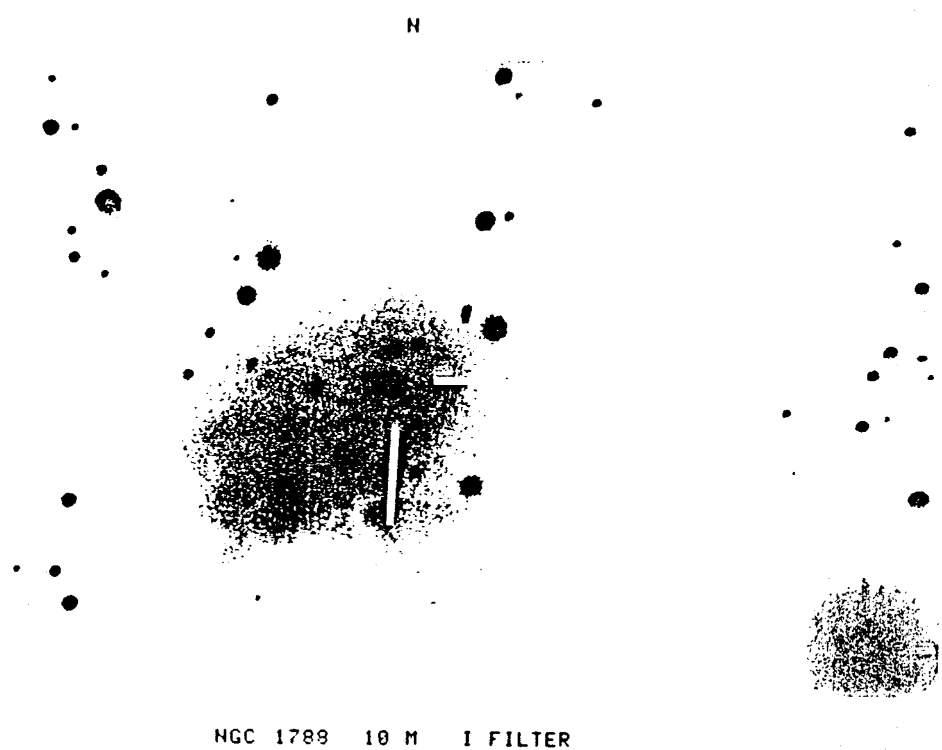

FIG. 3a

FIG. 3.—(a) Same as Fig. 1a, but for NGC 1788. (b) Same as Fig. 1b, but for HD 293815.

WITT AND SCHILD (see page 845)

Fig 6.1: Photocopy of Plate 62 from Witt and Schild (1986) showing an I band image of NGC 1788. The size of the field is 12'× 7' with North up and East to the left. The white bars indicate the location of HD293815, a B9V spectral type star. The nebula is nearly elliptical with the major axis at a position angle of 135°. The lengths of the major and minor axes are 3.7' and 2.1', respectively.

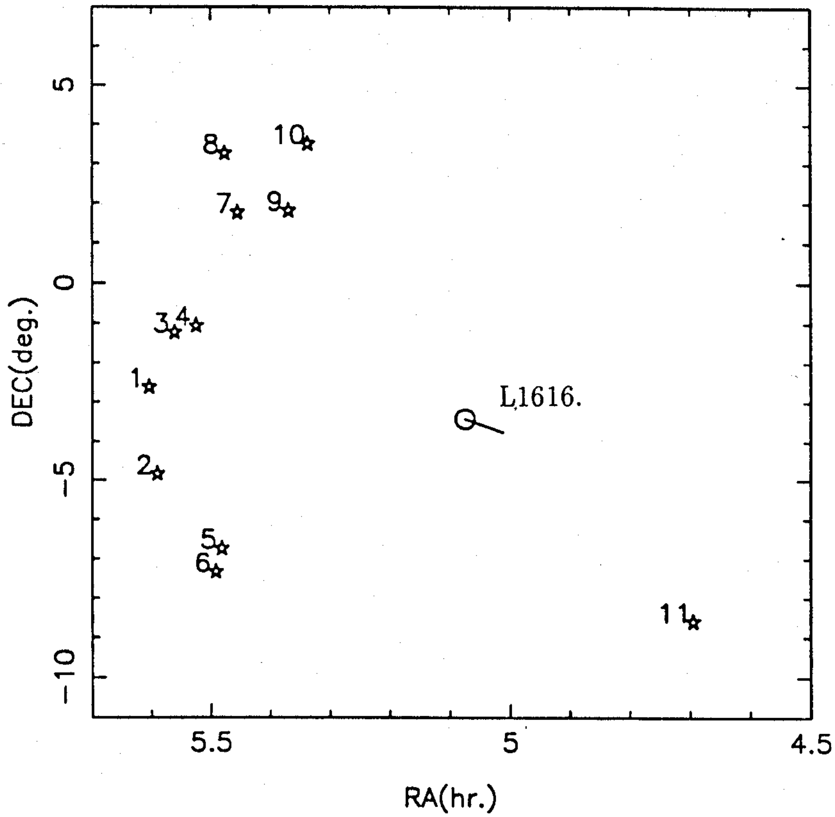

Fig. 6.2 : Cloud L1616 with a tadpole indicating its cometary tail and some bright Orion stars. Table 6.1 gives the details of the stars. The tail when extended points to a B0Ia spectral type star, ϵ Orionis. Star 4 is both less luminous as well as farther away as can be seen from the Table. It is argued in the text that the progenitor of ϵ Orionis is likely to be responsible for both the morphology of and the efficient star formation in the cloud L1616.

with luminous stars of spectral type B1 or later. This enables one to estimate the distance to the cloud from a determination of the distance to the exciting star (as described in section 4.3.1). The distance to L1616 cloud has been estimated by Racine (1968) to be ∼ 420 pc. Since the latitude of the cloud is $-25°$, its distance from the galactic plane is ∼ 180 pc. We will now argue that the stars in the cluster are likely to be of *third generation.*

Witt and Schild (1986) have measured the suface brightness of NGC 1788 in B,V,R and I photometric bands with a CCD detector and arrived at the following conclusions :

1. Such bright nebulae arise in moderately dense clouds with the stars embedded at an optical depth level of ∼ 1 and with dust of high albedo (– 0.7) and with strong forward scattering.
2. They must arise under almost optimal scattering conditions, which apparently are found when newly formed low mass clusters are still embedded in the parent material.
3. A poor cluster illuminates the nebula NGC 1788. One of the stars in the cluster is a B9V spectral type star HD 293815. The cluster however seems to lack faint stars.

Figure 6.1 is a photocopy of their plate 62. The plate size is 12' by 7' with North up and East to the left. As will be seen, the nebula has a nearly elliptical shape with the major axis having a position angle of 135° in this I-band image. The major axis is ∼ 3.4' and the minor axis is ∼ 2.1'. Figure 6.2 presents a wide angle view of the portion of the sky around the cloud L1616 with the bright early B type stars in the Orion region also marked. The details of the stars are given in Table 6.1.

Table 6.1 : Luminous stars near the cloud L1616

Index	SAO #	Dist. pc.	SpT	RA Hrs.	DEC Deg.
1	132406	500	O9.5V	5 36 14	–2 37 39
2	132387	540	B1.5V	5 35 25	–4 50 32
3	132346	370	B0Ia	5 33 41	–1 13 56
4	132269	560	B2V	5 31 31	–1 04 07
5	132210	550	B2V	5 28 55	–6 44 41
6	132222	560	BOV	5 29 31	–7 20 13
7	112830	560	B1.5V	5 27 19	$1 45 05
8	112861	470	B1.5V	5 28 37	$3 15 21
9	112734	490	B1V	5 22 09	$1 48 08
10	112697	470	B1V	5 20 12	$3 29 52
11	131451	460	B2V	4 41 41	–8 35 44
	L1616	420	Cloud	5 04 30	–3 25 00
			Tail	5 03 45	–3 29 00

NGC 1788, the nebula associated with L1616, has been detected by the IRAS survey and has been catalogued as an extended source, X0504-034. The detected fluxes of this source at 12, 25, 60 and 100 micron bands, respectively, are 30, 68, 323 and 594 Jy. Following Margulis et al. (1989), the IR luminosity of the source is given by

$$\begin{aligned} L_{IRAS} &= 4\pi d^2 \int S_\nu \, d\nu \\ &= 1.9\,(0.677\, S_{12} + 0.384\, S_{25} + 0.104\, S_{60} + 0.040\, S_{100})\; L_\odot = 197 L_\odot \end{aligned}$$

where a distance d = 420 pc to the nebula has been assumed. Since the flux densities are increasing with wavelength, a substantial fraction of the bolometric luminosity may be emitted at wavelengths longer than 100 μm. We estimate this bolometric correction dL to the luminosity by assuming that the maximum observed flux is also the maximum over the entire spectrum, and that the spectrum is like that of a blackbody for wavelengths longer than λ_{max} (100μm), the wavelength at which the flux density is maximum. Then, following Bhatt 1993, dL can be written as,

$$dL = 5.33 \times 10^{-5} \left(\frac{d}{pc}\right)^2 \left(\frac{S_{\nu_{max}}/Jy}{\lambda_{max}/\mu m}\right) L_\odot \tag{6.1}$$

Thus the bolometric luminosity $L_{BOL} = L_{IR} + dL = 253 L_\odot$. If one assumes that 30% of the radiation emitted by the stars is absorbed by the dust (albedo = 0.7) and re-radiated in the infrared (which is likely to be so because the emission increases longward) the net luminosity of the exciting stars must be $\gtrsim$ 845 $L_\odot$. The typical mass and luminosity of a B9V spectral type star are $\sim$ 4.0 $M_\odot$ and $\sim$ 130 $L_\odot$, respectively (Allen, 1976). Thus at least six stars of B9V spectral type star are required to account for the emission. This would imply that the total estimated mass in the stars is $\sim 24 M_\odot$. We discard the possibility of the chance proximity of the cluster and the molecular cloud. The stars are most likely to have been born there. The high albedo of dust in the cloud (Witt and Schild, 1986) and the location of the cluster within the cloud implies that the stars must have been formed recently.

The optical size of the cloud is $\sim 15'$, and the distance estimated using the stars exciting the reflection nebula is $\sim$ 420 pc. This implies a physical size $\sim$ 2 pc. If the average density is taken to be $\sim$ 500 cm^{-3} (typical of small molecular clouds like L1616), the estimated mass is $\sim$ 100 $M_\odot$ and the star formation efficiency is $\sim$ 24% which is much higher than the average. Further, The stars are located close to the edge of the cloud on the side facing the Orion OB association suggesting external triggering. Also, no IRAS young stellar object is found to be associated with the cloud. This may suggest that the formation of the star cluster has pre-empted any further star formation, a self regulatory process often invoked in the literature.

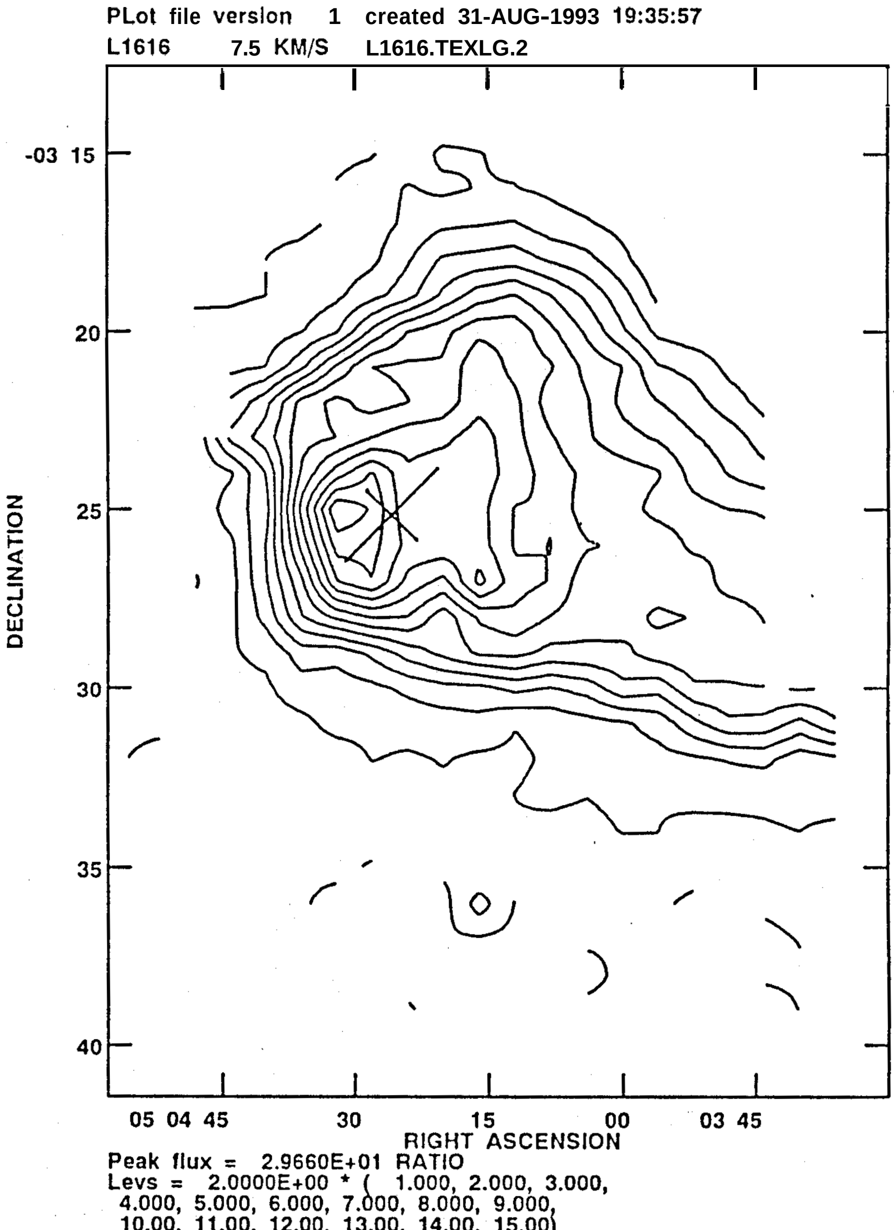

Fig **6.3:** The distribution of ^{12}CO excitation temperature in L1616. The major and minor axes of the elliptical I band image of NGC 1788 are also shown. The peak contour level is 30 K and the spacing is 2 K.

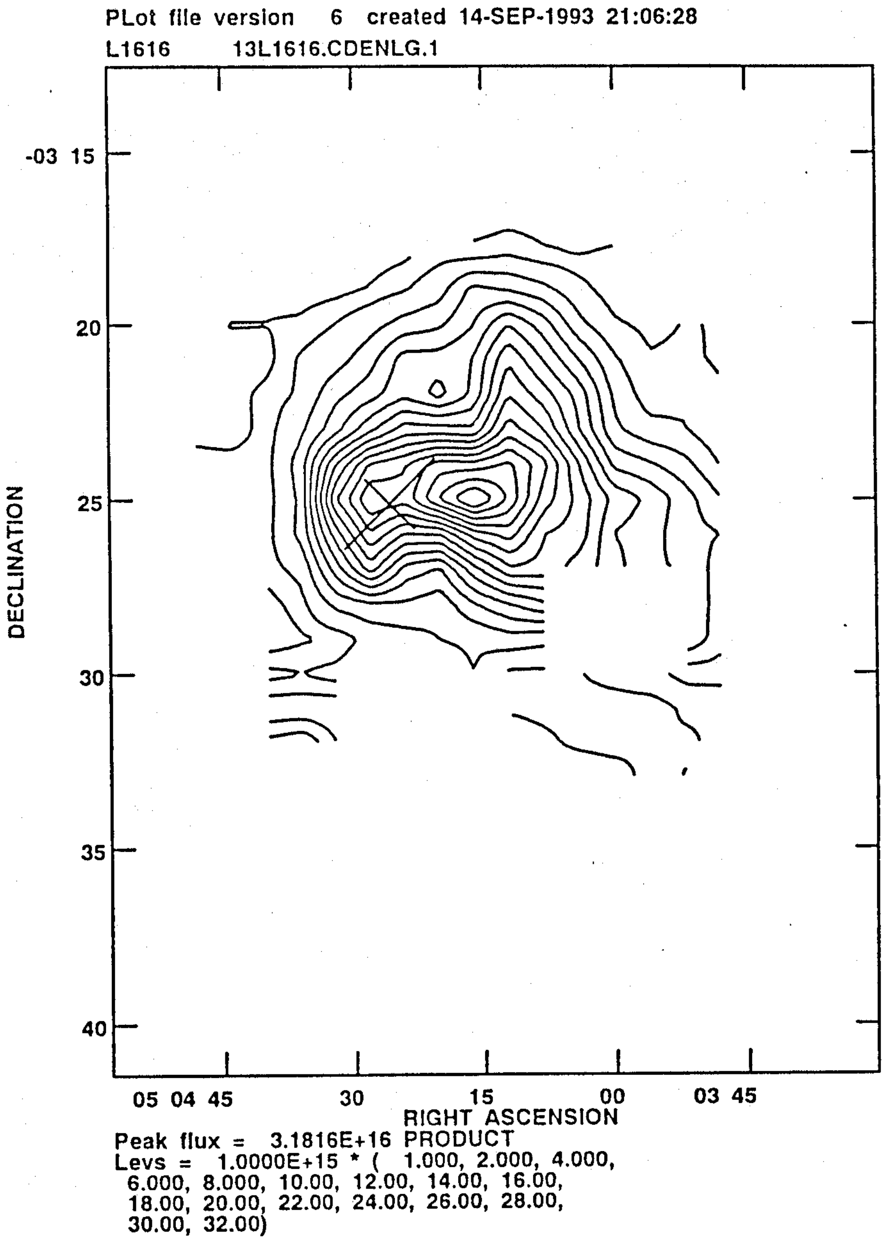

Fig 6.4: ^{13}CO column density distribution in L1616 with the major and minor axes of the elliptical I band image of NGC 1788. The peak contour level is 320×10^{14} cm^{-2} and the spacing is 20×10^{14} cm^{-2}.

We felt that a better determination of the cloud mass and the distributions of temperature, density and velocity from maps of the cloud in the $J = 1 \rightarrow 0$ transitions of ^{12}CO and ^{13}CO may enable one to further clarify if external triggering is responsible for the formation of the cluster. Also, a study of such a cloud which has recently formed at least one intermediate mass star is of interest because one will be able to investigate the heating and cooling in a cloud where there is an identifiable dominant energy source (but not as disruptive as one or more O stars) and the effects of such a heating on the molecular cloud, especially with regard to its fragmentation. Towards this end we mapped the cloud L1616 in both ^{12}CO and ^{13}CO. While we will not be attempting a detailed analysis of the data obtained, we do wish to present the maps of the various derived quantities commenting on them briefly. In the maps presented in the following sections, we have also shown the ellipse enclosing the I band image of Witt and Schild (1986). It is centered at the position of the IRAS source with RA $= 5^h\ 4^m\ 25.8^s$ and $DEC = -03°\ 25'5''$ and oriented $45°$ with respect to the West. We will hereafter refer to this position as the 'centre'.

6.2 Excitation Temperature Distribution

In section 3.2 the expression relating the antenna temperature and the excitation temperature (equation 3.1) was given. As already discussed, the ^{12}CO excitation temperature is very nearly the kinetic temperature of the gas. In figure 6.3 a contour plot shows the distribution of the kinetic temperature in L1616 derived from the measured antenna temperature. It will be seen that the temperature peak occurs at a position offset by 1' to the east of the centre. This translates to a linear distance $\sim$ 0.12 pc. The sharp rise in the temperature on the eastern side is due to the cluster being at the eastern part of the molecular cloud. However, the temperature distribution is more or less centered on the nebula indicating that the radiation from the stars is the dominant energy source. The peak temperature is $\sim$ 30 K and the average is $\sim$ 16 K.

6.3 Density Distribution

The ^{13}CO column density can be derived from the ^{12}CO and ^{13}CO spectra using standard equations of radiative transfer and assuming that they have the same excitation temperatures. We have derived the ^{13}CO column densities in L1616 using the relevant expression given in section 3.4. and have shown the contour plot in figure 6.4 As will be noticed, there is considerable difference between the temperature and column density distribution. First of all, the ^{13}CO column density peak occurs to the West of the center by $\sim 3'$ (which corresponds to $\sim$ 0.36 pc). Secondly, there is a "*shoulder*" in the distribution that coincides with

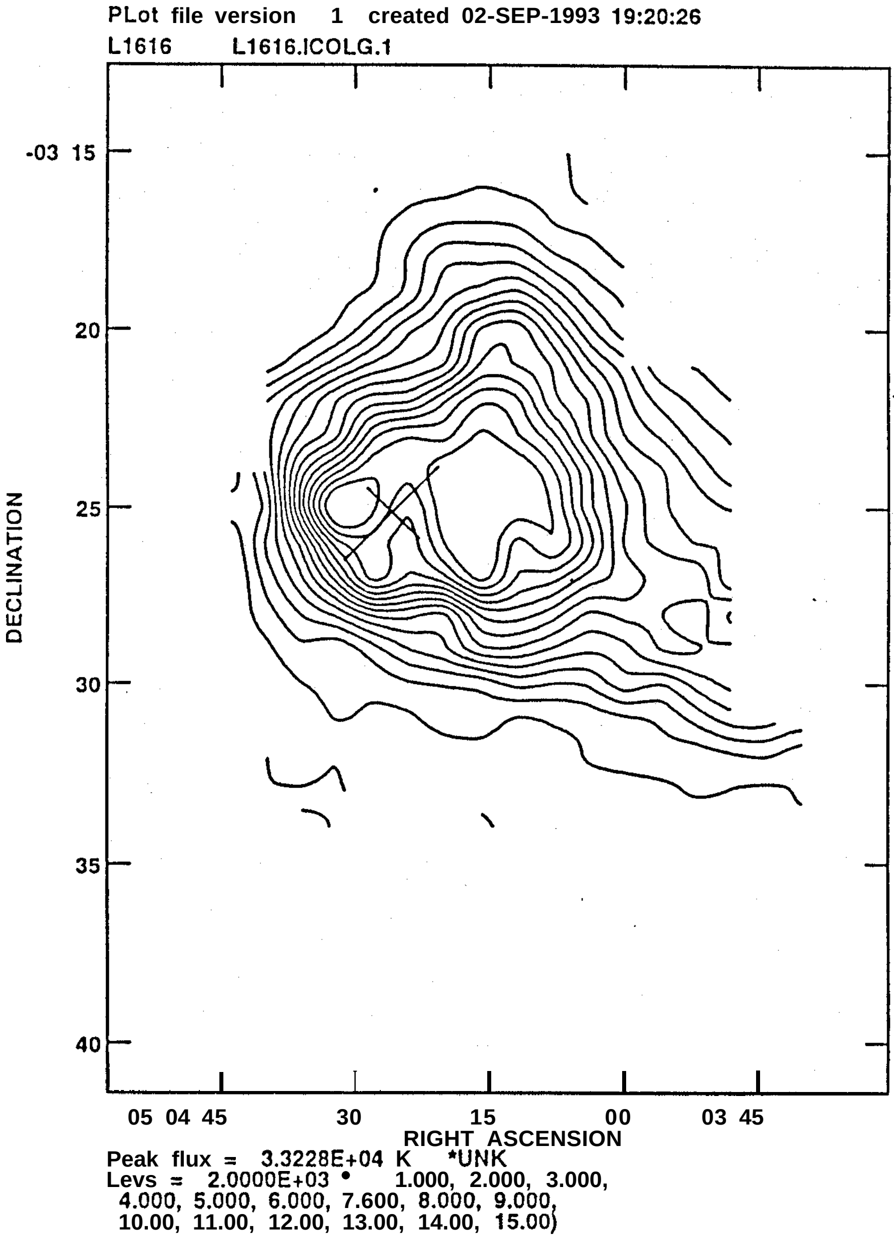

Fig 6.5: Integrated ^{12}CO line intensity distribution in L1616. The major and minor axes of the elliptical I band image of NGC 1788 are again shown. The peak value is 33 $Kkms^{-1}$ and the spacing is 2 $Kkms^{-1}$.

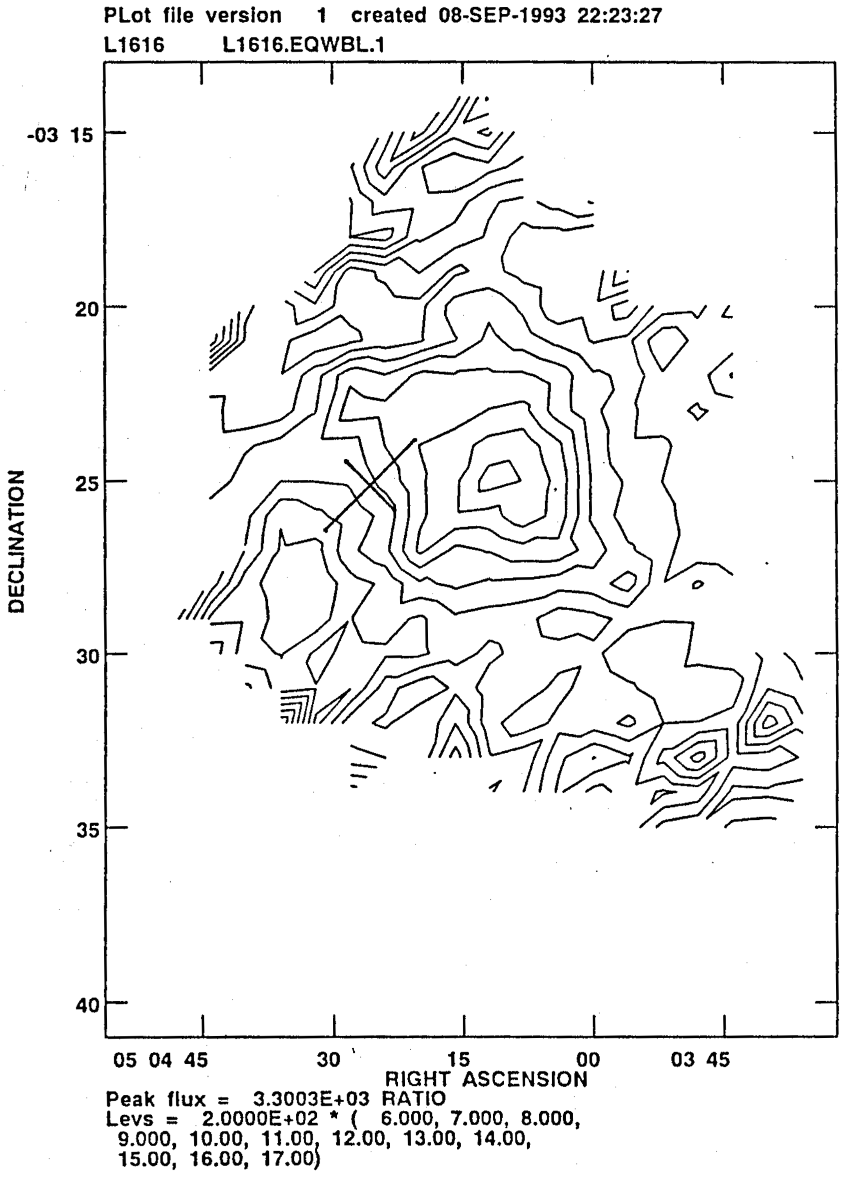

Fig 6.6: The line-width distribution in L1616 with the major and minor axes of the elliptical I band image of NGC 1788. The peak contour level is **3.3** kms^{-1} and the spacing is 0.2 kms^{-1}. The minimum contour level is 1.2 kms^{-1}.

the temperature peak. The star in the southeast portion of the nebula is close to this position. Though this star is about 2.7 mag. fainter in V than HD293815, part of the reason for its redder appearance (Witt and Schild, 1986) can also be due to a larger amount of material in its line of sight. Thirdly, these contours roll off more uniformly from the peak than in the temperature plot. Thus the material seems to be more uniformly distributed about this peak and the centre is offset to the east with respect to this material distribution. The ***peak column density*** is $\sim 320 \times 10^{14}$ cm^{-2} and the ***average column density*** is $\sim 80 \times 10^{14}$ cm^{-2}, which is in good agreement with the average value of 60×10^{14} cm^{-2} for the local dark clouds.

6.4 Integrated Intensity Map

Integrated ^{12}CO line intensities are often used in the literature (eg. Bally et al. 1991) to trace the column density distributions of molecular hydrogen. However, this is not always very reliable. The contour map of the derived integrated ^{12}CO line intensity distribution in L1616 shown in figure 6.5 substantiates this view. As will be seen, this map bears both the features of the kinetic temperature and ^{13}CO column density distribution. The two peaks, one each to the East and West of the centre, correspond to the temperature and density peaks, respectively. The roll off of the distribution though more uniform in all directions, similar to the density distribution, still has a somewhat sharper rise on the eastern side similar to the temperature distribution. Thus the ^{12}CO integrated line intensity map possibly has some column density information, but this is substantially altered by the distribution of the temperature in the cloud. L1616 is found to have a peak intensity of $\sim$ 33 K km s^{-1} while the average is $\sim$ 10 K km s^{-1}.

6.5 Equivalent Width distribution

The contour diagram in figure 6.6 shows the spatial distribution of the equivalent linewidths in L1616. As will be seen, most parts of the cloud have equivalent line widths greater than $\sim$ 2 km s^{-1}. Further the peak occurs very close to the density peak (fig. 6.4) and is more or less symmetrically distributed. The linewidths are smaller in the outer parts. This may be partly due to the fact that the effect of the local heating is reduced as one goes outward and partly due to optical depth effects (i.e. towards the periphery, the beam dilution for the clumps increases particularly away from the line centre, thus making the line widths smaller). The large line widths and their wide distribution indicate the disturbed state of the cloud due to the activity of the stars in the cluster. It is to be noted that the centre is offset with respect to the peak of this line width distribution. In fact it occurs in a region of transition from larger to smaller line widths. This can be

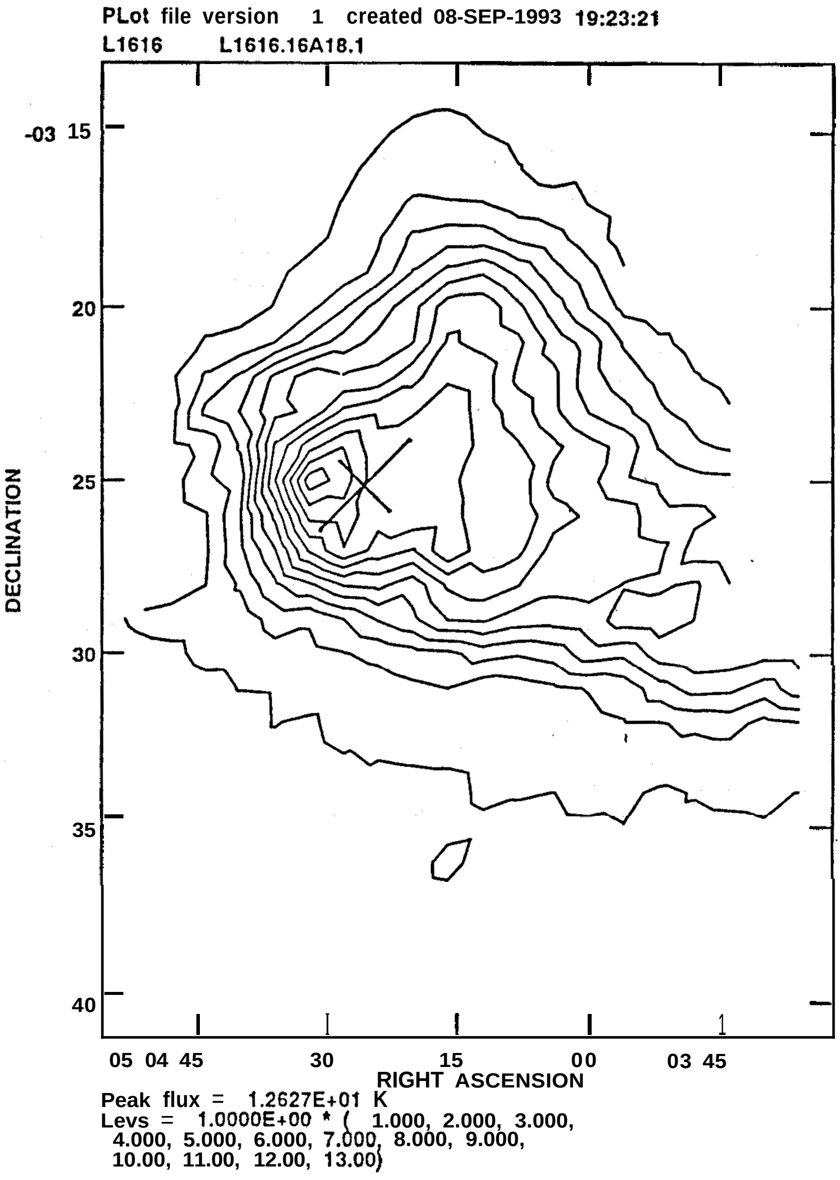

Fig 6.7: The distribution of ^{12}CO emission in L1616 averaged over the velocity range 6.7 to 8.7 kms^{-1} around the line centre (7.5 kms^{-1}). The major and minor axes of the elliptical 1 band image of NGC 1788 are also marked. The peak contour corresponds to 12.6 K and the contour spacing is 1 K.

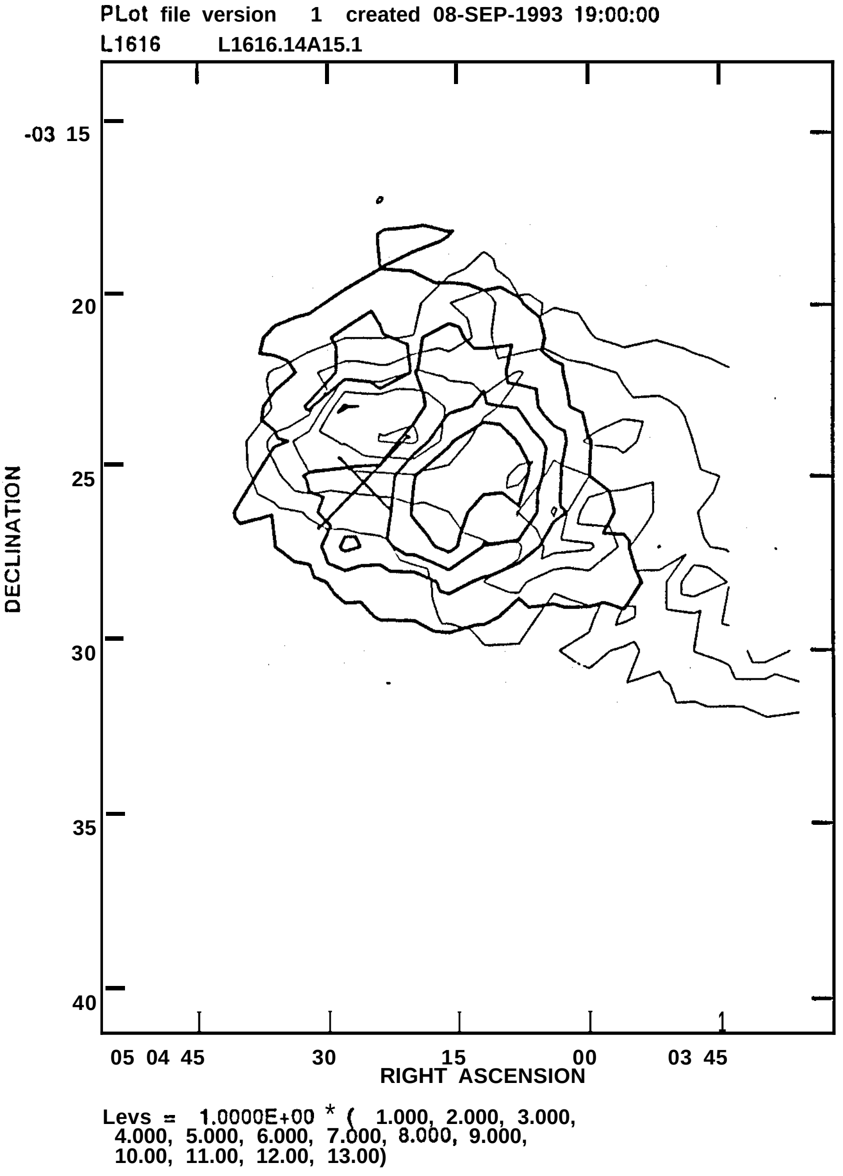

Fig.6.8: The thick and thin contours show the distribution of ^{12}CO emission in L1616 averaged over the velocity ranges 5.4 to 6.7 kms^{-1} and 8.7 to 10.4 kms^{-1}, respectively. The major and minor axes of the elliptical Iband image of **NGC** 1788 is also shown. The peak contour level is 5 K with a spacing of 1 K.

understood in terms of mass motions.

6.5.1 Mass Motions

In figure 6.7 we have shown the average line emission in the velocity range 6.8 to 8.8 km s^{-1} around the line centre (7.5 km s^{-1}). Figure 6.8 shows the average emission from the material in the velocity ranges 5.4 to 6.7 km s^{-1} (blue) and 8.7 to 10.4 km s^{-1} (red), respectively, superimposed one over the other. Clearly, there are mass motions around the cluster of stars. This is consistent with the conclusion of de Vries et al. (1984) who from a systematic survey of reflection nebulae found that 60% of the clouds with associated reflection nebulae have broad lines; the enhanced wing emission and local line broadening arise from the mass motions due to the dynamical interaction between the molecular cloud and the stars illuminating the nebulae. Noticeably, the red wing emission is more or less spherical like a blob, while the blue wing emission is more extended with a pronounced emission towards the north-east. The blob contributing to the red emission appears to have increased the local line width considerably that the line width peak coincides with the red emission peak and thus offset from the centre, where the source of energy lies.

6.6 Discussion

The mass of the cloud estimated from the ^{13}CO column density, and a ^{13}CO to H_2 conversion factor of 5 x 10^5 (Dickman, 1978) is $\sim$ 169 $M_\odot$. The mass found from the integrated ^{12}CO line intensity using a value of 2.3 x 10^{20} cm^{-2}/K km s^{-1} for the $I_{^{12}CO}/N_{H_2}$ ratio is $\sim$ 193 $M_\odot$. These are in agreement with our rough estimate presented in the beginning, though larger by a factor of 1.8. This could be largely due to an error in the size estimate. Still the star formation efficiency is –13% (estimated total mass of the stars/mass of the cloud) quite large compared to the average which is $\lesssim$ 3% (Evans and Lada, 1991). Further the cloud has a cometary appearance with a tail towards 30° southwest. An extension of this points to the star ϵ Orionis, a B0Ia spectral type blue supergiant at a distance of 370 pc (Hirshfeld and Sinnott, 1985). This implies that its present surface temperature and luminosity are $\sim$ 28000 K and 2.5 x 10^5 $L_\odot$, respectively (Allen, 1976). The mass and the lifetime of the corresponding main-sequence star are 35 $M_\odot$ and 4.3 Myr, respectively. This implies that the main sequence progenitor of ϵ Orionis must have been a 06 spectral type star. Such a star may have accelerated the cloud through the rocket effect (Oort and Spitzer, 1955), as well as causing the implosion of the cloud forming the star cluster. Owing to the confusion resulting from the mass motions in the cloud generated by the cluster, and also due to an insufficient velocity resolution at 115 GHz (0.65 km s^{-1}), we are unable to discern any velocity gradient along the tail at present. However, if the cloud is in virial equilibrium the detected mass would imply a turbulence line width of only $\sim$ 1.25 km s^{-1}, while we find the line width from the spectra averaged all over the cloud to be $\sim$ 3km s^{-1}. The corresponding virial mass required to keep the cloud bound is 1000 $M_{\odot}$, five times larger than the estimated mass. This would imply that the energy input from the stars in the cluster is **fragmenting** the cloud. Taking the excess speed over and above what would compensate gravity to be $\sim$ 2 km s^{-1}, and the size of the cloud to be 2 pc, we find that the cloud would double its size in a time of $\sim$ 2 Myrs. If the initial size of the cloud was $\sim$ 1 pc, the stars must have been formed in the past 2 to **4** Myrs, in good agreement with the age estimate of ϵ Orionis. On this assumption, the present physical separation between the cloud and the star of $\sim$70 pc would predict an average space velocity of $\lesssim$ 17 km s^{-1}. This is assuming the cloud to have been very close to the star to begin with and the age of expansion to be the age of the star which is 4.3 Myrs. The measured radial velocity is only $\sim$ 7.5 km s^{-1}. The estimated proper motion velocity would then be 15 to 17 km s^{-1} (depending upon how much of the radial velocity is due to galactic differential rotation). This would require that the difference in the distance to the star and the cloud from the Sun is not more than $\sim$ 20 pc. Though the estimated distances to ϵ Orionis and L1616 are 370 pc and 420 pc, respectively, the errors on them being $\sim$ 20% they are still consistent with ϵ Orionis being the external trigger. **A** measurement of the proper motion velocity of HD293815 will clarify this issue.

To summarise,

1. Our estimated mass of the cloud L1616 is $\sim$ 180 $M_{\odot}$. The masses determined from ^{13}CO column densities and the ^{12}CO integrated line intensity are in agreement with each other.

2. From the cloud-averaged line width of $\sim$ **3** km s^{-1} we estimate the virial mass to be 1000 $M_{\odot}$, which is much larger than the above estimate and suggests that the cloud may be disintegrating. The evidence for mass motions supports this.

3. The cometary appearance, the location of the star cluster near the edge facing the Orion association, and the estimated high star formation efficiency indicate that the cluster formation may have been externally triggered.

4. ϵ Orionis located opposite to the tail direction is the most likely external trigger. We estimate the mass, age and the spectral type of the main sequence progenitor of this B0Ia spectral type supergiant to be 35 $M_{\odot}$, **4.3** Myrs, and 06, respectively.

5. The physical separation between the cloud and ϵ Orionis is $\sim$ 70 pc. If the cloud is assumed to have been close to the star to begin with and travelled the 70 pc distance with a constant velocity in the past **4** Myrs, then one would expect the cloud to have a proper motion velocity of $\lesssim$ 17 km s^{-1}.

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