1993ApJ...418..767T

THE ASTROPHYSICAL JOURNAL, 418:767–773, 1993 December 1
© 1993. The American Astronomical Society. All rights reserved. Printed in U.S.A.

ON THE FORMATION OF SPHEROIDAL STELLAR SYSTEMS AND THE NATURE OF SUPERSONIC TURBULENCE IN STAR-FORMING REGIONS

GUILLERMO TENORIO-TAGLE AND CASIANA MUÑOZ-TUÑON
Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

AND

DONALD P. COX
Department of Physics, University of Wisconsin–Madison, 1150 University Avenue, Madison WI, 53711
Received 1993 January 5; accepted 1993 June 7

ABSTRACT

Models of the origin of spheroidal stellar systems, or cluster formation scenarios, need to account for empirical correlations both between scale and velocity dispersion σ and between luminosity and σ found in star-forming regions and relaxed spheroidal stellar systems. The model here proposed accounts for both correlations if the stellar system formation follows a particular sequence. This requires that the quasi-static collapse of a protocluster cloud be halted as soon as stars begin to form, and this occurs once fragments acquire stellar sizes, if the fragment temperature remains at a constant value of about 10 K. The collection of pre–main-sequence low-mass stars undergoing winds while moving with a velocity dispersion σ_* will soon stir the remaining cloud, providing it with an average turbulent motion $\sigma_{\rm gas} \sim \sigma_*$. The cloud agitation is here proposed to be caused by the endless supersonic passage of isothermal bow shocks, or "cometary" shocks, generated by the stellar wind sources ramming through the leftover cloud. These maintain supersonic turbulence and lead also to a distinct structure of the remaining cloud. This mechanism leads to an estimate of the total wind power required and the corresponding cluster luminosity. The latter agrees with observations both in general magnitude and in its correlation with velocity dispersion ($L_{\rm cluster} \sim \sigma^4$).

Following stability, star formation continues, at least at the rate needed to keep the cloud from collapsing any further until the birth of massive stars, which by means of photoionization heat up the remaining matter and inhibit any further star formation, and thus mark the end of cluster formation. H II regions produced by massive clusters will display broad lines reflecting the supersonic $\sigma_{\rm gas}$ acquired from the cometary passage of the wind-driven sources. Afterward, the supersonic H II region expansion, and/or any further localized major input of energy, such as supernova explosions, will rapidly lead to larger velocities and to the removal of gas from the star-forming region, causing broader but lower intensity emission lines. The model is confronted with recent data on giant H II regions showing excellent qualitative and quantitative agreement.

Subject headings: H II regions — stars: formation — turbulence

1. INTRODUCTION

For a wide range of star-forming as well as mature stellar systems, there is an observed correlation

$$\sigma \sim Ar^{1/2} \quad (1)$$

between the scale r of the system and its corresponding velocity dispersion σ. For finished stellar systems such as globular clusters (Illingworth 1976) and the nuclei of elliptical galaxies (Djorgovsky & Davis 1987), the relationship is between the stellar velocity dispersion (σ_*) and scale. For star-forming regions, including giant H II regions (Melnick 1977; Hippelein 1986; Arsenault & Roy 1988 and references therein), H II galaxies (Melnick 1992), and molecular cloud cores (see Silk 1980; Larson 1981; and corrections made by Sanders, Scoville, & Solomon 1985), the correlation is between gas velocity dispersion ($\sigma_{\rm gas}$) and scale.

In molecular cloud cores, giant H II regions, and H II galaxies, the velocity dispersions are supersonic and the corresponding energy is expected to be dissipated rather rapidly on roughly a free-fall timescale [$t_f \sim 1/(G\rho)^{1/2}$]. This time is generally short compared with the inferred lifetimes of the star-forming clouds, and, as a result, various mechanisms have been proposed for resupplying the velocity field (see Elmegreen 1991, 1992 for a review of mechanisms proposed to induce or maintain "turbulence" in giant molecular clouds). For giant H II regions, the action of thousands of strong stellar winds from coeval massive stars has been studied as such an agent (e.g., Dyson 1979; Rosa & D'Odorico 1982), as has the supersonic expansion of H II regions in their "champagne" phase by Gallagher & Hunter (1983) and Skillman & Balick (1984). These mechanisms, however, fail to explain the location of the various sources on the (σ, r)-plane, particularly when many of the available objects show equally broadened lines in both the nebular and the neighboring H I gas (see, for example, Table 2 of Terlevich & Melnick 1981). On the other hand, the wide range of scale of applicability of the correlation, extending from H_2 cloud cores to globular clusters, giant H II regions, H II galaxies, and the nuclei of elliptical galaxies, led Terlevich & Melnick (1981), Melnick et al. (1987), and Melnick, Terlevich, & Moles (1988) to postulate that virial equilibrium should play a crucial role in driving the gas motions. The span of the correlation suggests in fact that the σ-r correlation in these systems is intrinsically a gas-phase relationship during the star-forming phase, and that the stars produced acquire a σ_* of the order of $\sigma_{\rm gas}$, allowing the correlation to persist into the finished star clusters. Thus, the observed gas turbulent motions are related to the total gravitational energy of the star-forming systems, and in completed stellar systems the relationship is a relic of a former gas-phase correlation. In

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1993ApJ...418..767T

addition, it is suspected that dynamic feedback of star formation itself is the activity which stabilizes cloud properties during the star formation epoch, so that some threshold parameter of star formation is probably responsible for the pervasiveness of the correlation.

Here we add two ideas to the already extensive but incomplete discussion of the cluster and/or spheroidal stellar system formation sequence and the σ-r correlation. The first is that, in combination with the fragmentation behavior of a cloud, or section of a cloud, undergoing quasi-static collapse, the σ-r relation is a natural consequence of stars forming as soon as they are able to, from gas which generally has a temperature of about 10 K. The second idea is that stabilization of the collapsing cloud against dissipation of turbulence is quite likely caused by the stirring of the cloud by an ensemble of bow shocks produced by the motions of the stars generating stellar winds. With this mechanism, we can estimate the total wind power required and the corresponding cluster luminosity and find that the latter agrees with observations both in general magnitude and in its correlation with velocity dispersion ($L_{\rm cluster} \sim \sigma^4$).

The paper postulates the sequence of events throughout spheroidal system or cluster formation necessary to explain the observed correlations, and analyzes the consequences of our scenario in §§ 2 and 3. A summary of our conclusions is given in § 4.

2. THE OVERALL PHYSICAL MODEL

2.1. *The Cluster Formation Sequence*

The processes leading eventually to a relaxed cluster of stars very likely follow the following sequence.

1. *Quasi-static collapse.*—A gravitationally bound cloud dissipates energy, shrinks, and fragments.
2. *Stabilization.*—The onset of star formation stabilizes the cloud against further shrinkage.
3. *Star formation.*—Stars form at a rate required to maintain the cloud stability.
4. *Cloud exhaustion and disruption.*—Conversion of a large fraction of the original gas mass into stars and the disruptive effects of the more massive stars clear the star-forming region of the residual gas.
5. *Relaxation.*—The spatial and velocity distributions of the stars relax to a virialized state.

2.2. *Characteristics during the Quasi-static Collapse*

The behavior of a cloud during its quasi-static collapse includes processes involving the release of magnetic flux and angular momentum, generation of supersonic motions, dissipation of energy by those motions, shrinking of the cloud as a whole, and fragmentation into smaller gravitationally bound objects.

A cloud of mass M_c and radius r_c has a gravitational energy of roughly

$$U \sim -\frac{3}{5}\frac{GM_c^2}{r_c} \tag{2}$$

and a corresponding support pressure

$$p_c \sim -\frac{2}{3}\frac{(U/2)}{V} \sim \frac{3}{20\pi}\frac{GM_c^2}{r_c^4} . \tag{3}$$

A fragment within this cloud, with temperature T_f and primarily thermal support, has p_c as an external pressure and a central pressure

$$n_f k T_f \sim p_c + \frac{1}{2}\frac{GM_f \rho_f}{r_f} , \tag{4}$$

where $n_f = \rho_f/m$ and r_f are the density and radius of the fragment. For constant T_f, controlled by heating-cooling balance and insensitive to density, this configuration is gravitationally unstable for $M_f/r_f = 3kT_f/(2mG)$, or $p_c \geq \frac{1}{4} n_f k T_f$, with the usual result that *self-gravitating fragments are those with column densities comparable to those of the cloud as a whole*: $(r_f \rho_f) \sim (r_c \rho_c)$.

During much of the evolution of the cloud, we expect that the need to cope with magnetic fields and angular momentum will slow the condensation of fragments well below the otherwise expected free-fall rate. The result will be that those fragments able to form will likely retain column densities not much different from those of the cloud within which they form.

The characteristic speed of fragments in the potential well of their parent cloud will be

$$v_f \sim \left(\frac{GM_c}{r_c}\right)^{1/2} . \tag{5}$$

Because they lose energy in about the same timescale as that for encountering their own column density, and as the latter equals that of the cloud as a whole, they will lose the above velocity in a cloud crossing time, i.e., at the same rate at which they acquired it in the first place. As a result, the cloud evolution timescale is of order r_c/v_f, which is roughly that for free fall of the cloud as a whole. The cloud shrinks, the potential well deepens, and the fragments move faster, despite their losses. The column density of the parent cloud increases, and smaller mass fragments form, still with the same column density as the cloud. The fragment radii and masses will follow

$$r_f \sim \frac{3kT_f}{2mG}\frac{r_c^2}{M_c} , \tag{6}$$

$$M_f \sim \left(\frac{3kT_f}{2mG}\right)^2 \frac{r_c^2}{M_c} . \tag{7}$$

Thus the fragment size and mass decrease rapidly with decreasing cloud size.

2.3. *Stabilization and the Formation of Stars*

As we have stated in § 1, various authors have suggested that present-day molecular clouds are stabilized via vigorous winds (or bipolar outflows) of young low- to intermediate-mass stars (e.g., Norman & Silk 1980; Franco 1984). Similarly, we shall describe the stabilization of star-forming regions as deriving from the bow shocks and wakes caused by the winds from moving stars. For the present, we simply assume that the onset of star formation is sufficient to end the quasi-static collapse phase, bringing about stabilization.

Given the above result for fragment masses, star formation at mass $M_f = M_*$ becomes possible only when the cloud reaches a radius

$$r_{c,*} = \frac{2mG}{3kT_f}(M_* M_c)^{1/2} , \tag{8}$$

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1993ApJ...418..767T

at which point both it and the protostellar fragments have column densities

$$\rho_f r_f = \rho_c r_c \sim \frac{3}{4\pi M_*}\left(\frac{3kT_f}{2mG}\right)^2 , \quad (9)$$

the cloud pressure is

$$p_c \sim \frac{4\pi G}{15}(\rho_c r_c)^2 , \quad (10)$$

and the characteristic velocity of the forming stars in the gravitational well is

$$v_* \sim \left(\frac{GM_c}{r_c}\right)^{1/2} \sim \left[\frac{4}{3}\pi G(\rho_c r_c) r_c\right]^{1/2} \sim \frac{3kT_f}{2m}\left(\frac{r_c}{GM_*}\right)^{1/2} . \quad (11)$$

Given that the cloud has stabilized, stars will form over a relatively long period of time, during which the characteristic value of v_* remains as above. During this same period, fragments within the stabilized cloud will have similar velocities. As a consequence, we can identify the stellar and cloud gas dispersion velocities with v_*, and search the above relationships for causes of the observed $\sigma = Ar^{1/2}$ correlation.

Three plausible causative agents appear.

1. *A critical pressure for star formation.*—If the cloud must have a critical internal pressure $p_{c,*}$ to force star formation, then the corresponding column density is

$$\rho_c r_c \sim \left(\frac{15 p_{c,*}}{4\pi G}\right)^{1/2} , \quad (12)$$

and

$$\sigma_* \sim \left(\frac{20\pi G p_{c,*}}{3}\right)^{1/4} r_c^{1/2} . \quad (13)$$

Such a hypothesis can be advanced further for the general interstellar medium (ISM), by supposing that it too must be on the verge of star formation, so that occasional perturbations can generate star-forming clouds needed to stabilize the larger system. In that case, the background pressure of the ISM would need to be roughly $p_{c,*}/4$. The fact that the interstellar pressure and molecular cloud column densities are in appropriate agreement with this picture makes it very appealing.

In a weaker form of the pressure control argument, it is assumed that the ISM pressure arises for some entirely independent reason, but controls the column density of self-gravitating objects. It must then be regarded as accidental that the Jeans mass of cold (~ 10 K) cloud fragments is also a stellar mass.

2. *A critical column density for star formation.*—One can turn the above argument around by invoking a critical, or threshold, column density for star formation. Following Franco & Cox (1986), perhaps a cloud must have a sufficient opacity in dust, or H_2 self-shielding, for the central parts to be able to cool enough to make stars. In that case, the critical column density is the reason behind the critical pressure

$$p_{c,*} = \frac{4\pi G}{15}(\rho_c r_c)_*^2 ; \quad (14)$$

the velocity dispersion is then

$$\sigma_* \sim \left[\frac{4\pi}{3} G(\rho_c r_c)_*\right]^{1/2} r_c^{1/2} , \quad (15)$$

and may thus also define the appropriate level of the general interstellar pressure in a quasi-steady galactic disk. The fact that marginally self-gravitating clouds in the solar neighborhood are also marginally opaque lends support to this view.

3. *A typical temperature for star formation.*—The third possibility is that when the gas becomes dense enough to make stars, the heating-cooling balance will always drive the temperature to about 10 K, perhaps because of the steepness of the CO cooling coefficient at lower temperatures. In that case, it will be the downward sweep of the Jeans mass during the quasi-static collapse that brings a cloud to the star formation epoch. Once the fragment mass reaches a stellar mass, rapid star formation begins. In that case, the intrinsic σ-r relation is

$$\sigma \sim \frac{3kT_f/2m}{(GM_*)^{1/2}} r_c^{1/2} . \quad (16)$$

In this discussion it is important to realize that we have encountered yet another pair of the insidious ISM coincidences. The interstellar pressure, the opacity of self-gravitating features at that pressure, and the temperature of cloud cores are all consistent with the needs of star formation. The interstellar pressure may be under stellar control. Opacity and temperature are surely linked as well, but there is more than one way to ascribe cause and effect.

In this paper we take the point of view that opacity has a great deal to do with the details of cloud structure but very little to do with the temperature of its densest regions. A cloud with relatively little metallicity (and dust) may find it needs to arrange itself in a very centrally condensed structure to shield its densest parts, while one with high dust content may be able to reach low temperatures in much more open structures. Independent of that difference, however, both form stars from gas at 10 K.

With T_f adopted as the controlling parameter for star formation, the coefficient A in the relation $\sigma \sim Ar^{1/2}$ should be

$$A \sim \frac{3kT_f/2m}{(GM_*)^{1/2}} \sim 1.1\left(\frac{T_f}{10\ \mathrm{K}}\right)\left(\frac{M_*}{M_\odot}\right)^{-1/2} \mathrm{km\ s^{-1}\ pc^{-1/2}} . \quad (17)$$

From the observations the inferred value of A, when taken from the broad range of applicability of the correlation, i.e., from molecular cloud cores to the central regions of elliptical galaxies, is $A \sim 1.7$, in good agreement with the qualitative result given above. A search for an even better agreement resulting from the presence of a characteristic mass in the relationship, caused by the assumed constancy of T_f, leads to $M_* \sim 0.6\ M_\odot$. This is, however, regarded as having no particular consequence because the properties of stellar winds change so rapidly with M_*. A value of 1 $M_\odot$ might be appropriate for molecular clouds, while perhaps 10 $M_\odot$ would be preferable for giant H II regions. Also, given the scatter in the observed σ-r relationship, the complexities of defining comparable radii in systems of very different type, and the weak dependence of the coefficient on M_*, the actual spread in stellar masses and variations between systems of the characteristic value are of little consequence. It is similarly true that modest variations in T_f will not erase the correlation.

Figure 1 shows the properties of clouds undergoing quasi-static collapse while dissipating energy as they shrink (*from*

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1993ApJ...418..767T

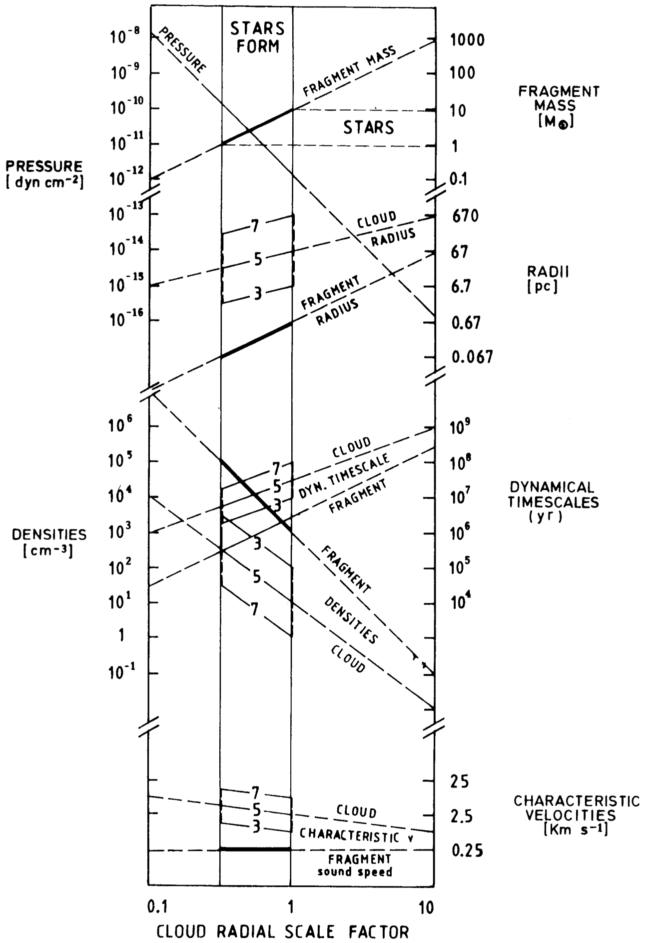

FIG. 1.—Cloud and fragment properties throughout quasi-static gravitational collapse. Pressure, density, dynamical timescale, and characteristic velocity dispersion for both collapsing clouds and resultant fragments, plotted as the cloud (with a mass of 10^3, 10^5, and 10^7 $M_\odot$) shrinks throughout the quasi-static collapse phase. Also indicated are the mass and radius of fragments, as the radial scale factor of the cloud(s) changes by two orders of magnitude, as well as the range in scale of unstable low-mass fragments.

right to left) to keep the gas temperature at the assumed T_f = 10 K. Stars are assumed to form as soon as fragments reach the smallest unstable mass. Under such conditions:

1. Star formation occurs at cloud internal pressures of 10^{-10} to 10^{-12} dyn cm^{-2}.
2. Fragment radii and densities at the time of star formation are in the ranges (0.0067 pc, 10^7 cm^{-3}) to (0.67 pc, 10^3 cm^{-3}), and thus their column densities are 2×10^{23} to 2×10^{21} cm^{-2}.
3. The velocity dispersion of the collapsing clouds, fragments within them, and newly formed stars soon exceeds the thermal sound speed of the cloud ($c_{10\,\mathrm{K}} = 0.3$ km s^{-1}), which is in itself the velocity dispersion within fragments.
4. Throughout the collapse, fragment column densities are the same as those of the cloud, irrespective of the original cloud mass.

During the star formation epoch, the fragments' dynamical timescale is 3×10^4 to 3×10^6 yr, significantly faster than that of clouds.

6. Other cloud properties depend significantly on the original total cloud mass. The curves shown are for M_c equal to 10^3, 10^5, and 10^7 $M_\odot$. Suppose the 10 $M_\odot$ end dominates, and that "cloud" has all scales, i.e., for an $M_c = 10\ M_\odot$, its scale $r = 0.65$ pc; for $M_c = 10^3\ M_\odot$, $r = 6.7$ pc; for $M_c = 10^5\ M_\odot$, $r = 67$ pc; etc. Thus,

$$M_c \sim 25\ M_\odot r_c^2$$

and

$$n_c = 10\ \mathrm{cm}^{-3}[10^5\ M_\odot/M_c(r)] = 670\ \mathrm{cm}^{-3}/r_c\ \mathrm{pc}\ .$$

2.4. *The Stabilizing Agent*

Following stabilization of a cloud, by whatever process, the dispersion velocity of the gas and the stars forming from it will be characterized by the depth of the gravitational potential, $\sigma \sim (GM_c/r_c)^{1/2}$. The gas velocity, however, is supersonic and is expected to dissipate on roughly a cloud crossing time, $t_c \sim r_c/\sigma$. As a consequence, a stable cloud must have a mechanism for replacing these velocities. It is also useful for this mechanism to be capable of destroying dense fragments within the cloud so it can regulate the star formation rate.

We propose that this can be accomplished by sweeping the cloud with bow shocks caused by the (supersonic) motion of multiple stellar wind sources: such shocks accelerate the encountered gas to the stellar velocity, which itself is just that needed by the gas. T Tauri winds have already been proposed as a mechanism to account for the energetics, dynamical structure and lifetime of dark molecular clouds (Norman & Silk 1980). In this view, the interaction of shells of swept-up matter leads to a hierarchical clumpy structure with a mass spectrum that defined the evolution of the cloud and out of which an initial mass function (IMF) could be inferred for long-lived clouds. However, the supersonic velocity widths cannot be accounted for with the interaction and collision of the wind-driven shells, since dissipative processes will soon erase any trace of the potential well out of the system. Thus, newly formed stars in such scenarios will not have the velocity dispersion required to stabilize the collapse of the cloud. The bow shock hypothesis, or collection of cometary sources, could, on the other hand, be adequate to maintain stability if the ensemble of bow shocks reaches all parts of the cloud in a cloud crossing time. If bow shocks have a cross section πR_{bow}^2 and move with a velocity v_*, then N such shocks will encounter a volume

$$V = \frac{N\pi R_{\mathrm{bow}}^2 v_* r_c}{\sigma} \tag{18}$$

in one crossing time. From $v_* = \sigma$, and $V = (4/3)\pi r_c^3$,

$$N = \frac{4}{3}\left(\frac{r_c}{R_{\mathrm{bow}}}\right)^2 . \tag{19}$$

An immediate consequence of our assumption is that the required number of stellar winds is proportional to r_c^2, i.e., to the area of the cloud. (The parameter R_{bow} is dependent on the effective pressure within the clouds, which we have previously inferred is the same for all star-forming regions.) Thus, the surface brightness of the star cluster,

$$S = \frac{L_* N}{\pi r_c^2} \tag{20}$$

(where L_* is the average luminosity of the N stars), is a constant, in agreement with observations of giant H II regions (Terlevich & Melnick 1981). Note, that this also applies to well-evolved systems such as the central regions of elliptical

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1993ApJ...418..767T

galaxies which for a wide range in absolute magnitude display the same mean surface brightness (Kormendy 1977a, b; Sargent et al. 1977).

We now attempt to estimate the cluster luminosity, assuming the winds to be radiatively driven.

A star of luminosity L_* has radial momentum L_*/c. If this momentum is communicated to the wind with efficiency ϵ, then $\dot{M}_{\rm wnd} v_{\rm wnd} = \epsilon L_*/c$, where $v_{\rm wnd}$ is the wind terminal velocity and $\dot{M}_{\rm wnd}$ the mass-loss rate.

When the star moves with velocity v_* through the cloud medium (density ρ_c), a bow shock is established where the ram pressures of the wind, $\rho_{\rm wnd} v_{\rm wnd}^2$, and the ambient gas, $\rho_c v_*^2$, are equal. Because the wind velocity is constant, $\rho_{\rm wnd}$ drops as $1/R^2$, following $\dot{M}_{\rm wnd} = 4\pi R_s^2 \rho_{\rm wnd} v_{\rm wnd}$. Thus the terminal shock occurs where

$$\rho_{\rm wnd} v_{\rm wnd}^2 = \frac{\dot{M}_{\rm wnd} v_{\rm wnd}}{4\pi R_s^2} = \rho_c v_*^2 , \quad (21)$$

implying

$$\pi R_s^2 = \frac{\dot{M}_{\rm wnd} v_{\rm wnd}}{4\rho_c v_*^2} = \frac{\epsilon L_*}{4c\rho_c v_*^2} . \quad (22)$$

We expect the bow shocks to have radii $R_{\rm bow} \sim 3R_s$ from numerical simulations (Tenorio-Tagle, Różyczka, & Franco 1993), so that the bow shock cross section is roughly

$$\pi R_{\rm bow}^2 \sim \frac{2\epsilon L_*}{c\rho_c v_*^2} . \quad (23)$$

Thus the required number of stars is roughly

$$N \sim \frac{2}{3} \frac{c\rho_c v_*^2}{\epsilon L_*} \pi r_c^2 . \quad (24)$$

The implied cluster luminosity is

$$L_{\rm cluster} = N L_* \sim \frac{2c\rho_c v_*^2}{3\epsilon} \pi r_c^2 = \frac{c}{2\epsilon} \frac{M_c}{r_c} v_*^2 = \frac{c}{2G\epsilon} v_*^4 , \quad (25)$$

where $M_c = 4\pi r_c^3 \rho_c/3$ and $v_* = (GM_c/r_c)^{1/2}$ have been applied. *The result is that the cluster luminosity is approximately $c\sigma^4/G$, independent of the stellar wind velocity or luminosity*, so long as the stars with radiatively driven winds dominate both the bow shock ensemble and the luminosity. The numerical result, assuming $\epsilon \sim 1$, is

$$L_{\rm cluster} = \frac{4c\sigma^4}{9G} = 0.5 \times 10^8\, L_\odot \left(\frac{\sigma}{10 \text{ km s}^{-1}}\right)^4 . \quad (26)$$

In conjunction with our previous result that $\sigma \sim A r_c^{1/2}$, and equation (17),

$$L_{\rm cluster} = 0.75 \times 10^4\, L_\odot \left(\frac{T_f}{10 \text{ K}}\right)^4 \left(\frac{M_*}{M_\odot}\right)^{-2} \left(\frac{r}{\rm pc}\right)^2 . \quad (27)$$

2.5. *Cloud Exhaustion and Disruption and Cluster Relaxation*

In order for the σ-r relation to survive into the mature stellar systems for which it is observed, much of the gaseous cloud must be driven into stars, so that the radius of the final cluster and the final velocity dispersion are not much altered by cloud exhaustion and disruption or the subsequent cluster relaxation. Because these are essentially the same criteria as those for binding the stellar system in the first place, it is not surprising that the relation survives in bound stellar systems. This also implies an enhanced star-forming efficiency compared with that inferred for present-day galactic clusters (see Myers et al. 1986; Larson 1992). A lower-limit estimate to the efficiency of stellar formation (ϵ_*), perhaps more accurate for massive stellar systems, results from the number of supernova explosions and their remnants required to disperse the cloud, which should at least provide, within a crossing time, an energy comparable to the total kinetic energy of the stabilized cloud ($E_k = 0.5 M_c \sigma^2$). The total number of supernovae depends on the IMF of the cluster. However, following Elmegreen, Kaufman, & Thomasson (1993), one can assume that the standard galactic mass function and, thus, ϵ_* times the original cloud mass fraction gone into supernova progenitors (f) times the ratio of the kinetic energy provided by each remnant ($E_{\rm sn}$) over the average mass of potential supernovae ($M_{\rm sn}$) leads to the total kinetic energy provided by supernovae over the lifetime ($\sim 6 \times 10^7$ yr) of the massive ($M_* \geq 7\, M_\odot$) supernova progenitors. $E_{\rm sn}$ and $M_{\rm sn}$ are expected to lie near 10^{49} ergs, and 14 $M_\odot$, respectively, and thus, by equating the above two energies over their corresponding time of applicability, one obtains

$$\epsilon_* f = 340.2 \times 10^{-6} \sigma^3/R ,$$

with σ and R in kilometers per second and parsecs, respectively. This compared with the Galactic value $(\epsilon_* f)_{\rm Milky\,Way} = 0.0024$ (Myers et al. 1986), and assuming a similar value of f in all systems leads for the objects considered in Table 1 to lower-limit efficiencies in the range of 10%–15% as opposed to the 2% Galactic value.

The appearance of massive stars in large numbers marks the end of cluster formation. This is due not to supernova events but rather to the heating caused via photoionization that inhibits any further collapse of fragments within the leftover cloud (Hoyle 1953; Cox 1983; Larson 1987). The radiative and mechanical deposition of energy from massive stars ($M_* \geq 25\, M_\odot$) also significantly erodes the parent cloud in a timescale comparable to their lifetime ($\sim$ a few times 10^6 yr). However, throughout the history of the region all remaining cloud sections, constantly traversed by the cometary bow shock sources, will retain a $\sigma_{\rm gas}$ comparable to the σ_* of the cluster. On the other hand, matter dispersed away from the cloud through winds, supernova explosions, and/or the supersonic H II region expansion may present broader lines exceeding the $\sigma_{\rm gas}$ induced by the stellar velocity dispersion. These lines however, will be weaker compared with the emission arising from the remaining cloud.

Note that the passage of the isothermal "cometary" bow shocks that keep $\sigma_{\rm gas}$, within the leftover cloud, of the order of σ_* continues to restructure the remaining matter by building tunnels, holes, filaments, and channels. These are to become apparent once ionization proceeds through, revealing a filamentary cloud structure while replenishing the H II region filling factor typical of these sources.

3. FURTHER CLUES AND OBSERVATIONAL EVIDENCE

Whether or not $\sigma_{\rm gas}$ reflects the gravitational energy of the system in giant H II regions has been a major issue in the literature for a number of years (see Melnick et al. 1988). Following our model, the way of sorting this out clearly implies direct measurements of σ_*. A first attempt, now underway, by means of the Ca II triplet (see Terlevich, Diaz, & Terlevich 1990) offers the best possibility. Meanwhile, the above scenario predicts that σ_* is equal to, and could be inferred from mea-

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1993ApJ...418..767T

surements of σ_{gas}. These measurements, however, should account for the contamination caused by the disruptive events typical of such regions. Beams intersecting the remains of the parent cloud should show lines with $\sigma_{gas} \sim \sigma_*$, very likely with broad wings caused by neighboring (low-density) gas presently being dispersed. These lines thus indicate the mass of the cluster, and thus by means of the σ versus scale correlation may be used as a distance indicator, as first suggested by Terlevich & Melnick (1981). On the other hand, observations avoiding the most intense sections of the emitting region (i.e., avoiding the leftover cloud) should show much weaker and very likely broader lines, a clear signature of the ongoing disruption of the parent cloud. Naturally, toward the end of the cloud dispersal phenomena most of the dispersed gas will sit around the cluster in shells of large radii and with a velocity dispersion that has little to do with the cluster mass.

The supersonic velocity dispersion of Galactic molecular clouds, which ranges from 1 to 3 km s^{-1}, implies, in the frame of our approach, the formation of low-mass clusters with $M_{cluster} \leq 10^3$–10^5 $M_\odot$ (see Fig. 1). Thus, a single Galactic giant molecular cloud may form several of these entities, causing typical Galactic H II regions (Larson 1992). However, these are very different from the high-mass clusters that energize giant H II regions and H II galaxies and maintain their σ_{gas} supersonic, above the 10 km s^{-1} induced via photoionization. An estimate of the virial mass required for a representative sample of these objects is given in Table 1. These have a linear dependence on the estimated radius of the object (see eq. [5]), and thus the values here given are upper limits, as they refer to the full dimension measured in Hα images, larger than those found by Melnick (1992), who used the core radius of the regions.

A further direct comparison with observations of giant regions of recent star formation is straightforward, given the qualitative agreement of the above results. Problems again arise from the scatter in the r-σ relation, the merely linear dependence of A on T_f (eq. [17]), and the imprecision with which one compares "radii" for different classes of objects. Thus, an exact agreement is not to be expected. Nevertheless, the virial theorem combined with the empirical correlation across the full range of applicability, i.e., from globular clusters to the nuclei of elliptical galaxies (from Terlevich & Melnick 1981) and molecular cloud cores (Sanders et al. 1985),

$$r\ (\mathrm{pc}) = 0.21\sigma^2\ (\mathrm{km\ s^{-1}})^2\ ,$$

leads to a constant column density equal to 6×10^{22} cm^{-2}. This value falls well within the expected range (see Fig. 1) and agrees with observations of giant H II regions (see, e.g., Arsenault & Roy 1988 and Table 1). Table 1 also gives the estimated bolometric luminosity ($L_{bol} = 166 L_{H\alpha}$, appropriate for H II regions) for several giant sources, also from the list of Arsenault & Roy (1988), selected with an increasing supersonic gas velocity dispersion. The bolometric luminosity is to be compared with the outcome of relations (26) and (27), the latter assuming $T_f = 10$ K and $M_* = 1\ M_\odot$. The agreement is excellent for equation (27), indicating that we have successfully modeled the L-r^2 relation, but is poor for equation (26) because this set of giant H II region data do not reliably follow the σ-$r^{0.5}$ relation. Even so, the order of magnitude is correct. In addition, the success with one relation that is dependent on the other seems to suggest that for these objects the σ corresponding to r are not well measured or that the distances are incorrect. The implication therefore is that the bolometric luminosity in giant H II regions is indeed dominated by those stars undergoing winds, which also cause the bow shock ensemble that maintains $\sigma_{gas} \sim \sigma_*$. The cluster luminosity being proportional to σ_*^4 in star-forming systems, as well as in finished stellar clusters such as the central regions of elliptical galaxies (Faber & Jackson 1976), implies that bound clusters are able to retain their σ_* throughout cloud dispersal and cluster relaxation phases.

4. CONCLUSIONS

The relationship between σ and scale shared by star-forming systems (e.g., H_2 cloud cores, giant H II regions, H II galaxies) and virialized stellar groups (such as globular clusters and nuclei of elliptical galaxies) provides fundamental clues about the cluster formation sequence. We have argued that the relationship holds because (*a*) throughout the formation of the cluster, stars form as soon as they can from gas at a temperature of 10 K, and (*b*) the parent cloud is continuously stirred to a velocity dispersion σ_{gas} defined by the onset of stellar formation. Furthermore, the stars themselves, those undergoing winds, have been identified as the agent that causes the stirring while they move supersonically through the remaining cloud producing bow shocks that maintain the velocity dispersion $\sigma_{gas} \sim \sigma_*$.

The acquired velocity dispersion is supersonic with respect to the cloud and the fragments' speed of sound and remains supersonic, in the case of massive clusters, even after the birth of massive stars which through photoionization cause a sudden increase in sound speed. Thus, all gaseous systems that display supersonic turbulent motions are infested by massive stellar clusters with a large number of wind sources providing the restoring energy that maintains turbulence supersonic. In less massive systems however, the ordered motions induced upon the appearance of massive stars destroy this clue about the cluster formation sequence.

There are two types of reasons why T_f might be a relatively constant value for star formation, which we will refer to as

TABLE 1

COMPARISON WITH OBSERVATIONS

Object	σ (km s^{-1})	R (pc)	N (cm^{-2})	M_T ($M_\odot$)	$L_{obs}(H\alpha)/L_\odot$	$L_{bol}/L_\odot$	$L_{bol}/L_\odot$ (eq. [26])	$L/L_\odot$ (eq. [27])
NGC 588	12.1	52.5	0.2E22	3.0E6	0.7E5	1.2E7	1.1E8	2.1E7
NGC 4449 (CM 39)	15.7	245	0.8E22	2.3E7	2.8E6	4.7E8	3.0E8	4.5E8
NGC 2366I	16.2	260	0.6E22	2.7E7	4.0E6	6.7E8	3.5E8	5.1E8
NGC 604	16.3	133	0.3E22	1.4E7	0.8E6	1.4E8	3.5E8	1.3E8
NGC 5471	21.3	330	5.0E22	5.8E7	0.4E7	6.7E8	1.0E9	8.2E8
NGC 5462	24.2	320	0.6E22	7.3E7	1.2E6	2.1E8	1.7E9	7.7E8
NGC 5461	24.7	215	1.2E22	5.1E7	0.7E7	1.1E9	1.9E9	3.5E8

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1993ApJ...418..767T

accidental or deterministic. The class of accidental reasons include all those in which incidental processes of heating and cooling bring condensing cloud fragments to a typical temperature of 10 K and keep it there as one enters the star formation epoch. It is quite likely that 10 K is the temperature in star-forming regions today because there is no cooling mechanism in molecular gas which is capable of driving the temperature lower, while the CO cooling is adequate to reach that temperature. Such thermostatic regulation of temperature is common at temperatures for which there is a rather sharp rise in cooling coefficient and is responsible for the 80 K temperatures of diffuse clouds and 8000 K temperatures of H II regions. Such temperatures are relatively insensitive to abundances because of the exponential Boltzmann factors in the collision rates.

The deterministic case differs in that it depends on some particular aspect of the star formation process being sensitive to temperature specifically (or to fragment column density or pressure). We do not know of such a sensitivity, but if there were one, it might have a very interesting effect in the early universe. If even dense clumps of gas were incapable of cooling below the microwave background temperature, the star formation will be suppressed until such a time is $(1 + z_{\rm gal})3\ {\rm K} = T_f$ (i.e., $z_{\rm gal} \sim 2$ for $T_f \sim 10$ K). At first sight it may seem that we have merely exchanged a magic column density or pressure in star-forming regions for a magic temperature. Any of the three can be supported by observations of present-day star-forming condensations, while none may seem directly relevant to conditions within globular clusters or elliptical galaxies at the time those systems formed stars.

We do not pretend to be experts on conditions in the dense environments required for star formation, or the dependence of those conditions on metallicity, dust content, radiative environment, and collapse timescales. For reasons such as those given above, however, we propose that it could be relatively easy to provide theoretical support for a characteristic star formation temperature and point out that such support would be an adequate basis for understanding the general relationship found between σ and r.

We gratefully acknowledge several turbulent conversations with G. Münch, J. Franco, R. Terlevich, and J. M. Vilchez, and our referee for a number of substantial comments. G. T.-T. and C. M.-T. acknowledge the hospitality of the Instituto de Astronomıa (UNAM) México, where some of this work was carried out, and acknowledge the DGICYT grant PB91-0531(GEFE) which partly financed their work. Don Cox is also especially grateful for an exciting and hospitable visit to the IAC, Tenerife. His work on this project was also supported in part by NASA grants NAGW-2523 and NAGS-629.

REFERENCES

Arsenault, R., & Roy, J.-R. 1988, A&A, 201, 199
Cox, D. P. 1983, ApJ, 265, 261
Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59
Dyson, J. E. 1979, A&A, 73, 132
Elmegreen, B. G. 1991, in Physics of Star Formation and Early Stellar Evolution, ed. C. F. Lada & K. Kalafis (Dordrecht: Kluwer), in press
———. 1992, in Protostars and Planets III, ed. E. Levy & M. Matthews (Tucson: Univ. Arizona Press), in press
Elmegreen, B. G., Kaufman, M., & Thomasson, M. 1993, ApJ, 412, 90
Faber, S. M., & Jackson, R. E. 1976, ApJ, 204, 668
Franco, J. 1984, AJ, 137, 85
Franco, J., & Cox, D. P. 1986, PASP, 98, 1076
Gallagher, J. S., & Hunter, D. A. 1983, ApJ, 274, 141
Hippelein, H. H. 1986, A&A, 160, 374
Hoyle, F. 1953, ApJ, 118, 513
Illingworth, G. 1976, ApJ, 204, 73
Kormendy, J. 1977a, ApJ, 214, 359
———. 1977b, ApJ, 218, 333
Larson, R. B. 1981, MNRAS, 194, 826
———. 1987, in Starbursts and Galaxy Evolution, ed. T. X. Thuan, T. Montmerle, & J. Tran Thanh Van (Gif-sur-Yvette: Editions Frontières), 467
———. 1992, in The Globular Cluster-Galaxy Connection, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), in press
Melnick, J. 1977, ApJ, 213, 15
———. 1992, in Third Canary Islands Winter School on Star Formation in Stellar Systems, ed. G. Tenorio-Tagle, M. Prieto, & F. Sanchez (Cambridge: Cambridge Univ. Press), 253
Melnick, J., Moles, M., Garcia-Pelayo, J. M., & Terlevich, R. J. 1987, MNRAS, 226, 849
Melnick, J., Terlevich, R. J., & Moles, M. 1988, MNRAS, 235, 297
Myers, P. C., Dame, T. M., Thaddeus, P., Cohen, R. S., Silverberg, F., Dwek, E., & Hauser, M. G. 1986, ApJ, 301, 398
Norman, C., & Silk, J. 1980, ApJ, 238, 158
Rosa, M., & D'Odorico, S. 1982, A&A, 708, 339
Sanders, D. B., Scoville, N. Z., & Solomon, P. 1985, ApJ, 289, 373
Sargent, W. L. W., Schechter, P. L., Boksenberg, A., & Shortridge, K. 1977, ApJ, 212, 326
Silk, J. 1980, in Tenth Advanced Course, Swiss Society of Astronomy and Astrophysics, ed. A. Maeder & L. Martinet 131
Skillman, E. D., & Balick, B. 1984, ApJ, 280, 580
Terlevich, E., Diaz, A. I., & Terlevich, R. 1990, MNRAS, 242, 271
Terlevich, R. J., & Melnick, J. 1981, MNRAS, 195, 839
Tenorio-Tagle, G., Różyczka, M., & Franco, J. 1993, MNRAS, submitted

© American Astronomical Society • Provided by the NASA Astrophysics Data System