Star Formation in Young Galaxies

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Some theoretical and observational reasons are given for regarding star formation as an induced process that proceeds in a series of bursts triggered by dynamical events, and it is suggested that intense bursts of star formation may have been particularly important for the early evolution of elliptical galaxies.

Since most of the visible matter in galaxies is in stars, a complete understanding of the early evolution of galaxies requires a knowledge of when and how the stars form. For example, if galaxies form by the condensation of diffuse pregalactic gas, their sizes and densities depend on how condensed this gas must become before most of it is turned into stars. The internal structure of a galaxy also depends on how the star formation rate varies with time in a collapsing protogalaxy: the formation of an elliptical galaxy or the bulge component of a spiral galaxy requires an early period of rapid star formation, while the formation of a disk requires much slower star formation, so that most of the gas can settle into a thin layer before turning into stars (Larson 1976*a*). Observations of the stellar content of galaxies show that most of the stars in elliptical galaxies did indeed form long ago, whereas in spiral galaxies star formation has proceeded much more gradually and in some cases is still going on as fast as ever (Tinsley 1978, 1980). Thus star formation in disk systems involves essentially processes that we observe at present in many spiral galaxies, while star formation in elliptical galaxies must have been more spectacular, involving processes that are no longer observed in most galaxies. An indication that star formation in elliptical galaxies was qualitatively, and not just quantitatively, different from that in spiral galaxies is the fact that most elliptical and bulge systems contain globular clusters, which are not observed to be forming at present in our own or other spiral galaxies.

A widely held view has been that star formation proceeds via the gravitational collapse of diffuse gas clouds that fragment into successively smaller and smaller condensations as the density rises and the Jeans mass decreases, until eventually protostars of stellar mass are formed (Hoyle 1953). Recent numerical work suggests, however, that unassisted gravitational collapse and fragmentation is an inefficient way to form low-mass protostars in a diffuse cloud. Simulations of three-dimensional collapse with a finite-particle scheme (Larson 1978*a*) suggest that successive fragmentation into smaller and smaller condensations is not important, and that the number of condensations finally formed is comparable with the number of Jeans masses initially present in the cloud. Calculations with a three-dimensional grid (Tohline 1980) suggest that even this amount of fragmentation may be difficult to achieve. These calculations show that one reason why fragmentation is limited is that the collapse is highly non-uniform, and that only a small fraction of the cloud's mass goes into the densest collapsing condensations and can therefore participate in the formation of even smaller condensations. The remaining more diffuse gas is unable to fragment further because its dynamics is dominated by the tidal forces produced by the already existing condensations, so it must eventually either be accreted by them or dispersed.

The amount of fragmentation that can occur in a diffuse cloud might be greatly increased if the cloud were compressed to a much higher density by external forces; the Jeans mass would then be decreased throughout the cloud rather than only in small condensations, and fragmentation into many low-mass protostars might be possible. A likely source of external pressure is collisions with other clouds; the importance of such collisions for star formation is suggested by the fact that the resulting dynamical pressure can produce directly a Jeans mass of order one solar mass (Larson 1976*b*, 1978*b*). The molecular clouds in which stars are observed to form suffer continual collisions with smaller clouds which they accrete (Kwan 1979; Scoville & Hersh 1979), and this probably plays an important role in producing the high observed densities in molecular clouds and in allowing fragmentation into solar-mass protostars.

Because most interstellar 'clouds' are not coherent objects and have large turbulent velocities (Larson 1979), they will probably not agglomerate efficiently into larger clouds unless some cohesive force, most plausibly gravity, holds the system of colliding clouds together and prevents it from dispersing. Such a large-scale gravitational effect could result from either (1) a large-scale gravitational instability of the gas layer, or (2) a density wave, either steady or transient, in the underlying stellar disk of a spiral galaxy. These mechanisms for initiating star formation are also among the most plausible ones for producing spiral structure in galaxies; thus the observed close connection between star formation and spiral structure might be explained by cloud collisions and agglomeration induced by either large-scale gravitational instabilities or density waves in the disks of spiral galaxies (Larson 1977).

Star formation in molecular clouds is actually a very inefficient process (Zuckerman & Palmer 1974), and therefore the star formation rate depends critically on the factors that determine the efficiency of star formation, or the mechanisms that induce star formation in molecular clouds. One factor influencing the efficiency is probably the density to which a molecular cloud is compressed before it begins to fragment; this is suggested by the three-dimensional collapse simulations, which show that the total mass in condensations increases with the density of the flattened disk-like layer that forms during the initial stages of the collapse (Tinsley & Larson 1979). This again suggests that dynamical compression may be important in initiating or enhancing the efficiency of star formation, and it therefore seems significant that the regions of most active star formation in molecular clouds are often located near their outer edges, as if the star formation had been triggered by external compression (Lada *et al.* 1978; Habing & Israel 1979). Possible triggering mechanisms include compression by an expanding H II region (Lada *et al.* 1978) or supernova remnant (Herbst & Assousa 1978), or a collision between two molecular clouds (Loren 1976, 1977). Recent data (Ho & Barrett 1978; Beckwith *et al.* 1979) suggest that the intense star formation in the Orion molecular cloud is occurring in a region where two cloud fragments are colliding and strong shock compression of the gas is taking place.

One reason why star formation is inefficient is that the collapse of the outer part of a protostellar cloud, which may contain a large part of its mass, is generally inhibited by rotation (and perhaps also by magnetic fields), even though the central part collapses to form a dense core. For example, in some of the calculations of Larson (1978*a*), an extended rotating accretion envelope forms around a central core, and further condensation of the envelope material is prevented by its angular momentum and by the tidal force due to the central core. Envelope material can continue to spiral inward and accrete on the core if the envelope possesses some viscosity, such as would be present initially due to turbulence, but this turbulence will soon die out unless external disturbances keep the envelope stirred up. Similarly, star formation is inhibited in spiral galaxies because the gas is spread out by its angular momentum into an extended disk whose average density is too low for self-gravity to compete with tidal forces; thus star formation cannot occur unless settling of the gas raises its density to the critical value required for gravitational instability (Goldreich & Lynden-Bell 1965), or unless the gas is locally compressed by dynamical perturbations (Larson 1977). Thus, in both protostellar clouds and spiral galaxies, external disturbances may promote star formation not only by directly compressing the gas but also by altering its angular momentum distribution, thus allowing more of it to condense into regions of high density where efficient star formation can occur.

For galaxies, a test of these ideas can be made by looking for evidence of enhanced rates of star formation in peculiar and interacting galaxies that have apparently experienced violent disturbances. This was done by Larson & Tinsley (1978), who examined the UBV colours of both normal and peculiar galaxies and found a significantly greater dispersion in the colours of the peculiar galaxies. They showed that the larger scatter in the colours of the peculiar galaxies can be explained if many of them have experienced recent bursts of star formation. Most of the scatter is produced by galaxies that are clearly interacting with companions, so there is evidence that bursts of star formation are triggered by violent interactions between galaxies. The actual mechanisms by which the interactions induce bursts of star formation are not known, but may include direct gas collisions, strong transient density waves, or infall of gas into the nuclei of the galaxies. Additional evidence for bursts of star formation in interacting galaxies is provided by infrared observations (Rieke 1978), which show large infrared fluxes from the central regions of many interacting galaxies, indicating high star formation rates near the centres of these galaxies.

Infrared and radio studies have revealed that the most spectacular bursts of star formation are not even observed optically because they occur in highly opaque clouds in the inner parts of galaxies such as M82, NGC 253, and NGC 1068 (Riecke 1978). Perhaps the most interesting of these galaxies is M82, which apparently has recently accreted fresh gas by interacting with M81 and is currently turning this gas into stars in a very intense burst of star formation (Solinger *et al.* 1977). M82 contains some young star clusters or associations that are much more luminous than any known in our galaxy (van den Bergh 1971); perhaps this is a hint that the intense early star formation that produced the globular clusters in elliptical galaxies was similar to the bursts of star formation that currently occur only in certain peculiar and interacting galaxies.

It is plausible that violent interactions were indeed important in causing rapid star formation in young elliptical galaxies; elliptical galaxies probably began with very irregular and inhomogeneous structures, and a great deal of interaction and merging of subsystems probably took place during their early evolution (Toomre 1977; Ostriker 1977; Rees 1977; Tinsley & Larson 1979). The initial perturbation spectrum postulated in gravitational clustering theories of galaxy formation (reviewed at this symposium by Jones, Fall and Aarseth) predicts initial masses of the order of 10^7–10^8 $M_\odot$, and the estimated Jeans mass in a collapsing protogalaxy is also of this order, so one might expect galaxies to begin as systems of subunits of this size. If the subunits contain large amounts of gas, then when they collide and merge, strong bursts of star formation may result. Tinsley & Larson (1979) have proposed a simple model in which all of the star formation in a proto-elliptical galaxy occurs in a sequence of bursts associated with a hierarchy of mergers of smaller units into larger ones, until a single merged system consisting mostly of stars remains.

This ‘burst’ model of star formation in elliptical galaxies makes a simple prediction that can be compared with observations: since larger galaxies have experienced more mergers, more bursts of star formation, and hence more complete processing of their gas into stars, they should have higher metal abundances than smaller galaxies. The observed metal abundances of elliptical galaxies vary with mass approximately as $z \propto M^{\frac{1}{4}}$, and this observation can be reproduced if the fraction of the gas turned into stars during a merger of two subsystems with total mass M is approximately proportional to $M^{\frac{1}{3}}$. A possible simple theoretical justification of this star formation 'law' has been given by Tinsley & Larson (1979). This law is qualitatively different from conventional formulations which regard star formation as a continuous process and express its rate as a function of quantities such as the gas density; here, star formation is regarded not as a steady process but as a series of discrete events, and is characterized not by a rate but by an efficiency that depends on the effectiveness of the interactions that trigger the bursts of star formation, and hence on variables such as the masses of the interacting systems. Perhaps this is the general type of star formation 'law' that further theoretical and observational work should attempt to test.

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