STAR FORMATION AND THE GALAXY

F. J. Kerr
Astronomy Program, University of Maryland
College Park, Maryland 20742, USA

1. INTRODUCTION

My task is to discuss the galactic context of star formation and to consider how large-scale phenomena in the Galaxy can influence the processes of star formation. This review, and the whole of the first session, are supposed to set the stage for the later consideration of protostellar and prestellar objects and smaller-scale effects in general.

As observational studies are primarily concerned with the present epoch and with objects in the galactic disk, I will mainly be discussing the problems of star formation in the disk, and in particular the role of the density-wave shock which is receiving much attention at the present time. However, it is also clear that some stars have been produced without the benefit of spiral density waves, and therefore brief mention must be made of some other possible star formation processes.

This review will also report on some tests of the relation between the density-wave shock and star formation, the rate of star formation, the role of magnetic fields, the tendency of stars to form in clusters, and the application of general galactic results to the solar neighborhood. I have received a substantial number of preprints from symposium participants and others describing recent work, and I thank the various authors for sending them to me. My account of most of these will necessarily be rather brief, but we will probably hear more details of most of these in the subsequent discussion.

2. FORMATION OF GALAXIES AND HALO STARS

This symposium is not directly concerned with the very large subject of galaxy formation, which will probably have a symposium to itself some day. However, I want to refer to two recent studies, where the authors propose models in which the process of formation of a galaxy

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depends on the amount of star formation taking place in the very early stage. Each paper is concerned with the distinction between spiral and elliptical galaxies.

Gott and Thuan (1976) propose that the key factor in this distinction is the amount of gas left over at the point of maximum collapse of the protogalaxy. The gas left depends on the ratio of the rate of star formation to the rate of collapse. Gott and Thuan start their discussion from the present big-bang cosmology, in which protogalaxies begin as density perturbations at the time of recombination ($z \sim 1000$). Then, assuming that star formation goes more quickly at higher densities, galaxies that form out of relatively larger density perturbations at recombination would use up their gas more quickly, leading to elliptical galaxies. If star formation is essentially completed fairly early, a dissipationless collapse occurs and a spheroidal or elliptical galaxy results.

On the other hand, a protogalaxy forming from a smaller density perturbation would form stars more slowly during the collapse, and star formation would be far from complete by the time of maximum collapse. Model calculations show that the leftover gas, being highly dissipative, forms the typical flat disk of a spiral galaxy, while the already-formed stars relax into a spheroidal Population II component. The lack of gas in the inner few kiloparsecs of a spiral galaxy such as our own is not specifically discussed, but we can imagine that the inner part of the collapsing protogalaxy could reach a sufficiently high density for star formation to proceed more rapidly and use up essentially all the gas, as in a collapsing elliptical galaxy.

Larson (1976) has also modeled the formation of spiral galaxies. Following Faber and Gallagher (1976), he suggests that the disk-to-bulge ratio is the most fundamental parameter distinguishing between different Hubble types. The models show that this ratio depends mainly on the assumed star formation rate and the way it varies with time. This in turn depends on the initial density or the velocity dispersion at the protogalaxy stage. The formation of a spiral galaxy seems to require two stages of star formation proceeding at very different rates. In this picture, an early stage of rapid star formation would produce a spheroidal component, but the formation of a disk requires much slower star formation at a later stage, to allow the residual gas to settle to a disk before forming stars. A surprise is that the decrease in the star formation rate from the earlier to the later stage is greater than predicted by a simple power-law function of gas density or velocity dispersion, suggesting that something is required to strongly inhibit star formation during the later stages of the collapse. A possible alternative scenario suggested by Larson is that the protogalaxy may already be inhomogeneous, with the denser "clouds" condensing rapidly to form stars in a spheroidal component, while the less dense intercloud gas condenses later to form a disk.

An interesting result from these model calculations is that the time scale for the formation of the outer part of the disk is quite long; stars will still be forming in the outer part after 10^{10} years. As an aside, this result suggests that the warp and the large z-extension commonly observed in the outer part of a spiral may merely indicate that the outer parts have not yet settled into a well-defined disk. Perhaps we should not be looking too hard for tidal interactions.

A good way to conclude this part of the discussion is to quote Larson: "To a large extent, the problem of understanding galaxy formation is the problem of understanding star formation".

The origin of globular clusters has always been something of a mystery. Peebles and Dicke (1968) suggested that primeval clusters formed a few million years after the big bang while the protogalaxy was still expanding cosmologically. The detailed evolution of such systems has been studied by several workers. Other suggestions have also been made about the origin of globulars, but there is as yet no general agreement on this question.

How about the general halo stars? It is common to assume that the star formation rate during the collapse was proportional to some power of the gas density, such as the square. The next step is to point to the importance of clouds in the collapsing protogalaxy. If clouds can develop through internal turbulence or through tidal interactions between neighboring systems, it is easier to see how early star formation could take place. Larson has suggested that the compression produced by high-velocity collisions between randomly moving gas clouds or streams might be a possible process leading to dense condensations and rapid star formation in protogalaxies. With gas clouds colliding at velocities of 100 km s^{-1} or more, compression by several orders of magnitude in density would be possible.

The existence of Population II stars shows clearly enough that stars can be formed without a spiral density wave. Also, the fact that even the oldest stars have appreciable metallicities implies that a significant proportion of the gas must have been processed through stars before the disk was formed.

3. DISTRIBUTION OF GAS IN GALACTIC DISK

We turn now to star formation in the disk in its large-scale aspects. The first important factor to be considered is the distribution of the gas in the disk, in particular the variation of gas density with radial distance from the center, R.

Until recently, this subject was dominated by the results for neutral hydrogen, from 21-cm observations. The HI volume density distribution is fairly flat over the range R = 4-14 kpc, and many people have remarked on the great difference between this and the

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distribution of total mass. The HI data are now known to be quite misleading if they are used for the total gas density. Evidence to the contrary has mainly come from observations of γ-rays and molecules.

The early γ-ray work by Kraushaar et al. (1972) with the OSO-3 satellite first showed the existence of a broad emission region along the Milky Way in the general direction of the galactic center. The more precise data of Fichtel et al. (1975) from SAS-2 showed that the peak emission extends over a range of longitude approximately 40° on either side of the center. The radial distribution of galactic γ-ray emission obtained by unfolding this longitude distribution shows a peak at R = 5-6 kpc (Stecker 1976). The main mechanism for producing high-energy (>100MeV) γ-rays in the Galaxy is the decay of Π° mesons by interactions of cosmic ray nucleons with interstellar gas nuclei. There is no reason to assume that the radial variation in cosmic-ray flux is large enough to give rise on its own to the 5-6 kpc peak. In fact, evidence from the distribution of supernova remnants (the presumed source of the cosmic rays) and from the strength of the nonthermal radio continuum emission indicates only a relatively small radial variation in the cosmic rays. The gamma-ray peak must therefore be due to a high gas density in the 5-6 kpc region, much higher than can be attributed to neutral hydrogen. The most likely identification for the additional gas is molecular hydrogen.

More detailed information about the total gas distribution can be inferred from the recent extensive observations of the 2.6-mm line from carbon monoxide molecules in and near the galactic plane (Scoville and Solomon 1975; Burton et al. 1975; Gordon and Burton 1976). The longitude-velocity diagrams for $^{12}C^{16}O$ emission observed along the galactic equator show several interesting features: (i) there is no emission at negative velocities in the first quadrant of longitude, showing that all the sources lie inside the solar circle, (ii) the distribution is much more clumpy than is the case for 21-cm emission from neutral hydrogen, (iii) the derived radial distribution of the CO emission sources shows a strong peak in the region R = 4-7 kpc.

In order to proceed to a derivation of the total gas density, it is necessary to assume that the CO emission is a good indicator of the distribution of molecular hydrogen, which must be present in greater abundance but cannot be observed directly in distant regions. CO column densities must first be estimated; this cannot be done from the $^{12}C^{16}O$ line, which usually appears to be saturated. Use is therefore made of the $^{13}C^{16}O$ line, which has too low an intensity for general mapping, but can be used to give representative values of column density, on the reasonable assumption of low optical depth. To go from a $^{13}C^{16}O$ column density to an H_2 column density requires estimates of the abundance ratio for the isotopic forms $^{12}C^{16}O/^{13}C^{16}O$ and for C/H. Solar abundances have generally been adopted. The fraction of carbon which is in the form of CO must also be estimated. Milman (1975) derives 10 percent as an upper limit for this fraction. There are clearly several uncertainties in the derivation, but the final estimates of the density of molecular hydrogen are not likely to be too much in error. In any case, most sources of error will be systematic, so that the shape of the distribution function should be fairly reliable.

Scoville and Solomon (1975) obtained values of 3 to 10 x 10^{22} cm^{-2} for the number of nucleons in the form of molecular hydrogen in the general direction of the galactic center. Corresponding values for the mean volume density in the annulus of strongest emission are about 2 cm^{-3}. The radial distributions of the volume densities of atomic and molecular hydrogen in the galactic plane show very striking differences (Figure 1, due to Gordon and Burton 1976). Burton et al. (1975) have collected together a number of radial distributions of Population I constituents. They show that the peak at R $\sim$ 5-6 kpc which is found in the γ-rays and the molecules is also seen for the H166α recombination line emission (Lockman 1976; Hart 1976), giant H II regions, and supernova remnants (Kodaira 1974). In addition to the radial distribution being different from that for neutral hydrogen, the above-mentioned constituents all have a smaller extent in the z-direction than does the neutral hydrogen (120 and 210 pc respectively).

An important comparison is that between the gas density and the total mass density. This has been done through projected surface densities by Gordon and Burton (1976). Adding the atomic and molecular hydrogen distributions, they compared the radial distribution of the projected surface density of hydrogen σ_H, with that of the total surface density, σ_t, as predicted dynamically by Innanen (1973). (See Figure 2.) The ratio of σ_H/σ_t is roughly constant at 4 percent over most of the Galaxy outside R = 5 kpc. This is clearly an important result in relation to the rate and efficiency of star formation; I shall return to it later. The much lower gas density inside R = 4 kpc is probably due to the gas having been more completely used up there in the original collapse.

The inferred results on molecular hydrogen have brought about a great change of viewpoint on the overall gas distribution. Until recently, based on the data for neutral hydrogen, the gas density was thought to fall slightly from the solar position towards R $\sim$ 4 kpc. This implied a big decrease inwards in the ratio of gas density to total density. As a result, several authors have written of gas depletion accompanying star formation in the inner part of the Galaxy.

We have seen however that with H_2 included the surface density of the gas is approximately proportional to the total density for R > 5 kpc. This implies either that gas is converted to stars with an equal efficiency over a large range of galactocentric radius, or more probably that star formation occurs in very limited regions at any given time and uses up only a small proportion of the gas. At the same time, gas is steadily coming back to the interstellar medium from the evolving stars. There is undoubtedly a partial balance between these two processes. There may also be some exchange of material in a radial

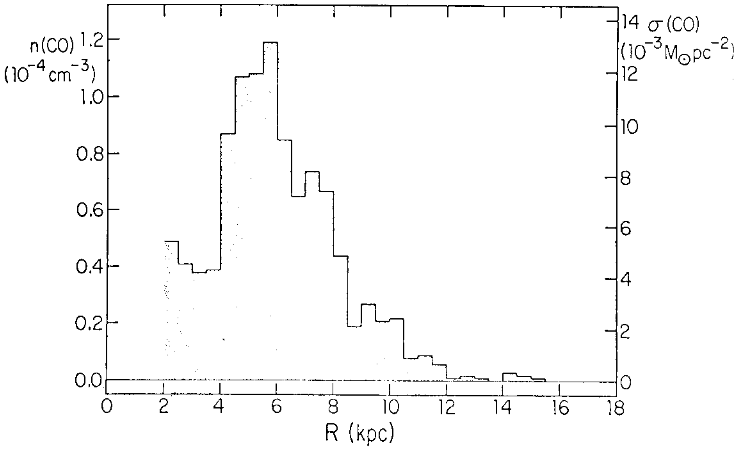
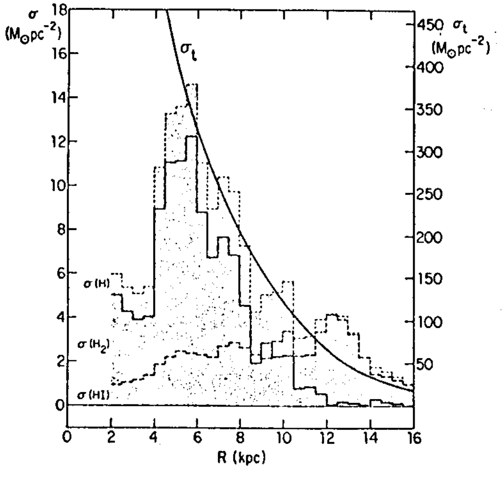


Figure 1. Radial distribution in the Galaxy of $^{12}C^{16}O$ volume densities at b = 0° (left hand ordinate) and of the projected $^{12}C^{16}O$ surface densities (right hand ordinate) (Gordon and Burton 1976).

Figure 2. Radial distribution of projected surface densities and differential masses of atomic and molecular hydrogen Gordon and Burton 1976).



direction. The long-continued existence of a central hole in the gas distribution may be telling us that gas can be transferred outwards more easily than inwards.

4. CLUMPS AND CLUSTERS

It was mentioned before that the distribution of the CO emission is very clumpy. Burton and Gordon (1976) have modeled the statistics of the observed distribution. Their model consists of a stochastic distribution of clouds, each having a diameter of 5 pc, an excitation temperature of 16K, a representative optical depth of 5, an internal dispersion of 2.5 km s^{-1}, and a cloud-to-cloud separation of 800 pc in the region of greatest CO emission. The estimated mass of one of these typical clouds is about $10^5 M_\odot$, if spherical symmetry is assumed.

The recombination-line emission from ionized hydrogen (Lockman 1976; Hart 1976) shows a similarly clumped distribution. It is also interesting to note that the distribution of neutral hydrogen derived from 21-cm studies is well known to have structure on a scale of 500-1000 pc (McGee 1964, Kerr 1971). This length may represent the size of an important major instability in the Galaxy.

It is tempting to identify the molecular clouds in the Burton and Gordon model with the sites where star clusters or associations are being formed. This identification is strengthened by the fact that the estimated z-thickness of the cloud layer between half-density points is 120 pc, about the same as that for young stars, at least in our vicinity.

It is generally accepted that stars tend to form in clusters or groups. The characteristics of O-associations in the solar neighborhood have been extensively discussed by Blaauw (1964). These are apparently the places where the most massive of the youngest stars have been formed. A typical association has some tens of O-B2 stars, though some are larger than this. The estimated total mass of a typical association, with its attendant gas, is a few thousand solar masses. Taking the mean lifetime of an O-association to be 12 x 10^6 yr, Blaauw found that 0.07 percent of the gas in our neighborhood is involved in the formation of these associations. Thus only a small fraction is involved at any given time.

Many associations contain subgroups of different ages, the youngest being very compact clusters, the older ones having already begun to expand. The indications are that the formation of these more massive stars is not a continuous process, but goes on episodically in various parts of a larger complex. It is noteworthy also that a large proportion of the stars in young associations are in double or multiple systems.

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5. DENSITY-WAVE THEORY

The main motivations for the development of the density-wave theory of spiral structure were the need to get around the overwinding problem which exists for material arms, and the interest in accounting for the so-called "beads on a string" appearance of H II regions in many galaxies. The theory envisages a spiral component of gravitational potential rotating with a uniform angular velocity. The instantaneous position of the spiral wave is outlined by a higher density of interstellar material and the presence of newly-formed stars.

There is now a lot of evidence in support of the density-wave theory, mainly from other galaxies. The <u>direct</u> evidence for the theory from our own Galaxy is rather slender, but there are several types of indirect evidence. It seems reasonable to accept the density-wave theory as a useful working hypothesis.

In considering the conditions for star formation, we are most concerned with the results of the nonlinear theory, which predicts the production of a shock front where the faster moving gas catches up on the rotating wave pattern. A model for the shock was developed by Roberts (1969), who studied the location of the shock at the inner edge of the background arms, and also the variation of the gas density along the streamlines. The stars respond only weakly to the spiral wave, although the resulting spiral gravitational field component does help to sustain the wave. The response of the gas to the wave is much greater; the resultant shock can lead to compression ratios of the order of 10, with the compression restricted to a quite narrow zone.

The strength of the shock and the degree of compression of the gas depend on the square of the ratio $W_\perp/a$, where $W_\perp$ is the velocity component of the gas normal to a spiral arm, and a is the acoustic speed in the gas, ~ 10 km s^{-1} for the intercloud medium. The linear rotation speed of the gas is approximately constant over the range R = 4-12 kpc. On the other hand, the linear velocity of the wave pattern decreases with decreasing R, because it has a constant angular velocity. Consequently, the velocity difference between gas and wave increases with decreasing R, leading to stronger compression of the gas in the shock.

Thus we can expect the galactic shock front to trigger molecule and star formation most effectively in the inner part of the Galaxy. The detection of substantial numbers of molecules indicates the presence of dense clouds, because molecules are known to be found mainly in such clouds, where the dust can shield them from dissociating radiation. Thus the observation that the molecular fraction reaches a peak value in the region R = 4-7 kpc can be attributed to the galactic shock, and can be taken as evidence for the compression produced by the shock. We noted before that several other constituents peak up in the same part of the Galaxy. They are ionized hydrogen, supernova remnants and pulsars, all of which are associated with stars, supporting the idea that star formation occurs most readily in this region.

We can see three reasons why the R = 4-7 region should be the most favorable for star formation: (i) the gas density is highest there, (ii) the frequency with which the gas strikes the density wave is higher as R decreases, and (iii) the compression due to the shock is highest there.

Roberts, Roberts and Shu (1974, 1975) have investigated 24 external galaxies from the density-wave point of view, and for each they have derived from the observed kinematics a theoretical curve for $W_{\perp}$ and hence the strength of the shock. They find a clear relationship in the sense that galaxies that are predicted to have strong shocks show a high degree of development of spiral structure, with narrow filamentary arms.

One surprise has been that the "clumps" of CO in our Galaxy do not delineate well-marked spiral arms. This may be partly because their distances are all derived kinematically, and hence they are rather uncertain, but it must also be recognized that no other spiral tracer (including H I) provides a very clear demonstration of a "grand design" pattern. Our Galaxy must be a spiral, according to many lines of evidence, but the pattern must be rather irregular. The various theoretical density-wave discussions must therefore be regarded as oversimplifications, because they depend on a regular pattern. The real Galaxy may have interference between different sets of waves, and also the wave pattern must be disturbed by departures from a symmetrical mass distribution in the Galaxy.

6. COMPRESSION MECHANISMS

A number of people have considered the way in which the galactic shock waves might trigger the gravitational collapse of gas clouds, leading to star formation. These studies are usually in the framework of the two-phase model of the gas, with cold clouds and a hot intercloud medium in rough pressure equilibrium with one another. Shu et al. (1972) discussed the way in which the shock could induce pressure changes which would force a transition of some of the hot intercloud gas into the cold cloud phase. The greater compressibility of the gas in the two-phase model would substantially reduce the critical mass required for the gravitational collapse of a gas cloud from that estimated for an isothermal gas.

Mouschovias, Shu and Woodward (1974) have proposed that large cloud complexes form as a result of the initiation of the magnetic Rayleigh-Taylor instability in the gas by the passage of a galactic shock. Their process leads to complexes with masses of about $10^6 M_{\odot}$, aligned along spiral arms with typical separations of about 1 kpc.

The most recent treatment of the effects of a shock is due to Woodward (1976). He follows the implosion of a standard interstellar cloud after it encounters a shock in the intercloud medium. Before the shock, a typical cloud has a radius of 15 pc and a mass of 500 $M_{\odot}$, and somewhat larger clouds are also considered. A cloud as massive as this should be stable in the interarm region, and therefore is already in existence before the gas enters the spiral arm. The low sound speed and rapid cooling within the cloud cause the implosion to be completed quite rapidly, as the compressed cloud is subjected to a very large ram pressure from the shocked interstellar gas. A feature of the model is that the cloud tends to flatten into a pancake shape, so that gravitational collapse of the whole cloud cannot occur. Instead it is easy for instabilities of the front cloud surface to lead to the production of a number of gravitationally bound subregions. This seems more realistic than the spherical collapse of a whole cloud.

Also in this model CO sources and subsequently young stars and H II regions will tend to be located on the outer edges of dense gas clouds, instead of at their centers. If CO sources have the proposed flattened shape, then mass estimates for them will be lower than has been the case for spherical clouds, say about 2000 $M_\odot$. In the overall picture, stars form only in a few high-density subregions, so that a 2000 $M_\odot$ cloud might give rise to 100 $M_\odot$ of stars.

A somewhat different view of the situation has been given by Baker and Barker (1974). They accept the common assumption that stellar density waves cause the visible spiral structure, but do not agree that a shock is essential for star formation. The normal theory for a density-wave shock has been developed for an isothermal medium, but they argue that in a two-phase medium a shock is not necessary and indeed cannot develop. Baker and Barker consider that the essential event leading to star formation is a thermal phase transformation. They show that the density wave can induce a transition to the cold, dense cloud phase. The cold material will have some motion imparted to it by the gravitational perturbation of the density wave, and it becomes what they call an "accretion front" moving through the hot gas and capturing it. The accretion fronts trigger thermal phase change on a large scale, and the resulting structures can reproduce the extent of observed cold clouds. These are massive enough for gravitational instability to occur, with subsequent star formation. The authors maintain that their work does not contradict the assumptions of Lin and his coworkers, but rather it avoids these assumptions where they are unnecessary.

Baker (1976) argues that the clouds must be young, because at least in the solar neighborhood we see in velocity space that the clouds in a region of the sky are organized into filamentary complexes at a velocity varying only slowly along the filament. This situation is seen in the 21-cm observations of Heiles and Habing (1974), as displayed by Heiles and Jenkins (1976). This is strong evidence that the cloud material formed in a coherent event that imparted momentum to the gas. If the clouds were older, their different initial velocities would have led to a greater mixing than is observed.

de Jong (1976) has considered the effects of photoelectric heating of the interstellar gas, and suggests that the gas is predominantly heated by photoelectrons from dust grains, these photoelectrons having been produced by absorption of ultraviolet photons of the interstellar radiation field between about 1200 and 912 Å. One result of this model is that considerably fewer low-energy cosmic rays are required to heat the gas, which has always been a difficulty in the two-phase model. Further, this process assists in stabilizing the hot intercloud gas against thermal instability. This presumably adds to the necessity for the spiral density-wave for inducing transitions from the intercloud to the cloud medium.

7. OBSERVATIONAL TESTS OF DENSITY WAVES AND STAR FORMATION

Direct tests of the connection between density waves and star formation are rather limited in our Galaxy, because the region where the star formation rate is predicted to be the greatest is so far away. It is therefore necessary to examine other galaxies; one such study, involving abundance variations, has recently been reported by Jensen, Strom and Strom (1976). The existence of radial gradients in certain emission-line ratios across spiral galaxies has been known since the early work of Aller (1942). In M101, for example, [O III]/Hβ increases by a factor of nearly 100 from the innermost to the outermost H II regions. The reasonable interpretation of this result is that the abundance of oxygen relative to hydrogen decreases from the inner to the outer parts of a spiral galaxy. Similar effects have been obtained with several other emission-line ratios. The absolute variation of abundances with radius cannot be accurately determined, but the trends of the variation are quite clear.

The greater abundance of oxygen and of other elements in the inner parts of a galaxy are presumed to imply a higher star formation rate, with a greater amount of processing of interstellar material through stars. Earlier authors have studied the chemical evolution problem and have been able to reproduce the composition gradients found in external galaxies, but they have needed rather ad hoc star-formation rates. Jensen, Strom and Strom have attempted to establish the mechanism. They have made new emission-line measurements across 15 galaxies, chosen to cover a large range of morphological type, mass, luminosity and kinematics. They looked for correlations of [O III]/Hβ with various parameters, and found the best relationship with two quantities related to the density-wave theory. Figure 3 shows a plot of log [O III]/Hβ against the quantity $(\Omega-\Omega_p)$, the difference between the material and pattern speeds, which is a measure of the frequency of star-forming events in the density-wave theory. $(\Omega-\Omega_p)$ varies from galaxy to galaxy, and with radius inside a galaxy. The abundance ratio O/H can be seen to increase with $\Omega-\Omega_p$.

Measurement of the compression is more difficult. Jensen et al. have used the estimates of mean compression strength made by van der Kruit from his measurements of radio synchrotron emission from arm and interarm regions. Figure 4 indicates that the O/H abundance ratio is higher (for a given $\Omega-\Omega_p$) for class C, high compression, than for class

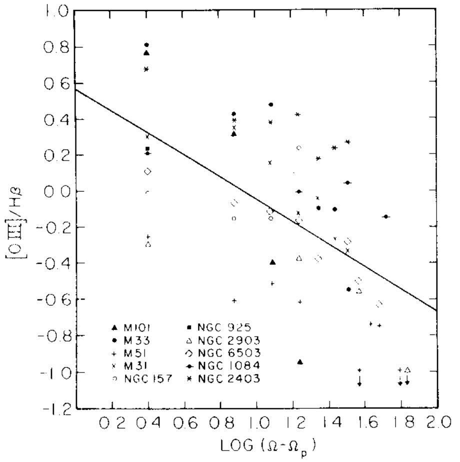

Figure 3. A plot of log [O III]/Hβ against the quantity (Ω-Ω_p) (Jensen et al. 1976). "Bins" of width 5 km s^{-1} have been used for each galaxy.

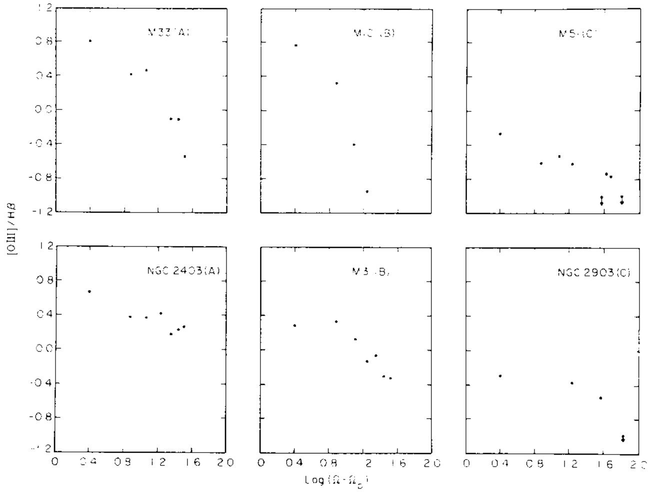

Figure 4. A plot of log [O III]/Hβ as a function of (Ω-Ω_p) for six galaxies with estimates of mean compression from van der Kruit. Low, intermediate and high compression are characterized by A, B and C (Jensen et al. 1976).

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A, low compression. The results for two other emission-line ratios support these general conclusions.

Other possible star-formation scenarios cannot be ruled out by these observations, but the results are consistent with density-wave-driven star formation.

Another type of test has been reported by Burki and Maeder (1976). They have studied the observed linear sizes of open clusters in the solar neighborhood, in relation to their distance from the galactic center. For the youngest clusters, those whose earliest stars are O-B2 (age $< 1.5 \times 10^7$ yr), the means of the diameters are

$$4.7 \pm 0.9 \text{ pc at } \overline{R} = 8.5 \text{ kpc}$$

$$\text{and } 9.9 \pm 1.6 \text{ pc at } \overline{R} = 11.5 \text{ kpc}$$

This variation is interpreted as due to an increase in the Jeans length with increasing distance from the center, the increase being due to the decrease of the mean gas density with R, and to the decrease of the compression produced by galactic shock waves or whatever other mechanism initiates star formation. Older clusters do not show this variation of size with radius, presumably because the larger clusters beyond R = 10 kpc must lose an important fraction of their initial mass.

8. RATE OF STAR FORMATION

The rate of star formation as a function of the gas density, ρ, has been studied by a number of people, beginning with Schmidt (1959) who proposed a rate proportional to ρ^2. The problem is now seen to be more complicated as several parameters must be involved. One of these parameters is the metallicity. Observational evidence indicates that stars of the same age can show quite large variations in metal abundance. Correspondingly, there is a paucity of low-metal-abundance stars of low mass. These facts must be fitted into any picture of star formation in the past.

Some workers have used a variable initial mass function in an attempt to solve this problem. Talbot and Arnett (1973) have discussed an alternative solution in a series of papers, namely metal-enriched star formation. The star formation rate can be expected to be higher in metal-enriched gas, because of the higher cooling rate.

The existence of a range of metallicity for stars of the same age is understandable if spatial variations in metal abundance exist in the interstellar medium. Reeves (1972) has studied the expansion of supernova remnants to estimate the mixing time of newly made material to the galactic gas. He found that the new elements pervade the active regions around the remnant quite rapidly ($\sim 10^6$ yr), but mix much more slowly with the rest of the galactic gas ($\sim 10^8$ yr for gas at the same

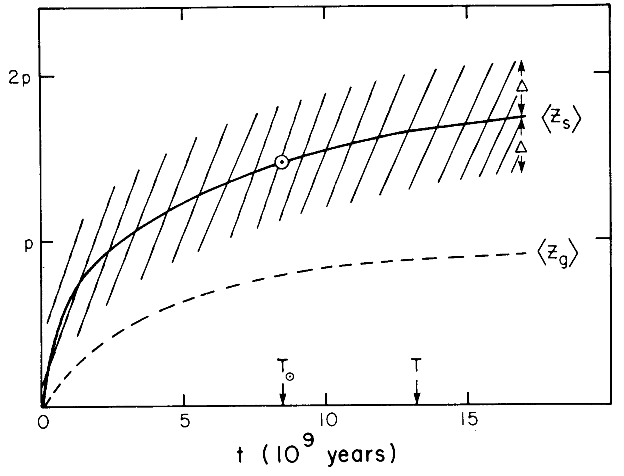

Figure 5. Evolution with time of the mean metal abundance in the interstellar gas (g) and in newly formed stars (s). The ordinate is in units of the metal yield of a generation of stars, p (Talbot, 1974).

radial distance). All the stars born in the vicinity of the remnant will have a higher Z.

Talbot (1974) has carried out detailed calculations on the sensitivity of the star formation rate to the interstellar heavy-element abundance. He has tested his model successfully against such observational results as the present mass fraction in the form of gas, the metal abundance of disk stars formed at various epochs, and the supernova rate. Figure 5 shows the evolution with time of the mean metal abundance, the curve for newly formed stars lying above that for the gas. The shaded area indicates the RMS spread about the mean abundance in the stars for a given age. A similar spread for the gas is not shown. In this model the rate of star formation per unit area varies with the density in such a way as to simulate a power law with an exponent of 1.7 to 2.3.

Both the observations and the model indicate an initial jump in Z, and then a slower increase. Reeves points out that the lack of much increase in the mean value of Z over many billions of years implies that star formation activity must be restricted to a rather small mass fraction of the whole galactic gas.

Mayor and Martinet (1976) have looked for new constraints on time variations in the stellar birthrate in the solar neighborhood, based on kinematics and counts of F, G, and K dwarfs. Their main conclusion is that, because of the uncertainties in both observational data and theoretical models, the time variation of the birthrate could be anywhere between a uniform rate and a decrease by a factor of seven during the life of the Galaxy.

9. SOLAR NEIGHBORHOOD AND OTHER SPECIAL REGIONS

Much of the discussion on protostellar and prestellar objects in later sessions of the symposium will be concerned with the solar neighborhood, so it is important to see how the characteristics of this region compare with those of the main starforming regions in the inner Galaxy. The overall picture we have been developing indicates clearly that the star formation rate is much lower in our neighborhood. As supporting evidence we can say, for example, that the CO and γ-ray emission are low, and there are no giant H II regions in our vicinity. We do however certainly see young clusters and associations, and many interesting objects will be discussed at this symposium. We should bear in mind however that phenomena could be qualitatively different in other parts of the Galaxy.

The largest structure in our neighborhood that seems to be connected with star formation is the Gould belt, a system of B stars and gas which seems to have been expanding for about 50×10^6 yr, and now has a radius of about 500 pc. This system is well known to be inclined to the galactic plane at 15°. A great deal of the local gas is in this system, but only a small fraction of it appears to have gone into stars, agreeing with remarks made earlier in other contexts. The most recent treatment of the Gould belt gas has been given by Grape (1976).

Another way in which local studies can illuminate large-scale processes is through deducing the birthplaces of stars seen in our neighborhood, by tracing their paths back through the required time periods. Lindblad (1975) has reported on a recent study of this kind by Grosbøl. His plot of stellar birthplaces seems to have a discontinuous break which may be evidence for a galactic shock. The argument is too lengthy to reproduce here.

Apart from effects connected with density waves, mention must be made of two other probable sites of star formation. Several authors have pointed out that the compression produced by supernova explosions might produce similar phenomena to those due to the galactic shock, but I am not aware of any detailed treatments.

In addition, we know that the centers of some galaxies, including our own, contain molecular clouds, thermal radio sources, and infrared sources, and the overall picture implies that some young stars must be there. The velocity dispersion is high in these central regions, and perhaps collisions between high-velocity streams can produce the compression that can lead to star formation.

10. SUMMARY

We have seen that major star formation seems to depend on the gas density, the frequency with which the gas meets the density wave, the strength of the compression produced by the density wave, and the metal abundance in the sample of gas. The two-phase model of the interstellar gas is also involved, and also the transition from the atomic to the molecular form; perhaps the magnetic field plays a role too. All of these elements have yet to be put together in a comprehensive overall picture.

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