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ON THE FORMATION OF MASSIVE STELLAR CLUSTERS

Guillermo Tenorio-Tagle,[1] Jan Palouš,[2,3] Sergei Silich,[1] Gustavo A. Medina-Tanco,[4] and Casiana Muñoz-Tuñón[2]

RESUMEN

Presentamos las propiedades del modelo la fábrica de estrellas, en la que una creación continua de estrellas resulta en un sistema estelar altamente concentrado y masivo. Mostramos que bajo condiciones muy generales, una inestabilidad a gran escala en el medio interestelar, que conlleve al colapso de una nube masiva, podrúciran con la ayuda de una generación espontánea de estrellas masivas, a un cascarón estacionario, denso, frío y de pequeño radio. A medida que mayor cantidad de masa es procesada, el cascarón se vuelve gravitacionalmente inestable y se fragmenta, permitiendo así la formación de más estrellas. El cascarón es capaz de mantener su posición gracias al balance que se establece entre la presión de empuje de la nube colapsante que aunada a la fuerza gravitacional que ejerce sobre el cascarón el cúmulo en formación, actua en contra de la energía mecánica depositada por la colección de nuevas estrellas. El modelo cuenta con un tratamiento completo de la retroalimentación de la formación estelar, así como del espectro de masas de los fragmentos que resultan de la continua fragmentación del cascarón estacionario. Este último coincide a ambos extremos del espectro con las propiedades de una función de masa universal. Se resaltan otras propiedades de los cúmulos resultantes.

ABSTRACT

Here we report on the properties of the star forming factory, in which the continuous creation of stars results into a highly concentrated, massive (globular cluster-like) stellar system. We show that under very general conditions a large-scale gravitational instability in the ISM, that triggers the collapse of a massive cloud, leads with the aid of a spontaneous first generation of massive stars, to a standing, small radius, cold and dense shell. Eventually, as more of the collapsing matter is processed and incorporated, the shell becomes gravitationally unstable and begins to fragment, allowing for the formation of new stars. The shell keeps its standing location thanks to a detailed balance established between the ram pressure from the collapsing cloud which, together with the gravitational force excerted on the shell by the forming cluster, act against the mechanical energy deposited by the collection of new stars. The model accounts for a full analysis of feedback, as well as for the mass spectrum of fragments that result from the continuous fragmentation of the standing shell. This matches well, at both ends of the spectrum, the properties of a universal IMF. Other properties of the modelled clusters are here stressed.

Key Words: **GALAXIES: STAR CLUSTERS — STARS: CLUSTERS**

1. INTRODUCTION

This paper uses several thousands of supernova, meant as fireworks to Peter's party. These result from a profound admiration and from massive evolved stars generated at the star-forming factory.

Up to 1996, the problem of how to form a massive concentration of stars, was posed exclusive by globular clusters in the Milky Way and in other nearby galaxies and clearly by starbursts or violent star forming regions, none of which recide in our galaxy. The observations pointed at a very efficient process that allowed for the conversion of a large amount of gas into collections of up to several times 10^6 M$_\odot$ in stars. The ideas at the time (see Tenorio-Tagle et al. 1993) pointed also at the existense of an stabilizing agent able to inhibit the formation of a supermassive black hole, leading instead to fragmentation or to innumerable smaller and smaller self-gravitating cloudlets out of which eventually resulted the ensemble of stars that today seem to have relaxed their spatial and velocity distributions into a virialized state.

Given the well known effects produced by photoionization as well as of stellar winds and supernovae, the question then arose as to which stars do actually formed first. We all know that the working hypothesis of a coeval burst is indeed an oversimplification to the problem and will love to understand how the process takes place. These issues have be-

[1]Instituto Nacional de Astrofísica Optica y Electrónica, México.
[2]Instituto de Astrofisica de Canarias, Spain.
[3]Astronomical Institute, Academy of Sciences of the Czech Republic.
[4]Instituto Astronômico e Geofísico, USP, Brazil.

come central now that we know that starbursts are powered by collections of young globular clusters or "super-star clusters" and thus clearly nature knows of a way of generating these extreme powerful units of star formation.

As pointed out by Ho (1997) young super-star clusters are overwhelmingly luminous concentrations of stars that present a typical half-light radius of about 3 pc, and a mass that ranges from a few times 10^4 $M_\odot$ to a few 10^6 $M_\odot$. The brightest ones have luminosities up to two orders of magnitude higher than R136 in 30 Doradus. Similar super-star cluster properties have been inferred from HST-STIS observations of AGN (Colina et al. 2002), and from radio continuum measurements of ultracompact HII regions not visible in optical images, fact that points to the youngest, densest and most highly obscured star formation events ever found (Kobulnicky & Johnson 1999; Johnson et al. 2001). The massive concentrations imply a high efficiency of star formation which permits, even after long evolutionary times, the tight configuration that characterizes them. A tight configuration that remains despite the impact through photo-ionization, winds and supernovae, believed to efficiently disperse the gas left over from star formation. It is thus the self-gravity that results from the high efficiency what keeps the sources bound together. The high efficiency is also a key issue regarding the formation of young clusters which has led to believe either on a delayed or a very rapid event, to avoid negative feedback (Larsen & Richtler 2000). The observational evidence points now to such massive units of star formation ($\sim 10^6$ $M_\odot$) present at the excitation centres of blue compact and starburst galaxies such as M82 (de Grijs et al. 2001, O'Connell et al. 1995; Lipscy & Plavchan 2004; Melo et al. 2004), and NGC 253 (Watson et al. 1996) as well as in galaxies of different types (see also Larsen & Richtler 2000 and Larsen 1999). This star-forming activity in which masses similar to the total gas content found in galactic giant molecular clouds (massive elongated structures that extend over 100 pc in length) are turned into stars, all in a very small volume ($\sim$ few pc) much smaller than the typical sizes of H_2 clouds, and thus the observations imply a rapid accumulation of matter before massive star formation and negative feedback affect the collapsing cloud.

Feedback is thus believed to be, right after massive star formation, a negative quantity. And only after a sufficient time, once it has affected a large enough region, it will change sign and lead to further star formation. Clearly for this to happen, gravity has to take over the affected region, or at least over a good part of it, and win over everything else. How the new star-formation events proceed despite massive star formation and feedback is however still poorly understood. A new possibility that considers many of these issues and in particular a detailed balance between negative feedback and gravitational collapse, leading to a self regulating star forming process, is that of our star-forming factory model (see Tenorio-Tagle, et al. 2003).

2. THE STAR FORMING FACTORY

The model assumes the gravitational instability of a large cloud ($M_c \sim 10^4 - 10^6$ $M_\odot$) to enter its isothermal ($T_c \sim 100$ K) collapse phase (Larson 1969; Bodenheimer & Steigart 1968; Foster & Chevalier 1993; Elmegreen et al. 2000), thereby developing the well known density and velocity structure. It is worth noticing that for a given plateau density, collapsing clouds present the same size plateau, regardless of the mass of the collapsing cloud (M_c). As the density in the plateau region (ρ_p) increases, smaller unstable fragments begin to form. These will first have (as ρ_p grows larger than 10^{-20} g cm^{-3}) a Jeans mass similar to those of massive stars.

The model further assumes that at that moment, a first generation of massive stars ($M_* = 100$ - 10 $M_\odot$) forms spontaneously in the central plateau region. From then onwards, through their winds and terminal supernova (SN) explosions, they will begin to have an important impact on the collapsing cloud. For this to happen however, massive stars ought to form in sufficient numbers as to jointly stop the infall at least in the most central regions of the plateau. Otherwise, individual stars, despite their mechanical energy input rate, will unavoidably be buried by the infalling cloud, delaying the impact of feedback until more massive stars form. We thus assume that the first generation of massive stars is able to regulate itself by displacing and storing the high density matter left over from star formation into a cool layer of shocked matter close to the knee of the density distribution (R_k), where both the infalling gas density (ρ_k) and velocity (v_{max}) attain their maximum values. There the mechanical energy deposited by the first generation of massive stars would favour the accumulation of sufficient infalling cloud mass as to drive the standing shell gravitationally unstable.

In our steady-state model everything happens at the same time. There is at all times a fine-tuned balance between the infalling gas ram-pressure and the energetics from the forming cluster. At the same time, gravitationally bound fragments continuously form in the unstable shell (at $R = R_k$) and then, due to their negligible cross-section, freely fall towards the centre of the configuration as they evolve into stars. The larger number of sources continuously enhances the forming cluster mechanical luminosity and with it the amount of mass returned as a wind into the shell ($\dot{M}_w$). At the same time, the continuous fragmentation of the shell and the infall of the resultant fragments, acts as a source of mass in the most central region of the collapsing cloud, and this rapidly modifies the balance previously established between the wind and the infalling gas ram pressures. Indeed the ram pressure exerted by the wind sources, in order to keep the shell at its standing location, will now have to balance not only the infalling gas ram pressure but also the gravitational force exerted on the shell by the increasing mass of the central star cluster. We have shown that very soon, after $t \approx 10^4 - 10^5$yr, the infall ram pressure becomes negligible compared to the gravitational pull provided by the forming cluster. Thus the shell becomes gravitationally bound.

An outcome of our model is that to support the shell against the gravitational pull exerted by the forming central star cluster, the mechanical luminosity (L_{eq}) would have to grow linearly with time.

A second constraint on the mechanical luminosity arises from a consideration of the star formation rate (SFR). This is defined by the sum of the two sources of mass at the shell: the rate at which the collapsing cloud is processed by the shell ($\dot{M}_{in}$), which is a constant, and that rate at which mass is ejected by the star cluster ($\dot{M}_w$), which increases linearly with time. Thus,

$$SFR(t) = 4\pi R_k^2 \rho_k v_{max} \left(1 + \frac{4\pi G \Sigma_{sh}}{v_w} t\right), \qquad (1)$$

is a function that increases also linearly with time. Such star formation rate defines the energy deposition (L_{sc}), expected from the increasingly more massive central star cluster. L_{sc} is to be derived from starburst synthesis models (e.g. Leitherer & Heckman 1995) taking into consideration the prescribed SFR.

Figure 1 shows that the energy input rate derived independently from the starburst synthesis models is in reasonable agreement with the equilibrium value over a considerable span of time, particularly when $\Sigma_{sh} \approx 0.7$ g cm^{-2}. In such a case both mechanical energy input rates agree within less than a factor of two over almost 25 - 30 Myr.

A star-forming factory then results from a profound self-regulation that accounts for the mass con-

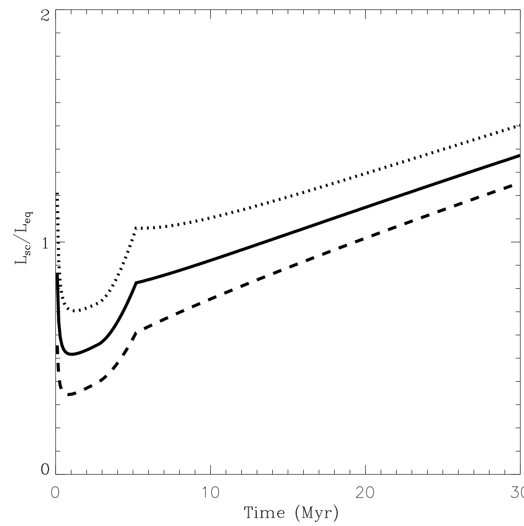

Fig. 1. Mechanical energy requirements. The figure compares L_{eq} (shown as straight lines) with the L_{sc} values that result from starbursts synthesis models that assumed a SFR(t), for different values of $\Sigma_{sh} = 0.5$ (dotted lines), 0.7 (solid lines) and 0.9 g cm^{-2} (dashed lines). All models have also assumed an upper and lower mass limits equal to 100 M$_\odot$ and 1 M$_\odot$ and a slope of -2.25 for the high mass end (as derived in section 3).

tinuously added to the forming cluster, as well as for the mechanical energy that results from this further addition of mass and its transformation into stars. Self-regulation keeps the shell at its standing location and thus with the same fragmenting properties, while the forming cluster remains hidden behind the shell and the collapsing cloud.

2.1. *The size of the resultant clusters*

The factory stops operating either because small clouds ($M_c \leq 10^5$ M$_\odot$) are rapidly processed by the standing shell or, in the case of larger clouds, because the mechanical energy input rate implied by the SFR condition (L_{sc}), here derived using starburst synthesis models, begins to largerly exceed the luminosity required (L_{eq}) to keep the shell in its standing location. This latter possibility arises after 25 - 30 Myr of evolution (see Figure 1), when the luminosity generated by the increasingly larger SFR begins to overwhelm the equilibrium condition, although not even by a factors of two. After this time the shell will loose its standing location while being disrupted as it accelerates into the skirt of the remaining cloud. Thus, the size of the largest resultant clusters in our factory model, is restricted to a few 10^6M$_\odot$, the amount of cloud mass that can be processed by the standing shell within this time interval.

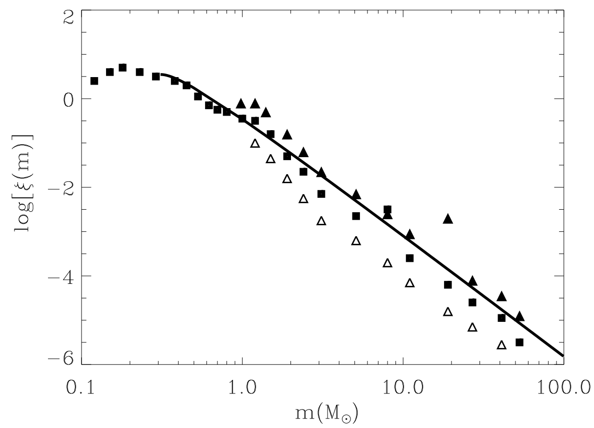

Fig. 2. The IMF - ξ (m) - as given by Binney & Merrifield (1998), is compared with our results normalized to the total cluster mass (solid line). The comparison assumes a 10^6 $M_\odot$ cloud, fully processed into stars during a time span of 23 Myr (see text)

3. THE MASS SPECTRUM OF FRAGMENTS

Mass accumulation leads to the gravitational instability of the standing shell with a well-defined mass and number of resultant fragments. The dispersion relation for gravitational instability of an expanding shell of radius R is (see Elmegreen 1994) $\omega = -\frac{3\dot{R}}{R} + \left(\frac{\dot{R}^2}{R^2} - \frac{\eta^2 c_{sh}^2}{R^2} + \frac{2\pi G \Sigma_{sh}\eta}{R}\right)^{1/2}$, where Σ_{sh} is the unperturbed surface density of the shell, c_{sh} its sound speed and G is the gravitational constant. The condition for instability demands ω to be real and positive. The wavenumber η is related to the perturbation wavelength λ by $\eta = 2\pi R\lambda^{-1}$, and the e-folding time of the perturbation growth is ω^{-1}. For a standing shell configuration (with $\dot{R} = 0$) this reduces to

$$\omega^2 = -\frac{\eta^2 c_{sh}^2}{R^2} + \frac{2\pi G \Sigma_{sh}\eta}{R}. \qquad (2)$$

From the dispersion relation of the linearized analysis of the hydrodynamical equations on the surface of the standing shell, the mass spectrum of gravitationally bound fragments presents a slope equal to -2.25 for massive objects. The distribution flattens in the neighborhood of η_{max} and peaks at $m = \frac{\pi c_{sh}^4}{4G^2\Sigma_{sh}}$. The minimum mass, obtained from the condition that ω is positive, lies at $2\eta_{max}$. Results are in good agreement with the stellar mass distribution (see Figure 2) inferred for star clusters (Moffat 1997; Hunter et al. 1997; Wyse 1997) and for the solar neighborhood (Salpeter 1955; Scalo 1986; Binney & Merrifield 1998).

4. THE STAR CLUSTER PROPERTIES

Several properties of the clusters resultant from the star-forming factory such as their UV production history, the evolution of their H_α equivalent width, their infrared luminosity, as well as the self-contamination caused by star formation out of the products from former generations of stars, are well documented in our paper.

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