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LARGE SCALE STAR FORMATION: MOLECULAR CLOUDS AND MASSIVE STARS

José Franco
Instituto de Astronomía, Universidad Nacional Autónoma de México

RESUMEN

Se describen las principales ideas sobre la formación de grandes nubes interestelares y sobre el papel que juegan las estrellas masivas en el ciclo de formación estelar. Las nubes masivas se pueden formar mediante inestabilidades a gran escala o mediante perturbaciones fuertes en un disco gaseoso con esfuerzos cortantes. La energía inyectada por las estrellas recién formadas puede destruir a sus nubes maternas y la actividad de formación estelar resulta ser autolimitada. El mecanismo más eficiente para destruir a las nubes es debido a la fotoionización de las estrellas masivas. El número máximo de estrellas OB que se pueden formar en las regiones densas de las nubes moleculares es del orden de 10 por cada 10^4 $M_\odot$ de gas. Suponiendo un factor de llenado de 0.1 para estas regiones densas, la eficiencia de formación estelar en los complejos moleculares es del 5%. Una vez que las nubes son dispersadas, el efecto combinado de los vientos estelares y las explosiones de supernova de las asociaciones OB generan grandes burbujas en expansión. Estas remanentes de multi-supernovas son responsables de mantener la estructura del gas interestelar y de controlar la actividad de formación estelar en galaxias aisladas.

ABSTRACT

The main ideas for the formation of large interstellar cloud complexes and the role of massive stars in the star formation cycle are reviewed. Massive cloud complexes can be formed via large scale instabilities or by the action of strong perturbations evolving in a sheared disk. The energy injected by new stars can destroy their parental clouds and, hence, the star forming activity in these clouds is self-limited. The most efficient cloud destruction mechanism is due to photoionization from massive stars, which limits the population of massive stars. The maximum number of OB stars that can form within a dense molecular cloud fragment is of order 10 per 10^4 $M_\odot$. Assuming a filling factor of 0.1 for these dense fragments, the resulting star forming efficiency within cloud complexes is roughly 5%. Once the parent cloud is dispersed, the combined action of stellar winds and supernova explosions from OB associations generate large expanding bubbles. These multisupernova remnants are responsible for the bulk properties of the general interstellar gas, and can control the overall star forming activity in isolated galaxies.

Key words: **ISM – CLOUDS — ISM – SUPERNOVA REMNANTS — STARS – FORMATION**

1. INTRODUCTION

The star forming activity of gaseous galaxies depends both on the internal structure of the host galaxy and on its interaction with other galaxies, or with the intergalactic medium. In the case of isolated galaxies. the activity is regulated by the internal sources of energy and by some basic system properties (such as the total mass distribution, the gas content, the distribution of angular momentum, the abundances of heavy elements, the magnetic field strength, etc.; see Elmegreen 1992 and Franco 1991,1992). For the case of systems undergoing a strong interaction with their environs (*i. e.,* tidal interactions with companions, mass stripped by an intercluster medium, direct collisions with other galaxies or with intergalactic clouds etc.), the resulting phenomena (and final galaxy configurations) depend on the nature and strength of the interaction. Dynamical friction among members of a galaxy cluster may result in the creation of massive central galaxies, whereas direct galaxy collisions can generate superluminous mergers with spectacular bursts of star formation (*i. e.,* Melnick & Mirabel 1990; Mirabel *et al.* 1991; see Mirabel 1992).

Obviously, actual galaxies are open systems and their evolution should pass through some quiet periods in relative isolation followed by "active" moments with interactions. All interactions can heavily modify any one of the basic system properties, and some may be totally disruptive, but the interactions occur at random intervals and it is difficult to evaluate their integrated effect during the lifetime of a galaxy. Thus, at present, it is not possible to create "realistic" tracks for the star forming history of any given open system, although some important aspects of the overall history have been observationally derived for different types of galaxies (see Larson 1992 and Kennicutt 1992). A much simpler task, at least in principle, is to evaluate the role played by different internal agents in defining the bulk structure of isolated galaxies. In particular, the creation of massive gas structures, with their corresponding star formation rates, and the interaction between gas and stars are relevant aspects in approaching these questions. There is a very extensive list of recent reviews and conference proceedings devoted to discussing some of these and related topics (*e. g.* Dickman *et al.* 1988; Dupree & Lago 1988; Pudritz & Fich 1988; Tenorio-Tagle & Bodenheimer 1988; Thuan *et al.* 1988; Efremov 1989; Hodge 1989; Reipurth 1989; Tenorio-Tagle *et al.* 1989, 1992; Torres-Peimbert and Fierro 1989; Blitz 1990; Capuzzo-Dolcetta *et al.* 1990; Henning 1990; Thronson & Shull 1990; Combes & Casoli 1991; Falgarone *et al.* 1991; Ferrini *et al.* 1991; Janes 1991; Kylafis & Lada 1991; Leitherer *et al.* 1991; Rana 1991; Young & Scoville 1991; Elmegreen 1992a; Matteucci 1992; Palouš *et al.* 1992; Franco *et al.* 1993b), and it would be very difficult to make a fair review of them in this short paper. Hence, here we will focus only on some of the main features of large scale star formation and the interaction between gas and young stars.

2. THE ORIGIN OF STAR FORMING CLOUDS

The formation of a star, or a stellar cluster, is the end product of a series of succesive condensations of the interstellar gas. There are a large number of questions about the details of the collapse under current investigation (see Bodenheimer 1992), but an important aspect of the early stages of the process is how and when molecular cloud complexes are formed. One can separate two different parts of this problem: i) the minimum conditions for molecular cloud formation, and ii) the type of processes leading the gas to reach those conditions.

First, a distinction must be made between self-gravitating and molecular clouds. A simple illustration of this distinction is given by small irregular galaxies: they are gas rich, self-gravitating systems, but most of their gas is atomic, not molecular. Self-gravity decouples the cloud from the ambient interstellar pressure, and drives it into a more compact structure, but does not neccesarily provide the conditions to increase the abundance of molecular species. The actual mechanism driving the atomic to molecular transition is *opacity*; molecules are destroyed by the ambient UV field and a minimum column density is required to reduce the photodissociation rate. The specific functional form and value of such a minimum column density is different for different molecular species. For H_2, which is the most abundant molecule, self-shielding is very important and the photodestruction of H_2 molecules in the external cloud layers is one of the main sources of opacity. In the solar neighborhood, the H-H_2 transition region requires column density values of order $\sim 5\times10^{20}$ cm^{-2} (*i. e.,* Hollenbach *et al.* 1971; Federman *et al.* 1979; Elmegreen 1989; Burton *et al.* 1990; Meixner & Tielens 1993). In the case of trace molecules, such as CO, the photodissociation rates are more uncertain but self-shielding seems to be important only at high-densities (*e. g.* Burton *et al.* 1990; Meixner & Tielens 1993; Turner 1993), and dust grains can provide the opacity at the low and moderate densities of the diffuse cloud medium. The resulting column density values for dust opacity are similar to those required by H_2 self-shielding, but the dust forming compounds introduce a dependence on the abundances of heavy elements, Z (Franco & Cox 1986). Given that H_2 is preferentially formed on dust grains, a similar Z-dependence can be introduced in the case of H_2 self-shielding (Elmegreen 1989). Thus, for regions with solar abundances, the formation of a molecular cloud (or a molecular core in a diffuse cloud) requires a shielding column density of order 5×10^{20} cm^{-2}, but for the case of galaxies with other abundances, the required value scales roughly inversely with metallicity. A recent study of the molecular cloud properties in the Magellanic Clouds (Rubio *et al.* 1991) corroborates this view.

The second aspect, the compression of diffuse interstellar regions to reach the required column densities, includes at least 3 different mechanisms: shock fronts in colliding streams, thermal instabilities, and gravitational instabilities. Each of these processes (and any combination) can operate under a wide variety of different conditions and molecular cloud formation can proceed through a series of different channels (*e. g.* Struck-Marcell & Scalo 1984; Kwan 1988; Larson 1988; Tenorio-Tagle & Bodenheimer 1988; Elmegreen 1991, 1993; Franco 1991, 1992; Palouš *et al.* 1993; Vazquez *et al.* 1993). Thermal instabilities are important because, due to the difference in density dependence in the cooling and heating functions, small density fluctuations can be amplified under a variety of radiative cooling regimes (*e. g.* Field 1965; Balbus 1986; Ferrara & Einaudi 1992; Elmegreen 1993). Thus, this instability should be operative in the conversion of the ionized to atomic gas phases and in the cooling of a cloudy fluid. Recent numerical models indicate that such thermal instability may be a key mode of cloud production when supersonic turbulence dominates the interstellar velocity field: the compressive component of the turbulent velocity field triggers thermal instabilities, which in turns triggers gravitational instabilities and forms massive clouds (Vazquez *et al.* 1993). Stellar activity maintains the turbulent energy content in these models and the results of Vazquez *et al.* (1993) confirm that the bulk structure of the interstellar medium and the star formation rate could be regulated by the stellar energy injection, as has been discussed in the literature for the last two decades (*e. g.* Cox & Smith 1974; McKee & Ostriker 1977; Gerola & Seiden 1978; Franco & Shore 1984; Mac Low *et al.* 1989; McCray 1988; Tenorio-Tagle & Bodenheimer 1988; Franco 1992; Palouš *et al.* 1993). In particular, the shocks created by the stellar activity produce large gas concentrations which eventually can become star-forming clouds. This issue is further discussed in the next section.

Gravitational instabilities operate at a variety of different scales, and the details of the instability depend on the shear generated by differential rotation and on the magnetic field strength and orientation (*e. g.* Chandrasekhar 1954; Safronov 1960; Toomre 1964; Mestel 1965; Parker 1966; Quirk 1972; Shu 1974; Jog & Solomon 1984; Elmegreen 1987). The shear and gas velocity dispersions provide support against collapse, and a minimum disk column density is required to enter into the unstable regime. This threshold condition is usually called the "Toomre" criterion (see Elmegreen 1993 for an alternative definition of this type of criterion), and spiral waves appear whenever the stellar fluid reaches this criterion. The gaseous disk, which is usually cooler than the stellar disk, has a stronger response to the instabilities and large interstellar masses can collapse in the gravitational well provided by the spiral wave (see Elmegreen & Thomasson 1993 and references therein). When a B-field is present, there are several possible outcomes because the instabilities develop following the orientation of the lines. For plane parallel geometries with partial magnetic support, the compression generated by a spiral wave changes the magnetic field downstream and the gas driven by the distorted field lines accumulates large mass clouds along the arms. This is called the "Parker" instability and, as in the case of the Toomre instability, it can also gather giant cloud complexes at the spiral arms (*e. g.* Mouschovias *et al.* 1974; Shu 1974; Elmegreen & Emegreen 1986). When both shear and magnetic stresses are included, the threshold conditions disappear and instabilities can be triggered by any strong perturbation (*e. g.* Elmegreen 1987). The inclusion of all of the forces driving these separate instabilities in a sheared disk has been recently discussed by Elmegreen (1993). The resulting "combined" instability (*i. e.,* thermal, gravitational, and Parker) depends on the relative strength of all the terms involved, and seems to have growth rates scaling with the gas density to a power ranging from ~ 0.3 to 0.5. The characteristic wavelength is large, about 2.5 kpc, and the instability can collect masses of order 10^7 $M_\odot$.

Cloud-cloud collisions in a diffuse cloudy medium can have similar effects and cloud growth by collisions has been extensively studied with analytical and numerical models (see reviews by Kwan 1988 and Elmegreen 1991). In the absence of magnetic fields, the outcome of collisions among pressure bounded clouds depends on their column densities and shock velocities. The cooling column density is one of the main parameters; a shock front evolves in a quasi-adiabatic mode before sweeping a cooling column density, N_c, and becomes strongly radiative afterwards. If the cloud collision ends before N_c has been collected, the hot gas re-expands and disperses into the ambient medium. Otherwise, if the gas is already cool at the end of the collision, the colliding clouds can merge and form a denser and more massive structure. Numerical simulations with self-gravity indicate that collisions among identical clouds tend to induce gravitational instabilities, but the interaction tends to be more disruptive when the clouds have different densities or sizes (*e. g.* Hausman 1981; Gilden 1984). Here the criterion for coalescence is that the re-expansion velocity should be smaller than the escape velocity of the system which, again, can be written in terms of a column density. Thus, either with or without self-gravity the outcome of the collisions depends on the column densities and velocities of the interacting clouds. Similar criteria can be applied to the interaction of high-velocity clouds with the disk of the Galaxy (*i. e.,* Tenorio-Tagle *et al.* 1986, 1987; Franco *et al.* 1988; Comerón & Torra 1992), or to a variety of other interactions involving cooling shocks. When a B-field is included, the energy and momentum transfer along the field lines increases the energy dissipation and a magnetic cloud fluid tends to be more "viscous" than a non-magnetic fluid (*e. g.* Zweibel & Josafatsson 1983; Elmegreen 1985, 1988).

The action of shock fronts may be important through out the whole history of any given galaxy. Whether the shocks are due to a vigorous internal activity or due to interactions with other galaxies (or with extragalactic clouds), the compression of the gas and its subsequent cooling is an efficient mechanism to form massive and cool clouds. Also, the appearance of shocks indicates the existence of strong supersonic perturbations in the general velocity field of a region which generates torques in the gaseous disk. The resulting angular momentum redistribution is accompanied by mass exchange among different disk regions, generating a network of radial gas flows. These flows can provide a continuous gas influx towards the central regions of galaxies, which can feed the formation of the observed central molecular clouds and may trigger bursts of star formation at the center (*e. g.* Lo *et al.* 1984). These starbursts require a rapid gas supply and recent numerical simulations indicate that shocks in a cloudy fluid with fast dissipation can effectively drive gas into the center of the host galaxy (*e. g.* Wada & Habe 1992). In fact, the large IR luminosity of ultraluminous IRAS galaxies is due to central stellar bursts triggered by direct galaxy collisions (see Mirabel 1992) and, given that they can reach very large luminosities, starbursts have been proposed as a possible formation mechanism for AGN (*e. g.* Terlevich *et al.* 1992).

3. THE INTERACTION OF YOUNG STARS AND GAS

Young stars display vigorous activity and their energy output stirs and heats the gas in their vicinity. Low-mass stars affect only small volumes but their collective action may provide partial support against the collapse of their parental clouds, and could regulate some aspects of the cloud evolution (*e. g.* Norman & Silk 1980; Franco & Cox 1983; Franco 1984; McKee 1989). In contrast, the strong radiation fields and fast stellar winds from massive stars are able to excite large gas masses and can even disrupt their parental clouds (*e. g.* Whitworth 1979; Tenorio-Tagle 1982; Elmegreen 1983; Larson 1987, 1992; Franco *et al.* 1993c). They also produce the hottest gas phases, and are probably responsible for both stimulating and shutting off the star formation process at different scales. The combined effects of supernovae, stellar winds, and H II region expansion destroy star-forming clouds and create large expanding bubbles. The mass collected by these structures can produce, at some distance and later in time, the conditions for further star formation. This property indicates that the transformation of gas into stars may be a self-stimulated process, but other arguments indicate that is also self-limited.

Star formation can transform only a limited fraction of the mass of the parent cloud into stars. This fraction, or the efficiency of the star forming process, is rather low in average cloud complexes, and may depend on the actual cloud destruction process (*e. g.* Elmegreen 1983; Franco 1984; Larson 1988, 1992). The most efficient mechanism for cloud destruction is due to photoionization. As long as OB stars are formed, more H II regions are created, whose expansion is ultimately responsible for ionizing and photodissociating all of the environmental gas. Eventually, when the whole cloud is completely ionized, star formation ceases. The expansion reduces the mass available for further star formation, limiting the rate of new star formation and placing a severe constraint on the total number of OB stars that can be created (Franco *et al.* 1993c). The maximum number of OB stars that the cloud can form is defined by the number of expanding H II regions required to ionize the whole cloud. The HII region growth depends on its location; ionization bounded regions, which are internal to the cloud, expand at a different rate than the blisters located near or on the cloud boundary. In this case, champagne flows evacuate the ionized gas in a very efficient way, and blister erosion produces the lowest efficiency of star formation. The number of massive stars required to photoionize a mass of 10^4 $M_\odot$ of dense molecular gas (with $n_{H_2} \sim 10^3$ cm^{-3}) is about 10. These densities correspond to the average density of a dense cloud fragment, and one has to include the clumpiness of a typical cloud in order to extrapolate this result to a cloud complex. Assuming a filling factor of 0.1 for these dense fragments and a "normal" initial mass function, the limiting number of massive stars per 10^4 $M_\odot$ of *average* molecular gas in the Galaxy is roughly 1, and the overall star forming efficiency is approximately 5%.

After a star forming cloud is destroyed by a new stellar cluster, the energy injection from the stars begins to accelerate the surrounding ambient medium. In particular, wind-driven shells and supernova remnants create a collection of interstellar holes and shells, with a wide range of sizes, that eventually merge into a single composite superstructure. Many details in the evolution of these large interstellar bubbles, whether they were carved by a single star or by an entire stellar association, depend on the initial ambient and ejecta conditions (*e. g.* Bruhweiler *et al.* 1980; Tomisaka *et al.* 1981; Tomisaka and Ikeuchi 1986; McCray and Kafatos 1987; Tenorio-Tagle *et al.* 1987a; Mac Low & McCray 1988; Mac Low *et al.* 1989; Igumentshchev *et al.* 1990; Palouš *et al.* 1990; Tenorio-Tagle *et al.* 1990a; Ferriére *et al.* 1991; De Young & Gallagher 1992; Tomisaka 1992; Franco *et al.* 1993a). Their growth is affected by the existing density gradients and B-fields, and galaxy differential rotation produces large scale deformations at late evolutionary times. The mass ejected by the stars, on the other hand, can be clumpy and shell excitation and acceleration are in general anisotropic. Ejecta thermalization leads to multiple shocks which propagate through the shell, into a complex velocity field within the remnant (see Franco *et al.* 1991a). This generates a series of time-dependent effects and small scale anisotropies, but the main distortions are defined by external effects.

The evolution of these superbubbles, or multi-supernova remnants (MSR), can lead to the formation of a rich variety of gaseous structures which may be responsible for many of the observed large scale "holes" and "superbubbles" (see reviews by McCray 1988; Tenorio-Tagle & Bodenheimer 1988; Różyczka 1989; Franco *et al.* 1992). Except for the largest and most energetic interstellar structures, which can be better ascribed to collisions of infalling high-velocity clouds with the gaseous disk (*e. g.* Tenorio-Tagle *et al.* 1987b; Franco *et al.* 1988; van der Hulst & Sancisi 1988; Alfaro *et al.* 1991), two and three dimensional numerical models of non-magnetic MSR driven by typical young stellar groups can indeed produce cavities and shells with properties corresponding to the observed ones. The details of the structure of large MSR are basically determined by cooling instabilities and large scale environmental effects: blow-out when a steep density gradient is present; disk containment when a large scale height or a B-field is included; and large distortions due to galactic shear. The growth along the z-axis defines the mass exchange between the disk and the gaseous halo. The evolution in the z-direction is sensitive to the mass distribution perpendicular to the plane of the disk, and to the perpendicular component of the gravitational force. If the disk scale height is larger than a few hundred pc, or a B-field is present, the remnants slow down considerably and acquire an elongated shape. The amount of gas pushed to high z is always less than 10% of the total overtaken mass. Thus, most of the MSR matter remains within the disk of the galaxy.

The large scale distortions, on the other hand, represent the link between the MSR growth and the star formation process. These distortions are due to the epicyclic motion of the perturbed gas and they drive a continuous gas flow towards the tips of the distorted MSR. Mass is accumulated at the tips, where large clouds can be created (*e. g.* Palouš *et al.* 1990, 1993). Depending on the energy injected and galactocentric location of the remnant, clouds with masses above 10^6 $M_\odot$ can be generated. Thus, massive molecular clouds are formed with this process, and the resulting star formation is stable and self-sustained. The model predicts star formation rates similar to those observed in "normal" spirals, and indicate that this self-propagated mode can maintain a vigorous star forming cycle in rotating galaxies.

4. DISCUSSION

The population of OB associations represents a rich energy source for a gaseous galaxy. They can control the main properties of the general interstellar medium and their associated large-scale star formation can be self-propagated and self-regulated. This view is certainly not new (the apparent stability and low efficiency of star formation were used to suggest that stars themselves are resposible for regulating the process; see Hoyle 1953; Elmegreen & Lada 1977; Gerola & Seiden 1977; Cox 1983, 1985; Franco & Cox 1983; Franco & Shore 1984; Larson 1988; Dopita 1990; Tenorio-Tagle 1991), but recent studies indicate that propagating star formation can operate under a wide variety of situations, and can reproduce both the star formation rate and some of the main interstellar properties in galaxies (e.g., Tenorio-Tagle & Bodenheimer 1988; Ikeuchi 1988; Matteucci et al. 1989; Franco 1991, 1992; Elmegreen 1992a,b; Ferrini 1992; Firmani & Tutukov 1992; Shore 1993; Neukirch and Hesse 1993).

Massive stars in the Galaxy and in nearby galaxies often appear to be embedded within compact stellar groups. Usually, there are a few dominant massive stars, and in the case of some regions, a few massive subcomplexes. Surface H II regions dominate the destruction of clouds and shut off any continuing star formation in their environs. The destructive effects of HII regions were first described by Whitworth (1979), and Cox (1983) pointed out the self-limiting aspect of photionization-regulated star formation and noted that a quadratic dependence of the star formation rate on the gas density can be produced in such a case. A similar analysis for stellar winds from low-mass stars was explored by Franco & Cox (1983), and later Franco & Shore (1984) extended this approach to the energy from OB associations, concluding that the current Galactic global rate of star formation can be maintained through stimulated star formation. As described in the previous sections, more recent studies corroborate these conclusions: the strong mechanical energy input generates hot and overpressured regions and the resulting bubbles are believed to generate most of the observed structuring and may be responsible for self-regulation of global star formation in disk galaxies. Actually, many observed structures in the Milky Way and in external galaxies have been ascribed to this stellar energy injection, and the expanding shocks, aside from sweeping the ambient gas, have been suspected of inducing further star formation,

Aside from providing a feedback control to the star forming activity at large scales, the energy input can drive the mass exchange among the different gas phases and, depending on the star formation rate, may even exchange mass with the halo and create "fountains" or winds at galactic scales (*e. g.* Shapiro & Field 1976; Chevalier & Oegerle 1979; Bregman 1980; Cox 1981; Ikeuchi *et al.* 1984; Corbelli & Salpeter 1988; Norman & Ikeuchi 1989; Heiles 1990; Houck & Bregman 1990). In a closely related study, Firmani & Tutukov (1992) analysed the evolution of disk galaxies under the assumption that the disk z-structure is determined by the balance between the stellar energy input and the energy dissipation of the turbulent gas. They find reasonable agreement between the model results and observations and, as in the case of the photoionization-limited scheme, they predict a square density dependence of the star formation rate. If stellar activity is truly responsible for the bulk properties of the general interstellar gas, then the evolution of either single or composite bubbles represents a fundamental tool in our understanding of the structure and activity of star-forming galaxies. The action of a differentially rotating disk completes the star formation cycle, making it self-propagating and self-regulating, but large-scale gravitational instabilities can also trigger the formation of giant molecular clouds and may create additional star forming cycles. Such complexity is difficult to handle in simple models but has been addressed by some authors (see Shore et al. 1987; Ferrini 1992; Shore 1992), and future work of this kind may add new routes to this fascinating process.

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José Franco, Instituto de Astronomía, UNAM, Apartado Postal 70-264, México D.F. 04510, México.