DISCUSSION FOLLOWING REVIEW BY F.J. KERR

Scenarios of star formation, metal enrichment, compression mechanisms.

LARSON : Although it is true in general that a better understanding of galaxy formation requires a better understanding of star formation, it is perhaps also true that one can get some clues about star formation by studying galaxy formation. In particular, the necessity for two stages of star formation proceeding at very different rates suggests that the formation of a spheroidal system requires a strongly enhanced star formation relative to that "normally" occurring in spiral disks. One parameter that would differ markedly between spiral disks and proto-elliptical galaxies is the random velocity with which different gas elements collide. If this is of the order of 100 - 200 km/s^{-1} and the gas density is not too low (eg. if the gas is concentrated in clouds), collisions are followed by rapid cooling and compression by several orders of magnitude to extremely high densities. By contrast, the non-circular velocities in spiral disks are much smaller, $\sim$ 10 km/s^{-1} , and much less compression is possible in the collisions or shocks produced, for example, by density waves. Observational tests of the hypothesis that the velocity dispersion is an important parameter might be made by looking for differences in star formation characteristics between systems with different characteristic velocities, or systems of different mass. Perhaps also nature provides experiments in the form of colliding galaxies, where the effects of high velocity collisions on star formation can be observed. I believe that there are in fact some indications of bursts of rapid star formation triggered by such collisions, for example in the ring galaxies which have recently been explained by Toomre on the basis of collisions.

BOK : By what process is the thin galactic disk of gas formed in what began as an ellipsoidal gas cloud ?

LARSON : If a galaxy retains a significant amount of dissipative gas, for example in the form of colliding clouds, the random component of the gas motion is gradually dissipated and only the large scale rotational motion remains. Once the random velocity becomes much smaller than the rotational velocity, a flattened gas distribution results, although the gas layer may initially be rather warped and uneven.

Mc CREA : I have proposed a model having various features like those of Larson's model, but combined in a different way. I suggest that galaxies themselves were formed in the collision of gas clouds at about the recombination epoch of the big-bang universe. I think the first condensations in the compressed material were of the mass of globular clusters - about 10^6 such condensations in any one case. Further, I suggest that the first stars were formed in these condensations, this corresponding to Larson's early quick formation, but I should envisage in the first place massive short-lived stars. The condensations then presumably mostly disperse with a flattening of the system as a whole. The observational support for the model is that Kinman long ago showed that the mean angular momentum per unit mass of the surviving globular clusters is the same as that of the stars (in our own Galaxy) and that the stars in these clusters must have been formed in situ. After the flattening one or more further generations of stars would have arisen - the "disk" population.

STROM : Study of a selection of E and SO galaxies suggests that isochromes - lines of constant color (and presumed constant metallicity) - follow the lines of constant surface brightness. This result seems to suggest (following Larson's model) that star formation proceeds contemporaneously with collapse of a protogalactic gas cloud. It is difficult to understand galaxy - wide color gradients if star formation much precedes the formation of the galaxy.

L.F. SMITH : You mentioned the lack of low-metal abundance stars, which has been used as an argument for sudden metal enrichment in early phases of the galaxy. It is pointed out by Biermann (in press, Astronomy and Astrophysics) that this argument was made at a time when the age of the Galaxy was believed to be 10^{10} years, and the stars used were F + G stars. The present estimate of the age of the Galaxy is 1.4 10^{10} years. To make a statement about stars dating from early phases of the Galaxy, one must observe K + M stars, for which adequate data is not available. The distribution of metal abundances among F + G stars is perfectly consistent with steady enrichment and an age of 1.4 10^{10} years.

FIELD : In the light of Strom's colour index gradients, it appears that metallicity increases toward the centre of a galaxy. He claims this is because metals are produced more rapidly in the dense regions. Presumably this occurs within globular clusters as well as the halo population generally. Yet I cannot see how metals produced in supernovae exploding within globular clusters can be retained, in view of the low escape velocity.

LARSON : Another possible solution to this problem would be to allow several generations of globular clusters, such that later generations form from gas already enriched in heavy elements by supernovae in previously formed clusters. In fact, such a picture seams necessary to account for a systematic radial variation in the metal abundance of globular clusters as a function of distance from the galactic center.

FREEMAN : A comment on Field's remark about metal formation in globular clusters. At Stromlo we have observed the color distributions in many Milky Way globular clusters : clusters with long relaxation times show color gradients entirely comparable with those shown by Strom for ellipticals. Chun and I interprete these gradients as metal abundance gradients in these clusters, set up at the time of formation. In clusters with long relaxation times, there has not been time for the abundance gradients to diffuse away.

LYNDEN-BELL : A supernova at the center of a globular cluster that is still gaseous does not necessarily scatter its products around the galaxy-the debris can be retained ; it is sufficiently slowed down by colliding with the gas.

KERR : Also, the proto-globular clusters were probably more massive than the present clusters and therefore had a higher escape velocity.

BOK : The organizers of this beautifully planned and executed Symposium, seem to have overlooked the importance of the Large and Small Magellanic Clouds for studies of conditions under which star formation takes place. Nowhere in our own galactic system do we find observational evidence as readily available and as neatly laid out as in the Magellanic Clouds. The past few years have provided us with several 4 meter optical telescopes and with some new large Schmidt telescopes in the southern hemisphere capable of producing evidence for stars intrinsically as faint as our sun. Adequate radio-astronomical equipment for studies of CO is now available at the Radiophysics Laboratory of the C.S.I.R.O. in Sydney and in Parkes.

Some early photographs by Westerlund, one in near infra-red light (IN emulsion), the other in the near ultraviolet (IIaO emulsion and UG2 filter) show dramatically the extent of recent star formation in the Large Magellanic Cloud. The near infra-red photograph is dominated by the axis of the Cloud, but some of the blue associations register weakly. On the ultraviolet photograph the whole Cloud lights up like a Christmas tree ! The Tarantula Nebula (30 Doradus) shines forth in all its majesty and, associated with it, we have 100 or so sparkling OB supergiants, some of them with absolute magnitudes as high as $M_V = -9$. Clusterings of OB supergiants are shown in many places. Some of these are seen in relatively empty sections of the Cloud, with no other special star formation activity appearing within half a degree (500 parsecs) of the OB association and its emission nebulosity. Harlow Shapley baptized some of these : constellations. Small amounts of interstellar dust are seen projected against the emission nebulosities, but the unbelievably blue colors, U-B = - 1.00, show that there is relatively little dust in these objects. The Tarantula Nebula and the 30 Doradus Complex show the greatest dust concentrations, but nowhere do we find large dust complexes similar to our Ophiuchus and Taurus Clouds.

The maximum ages since formation assigned to the OB associations in the Large Cloud are certainly no greater than 10^7 years. The velocity dispersions of the OB stars in associations are of the order of 10 km s^{-1} . One of these OB stars will have moved 100 parsecs at most from its place of birth. In the Clouds the scale is one degree of arc equal to about

1000 parsecs. This means that the star is now observed within 6 minutes or arc of its birthplace. Not only have we good evidence for the presence of a young star, but we can locate its birthplace to within a few minutes of arc on our photographs. Radio and optical observations combined will give us the conditions under which the star was presumably formed. Constellation I of Shapley is a good example. It was the favorite association of Priscilla and Bart Bok. It is located in an empty-looking section of the Large Cloud. How was it formed, where and why ? [....] .

De Vaucouleurs, Schmidt-Kaler and Ardeberg are of the opinion that the Large Cloud exhibits spiral structure. I disagree. While there are a few extended string-like patterns in the distribution of the HII regions and OB associations, I fail to see in the Large Cloud anything resembling the familiar arms of spiral galaxies. I would not know how to draw for the Large Cloud a pattern of spiral density waves with associated Roberts Shock Waves.

How did the recent burst of star formation in the Large Cloud get its stars ? What are the conditions that continue to favor star formation on a grand scale in our smallish companion galaxy ? I do not know and,as a matter of fact, we have not begun to answer these questions during our Symposium. By not paying now careful attention to Magellanic Cloud problems of star formation, we stand in danger of overlooking a whole complex of possible processes, some of which should be applicable to our Galaxy as well. [....] .

May I suggest in conclusion that at this Symposium we pay some attention to the roles that supernova explosions may be playing in the processes of star formation within our Galaxy as well as within the Magellanic Clouds. Over the past fifteen years, there has been a small but steady stream of papers stressing the possible importance of supernova explosions for star formation in our Galaxy. The most recent paper in this class is a highly persuasive article by Ögelman and Maran. Personally, I do not assign great importance to studies of star formation involving supernova explosions, but, at the same time, I feel that at this Symposium we should not have essentially ignored the topic.

LEQUEUX : A fact which looks rather surprising in the light of current ideas on stellar formation is the lack of CO and H_2CO in the 30 Doradus region where star formation is active (CO observations of T. Phillips et al. and H_2 CO observations at Parkes). This is to be related to the relative lack of dust mentioned by Bok.

MOUSCHOVIAS : Has the magnetic field been mapped in the two Magellanic Clouds?

BOK : The work of Mathewson is the most noteworthy in this area.

LOREN : In response to Dr. Bok's request for an examination of mechanisms of star formation that do not depend on spiral density wave shock compression of clouds, at least three ways exist for raising the external pressure of a cloud to the point that the critical mass is low enough for star formation to be triggered. These are : (i) cloud-cloud collisions, (ii) compression of bright rimmed dust clouds embedded in HII region complexes by a shock wave advancing ahead of the ionization front, (iii) collision of an expanding SNR with clouds.

There exists observational evidence for all three of these mechanisms. For the first method the molecular and infrared observations of NGC 1333 (Loren, 1976 Astrophys. J., Oct. 15 ; Strom, Vrba, and Strom 1976, Astron. J. 81, 314) indicate that two clouds are colliding and that stars are forming as a result of this collision. [....]

The second method of star formation is indicated by observations of Loren and Wootten (1976 in preparation). In a bright rimmed dust cloud on the east of the IC 1848 HII complex (Rim A in the notation of Pottasch, 1956, Bull. Astron. Inst. Netherlands 13, 77) a dense molecular cloud has been found. The dense core is indicated by detection of HCN, HCO^+ and 2 mm H_2CO emission. The existence of a region of enhanced CO excitation temperature (T_A^* (CO) $\sim$ 250K) and line broadening (Δ V(FWHM) = 3.9 km s^{-1}) associated with this bright rim suggested an embedded stellar heating source of spectral type roughly B1. [....] .

The third method of triggering star formation by surpernova remnants is shown in recent work by Wootten (1976, Astrophys. J. Letters, submitted). Wootten finds that dense molecular complexes occur near the positions of maximum radio continuum emission in W44 and W28. In these complexes the CO shows enhanced excitation and broadening and some change of the velocity structure. Wootten finds that the column density of CO peaks at positions just outside the radio shell. Wootten also finds a 2μ source associated with a compact HII region in the molecular cloud associated with W44. [....]

FIELD : Interesting that your three mechanisms, like that of the spiral density wave, are all based on shock waves. Kahn predicted shock waves to be a consequence of cloud-cloud collisions in 1951 or so, and yet little observational work has been done. The recent detection of H_2 vibrational excitation by Gautier et al. is an interesting exception. I think there is a rich future ahead for those studying IR emission in the H_2 vibrational lines ($\sim$ 2 μ) and H_2 rotational lines (< 28 μ) ; they will find shock waves in profusion.

SILK : In addition to the vibrational excitation of H_2, emission by other molecules specific to shocked regions may also provide an important diagnostic of shocks in molecular clouds. At Berkeley, Iglesias has developed a programme which computes the time-dependent chemistry in a shocked molecular cloud. Prolific amounts of H_2O are formed by endothermic excitations in the hot shocked gas, thereby producing a potential chemical diagnostic distinct from the chemistry of cold molecular clouds.

ROBERTS: Dr. Kerr has asked me if I would like to make some comments on density wave theory and on the concept of the galactic shock as a possible triggering mechanism for star formation on the large scale. At the outset it is important to recall that the density wave theory was largely motivated by observations of external spiral galaxies for which we enjoy a bird's eye view, and for which the optical appearance of the disk often reveals the presence of large-scale spiral structure with luminous spiral arms. In the density wave interpretation of such spiral structure, the enhanced luminosity of a spiral arm is believed to originate in the very young, newly-formed stars whose births from interstellar gas clouds have been triggered by the passage of the crest of a spiral density wave. The background spiral gravitational field underlying a density wave pattern is found to be capable of driving the component of interstellar gas into a rather large and non-linear response in which shock waves form along the arms of the background pattern. It is in turn the galactic shock wave which is thought to form a possible triggering mechanism for the gravitational collapse of gas clouds, leading to the formation of stars, molecules, and perhaps other tracers along a spiral arm.

Galactic shocks form if the interstellar gas is driven sufficiently stro gly so as to force the velocity component normal to a spiral arm $W_\perp$, to oscillate about its unperturbed value, $W_{\perp 0}$, and achieve transonic values. There are actually two regimes of shocked gas flow. For regime (i), $W_{\perp 0} >$ the sonic speed a, the shocks tend to be *strong* and give rise to *narrow* regions of *high* gas compression. For regime (ii), $W_{\perp 0} < a$, the shocks tend to be *weak* and yield *broad* regions of *low* gas compression. This difference is thought to underlie the observed differentiation between the *narrow*, *filamentary* spiral arms observed in some galaxies and the *broad*, *massive* spiral arms observed in other galaxies. The galaxy M 81 is a sample galaxy which characterizes regime (i). The well-developed, filamentary spiral structure observed in M 81 is thought to be a consequence of the potentially strong shocks possible there. In the work of Rots (1975) on neutral hydrogen observations of M 81, the arm peaks are substantially narrower than the interarm troughs altogether indicative of non-linear wave phenomena ; and some peaks even show the skewed character of steep rise followed by more gradual fall off, quite characteristic of strong shocks.

We can now view our own Galaxy in perspective with M 81 and other extragalactic systems. Roberts, Roberts, and Shu (1975, Ap.J. *196*, 381) made a semi-empirical study of the theoretical wave patterns predicted in the models of 24 external galaxies. One result from this work shows a trend for the sample of 24 galaxies considered, indicative of a possible correlation between $W_{\perp 0}$ and potential shock strength on the one hand and luminosity classification and degree of development of spiral structure on the other. Those galaxies, in which potentially strong shocks are possible, are found to exhibit long, well-developed spiral arms. Those galaxies in which weak shocks are predicted are found to exhibit poorly-developed spiral structure.

We can ask : where does our own Galaxy fit in ? To answer this question I would note that $W_{\perp 0}$ and potential shock strength in turn depend on two even more fundamental physical parameters : (1) the total mass of the galaxy divided by a characteristic dimension, and (2) the concentration of mass toward the galactic centre. A galaxy with a mass distribution of moderate central mass concentration is found to lie near the ridge of the $W_{\perp 0}$ surface in fig.9 of Roberts, Roberts and Shu. Such a galaxy high on the $W_{\perp 0}$ ridge, like M 81 (NGC 3031), is capable of forming rather strong shocks and exibiting well-developed, filamentary spiral structure. Our Galaxy is also found to lie well up on the $W_{\perp 0}$ ridge near M 81, and this suggests the possibility of potentially strong shocks together with filamentary spiral structure in our Galaxy as well.

At this point one important question should be addressed in regard to the recent CO observations of our Galaxy. If the large-scale CO features are indeed likely tracers of large-scale spiral structure in our Galaxy, we must ask : why do they not appear as sharper features ? This important question, which also applies to other tracers in our Galaxy such as the neutral hydrogen, is presently being investigated by Burton and myself through a simulation of the cloud component of gas flow in a spiral density wave model for our Galaxy based on the two-phase concept and with refinements of the cloud-intercloud medium interaction due to turbulent viscosity following Sawa (1975). In this picture, the clouds are viewed as embedded bodies which expand or contract to adjust to changes of the ambient pressure in the intercloud medium ; and the increase in pressure across a galactic shock occurring in the hot intercloud phase is in turn transmitted to the cold clouds, leading to star formation and molecule formation. The cloud component plows supersonically right through the shock and beyond until the drag force due to turbulent viscosity can slow it down. Consequently a smooth peak, rather than a sharp one, forms in the overall density distribution of the cloud component, unlike the sharppeaked intercloud component at the shock. We simulate the CO emission by generating synthetic profiles corresponding to a stochastic assemblage of clouds in the model. The results show that the synthetic features computed from the spiral model are not sharp features despite the presence of large-scale shocks in the model but are indeed smooth and bear close resemblance to the observed CO features in the observations.

Consequently if large-scale shocks are present in our Galaxy, they, as well as the large-scale spiral structure, may be very difficult to see clearly, partly because of these effects of smoothing already mentioned in the model simulation and partly because from our position within our own system the determination of distances is very difficult, and we suffer from not being able to see clearly "the large-scale forest because of the trees".

BAKER : My first comment is intended to supplement Dr. Kerr's general remarks on HI. If one tries to seperate from the many states of atomic hydrogen just that one most closely related to star formation - the cold cloud phase - one usually finds such gas lies in large sheets. The existence of such large, velocity-coherent structures indicates that some large scale mechanism connected probably to spiral structure is at work. While one may say that this cloud gas, averaged over the whole sky, has some random velocity distribution, sometimes we see only one systematic velocity. In those cases apparently the visible cold gas has not had time to mix i.e. the different velocities are not represented in the same volume of space. Thus the gas is young ($< 10^7$ years). I point out that Heiles cloud 2 located in one of these sheets shares the space motion of the low density material.

I turn now to the work of Barker and myself on stellar density waves in general and the formation of large cold HI complexes in particular (Baker & Barker, A & A 36, 179, 1974). At the beginning it disturbed us that a key piece in the star formation puzzle, Robert's shock hypothesis is based on the periodic, time invariant, Grand Design conception, which is unlikely to be realized in actual galaxies. Therefore we used instead stellar density wave packets - aperiodic perturbations of limited extend in the stellar distribution - and showed that these too induce shock waves. In practice then, Robert's hypothesis is applicable to irregular spirals. Moreover, if suitable density waves exist, shocks and presumably stars can form in interarm segments and perhaps even in the halo during early stages of Galaxy formation. The hitch is that our studies confirm that a shock wave must show a higher sound speed in the post-shock region than in the pre-shock gas. This condition is not always fulfilled in the ISM. By combining the treatment of hydrodynamics, thermodynamics and most importantly by retaining the gravitational perturbation of the stellar wave we could follow the history of the gas for realistic conditions. The stellar density wave makes a pressure jump in the gas that produces a corresponding density jump. The gas cools efficiently and the resulting temperature drop enhances the density jump - that is, makes the gas more compressible. This positive feedback between temperature and density can run away into the thermal instability. In a stellar density wave another instability also occurs. The density jump causes the gas to slow down ; it tries to satisfy the equation of continuity approximately. This slow down increases the time the gas spends interacting with the wave and increases the momentum transferred from the stars to the wave. This momentum impulse is so directed that it enhances the pressure jump which began the chain of events. If this positive feedback path goes unstable it leads to the efficient conversion of hot gas into a front of cold gas moving with the group velocity of the wave. The cold gas then continues to trigger thermal phase change on its upstream side and grows. Although in one sense this effect represents an amplification mechanism for the galactic shock, the essential point is the growth of large, velocity-coherent cold gas layers. To emphasize this point, we call the objects accretion fronts.

TALBOT : I have two comments : one on the metal-dependence of star formation and the other concerning the dynamic processes on a galactic scale which govern the star formation rate.

Within the two-phase model of the interstellar medium, the temperature and density of the gas is governed by the heating and cooling rates. These rates determine a curve P (n) in the pressure-density diagram. The hydrostatic pressure for a parcel of gas is determined by the weight of the gas above it. The evolution of the gas is a combination of its tendency to adjust to hydrostatic equilibrium pressure and to adjust its density towards that given by the curve P (n).

Because the cooling rates are roughly proportional to the abundance of heavy elements Z, a parcel of gas with Z greater than the average abundance can more easily move from the low density phase to the high density phase. Since it is generally agreed that stars form from high density clouds, the Z for stars should be systematically slightly larger than the abundance of the average gas. It is not known how large this effect is since the magnitude of chemical inhomogenities are not known on the small scale (pc to kpc). This question needs to be investigated by observations. In the present environment of the galactic disk the ratio Z_{star}/Z_{gas}, may be very near unity. The importance of the effect is that that ratio may have been much larger in the early phase of the galaxy, and it may be one of the processes which contributes to the solution of the problem of too few metal-poor G dwarfs.

Earlier Larson briefly discussed the rate of star formation adopted in models of the collapse phase of galaxies; the star formation rate is proportional to the inverse of the dynamic time scale $\tau_{dyn} \alpha (G \rho)^{-\frac{1}{2}}$ Most of the discussion of star formation is within the context of the spiral density wave theory. In this case, the mean star formation rate is proportional to $(V(r) - V_p)$. There is a third dynamic process which is important; it is the generalization of the Jeans instability. Lin (1970, in Galactic Astronomy, ed. Chiu and Muriel, Gordon and Breach, New-York) has suggested that this may be one of the processes which generate spiral density waves. Since evolutionary models of disk galaxies can be made only by having a model for the history of Ω_p, this suggestion by Lin provides a useful specific model. In addition, the dynamical motions of the gas induced by the Jeans instability may also generate compression of the gas which instigates star formation. Models of galaxies (in preparation for publication) have been developed incorporating these three dynamic processes. The results suggest that the relative importance of the spiral density wave mode versus the Jeans instability mode is at least part of the process which distinguishes between the galaxies with narrow well-defined spiral arms and those with broad diffuse arms. The limiting case of the latter are Magellanic irregular galaxies with patchy, ill-organized patterns of star formation.

STROM : As F. Schweizer has indicated, Hubble's observations of Cepheid variables in M 33 suggest that not all of these presumed "spiral tracers" are located near the spiral arms.

Hence, it would appear that one must invoke a model demanding a "delay" in the formation of some stars in order to explain the disparity in Cepheid distribution and spiral arm in M 33.

MOUSCHOVIAS : I would like to make a remark, which is complementary to those of Strom ; namely, that the collapse of dense clouds proceeds at a rate slower than free fall. It was a decade ago that Dr. Mestel pointed out that the magnetic field can slow down the free fall of a cloud. I would like to go further and suggest that the magnetic field, which threads both the clouds and the intercloud medium, can prevent altogether the collapse of the outer envelope of a cloud, that has mass over the limit of gravitational instabillity. The traditional argument, that magnetic forces cannot catch up with gravitational forces once collapse sets in, is not correct. But this matter belongs to the Thursday session, and I reserve further comments for that time.

WOODWARD : I would like to give a preliminary description of new calculations of shock-driven cloud implosion which were made last month at the Lawrence Livermore Laboratory in California. Calculations already published (Ap.J. 207, 484) have assumed a polytropic equation of state, with $\gamma = 5/3$, for the intercloud gas. Thus the spiral shock in those calculations had a density jump of about a factor 3. If cooling in the intercloud gas is allowed, this density jump should be a factor of about 10. Because the ram pressure on the front cloud surface is linearly proportional to the density of the shocked intercloud gas cooling in this gas results in about a threefold increase in the nearly one-dimensional compression of the originally spherical cloud. This high compression is nearly impossible to treat with the coupled Eulerian-Lagrangian (CEL) code used in the published calculations.

New computations have been performed with an isothermal equation of state for the intercloud gas. A different numerical technique was used to handle the high compression and deformation of the originally spherical cloud. A fully Eulerian hydrocode BBC, using a very simple and fast treatment of fluid interface, the SLIC method, was used to compute implosions of standard interstellar clouds driven by spiral shocks of 4 different strengths. The multi-fluid Eulerian method has the advantage of great speed and convenience when contrasted to the earlier CEL method, but the treatment of the cloud boundary is less accurate. In particular, slip of intercloud gas along the cloud boundary is inhibited in boundary zones (it occurs a zone or two away) so that the Kelvin-Helmholtz instability of the boundary is not properly represented in these most recent calculations. A compensating advantage of the method is that high deformation of the cloud, and even its eventual break-up into separate blobs, presents no special difficulty to the logic of the cloud boundary calculation, so that the cloud evolution can be followed as far in time as is desired.

The most recent calculations have been carried out about twice as far in time as those already published. Again, the clouds are highly flattened in the initial implosions and clumps are formed on the axis of symmetry, where the density now exceeds 10^3 cm^{-3} . After a cloud is flattened, a shock is driven into the intercloud gas behind the cloud while a strong rarefaction wave travels into the cloud from its back surface. Because of the continued ram pressure of shocked intercloud gas upon the dense central clump of the cloud, this rarefaction produces a very long, thin tail of expanding cloud gas stretching behind the dense clump and giving it a "cometary" appearance. Stars seem likely to form in the dense clump, but not in the cometary tail behind it. As the cloud is accelerated downstream these stars would of course be left behind, yielding a general cloud and star morphology rather different than that discussed for earlier stages of cloud evolution in the work already published. In the later stages of its history, the cloud would appear elongated parallel rather than perpenticular to the direction of relative flow (hence to the galactic plane) and to the trail of newly formed stars. Cloud tails of 20 pc in length have been obtained for 500 solar mass clouds in the 12 to 15 x 10^6 yrs running times of the calculations (flattening of the cloud requires about 6 x 10^6 yrs).

ELMEGREEN : The boundary condition on pressure at the axis of symmetry in your calculations seems to be reflective and therefore artificial. To what extent could this boundary condition exaggerate the pressure and density enhancement found to occur along this axis ?

WOODWARD : The axial symmetry of the two-dimensional cloud implosion calculation does indeed give a perfect fraising of transverse motions at the axis of symmetry. If a three-dimensional calculation were performed for a non-spherical cloud, the region on the cloud surface where the intercloud flow would stagnate would correspond to the region near the symmetry axis in the two-dimensional calculation. Transverse motions would again be focussed about this stagnation region, but not so perfectly as in the 2 - D calculation. However, such perfect focussing is not needed in order for gravitational collapse and hence star formation, to result. Only densities of a few hundred per cm^3 are required, not those of about 10^4 which are obtained in the most recent calculations.

BURKI : Dr. Maeder and I have made two observational tests of star formation. The first test concerns the fragmentation of the interstellar protocluster clouds. It is based upon open star clusters younger than 15.10^6 years. The brighter part of the luminosity function of these clusters may be used to study the upper part of the initial stellar mass spectrum.
The aim of our study was to examine the dependance of the initial stellar mass spectrum on the size of clusters. Twenty-nine clusters have been selected according to some quality criteria. They have first been divided in 3 groups according to their linear diameter D and the mean normalized luminosity functions have been calculated for these 3 groups. The slope the luminosity function is steeper in the case of the small clusters than in the case of the larger clusters. This means that the rate of massive star formation is smaller in the small clusters than in large ones. This rate may be studied through the ratio of the number of stars brighter than absolute magnitude -3, divided by the number of stars brighter than -1. We observe a strong increase of the rate of massive stars with increasing cluster diameter. The value of this ratio

is 0.15 in the case of small clusters ($D < 4$ pc) and 0.34 in the case of large clusters ($D > 8$ pc). Consequently, during the fragmentation of the protocluster clouds, the variation of the minimum Jeans mass for star formation seems to be a function of the size of the cloud. In the second test, we have examined the behaviour of the mean axial rotational velocities for main sequence B stars, in the accessible part of the Galaxy. The basic data for this are the Catalogues of Bernacca and Perinotto (Contrib. Asiago No 239 and 250). The galactic plane has been divided in 6 sectors of 60° in galactic longitude. The main sequence B stars were divided in groups of spectral types and the mean rotational velocity was calculated for each galactic sector. The mean vsini in the case of B0 - B4 V stars is about 60 km/sec higher in the range containing the galactic center than in the other directions of observation, whereas this effect disappears for the stars later than B4. The distribution of vsini in the case of early B-type stars suggests a decrease of the mean vsini with the increasing galactocentric distance, in the accessible part of the Galaxy. On the basis of the observational data available at the present time, it is not possible to know if such a gradient extends beyond the local arm. In any case, this result confirms that fundamental quantities related to star formation have large scale variations throughout the Galaxy.

FIELD : I have a question and a comment. Are you sure that you have eliminated observational selection effects ? People working on clusters of galaxies report that the large ones are more likely to have a bright member. But this is a natural consequence of the small numbers of bright galaxies expected in a steep luminosity function. The Salpeter function is steep, and one might expect a similar effect.
It would be interesting to plot $< v \sin i >$ against the local rotational velocity of the galaxy. Your data would suggest a proportionality between the two. Such a relation would be predicted by some theories.

BURKI : The number of stars in the group of small clusters (166) is sufficient to be sure that the observed variation in the rate of formation of bright stars is not only a statistical effect.
The variation of $< v \sin i >$ is valid of the accessible part of the local arm and must not be simply extrapolated towards the galactic center or anticenter. In particular the region of the double cluster h and χ Per is known to have many rapid rotators.

CASWELL : Provided that similar total masses are present in each of the three ranges of clusters sizes (i.e. the number of small clusters is greater than the number of large clusters considered), then no spurious effect of the type suggested by Dr. Field should be present.

LEQUEUX : What guarantee have you that the diameters of the clusters reflect those of the initial cloud and that there is not an age effect.

BURKI : We have checked this point and there is no correlation between the diamater of the clusters of our sample (younger than 15 millions years) and the ages determined on the basis of isochrone lines given by models of stellar evolution.

DE JONG : Assuming that the diameters of open clusters are a measure of the total mass of the cloud from which the cluster formed, I would like to ask whether the change in the luminosity function with cluster diameter that you find means either that the slope of the luminosity function changes with cluster diameter or that the slope is constant but the luminosity function extends to higher masses (luminosities) in the larger clusters.

BURKI : The most massive star which is formed in a cluster is on the average about 30 $M_\odot$ in clusters with diameters $\leqslant$ 4 pc and about 50 $M_\odot$ in clusters with diameters $>$ 8 pc.

Molecular clouds as tracers of spiral structure.

SOLOMON : I would like to report on our recent data obtained in a survey of CO emission in lattitude as well as longitude. We observed CO emission at latitude $- 1.4^\circ < b < 1^\circ$ between $\ell = 0^\circ$ and 50° every 2° of longitude and with wider spacing at $\ell > 50^\circ$. At several locations close spacing every 3 or 6 arc minutes was used to determine the scale size of the clouds. In addition ^{13}CO emission was observed at 4 positions in order to translate the ^{12}CO survey data into molecular hydrogen densities. This aspect of the survey has just been started but is vital to a determination of the mass of H_2 clouds [....]. On the basis of the data we have derived the following parameters for the scale height of molecular clouds in the galaxy :

(1) Between 1 - 8 kpc Z_{FWHM} = 105 pc corresponding to a scale height of 73 pc.
(2) The distribution is bumpy as would be expected for dense clouds.
(3) The center of the distribution is about 30 pc south of the galactic plane between 6 - 8 kpc from the center and closer to 0 pc nearer the center.
(4) This scale height of dense molecular clouds is less than half that of HI but is similar to OB stars and dense HII regions and nearby dust. These are true population I .

[....] . The major features of the distribution of H_2 derived from the CO data are similar to our early results (Scoville and Solomon, Ap.J. 199, L105, 1975). The 4 - 7 kpc ring like feature dominates the distribution along with the strong emission from the inner 300 pc. Using data from many lattitudes smoothes out the longitude distribution since we are now sampling a much larger number of clouds at each longitude. The total mass in H_2 is approximately 3×10^9 $M_\odot$. ^{13}CO data has been used to quantitatively normalize the hydrogen molecule density.

SPITZER : I would like to ask Dr. Solomon how the ratio of CO to H_2 was determined and how much confidence he has in this determination.

SOLOMON : The ratio which is determined and used to calibrate the survey is that of ^{13}CO to H_2. We use observations of emission from about 6 clouds of $J = 2 - 1$ and $J = 1 - 0$ ^{13}CO intensities to fix the ratio of $^{13}CO/H_2$. This involves the use of collision cross sections and radiative transfer in a matter similar to that presented in a paper on line formation (Scoville and Solomon, Ap.J. 187, L67, 1974). We find $^{13}CO/H_2 \simeq 1.3 \times 10^{-6}$. This is similar to the result of Encrenaz obtained by a completely different method in nearby dark clouds. We assume this ratio is constant and determine the hydrogen densities in the galactic plane clouds at the few locations where we have ^{13}CO data. This is used to normalize the entire distribution. Better numbers require more complete data on ^{13}CO in both $J = 1 - 0$ and $J = 2 - 1$.

C.J. CESARSKY : I want to point out that, in the transformation of CO line data to molecular hydrogen densities which have been discussed, there could be a systematic error which could alter the shape of the galactic distribution of H_2. Given the abundance gradients observed in external spiral galaxies, it seems quite possible that the abundance of ^{13}C relative to H could depend on galactocentric distance. For instance, if at 5 kpc from the centre $^{13}C/H$ was higher by a factor of α than at 10 kpc, the maximum in the surface density would be reduced by the same factor. Theoretical studies of the chemical evolution of the galaxy show that the expected abundances in a given region are partly determined by the ratio of surface densities of gas (σ_g) to stars (σ^*). Gordon and Burton found this ratio to be constant between 5 and 10 kpc; but if there is a gradient in the abundance of ^{13}C, then :

$$(\sigma_g / \sigma_*)_{5\ \mathrm{kpc}} = \alpha^{-1} \ (\sigma_g/\sigma_*)_{10\ \mathrm{kpc}}$$

This corresponds to more efficient star formation at 5 kpc, as would be expected if the ^{13}C abundance is higher there.

SOLOMON : The abundance of $^{13}CO/^{12}CO$ appears approximately constant between 4 and 10 kpc in the Galaxy. The ^{13}CO line in fact can be used in conjunction with the ^{12}CO line to better determine the hydrogen molecular density. $T\ (^{13}CO)/T\ ^{12}CO)$ will increase with increasing H_2 density in a predictable manner.

STROM : While spiral structure in our own Galaxy may be difficult to observe in CO, optical observations of external galaxies with well-defined spiral structure suggests that dust lanes are located on the inner parts of spiral arms. The dust lanes presumably locate regions similar to CO clouds in our own Galaxy. Is there any tendancy for CO clouds to be discovered in regions where star formation has already taken place ? That is, does heating from nearby or embedded "new" stars make it easier to see the CO. If it takes a while for stars to form in a given cloud complex, then the CO distribution, if influenced by the above selection effect, might not outline the spiral structure well.

SOLOMON : I believe we are obtaining a fair sample of all molecular clouds with temperatures in excess of about 7^{o} K and densities $> 300\ cm^{-3}$, when we randomly point the antenna in the galactic plane. The percentage of locations where we actually sample very close to the recent formation of a massive star is very small.

GORDON : Bash and Peters have the answers : ballisitic behavior of clouds after formation in the shocked area of the density wave.

BASH : Peters and I (Ap.J., 205, 786, 1976) have shown that it is possible to associate the terminal velocity of $^{12}C^{16}O$ profiles (taken from a CO survey of the galactic plane) with those of ballistic particles born in the two-armed spiral-shock wave. These particles orbit under the influence of a smooth, radial galactic potential, perturbed by the gravitational potential in the spiral arms. The radial velocity of the terminal portion of the CO profile agree well with the orbital velocity of stars of dynamical age 30 x 10^6 years.
Subsequent work, in progress, shows that this relationship continues into $\ell = 20^{o}$, but not inside of the place where the line-of-sight extends inside R = 3.5 kpc.
Elisabeth Green has an observational test in progress in which a list of open cluster of a range of ages is being systematically surveyed. Preliminary results suggest that observable CO emission is no longer associated with open clusters with main-sequence turn-off ages older than B0.
It is hoped that a continuation of this work will result in :
(a) confirming data regarding star formation triggered by the density wave, (b) another time scale to compare with pre-main sequence and main sequence lifetimes, and (c) some information to illuminate the process which cuts off the CO emission.

FIELD : Two points : first, I understand that you explain the low contrast between arms and interarm regions in CO as due to the filling in of the interarm regions by old molecular clouds, $\tau \sim 3 \times 10^7$ years. Is that correct ?
Second, if this interpretation is correct, it provides a significant constraint on theories, because the free-fall time of a molecular cloud is only $\sim 10^6$ years. Something must be delaying collapse of these clouds.

ZUCKERMANN : Dr. Solomon has raised the question as to whether CO clouds in the Milky Way galaxy trace out the (presumed) spiral structure. It should be possible within the next few years to map out the distribution of extragalactic CO in some nearby spiral galaxies. Spatial resolution of 10" should be obtainable with single antennas and even higher resolution might be obtained with interfermeters if the surface brightness of the extragalactic CO is high enough.

C.J. CESARSKY : In connexion with the question of spiral structure and interstellar gas, it is interesting that the secondary peaks superimposed on the broad central maximum of the galactic gamma ray distribution occur at directions that are tangential to the spiral arms delineated recently by Y. Georgelin.

BURTON : I would comment that the evidence for spiral structure found in the CO observations is also found in the 21 cm hydrogen observations made of the corresponding part of the Galaxy. In both cases, the large-scale irregularities in the run of terminal velocities with longitude, which have been attributed to motions gravitationally induced by mass concentrations, provide the best, if not the only (but still quite circumstantial), evidence for spiral structure in the interstellar material in the part of the Galaxy at $R < R_o$.
Apropos of the discussions on the large amount of galactic mass hidden in the molecular hydrogen, we perhaps should not forget that an equivalent amount of mass ($\sim 2.3 \times 10^9 M_\odot$, Baker and Burton, Ap.J. 198, 1975) is contributed by atomic hydrogen.
CO is not commonly observed in absorption because of the general lack of suitable background sources of mm-wave radiation. The sources of intense and broad CO emission near the galactic nucleus do provide a suitable background, and CO absorption is observed there (Liszt et al. Ap.J. 198, 1975 and Ap.J. submitted). The interesting point in the present context is that the CO which appears in absorption is so cold ($T \sim 3K$) that is would not appear in our surveys of emission. We cannot estimate the total mass contribution of this generally undetectable CO, but it may not be small.

THADDEUS : Cohen has recently done an out-of-plane CO survey in the first quadrant with a 9' antenna beam. His observations yield the CO intensity, thickness, and displacement of the molecular ring over the galactocentric range $4 \lesssim R \lesssim 8$ kpc. The intensity agrees well with previous work in the vicinity of the peak of the ring, although there may be some disagreement with the results of Gordon and Burton when $R \simeq 4$. The thickness (FWHM) mimics HI, but is only 1/2 to 3/4 as large ($\sim$ 120 pc). The ring also seems to be slightly displaced to negative latitudes by about 30 pc.

ROBINSON : The gas distribution in Dr. Thaddeus's CO Survey agrees well with that of Gordon & Burton for $R \gtrsim 4$ kpc. However, the Gordon and Burton gas distribution shows gas for $2 < R < 4$ kpc at about 30% of the peak near $R = 5$ kpc, while Dr Thaddeus's results show no gas for $2 < R < 4$ kpc. Would Dr. Thaddeus comment on this difference ? Could it be a result of the undersampling (in ℓ and b) in both surveys ?

GORDON : This may be partly a function of comparative sensitivity of NRAO and Goddard telescopes. The CO is weak at $5^{\circ} < \ell < 20^{\circ}$, which corresponds to this region.

BURTON : The determination of the radial abundance distribution requires that a rotation curve be adopted. The differences, at $R < 4$ kpc, between the CO abundance distribution found by Cohen and Thaddeus and that found by Gordon and myself (see Ap.J. 208, 1976) can probably be attributed to the different rotation curves used. Gordon and I redetermined the galactic rotation curve (assuming simple rotation) from new HI observations, and found this curve also quite compatible with the CO terminal velocities at low longitudes.

GORDON : As a function of galactic radius R, the degree of compression predicted by density wave theory seems to agree well with the deduced ratio of $N(H_2)/N(\Sigma H) \propto R$ except for the region $2 < R < A$ kpc, where the gas appears to be in the form of H_2 entirely. Here density wave theory would predict no compression because of the inner Lindblad resonance.

MATSUDA : I would like to make a comment on the ring like distribution of molecular hydrogen in our Galaxy. There are sharp cut offs of the abundance of the molecular hydrogen at about 4 kpc and 8 kpc, and these could be explained in terms of galactic shock theory. As to the outer cutt off, Burton et al. and Stecker suggested that the transition of the strong shock, that is $W_{\perp} > a$, to the weak shock occurs at about 8 kpc. In order to have such a transition, the pattern speed of the density wave, Ω_p , should be of the order of 20 km/s kpc, which contradicts with the value of 13.5 km/s kpc adopted by Lin, Shu and others. A.H. Nelson and myself constructed a model of galactic shocks assuming $\Omega_p = 20$ km/s kpc, and computed 21 cm line profiles in the direction of the galactic anticentre. Similar work has been done by Roberts, but we found an error in his comparison of the computed line profiles with observational data. Correcting this, we found that $\Omega_p = 20$ km/s kpc gave us better agreement.

The deficiency of the molecular hydrogen as well as atomic hydrogen within 4 kpc is difficult to explain on the basis of the current shock wave theory because there should not be spiral density waves within the inner Lindblad resonance situated at about $2.5 \sim 4$ kpc, the precise position of which depends on the choice of Ω_p. If we assume a stellar bar at the galactic centre, we could have strong shocks there. The numerical simulation of gaseous flow in barred spirals recently performed by Sorensen, Fujimoto and myself confirmed the idea. Gas plunging into the shock loses angular momentum as well as energy, and falls into the centre. The gas which originally filled the 4 kpc region was swept by the bar-shock towards the galactic centre. This idea could explain the central peak of the distribution of molecular hydrogen shown by Solomon as well as the depletion of gas within 4 kpc.