STAR FORMATION AND GALACTIC EVOLUTION

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1 Introduction: Basic Problems

Galaxies are, in their observable constituents, basically large bound systems of stars and gas whose components interact continually with each other by the exchange of matter and energy. The interactions that occur between the stars and the gas, most fundamentally the continuing formation of new stars from the gas, cause the properties of galaxies to evolve with time, and thus they determine many of the properties that galaxies are presently observed to have. Star formation cannot be understood simply in terms of the transformation of the gas into stars in some predetermined way, however, since star formation produces many feedback effects that control the properties of the interstellar medium, and that thereby regulate the star formation process itself. A full understanding of the evolution of galaxies therefore requires an understanding of these feedback effects and ultimately of the dynamics of the entire galactic ecosystem, including the many cycles of transfer of matter and energy that occur among the various components of the system.

Present data show strikingly that the structure and dynamics of the Galactic interstellar medium (ISM) are extremely complex, and it is clear that no simple model can represent adequately all of its important properties. This complexity is well illustrated, for example, by the results of the recently completed Leiden/Dwingeloo survey of the atomic hydrogen which is the dominant component of the Galactic ISM (Hartmann 1994; Hartmann & Burton 1995); six images representing different velocity slices from this survey are shown in the special color section of this volume. Even a superficial glance at these results shows immediately that the ISM is in a violently turbulent state, and on closer inspection one sees that features such as bubbles, loops, and filaments are almost ubiquitous, demonstrating the role of explosive energy input from massive stars in keeping the ISM in a vigorously bubbling and turbulent state. Also evident in this and other surveys is the intricate wispy structure of interstellar clouds, which resembles that of many terrestrial clouds. Observation of the terrestrial clouds with wispy shapes shows that they are in a highly dynamic state and that individual features are very transient, constantly forming, changing in structure, and evaporating. Much of the cloudy structure of interstellar clouds must also be very transient, so it is important to understand both the dynamical processes responsible for forming and structuring interstellar clouds and the thermal processes by which they may exchange matter with the surrounding more diffuse medium.

The system of interacting stars and gas phases in a galaxy may resemble in some respects a biological ecosystem, in which a great variety of interactions and cycles of exchange of matter and energy can occur among the various components. This makes possible very complex behaviors for the system, but under normal circumstances such an ecosystem tends to evolve toward a quasi-steady state in which all processes are more or less in balance and everything is effectively regulated by everything else, making it difficult to separate cause and effect. Galaxies, too, tend to settle into such quasi-equilibrium states in which they evolve only slowly and the entire complex system behaves in a regular and predictable way. This is demonstrated, for example, by the UBV colors of galaxies, which provide evidence about their star formation histories; although some peculiar galaxies may show a large scatter in color, the great majority of normal galaxies fall along a single well-defined sequence in the two-color diagram and have colors that apparently depend on a single parameter which is closely correlated with Hubble type (de Vaucouleurs 1977; Larson & Tinsley 1978). This color sequence is well accounted for by simple models of galactic evolution in which the only parameter that varies is the decay time for a postulated exponential decline of the star formation rate with time; the observed color range is reproduced if this decay time varies from less than 2 Gyr for elliptical galaxies through about 10 Gyr for intermediate-type galaxies like our own to effectively infinity for the latest-type spiral and irregular galaxies (Kennicutt 1986, 1992, and this conference; Larson 1991a, 1992b.) This trend reflects an increase along the Hubble sequence in the timescale for the conversion of gas into stars, which in turn probably reflects an increase along this sequence of the various dynamical timescales relevant to star formation; the most important underlying physical parameter may in fact just be the average density of galaxies, which decreases systematically along the Hubble sequence (Larson 1977, 1988, 1992b). In any case, it is clear that the timescale for gas depletion is the property of star formation that is most important for the overall evolution of galaxies. The various physical effects that determine this timescale will be discussed further in Section 2.

A second basic property of star formation which, together with the timescale, determines the colors and various other observed properties of galaxies is the distribution of masses or 'initial mass function' (IMF) with which stars are formed. A question which has long been debated is whether the IMF is universal or whether it varies importantly with location; although this issue has not yet been completely settled, most of the present evidence seems consistent with a nearly universal IMF that has two basic characteristics: (1) an approximate power-law form for masses above one solar mass, similar to the power law originally proposed by Salpeter (1955), and (2) a turnover at a mass somewhat below one solar mass where the IMF begins to fall well below an extension of this power law (Scalo 1986; Larson 1991b, 1992b; Zinnecker, this conference). The lower end of the IMF remains uncertain and may even be variable, but nevertheless it now seems clear that there cannot be much mass in very low-mass stars or 'brown dwarfs', and that with a standard IMF, most of the mass goes into stars with masses not very far from one solar mass. In other words, star formation makes stars with a characteristic mass of the order of one solar mass. This fact is obviously of great importance for astronomy generally, so it should be explainable by any quantitative understanding of star formation. The origin of this characteristic stellar mass and its possible relation to the properties of the interstellar medium will be discussed further in Section 3.

Since the alternative suggestion has been made that the typical stellar mass is determined by the internal physics of stars and not by the star formation process or the properties of the ISM (Shu, Adams, & Lizano 1987; Silk, this conference), it is worth noting that there is now some empirical evidence bearing on this question. An analysis of the spatial distribution of the T Tauri stars in the Taurus-Auriga clouds shows two distinct regimes, a regime of self-similar clustering at large separations and a regime of typically binary systems at smaller separations, with a clear break at a separation of about 0.04 pc (Larson 1995). The existence of this break implies that the clustering hierarchy is built up of basic units with a characteristic radius of about 0.04 pc, and this dimension thus appears as an intrinsic length scale in the star formation process. The associated star-forming cloud substructures can be identified with the dense 'ammonia cores' of the Taurus-Auriga clouds, which have typical diameters of about 0.1 pc and masses of about 1 $M_\odot$ (Myers 1985, 1987). Since star-forming units of this size form on the average just two stars, i.e. binary systems (Larson 1995), the expected mass of an individual star is about half of this core mass or about 0.5 $M_\odot$, in good agreement with the typical masses of the observed T Tauri stars. Thus there is evidence, at least in the Taurus-Auriga region, that star formation occurs in units of a characteristic size that is closely related to the typical stellar mass.

For the standard IMF mentioned above, only about 10 percent of the mass goes into those stars with masses greater than 10 $M_\odot$ that are responsible for most of the important feedback effects. This fraction depends on the form of the upper IMF, which is therefore another feature of star formation that is important for galactic evolution. Unfortunately, the properties of the upper IMF cannot be predicted at present because a quantitative understanding of the formation of massive stars does not yet exist, and is probably well beyond the current state of the art. The only approach to understanding this subject that is possible at present is therefore one based on phenomenology, and in this regard it is noteworthy that massive stars appear to form only in large clusters or associations along with large numbers of less massive stars. The formation of massive stars is thus evidently closely associated with the formation of clusters and associations. Some phenomenological aspects this subject will be discussed briefly in Section 4.

2 Star Formation Rates and Interstellar Recycling

The star formation rate in a galaxy depends on two types of processes: (1) effects that drive star formation by creating massive, dense star-forming clouds, and (2) negative feedback effects that limit the efficiency of star formation by destroying these clouds before most of their matter has been turned into stars. Although star formation may in some circumstances also produce positive feedback effects that stimulate further star formation (see Section 4), the net feedback effect of star formation must be negative rather than positive, otherwise all of the gas in galaxies would have been consumed long ago in a runaway process lasting only a small fraction of the age of the universe.

2.1 Effects Driving Star Formation

As reviewed by Larson (1988, 1992b), it seems likely that star formation is normally driven primarily by the large-scale self-gravity of the gas layer in a galaxy, perhaps assisted or organized by density waves. A gas disk is gravitationally unstable if the stability parameter $Q = c\kappa/\pi G\mu$ is smaller than about unity, where c is the velocity dispersion of random gas motions, κ is the epicyclic frequency, and μ is the surface density of the gas layer. Swing amplification, a kind of truncated instability that amplifies shearing density perturbations by a finite amount

(Goldreich & Lynden-Bell 1965; Toomre 1981, 1990), can occur for somewhat larger values of Q up to about 2, and is probably the mechanism usually responsible for collecting the interstellar gas in galaxies into the large complexes or spiral arm segments in which most star formation occurs. The requirement that Q must be less than a critical value of the order of unity for such large-scale gravitational instability effects to occur implies that, for given values of c and κ, large gas complexes should form and extensive star formation should ensue only if the gas surface density μ in a galaxy exceeds a minimum or threshold value. There is indeed evidence that significant star formation in galaxies occurs only where the gas surface density exceeds a threshold value that agrees quantitatively with the value predicted if star formation is driven by swing amplification effects (Kennicutt 1989; Larson 1991a, 1992b).

The time required to collect the interstellar gas into large cloud complexes is expected to be comparable to the growth time of the above instability, $\tau \sim c/\pi G\mu = Q/\kappa$, and this is about 50 Myr locally. The timescale for converting the gas into stars will, however, be much longer than this because star formation is observed to be a very inefficient process that converts only about 2 percent or less of the gas in a star-forming complex into stars before the rest is dispersed by the processes to be discussed below (Myers et al. 1986; Leisawitz et al. 1989; Evans & Lada 1991). In addition, with a standard IMF, only about half of the mass turned into stars remains permanently locked in low-mass stars, and the rest is eventually returned to the ISM by stellar mass loss; therefore only about 1 percent of the gas in a star-forming complex is permanently removed from the ISM. The expected timescale for gas depletion is then two orders of magnitude longer that the timescale for cloud formation, or about 5 Gyr locally. This predicted timescale for gas depletion is almost the same as the empirical timescale of about 7 Gyr inferred from the observed properties of galaxies like our own (Larson 1991a, 1992b), so it appears that this basic timescale for galactic evolution can be understood, at least in order of magnitude, if star formation is driven by the large-scale self-gravity of the interstellar medium.

2.2 Feedback Effects and the Efficiency of Star Formation

This result of course depends crucially on the observed low efficiency of star formation, so it is necessary for a full understanding of galactic evolution to understand what determines this efficiency. The formation of massive stars leads to a number of negative feedback effects including ionization, stellar winds, and supernova explosions that reduce the efficiency of star formation by destroying star-forming clouds and dispersing their gas before most of it has been turned into stars. All three of these effects probably play important roles in cloud dispersal, but the one that is probably most important in accounting for the very low efficiency of star formation is ionization. This is because stellar winds and supernovae are not by themselves very effective in destroying dense molecular clouds, since the associated shocks just tend to sweep around these clouds, ablating their outer layers but doing relatively little damage to their denser inner regions. By contrast, ionization simply evaporates even very dense clouds, and this destroys them very effectively at a rate that is not strongly sensitive to the cloud structure or density. Some of the ionized gas evaporated from star-forming clouds may stream away in 'champagne flows' with velocities of up to a few tens of km s^{-1} (Tenorio-Tagle 1979, 1982), but even without such flows, the ionized gas will be much more susceptible than the original molecular gas to being swept up by stellar winds and supernova shocks and dispersed in expanding shells. Therefore ionization is probably an important first step in the destruction of many star-forming clouds, and the amount of gas that is eventually removed from these clouds may depend mainly on the amount that is initially ionized, even though winds and supernovae may later play more important roles in actually dispersing this gas.

The amount of cloud gas that can be ionized by a cluster of newly formed stars has been estimated by Whitworth (1979) and Franco, Shore, & Tenorio-Tagle (1994) to be approximately 25 times the total mass of stars formed, assuming a standard IMF; this result depends only weakly on the structure or density of the star-forming cloud. If star formation continues over a period of time in a star-forming complex until all of the gas has been ionized, the efficiency of star formation is then predicted to be only about 4 percent. The actual efficiency can be expected to be even smaller than this because some of the cloud material can also be dispersed in neutral form as shells or fragments without ever being ionized; for example, if only half of the cloud material is ionized and the other half is dispersed in neutral form, the predicted star formation efficiency becomes only about 2 percent, similar to what is observed. Thus, the feedback effects of massive star formation can plausibly prolong the timescale for gas depletion from a gravitational timescale to a time much closer to the Hubble time, as is required to account for the observed properties of galaxies.

2.3 Interstellar Gas Cycling and Cloud Motions

Another consequence of cloud ionization is the large implied rate at which cloud gas is cycled into a more diffuse medium: the total rate of star formation in our Galaxy is about 3 $M_\odot$ yr^{-1}, so that if 25 solar masses of gas are ionized for every solar mass converted into stars, gas is ionized at a total rate of about 75 $M_\odot$ yr^{-1} throughout our Galaxy. This is a far larger mass flux between different phases of the ISM than any that is thought to be associated with more energetic phenomena such as supernova heating; for example, estimates of the rate at which gas is cycled through a supernova-heated hot medium or a galactic fountain are typically only a few $M_\odot$ yr^{-1}. Since the total mass of interstellar gas in our Galaxy is about 4×10^9 $M_\odot$, this ionization rate implies that the entire interstellar medium is cycled through an ionized phase every 50 Myr, on the average; a similar estimate for the local region yields an ionization cycling time of about 100 Myr (Larson 1988, 1992b). If half of the mass in a star-forming cloud is dispersed without being ionized, as suggested above, then the timescale for cycling the local ISM through the processes of cloud destruction is about 50 Myr, in agreement with the above estimate for the timescale for cloud formation by large-scale gravitational effects.

The gas evaporated from star-forming clouds must be a major source of new intercloud gas, and it is probably the most important source of replenishment for the warm intercloud medium that occupies much of the volume of interstellar space (Kulkarni & Heiles 1987; Cox 1990, 1991). The neutral component of the intercloud medium may be partly created by the recombination of ionized gas, and it is also possible that non-ionizing ultraviolet radiation from hot stars may heat and evaporate clouds to produce directly a neutral intercloud medium (Wolfire et al. 1995). In addition, the debris from star-forming clouds that is dispersed in the form of neutral shells or fragments must be a major source of new interstellar clouds, as was originally proposed by Oort (1954). Much of the cloud structure in the ISM may in fact belong to expanding shells or to the remnants of such shells, a possibility that is suggested by the ubiquitous appearance of shell-like or filamentary features in surveys such as the Leiden/Dwingeloo survey of the Galactic atomic hydrogen (Hartmann 1994; Hartmann & Burton 1995; see the color illustration in this volume.) The destruction of star-forming clouds by the various effects of star formation may thus account for much of the observed structure of the ISM.

Oort (1954) also proposed that the acceleration of cloud fragments by the 'rocket effect' associated with ionization could account for the observed random motions of interstellar clouds. In more recent discussions of this problem, most authors have regarded supernovae as the main energy source for cloud motions (e.g., Spitzer 1978). However, it is worth keeping in mind that the effects of supernovae on the dynamics of the real ISM, as distinct from simple models of the ISM, are complex and poorly understood, and that the role of supernovae in accounting for cloud motions therefore remains uncertain. In contrast, the physics of ionization is relatively simple, and its dynamical effects can be predicted with much less uncertainty: both the ionized outflows and the neutral cloud debris accelerated by the effects of ionization are predicted to acquire velocities of the order of 10 km s^{-1}, which is just the sound speed in the ionized gas. It is notable that the observed velocity dispersion of random gas motions in galaxies is also typically about 10 km s^{-1}, so that this characteristic velocity dispersion could be accounted for naturally as a consequence of ionization effects if these motions are not dissipated faster than they are generated by the destruction of star-forming clouds. At least some interstellar motions must have long dissipation times comparable to the period of vertical oscillation in the Galactic disk, since a significant part of the ISM is observed to be organized into structures whose size is comparable to the thickness of the gas layer (see again the results of the Leiden/Dwingeloo survey). Cloud debris or shells ejected from the Galactic plane will fall back into the plane after about half of a vertical oscillation period, or about 40 Myr locally, and the associated gas motions will then be dissipated; since this dissipation time is comparable to the timescale for cycling of the ISM through star-forming clouds, ionization effects alone might indeed account for a significant fraction of the turbulent motions in the ISM, as proposed by Oort (see also Larson 1987, 1994; Tenorio-Tagle & Bodenheimer 1988). Of course, velocities much larger than 10 km s^{-1}, which are not rare, can only be generated by more energetic phenomena such as stellar winds and supernovae.

If gas evaporated from star-forming clouds is cycled into an intercloud medium at a rate of $\sim 75\ M_\odot\ yr^{-1}$ throughout our Galaxy, then in a steady state, intercloud gas must condense back into clouds at the same rate. It is not presently understood just how and where this condensation of intercloud gas back into clouds takes place. However, it is known that the intercloud medium in our Galaxy has a relatively large scale height, especially the ionized component which has a scale height of about a kiloparsec (Kulkarni & Heiles 1987; Cox 1990; Reynolds 1991). If the ionized gas now observed at considerable distances from the Galactic plane originated in star-forming regions closer to the plane, and if it eventually recombines and cools when it no longer has a source of ionizing radiation, the cool neutral gas so produced may rain back down into the Galactic plane at velocities of a few tens of km s^{-1}. Such a moderate-velocity inflow of neutral gas is in fact observed, and it is clearly evident in the results of the Leiden/Dwingeloo survey, where at high latitudes above and below the Galactic plane the sky is seen to be filled with gas at moderate negative velocities of a few tens of km s^{-1} which has no counterpart at the corresponding positive velocities (see the color illustration in this volume). This high-latitude inflow has been known for some time, but its magnitude and significance have remained unclear because the distance of most of this gas is unknown. The fact that it is widely distributed on the sky suggests that most of it may not be very distant, and if this is the case, the inflow rate can be very large. According to Mirabel (1989), the net rate of inflow of moderate-velocity gas into the Galactic disk is about $10\,z(\mathrm{kpc})^{-1}\ M_\odot\ yr^{-1}$, where z(kpc) is the typical distance of this gas in kiloparsecs from the Galactic plane. If the typical distance of this gas should be as small as, say, 200 pc, then its net inflow rate would be ~ 50 $M_\odot\ yr^{-1}$, comparable to the rate at which gas is ionized in our Galaxy. Such an inflow might then account for much of the replenishment of cool cloud gas that is required in the Galactic disk. Perhaps something like a terrestrial precipitation cycle occurs, in which gas evaporated from star-forming clouds near the Galactic plane rises to heights of a few hundred parsecs where it recondenses into cool neutral clouds and then rains back down into the plane. Clearly it will be of great importance to establish whether such circulations actually occur, because if so they could constitute the dominant cycling phenomenon in the ISM.

3 The Mass Scale for Star Formation

3.1 Cloud Fragmentation and the Jeans Mass

Most star-forming clouds are sufficiently massive and dense that they are strongly self-gravitating and are expected to be able to fragment into many smaller gravitationally bound clumps; such dense clumps or 'cores' are indeed often observed in them, and they are the birth sites of stars and groups of stars (Myers 1985, 1987). If star-forming clouds collapse into sheetlike or filamentary configurations before fragmenting, as is suggested by their observed shapes and also by numerical simulations, gravitational stability analyses predict that they should fragment into clumps with a characteristic mass or 'Jeans mass' that depends on the cloud temperature and surface density. Nearby star-forming clouds are all observed to have similar temperatures and surface densities, and for these typical values, a Jeans mass of the order of one solar mass is predicted (Larson 1985).

More generally, regardless of its shape, a self-gravitating cloud with a given surface density has an internal gravitational pressure proportional to the square of its surface density, and this pressure together with the cloud temperature again determines a mass scale for fragmentation. The structure and dynamics of star-forming clouds are still poorly understood in detail, but it is clear that throughout most of the volume of such a cloud the pressure is not primarily thermal but is mainly supplied by turbulent motions or magnetohydrodynamic phenomena such as Alfvén waves; only in the densest core regions does the thermal pressure become comparable to the ambient non-thermal pressure, which is found to have a similar characteristic magnitude in clouds with a wide range of sizes (Larson 1981; Myers & Goodman 1988). This suggests that protostellar clumps may form in approximate pressure balance with a characteristic ambient cloud pressure, and that this cloud pressure may be the most physically significant quantity controlling the mass scale for fragmentation. The Jeans mass can then be estimated as the mass of a critically stable isothermal sphere or 'Bonnor-Ebert sphere' with a boundary pressure equal to the ambient cloud pressure, and this critical mass is $1.18\,c^4/G^{3/2}P^{1/2}$ where c is the sound speed of the isothermal sphere and P is its boundary pressure (Spitzer 1968).

The cores of nearby molecular clouds such as the Taurus clouds have temperatures near 10 K and typical particle densities of about 3×10^4 cm^{-3} (Myers 1985, 1987), implying pressures of about 3×10^5 cm^{-3} K. The same value for the typical pressure in molecular clouds is implied by the surface density of ~ 100 M$_\odot$ pc^{-2} of these clouds (Larson 1981), assuming that they are gravitationally bound; for example, a flattened (but not necessarily sheetlike) cloud of surface density μ has a midplane pressure $\pi G \mu^2/2$, which for $\mu \sim 100$ M$_\odot$ pc^{-2} again yields a pressure of $\sim 3 \times 10^5$ cm^{-3} K. Substituting this pressure and the sound speed of 0.19 km s^{-1} appropriate for a temperature of 10 K into the above expression for the mass of a critically stable isothermal sphere, we obtain a mass of about 0.7 M$_\odot$, and the radius of such a sphere is about 0.03 pc. These predictions agree well with the evidence discussed in Section 1 that stars are formed with a characteristic mass of the order of one solar mass and that, at least in the Taurus-Auriga clouds, star formation occurs in cloud subunits with a radius of about 0.04 pc (Larson 1995). Thus, the classical idea that typical stellar masses are determined basically by the Jeans mass can perhaps now be applied with some confidence in the orders of magnitude involved, and it appears to fare well in comparison with the available evidence.

An alternative view of the origin of stellar masses supposes that stars form from singular isothermal spheres of indefinite size, and that they grow in mass by accretion at a constant rate until the accretion process is shut off by a stellar wind (Shu et al. 1987; Silk, this conference.) However, in a real star-forming cloud it does not make sense to consider an isothermal sphere of indefinite size, because at some radius the thermal pressure in such a sphere will drop below the ambient non-thermal pressure; beyond this point departures from spherical symmetry will probably become very important, and the dynamics will no longer be controlled by a static balance between thermal pressure and gravity but by the more chaotic and violent phenomena of turbulence and magnetohydrodynamic waves that provide the dominant form of pressure support in molecular clouds. These effects will probably tend to inhibit or prevent the accretion of more gas from the surrounding region, but whatever may happen in detail, it clearly cannot be assumed that accretion will continue at a constant rate after the gas in the thermally supported region has been accreted. The mass contained in the thermally supported region is essentially the Jeans mass as calculated above.

3.2 Cloud Pressurization

If the characteristic stellar mass depends on the pressure in star-forming clouds, what then determines this pressure? The typical internal pressure in such clouds exceeds by two orders of magnitude the thermal pressure in most of the interstellar medium, and by one order of magnitude the overall pressure generated by the weight of the ISM (Cox 1990, 1991; Boulares & Cox 1990). Therefore the high pressure in molecular clouds must have a dynamical origin, and it must be generated by the cloud formation process itself. Large molecular clouds are probably built by the collisional agglomeration of smaller mostly atomic clouds in those regions where the large-scale self-gravitational effects discussed in Section 2.1 cause the interstellar gas to pile up (Larson 1988, 1994; Elmegreen 1993). This collisional agglomeration process generates a dynamical pressure ρv^2, where ρ is the density of the colliding clouds and v is the velocity with which they collide. For atomic clouds with a typical particle density of 20 cm^{-3} (Spitzer 1978) colliding at a velocity of 10 km s^{-1}, the ram pressure generated is about 3×10^5 cm^{-3} K, which is the same as the typical internal pressure in molecular clouds; therefore this process can plausibly account for the high pressures discussed above. It was already suggested in Section 2.3 that the typical cloud velocity of $\sim$ 10 km s^{-1} may be explainable largely as a consequence of ionization effects, so the remaining quantity needing to be accounted for on some physical basis is the typical density of the atomic clouds.

In the classical two-phase model of the ISM (Field, Goldsmith, & Habing 1969), the density of the atomic clouds is determined by a pressure balance between these cool clouds and a warm intercloud medium. A similar two-phase model may still apply to the bulk of the Galactic ISM, since the clouds and the intercloud medium together account for nearly all of the mass of the ISM, and occupy a substantial fraction of its volume. An approximate balance in thermal pressure might also be expected to exist between the atomic clouds and the intercloud medium, even though the overall pressure of the ISM is provided mostly by turbulent motions and magnetic fields (Cox 1990, 1991), because thermal pressures should still tend to equalize along magnetic field lines. Given the typical temperature of the atomic clouds, which is controlled by radiative processes, the typical density of these clouds is then determined by the thermal pressure of the intercloud medium. The physics of the two-phase model has been reexamined in detail by Wolfire et al. (1995), who find that with current estimates of the efficiency of photoelectric heating, the thermodynamic properties of both the atomic clouds and the intercloud medium can be accounted for satisfactorily on the assumption that they are in thermal and pressure equilibrium. As in the original two-phase model of Field et al. (1969), pressure balance between the clouds and the intercloud medium can exist only for pressures within a limited range of values that depends on several parameters including the flux of ultraviolet radiation responsible for the photoelectric heating. For typical values of these parameters, Wolfire et al. (1995) find that the maximum pressure that is possible for a two-phase system is about 3600 cm^{-3} K; any increase in the pressure above this value would cause all of the intercloud gas to condense into clouds. In the presence of star formation, which evaporates star-forming clouds and thereby replenishes the intercloud gas, it seems likely that the pressure of the intercloud medium will be regulated to remain near this maximum value, since cloud evaporation will tend to increase the intercloud pressure until the maximum value is approached and intercloud gas begins to condense back into clouds at a rate sufficient to balance evaporation. The thermal pressure predicted on this basis is, in fact, in good agreement with observational estimates of the thermal pressure in much of the ISM (Kulkarni & Heiles 1987; Wolfire et al. 1995).

If, for example, we assume a thermal pressure of 3000 cm^{-3} K and a typical cloud temperature of 100 K, the predicted typical cloud density is 30 cm^{-3} and the dynamical pressure produced by collisions between such clouds is about 4×10^5 cm^{-3} K, quite sufficient to account for the internal pressures of molecular clouds. Thus, the cycling of interstellar gas between clouds and an intercloud medium by the effects of star formation may account for not only the structure but also the thermal properties of the bulk of the ISM, including those that regulate the mass scale for star formation.

4 The Formation of Massive Stars and Stellar Aggregates

The preceding sections have addressed two basic properties of star formation, namely the timescale for gas depletion and the origin of the characteristic stellar mass, and have suggested that these properties can be understood, at least in part, as consequences of cloud evaporation and the thermal control of the ISM by ultraviolet radiation from massive stars. Another crucial property of star formation is thus the fact that, with a standard IMF, approximately 10 percent of the stellar mass goes into those stars with masses above 10 $\mathrm{M}_\odot$ that are responsible for most of these effects. The discussion of the mass scale for star formation in Section 3 implies that the formation of massive stars must be a more complex and chaotic process than the formation of low-mass stars, probably involving the accretion of gas with a clumpy non-spherical distribution and supersonic turbulent motions. It is possible that the accumulation processes involved in the formation of massive stars proceed hierarchically and are controlled by fractal-like cloud geometry (Larson 1992a), but there is at present no quantitative model for the formation of massive stars. Therefore, to make further progress, it is necessary at this point to abandon any further attempt at a complete physical understanding of things and resort to phenomenology.

It has long been clear that the formation of massive stars occurs preferentially, if not exclusively, in large clusters and associations (Blaauw 1964, 1991), and there is even some evidence suggesting that the most massive stars tend to form near the centers of the most massive clusters (Larson 1982; Lada et al. 1991; Zinnecker, McCaughrean, & Wilking 1993). The formation of massive stars is thus evidently closely linked to the formation of large aggregates of stars. In recent years infrared observations have greatly expanded our observational knowledge regarding the formation of groups and clusters of stars, and this subject has been reviewed by Lada & Lada (1991), Lada, Strom, & Myers (1993), Zinnecker et al. (1993), and Larson (1993). Stars and groups of stars are observed to form only in the dense core regions of molecular clouds, and large clusters are observed to form only in the densest and most massive cores of the most massive molecular clouds (Lada et al. 1993; Carpenter, Snell, & Schloerb 1995); thus, to understand the formation of massive stars it is necessary to understand the origin of these dense and massive cloud cores.

The formation of dense clumps and of associated groupings of stars with a hierarchy of sizes is apparently a rather universal feature of star formation. Even in the Taurus-Auriga clouds, which have often been considered to represent an 'isolated' mode of star formation (Lada et al. 1993), the observed T Tauri stars are actually distributed in a hierarchy of small groupings (Gomez et al. 1993; Larson 1995). The origin of the clumpy molecular filaments from which they have formed is not known, but it has been noted that these clouds may be associated with the remnants of an old OB association, the Cassiopeia-Taurus association (Blaauw 1991). A larger and more concentrated grouping of newly formed stars, which has been much studied as a possible candidate for a young open cluster, is found embedded in the dense core of the ρ Ophiuchi cloud (Wilking, Lada, & Young 1989; Wilking 1992; Greene & Meyer 1995); this cluster contains most of the newly formed stars associated with the ρ Oph cloud, and it is also the most active current site of star formation in the entire Ophiuchus-Scorpius-Centaurus region, where several previous episodes of star formation have produced an OB association with several subgroups (Blaauw 1991). In this case there is suggestive evidence concerning the origin of the observed cloud structure: the ρ Oph cloud core forms the head of a filamentary comet-shaped cloud located on the edge of the youngest subgroup of the OB association, the Upper Scorpius subgroup, and the long tail of this cloud points away from the center of this subgroup (de Geus, Bronfman, & Thaddeus 1990; de Geus 1991; Blaauw 1991). Several smaller molecular clouds in the vicinity also have windswept appearances suggesting that they have been ablated by outflows from the Upper Scorpius subgroup. The occurrence of an explosive phenomenon this region is clearly indicated by the fact that the distribution of atomic gas shows a large cavity bounded by a shell expanding away from the Upper Scorpius OB subgroup (de Geus 1991; Blaauw 1991). The molecular clouds mentioned above are located just outside this cavity in a region where the expanding shell appears to be interacting with denser gas closer to the Galactic plane, and they are elongated away from the center of the cavity. This evidence strongly suggests that these clouds have been shaped, and perhaps also compressed, by an energetic outflow or expanding shell emanating from the Upper Scorpius OB subgroup.

Similar phenomena appear to be occurring on an even larger scale in the Orion region. The Orion A and B molecular clouds border on the Orion OB1 association, and they both show evidence of being ablated and compressed by energetic outflows from this OB association (Blaauw 1991; Bally et al. 1991). Most strikingly, the Orion A cloud, which contains the Trapezium cluster in its densest core region, again has an elongated comet-like shape with a tail pointing away from the center of the OB association. The Trapezium cluster is a large and highly concentrated cluster of newly formed stars (Zinnecker et al. 1993) which contains some of the most massive stars in the entire Orion region, including the single most massive star θ^1C Orionis, located in the Trapezium system at its center. The Orion B cloud is not as elongated, but it is nevertheless clearly asymmetrical in its structure: the edge closest to the center of the OB association is relatively sharply bounded and is marked by a string of massive clumps, some of which again contain compact embedded clusters similar to but smaller than the Trapezium cluster (Lada 1992; Lada et al. 1993). Many smaller cometary clouds are observed throughout the Orion region, and they too all have tails pointing away from the center of the OB association (Bally et al. 1991). The entire Orion star forming region is surrounded by the very large Orion-Eridanus shell of atomic gas, whose rapid expansion has probably been powered by stellar winds and supernova explosions produced by stars formed in the Orion OB1 association, possibly including runaway stars (Brown, Hartmann, & Burton 1995). All of this evidence leaves no doubt that explosive phenomena in the Orion region have strongly influenced the structure of the remaining molecular clouds, ablating them into the observed cometary shapes and perhaps also compressing their densest parts yet further to produce the very dense cores in which the observed clusters of stars have formed (Bally et al. 1991; Elmegreen 1992; Larson 1993, 1994).

While these examples can hardly be considered as definitive, they do suggest that the formation of star clusters can be influenced, and perhaps even caused, by the effects of prior episodes of massive star formation in the same region. Some further examples of apparently similar phenomena have been discussed by Elmegreen (1992), Carpenter et al. (1995), and Goldsmith (this conference). The processes involved are evidently more energetic than those discussed in Section 3 in connection with the formation of low-mass stars, and stellar winds and supernovae must be involved in producing the large expanding shells that have been observed (de Geus 1991; Brown et al. 1995). The formation of dense star clusters may thus represent a type of triggered star formation (Elmegreen 1992; Larson 1993), although this does not necessarily imply that star formation is generally a triggered process, since not all stars, or even all massive stars, are formed in such compact clusters (Blaauw 1991). In any case, it would appear that the formation of massive stars and stellar aggregates requires more extreme conditions and involves more energetic feedback effects than does the formation of low-mass stars.

Our prime laboratory for studying the various feedback effects of star formation on the ISM is of course the Large Magellanic Cloud, and this is evidenced by the many contributions to this conference dealing with the LMC and the numerous stellar groupings and shell structures of all sizes that it contains. There has been much speculation in the literature that star formation in various parts of the LMC has been triggered by expanding shells or supershells, or by interactions between such shells (Bruhweiler, Fitzurka, & Gull 1991; Elmegreen 1992; Larson 1993). For example, the most luminous H II region in the entire Local Group of galaxies, the 30 Doradus H II region or 'Tarantula Nebula' in the LMC, contains several luminous young clusters and a plethora of violently expanding and interacting shell structures (Meaburn 1984), and it is possible that continuing star formation in this region has been triggered by the expansion and interaction of these shells (Hyland et al. 1992). On a larger scale, the 30 Doradus complex itself appears to be located near a point where two very large supershells overlap, and it has been suggested that the expansion of these supershells has triggered the star formation activity in the 30 Doradus region (Bruhweiler et al. 1991). However, such effects, energetic though they might be, cannot plausibly account for the very large and massive concentration of gas that is observed to be associated with 30 Doradus, which has a size of about 2 kpc and a total mass of about 10^8 $M_\odot$; the origin of this large gas complex is probably related instead to the fact that it is located near the end of the LMC bar, which is a location where the gas flows in barred galaxies tend to converge and the gas tends to accumulate. Large complexes of gas and young stars are in fact often seen in such locations, for example in M83 where a large star-forming cloud complex of similar size and mass is found near the end of the bar (Kenney & Lord 1991).

Regardless of its origin, the 30 Doradus complex is worthy of extensive study because it shows examples of nearly all of the types of feedback effects that have been discussed, including ionization, wind-blown bubbles, supernova remnants, and large expanding shells produced by groups of massive stars (Wang, this conference; Chu, this conference). At the center of the 30 Doradus H II region is the most massive young star cluster in the Local Group, NGC 2070, also called the R136 cluster after its luminous central grouping of massive stars; in several ways it resembles the Trapezium cluster but is scaled up by about two orders of magnitude in mass, making it a candidate for a young globular cluster of modest size (Hunter et al. 1995). Hubble Space Telescope observations of the stellar content of this cluster show, perhaps surprisingly, that it has a quite normal stellar IMF down to the smallest masses that can be studied (Hunter et al. 1995), suggesting that processes similar to those that occur in nearby star-forming regions may also operate on larger scales and in more extreme circumstances such as those relevant to the formation of globular clusters. As many of the contributions to this conference make clear, the study of these processes is rapidly becoming less a subject based on speculation and more a subject based on a large body of observational fact.

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Figure Caption:

This illustration shows six images representing six velocity slices from the Leiden/Dwingeloo Survey of Galactic Neutral Hydrogen, by Dap Hartmann & W. B. Burton, Leiden Observatory; to be published by Cambridge University Press, 1995. Images supplied courtesy of Dap Hartmann.