The Role of Hydrogen on Mass Loss from Proto-Globular Clusters

ROBERTO CAPUZZO–DOLCETTA

Institute of Astronomy, University La Sapienza, Roma, Italy

ABSTRACT. This short report is concerned with the well known and not yet satisfactorily answered problem of the existence of two well distinct typical mass scales of primordial halo objects: solar size objects (halo field stars) and globular cluster size objects ($10^5$ solar masses and more). A likely possibility is that almost all the gaseous content of the halo fragmented into massive clouds, which, in their turn, recycled part of their gas to the environment in either a quiescent either a violent way. The modes and quantity of mass loss depends on thermodynamic properties of gas clouds, determined, in a zero-metal environment, mainly by hydrogenic components evolution and influence on the equation of state. It is logical to expect that, due to the different dynamical and thermodynamical conditions of the recycled gas, another typical fragmenting mass scale is settled.

1. Introduction

Globular clusters constitute a relevant part of the halo of a galaxy, nevertheless they contain less than 1% of its mass. For example, in our Galaxy the average mass of globulars is $\sim 3 \times 10^5 \, M_\odot$, which means a total cluster mass of about $4.5 \times 10^7 \, M_\odot$, while the spheroid mass is about $10^{10} \, M_\odot$. It is known that globular clusters are among the oldest objects in galaxies, aging around 15 Gyr. In spite of the lack of direct determination of the age of bulge's stars, it is, nevertheless, commonly accepted for the halo field stars an age comparable to that of globulars, inferred also from their low metal content.

A diffuse paradigm is that the two components of the galactic halo (individual stars and globular clusters) are almost co–eval, in the sense that the difference in the formation epoch was probably just a fraction of the protogalactic halo free–fall time, which is a relatively short time (of the order of a twentieth of the clusters' age). This paradigm is supported by the evidence of the similar space distribution of globular clusters and halo stars, even if these latter seem to be more centrally peaked than globulars.

The question whether or not field stars and globular clusters are coeval is out of the purposes of this paper; if we assume that it is logical to ask: how can the typical fragmenting mass change for 5 order of magnitudes in the short time interval that is required to allow both solar mass size objects and globular cluster to fill almost the same volume (the halo)?

The use of the Occam’s razor make me think that the scientifically most economic point of view is that almost all the available gas fragmented during the proto–halo collapse into masses of just one typical size (of either stellar or globular cluster scale) and later, shortly later, a merging or a sub–fragmentation lead to the other condensed phase. I don’t believe as very plausible the bottom–up picture (stars formed earlier and
partly merged to globulars); much more physically viable is, instead, the idea that large clouds condensed first and released later part of their mass to the environment, which, consequently, is replenished of some material available to fragment furtherly on another scale.

2. A simple picture of halo’s structures formation

In recent years many theories of globular cluster formation have been presented in the literature. Most of them are developments of a Fall and Rees (1985) idea. Fall and Rees semi–quantitatively supported the framework of cluster formation in a two–phase gaseous system: a hot ($10^9$ K), dilute gas where clumps are present which are not able to cool below $10^4$ K. In this scheme spheroid stars formed earlier.

It is interesting to note how various authors, starting from almost the same picture of Fall and Rees, reached very different, sometimes contradictory, conclusions. Palla and Zinnecker (1987) found, in a simplified picture, that non–equilibrium H2 cooling allows the clumps to cool down to about 100 K, so that the Jeans’ mass drops to stellar values within the clumps. Even if this could explain star formation within clumps, i.e. within protoglobular clusters, this does not explain the field (bulge) star formation. Ashman (1990) confirms the possibility for the gas to cool to 100 K, but he found that dark clusters (composed by jupiters) are formed from low mass clouds as well as globular clusters from high mass clouds. Some more detailed scheme and deeper calculations by Murray and Lin (1989) show that large amplitude perturbations allow cooling and Pop. III star formation, whose flux delays globular cluster formation. Another, more recent, paper by Vietri and Pesce (1995) gave hints to the idea that imploding shocks may leave stars behind the front.

To summarize, very different conclusions are drawn, and so the question of how globular clusters and spheroid stars have been formed is actually still open.

In this report, we prefer to start, rather than with the Fall and Rees two–phase gas, with the generally accepted scheme of a halo which is at its virial temperature, in the range $10^5$-$10^6$ K, so that the actual fragmenting mass, of the scale of the Jeans’ mass, is much larger ($> 10^7$ M⊙) than the typical globular cluster mass. These large gaseous clouds collapsed in a more or less violent way in dependence on how far from equilibrium they were. This collapse, with its implications on the cloud thermodynamics and thus on the equation of state of the gas, results in a violent or gentle bounce of the structure. In both cases, the existence of a tidal cut-off necessarily implies that part of the gas mass is lost through the tidal radius to the environment, on a time scale of the order of the cloud free-fall time. This way, the halo can be replenished with "processed" gas (shocked or not), which is, in any case, likely in a quite different thermodynamical state than before. This would naturally give a diffuse halo at a density and temperature significantly different from that in the original big clouds, meaning a significantly different Jeans’ mass.
3. Violent and quiescent mass loss

The role of the EOS in the evolution of a self–gravitating gas cloud is important, due to the mutual feedback between dynamics and thermodynamics of the cloud. It is well known, indeed, that a soft EOS induces a much more violent collapse than a harder EOS in an unstable cloud. The writing of the EOS in the usual form

\[ p = (\gamma - 1) \rho u \]  

(1)

(where \( p \) is the gas pressure, \( \rho \) is the mass density and \( u \) is the internal energy per unit mass) corresponds to a definition of the adiabatic exponent \( \gamma \) as

\[ \gamma = \frac{2}{3} \left( 1 - \frac{u_{nt}}{u} \right) + 1, \]  

(2)

\( u_{nt} \) being the non–translational part of the internal energy.

Of course, softer EOSs correspond to situations where \( u_{nt} \) dominates the internal energy (dissociations, ionizations): in self–gravitating clouds this means that the work of gravitation during a collapse goes into breaking molecular and/or ionic links among components and not into the thermal motion which would help the structure to resist the collapse. It is quite possible to have clouds in condition of apparent equilibrium, in the sense that the gas appears almost virialized but the equilibrium is very unstable because the gas density and temperature are such that just a small compressional perturbation makes \( \gamma \) to decrease abruptly inducing the overall structure to fall under its own gravitation. A possible fate is that of a violent collapse, which induces high densities and temperature to be reached in the central regions, eventually hardening significantly the EOS at a level that matter in the centre of the clouds becomes a sort of hard core against which the infalling outer layers 'splash' and bounce back at supersonic speed, in form of shock waves which carry out of the system a non–negligible part of the initial mass of the cloud.

This is what we call violent mass–loss from protoclouds.

A careful investigation of such a phenomenon implies the development of very detailed and carefully controlled hydrodynamic models, for it is known how deep collapses of self–gravitating structures are very difficult to be numerically followed because, with acceptable time steps, computational error becomes exceedingly large so to make the further dynamical evolution absolutely unreliable.

Note that the numerical error of integration induces quite naturally a large error in the total energy, which explains why it is possible to have non–realistic ‘explosions’ of the whole structure.

An explanation of this can be given through the following simple example.

It is easily seen that a model of cloud collapse represented by the equation

\[ \ddot{R} = \frac{p}{\rho} - \frac{GM}{R^2} \]  

(3)

(where \( \dot{R}(t) \) is the second time derivative of the radius of the uniformly, \( \rho = \rho(t) \), collapsing gaseous sphere, \( p \) is the pressure at the boundary and \( M \) the mass of the
Evolution of the average temperature, adiabatic exponent and ratio of the mass lost to the total for a $10^8 \, M_\odot$ initially uniform cloud. Left panels refer to a cloud with $T_0 = 10^4$ K; right panels to $T_0 = 800$ K. Time is in unit of free-fall time.

cloud) leads to unavoidable infinite collapse when the adiabatic exponent $\gamma$ in the EOS is less than 4/3. Of course, in real situations $\gamma$ varies during the cloud evolution, and this has crucial consequences on the energetic balance. Actually, the relative error in the total energy, $\Delta E/E_0$, is contributed by a kinetic term which scales as $-1/R^2$, a gravitational term proportional to $1/R^2$, and an internal-energy error term scaling as $R^{2-3\gamma}$. The coefficient of $1/R^2$ in the gravitational error term is estimated to be greater than the kinetic one, so it is clear that $\gamma < 4/3$ makes the energy to explode positively as $R$ goes to zero, thus reverting the (correct) extreme collapse to an eventual explosion whenever the error in $R$ is not kept very well under control. Actually, if the error in $R$ has grown too much, it happens that even if $\gamma$ re-increases above the critical 4/3 the energy may have definitely changed sign from negative to positive, implying unboundedness of the system through an eventual explosion, while the correct re-expansion, if any, would have been very different.

The study of violent collapses, and their physical consequences, requires, so, a very
careful attention. I postpone a deep discussion of this to future work, limiting here to the report of some results related to the much easier controlled quiescent mass loss. The quiescent mass loss is what expected when the gas cloud experiences a gentle contraction and re-expansion and part of the mass of the cloud escapes through the tidal radius. I have made some simulations of collapses of self–gravitating gas of primordial compositions, using our own SPH code (Capuzzo Dolcetta & Di Lisio, 1994). Of course the adiabatic exponent is allowed to vary, and its evolution is determined by the evolution of the chemical species constituting the gas:

\[ H, H^+, H^-, H_2, He, He^+, He^{++}, e^- \]

I don’t go here into details of the models, it suffices to say that the time evolution of the chemical abundances is followed with a sophisticated implicit method which is able to reduce the error in their evaluation and their feedback on the overall evolution to a very low value. Molecular and atomic cooling have been included in the energy equation.

As an example of the results, the time evolution of some characteristic quantities is shown in Figure 1, for two spherical and initially uniform (both in density and temperature) gas clouds of same mass \( M = 10^8 \, M_\odot \) and initial radius \( R_0 = 200 \, \text{pc} \), but different initial virial ratios \( Q_0 \), namely \( Q_0 = 0.27 \) and \( Q_0 = 0.06 \) (hot and cold clouds). The clouds are supposed orbiting around the centre of the mother galaxy at a distance such that the tidal radius is initially \( r_t = 400 \, \text{pc} \).

In both the considered cases the collapse is deepest at about 1.2 free-fall times, and the re–expansion leads to a loss of about 20% of the total mass in a time shorter than \( 5t_{ff} \) \( (t_{ff} = 4 \, \text{Myr}) \). Note that, whether the characteristic fragmenting mass from the virial gaseous halo has been of the order of \( 10^8 \, M_\odot \), a loss of \( 2 \times 10^7 \, M_\odot \) per cloud means that 500 such clouds may have recycled a quantity of material of the order of the presently estimated bulge mass \( (\sim 10^{10} \, M_\odot) \).

4. Conclusions

It has been shown how delicate is following the evolution of a self–gravitating zero–metal cloud in primordial conditions, due to the variation of the EOS as consequence of dissociations and ionization of hydrogenic molecules and ions.

As preliminary result of a more extensive future work, I showed that the quiescent mass loss from protoclouds of the size or greater than the Jeans’ mass in a virialized protohalo can provide a substantial fraction of the mass later condensed into stars of the spheroidal bulge.

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