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Cooling Clouds by Varying Metallicities: Origin of Globular Cluster Bimodality

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ABSTRACT
Globular Clusters

Key words: globular clusters - methods:numerical

1 INTRODUCTION

Globular clusters (GCs), with typical masses of 10^5-10^6 M$_\odot$ are particularly interesting relics of star formation for a number of reasons: (1) the are very concentrated, with half-mass radii of a few parsecs, indicating that star formation occurred in a particularly dense environment; (2) the stars in a given GC generally have a very narrow spread in ages and metallicity, implying a single stellar population (although recent results have revealed a more nuanced situation here, as we will discuss briefly later), and (3) the metallicity distribution of GCs in external galaxies is generally bimodal (or at least very different from the metallicity distribution of stars in the galaxy as a whole), with a large number of low-metallicity GCs. Reviews of their properties include Brodie & Strader (2006), Renzini (2008, 2013), and see also Protegies et al (2010).

This bimodal, or possibly skewed metallicity distribution (e.g. Strader et al. 2003, Peng et. al 2006) is sometimes interpreted as indicating that there are two formation modes: one that produced low-metallicity, old systems and a second for the generally younger, higher-metallicity component. For instance, Ashman & Zepf (1992) suggested that metal-rich GCs are formed in gas rich mergers and metal-poor GCs are donated by progenitor spirals. However, their work did not incorporate a cosmological model, and their predictions of the number and color distribution of GCs in massive Es galaxies were not consistent, as pointed out by Forbes, Brodie & Grillmair (1997). Other models explored reionization for setting the bimodality (e.g., Santos 2003; Harris & Pudritz 1994).

Beasley et al. (2002) augmented this picture by incorporating a semi-analytical model of combined galaxy and GC formation in a cosmological context. In that work, each mode of GC formation was assigned a fixed efficiency relative to the field stars. However, to match observed values, the formation of metal-poor GCs had to be artificially truncated after $z = 5$. Recently, investigations have explored more empirical, hierarchical galaxy formation models in a cosmological setting. Muratov & Gnedin (2010) have modeled the formation of GCs using the assembly history from cosmological simulations combined with observed scaling relations. In their model bimodality naturally arises from the rate of galaxy mergers. Early mergers preferentially produce metal-poor GCs and a few late massive mergers can produce a significant number of metal-rich GCs. However their model produces metal-rich GCs that are too young, which is at odds with observation that some of metal-rich GCs are old as metal-poor GCs. In addition, their model is again semi-analytic and doesn't explicit deal with how star formation proceeds in low-metallicity, high-density gas.

Essentially none of the models discussed above attempt to model the detailed structure of star formation within globular clusters. In particular, it is not clear how to get a large amount of gas (10^6 M$_\odot$) into a very small region without star formation occurring during the collapse, which would result in a wide spatial distribution of stars and perhaps even prevent the collapse.

As an aside, we note that, quite recently, observations have demonstrated that globular clusters are not a single stellar population, but may be composed of multiple generations showing enhanced He and specific abundance changes, particularly those associated with proton-capture processes (e.g., Norris et al 1981; Kraft 1994; Gratton et al. 2001; Carretta et al. 2009). In addition, photometric data shows a splitting of the man sequence in many GCs (e.g., Piotto 2009; Anderson et al. 2009; Milone et al. 2010). This has been challenging to explain because, with a few possible exceptions, the Fe abundence distribution is generally very narrow (consistent with observational errors), indicating that supernova self-enrichment plays no role. A wide range of models have been proposed to explain these abundance irregularities, beginning with the possibility that AGB stars in the 4-8 M$_\odot$ mass range can produce the necessary elements through hot bottom burning (e.g., D'Ercole et al 2010; Ventura et al. 2013). Other ideas include the existence of Fast Rotating Massive Stars (FRMS; Krause et. al 2013), supermassive stars (Denissenkov & Hartwick 2014; Denissenkov et. al 2015), and massive interacting binaries (e.g. Mink 2009; Bastian et al. 2013). All of these solutions are problematic for a number of reasons (e.g. Renzini et al. 2015; Bastian et al. 2015), including the mass budget required to

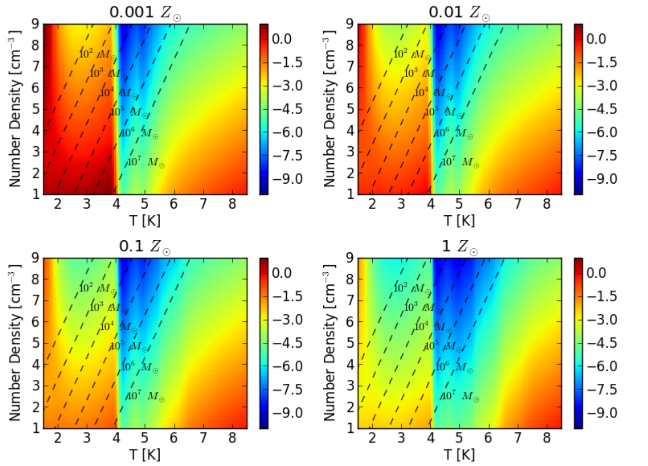

Figure 1.

The ratio of cooling time to dynamical time for gas with a range of density, temperature and metallicity values, as labelled.

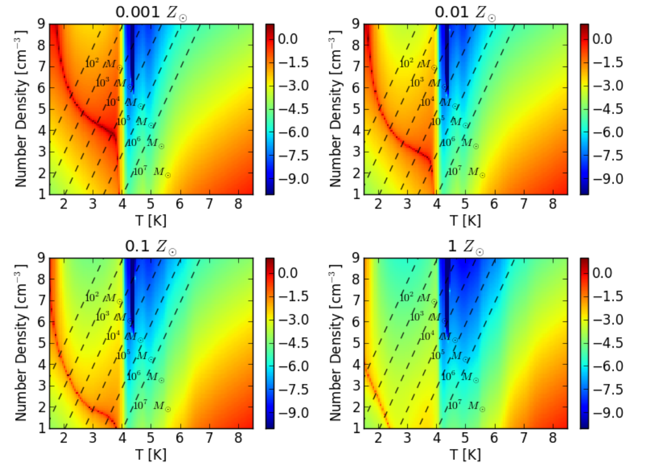

Figure 2.

The ratio of cooling time to dynamical time for gas with a range of density, temperature and metallicity values, as labelled. This plot is similar to Figure 1, except that we include a radiative heating source as specified in Haardt & Madau (2012), at $z = 0$

generate the observed number of second generation stars. However, in this work, we will not explicitly explore this second generation, instead focusing on the problem of understanding star formation in low-metallicity gas.

2 BASIC IDEA

In this paper, we explore a simple idea: can the cooling properties of low-metallicity gas clouds themselves influence how star formation proceeds? High-metallicity (by which we mean approximately solar metallicity, or even lower – we will address this point more precisely below) gas cools rapidly, typically on a timescale shorter than the dynamical time, meaning that present day large gas clouds, with masses in the GC range, are typically "cold", with temperatures well below their virial temperatures and so rapid fragmentation is inevitable. This generally means that high-metallicity giant molecular clouds will rapidly produce stars before they are completely collapsed and feedback from those stars will result in a low star formation efficiency (REF). However, for a low enough metallicity, the gas may cool slowly so that the cloud will collapse coherently, not fragmenting until the central gas density is very high. These high densities promote rapid star formation resulting in high efficiency. In this way, paradoxically, inefficient cooling may result in more efficiency star formation.

To futher investigate this simple idea we have created one zone models of a cooling parcel of gas. In this scenario, the parameter space consists of density, temperature, and metallicity. Once the parameters are chosen the evolutionary timescales are computed: the quantity of interest is the ratio of the absolute value of cooling time to dynamical time $|t_{cool}|/t_{dyn}$. In our simple one zone model, cooling is computed using the publicly available GRACKLE chemistry library; details of implementation and functionality can be found in The Enzo Collaboration et al. (2013).

Figure 1 is a panel showing the ratio of $\log(|t_{cool}|/t_{dyn})$ for metallicity values $Z/Z_\odot = 10^{-3}, 10^{-2}, 10^{-1}, 1$. To begin, we focus on the lowest metallicity (upper-left) panel of Fig 1 – we see that there are two regions where cooling and dynamical time are comparable (shaded red). The first is in the temperature range $10^1 - 10^4$K (the sharp cutoff at 10^4K is due to efficient cooling from HI line emission), and the second is in the bottom right corner. It is the former region in which we are most interested because this area is where we expect to find gas clouds with values conducive for globular cluster formation. Over each heat map, we plot lines of density and temperature corresponding to constant Bonner-Ebert mass (see Section 3 for details on how this is computed). It is clear from the plot that, for gas clouds with masses typical of globular clusters, there are values in the region where cooling is relatively inefficient, allowing the gas to collapse coherently before it can cool and fragment. Further, as the metallicity increases this region becomes less pronounced and the gas becomes more efficient in cooling, which will allow the gas to cool and fragment before global collapse sets in.

This is all computed in the absence of any radiative background. In Figure 2, the one zone models are recalculated as previous except allowing for radiative heating. Although the radiative background is uncertain, we adopt the radiative background from Haardt & Madau (2012) at $z = 0$ in order to show the kind of effect we expect. This does not change the high gas cooling rate, but it does affect the lower-temperature gas cooling time. In particular, we see that an equilibrium curve is present where heating and cooling are balanced. We no longer have the extended region where cooling and dynamical time scales are comparable but now are concentrated along the equilibrium curve. Furthermore, it should be expected that gas will naturally seek the equilibrium curve values. Therefore, for values above and below the curve there should be a migration to high density low temperature for values above and low density high temperature for values below. Moreover, when the the metallicity increase the equilibrium curve shifts downward, decreasing the possibility of having globular cluster like conditions.

This is all determine by computing cooling and dynamical times for gas with a characteristic density and temperature, demonstrating that the idea of inefficient cooling may be appropriate for low-metallicity gas (or gas with a somewhat higher metallicity but stronger radiative background). We now turn to space- and time-dependent numerical simulations to explore this idea further. Ideally, we would carry out cosmological simulations that included the full range of dynamical processes relevant for star formation at high-redshift with low (but non-zero) metallicity. However, this is computational intractable, and therefore we instead investigate a simple, idealized set up. We expect that gas cloud collisions during mergers at high-redshift will result in the accumulation of gas in relatively dense knows. These clouds will rapidly cool to temperatures around 10^4 K. Therefore, we set up turbulently perturbed Bonner-Ebbert spheres with masses typical of globular clusters, and densities/metallicities motivated by Figure 1. In future work, we will explore more complicated dynamics, such as colliding flows; however, here we explore perhaps the most simple possible test of this idea.

3 NUMERICAL MODELS

3.1 Numerical Method

This simulations were performed with the publicly available Eulerian three-dimensional hydrodynamical adaptive mesh refinement Enzo code (The Enzo Collaboration et al. 2013). The domain box size of the simulation was 150 pc with a top level root grid resolution of 128^3, and a maximum refinement level of 3 for a cell size of 0.125 pc. Cell refinement was dictated by baryon mass such that a cell was refined whenever the its mass became larger than 0.1 $M_\odot$ as well as a refinement based on the Jeans length such that the Jeans length was always refined by 4 cells. Our simulations included self gravity and radiative cooling using the Grackle library; details described in The Enzo Collaboration et al. (2013). The metal cooling (and heating) rates are computed using a non-equilibrium model for H, H^+, He, He^+, He^++ and e^- and a table computed from Cloudy for metal-line cooling (and heating), as described in Smith et al. (????). When a radiative background is included, we use Haardt & Madau (2012) at z =0

3.2 Initial Conditions

Our initial conditions consist of a cloud in pressure equilibrium with an ambient density and temperature background. The internal structure of the cloud is modeled by a Bonner-Ebert sphere Bonnor (1956); a self-gravitating isothermal gas sphere in hydrostatic equilibrium embedded in a pressurized medium. To fully describe a Bonner-Ebert sphere, a mass M_{BE}, temperature T_{BE}, and an external pressure P_{ext} must be chosen. Following our assumptions outlined in Section 2, we choosed $M_{BE} = 10^6$ $M_\odot$, $T_{BE} = 6000$ K, and $P_{ext} = 1.8 \times 10^5 \times k_B$ (k_B : Boltzmann constant). This corresponds to a cloud on the cusp where heating and cooling balance.

In addition, we add turbulence to the cloud following a power spectrum of $v_k^2 \propto k^{-4}$ for the velocity field. We include only models between $k_{\min} = 9$ and $k_{\max} = 19$ such that the input modes are well resolved and have wavelengths smaller than the cloud radius. We set the turbulent velocites such that rms velocity of the gas is XXX km/s. Figure 3 is a panel of the initial number density, temperatue, velocity magnitude and pressure for all the simulations in discussion.

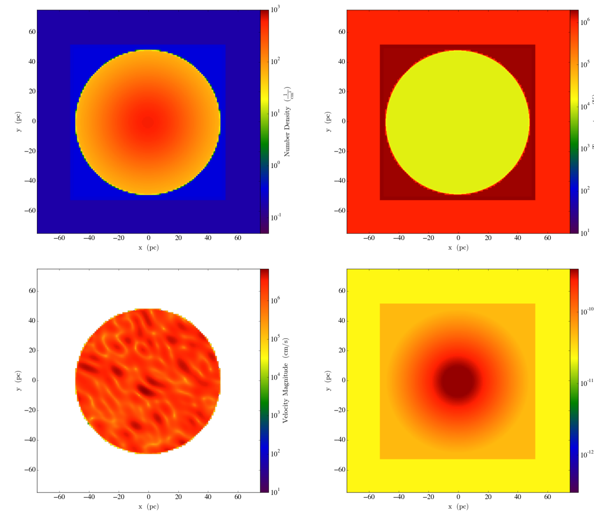

Figure 3.

Slices of inital number density, temperature, velocity magnitude and pressure for all simulations in this paper.

4 RESULTS

4.1 No Heating Runs

In the top hand panel of Figure 4, are density profiles given at multiple time steps for the $Z = 10^{-3} Z_\odot$ run. The cloud, which initially stable, starts to change dynamically due the added turbulence and cooling. The the free fall time of the cloud is $t_{ff} \approx 6$ Myr. However, the added pressure due to turbulence has prolonged any large scale collapse. Noting the several outputs, the cloud initially starts to drive mass outward. This is due the increase in pressure from turbulence. The outter rim of the cloud begins to drive outward decreasing the amount of mass in each radii. The expansion only last for ≈ 15 Myr. At this point, gravitational collapse sets in and the formation of a core begins, see Figure 5. The bottom hand panel of Figure 4, demonstrates the inability of the cloud to cool sufficiently. As expected from the one zone model, the cloud cannot efficiently cool before global gravitational collapse sets in.

We repeat the previous run except we change the metallicity to $Z = 10^{-2} Z_\odot$. In this case there is a significant difference in the run. The gas is now allowed to cool efficiently, as evident in the temperature profiles – see Figure 6. The center of the gas cloud, up to radii of ≈ 10 pc, has cooled to ≈ 200 K in less than a million years. The added effect of the turbulence allows the cold gas to condense into dense pockets. Therefore, reaching higher densities untill local fragmentation sets in. In Figure 7, it is apparent from the density knots that local fragmentation has set in disallowing the gas to collapse globally at time 2.25 Myr. Hence, our numerical runs

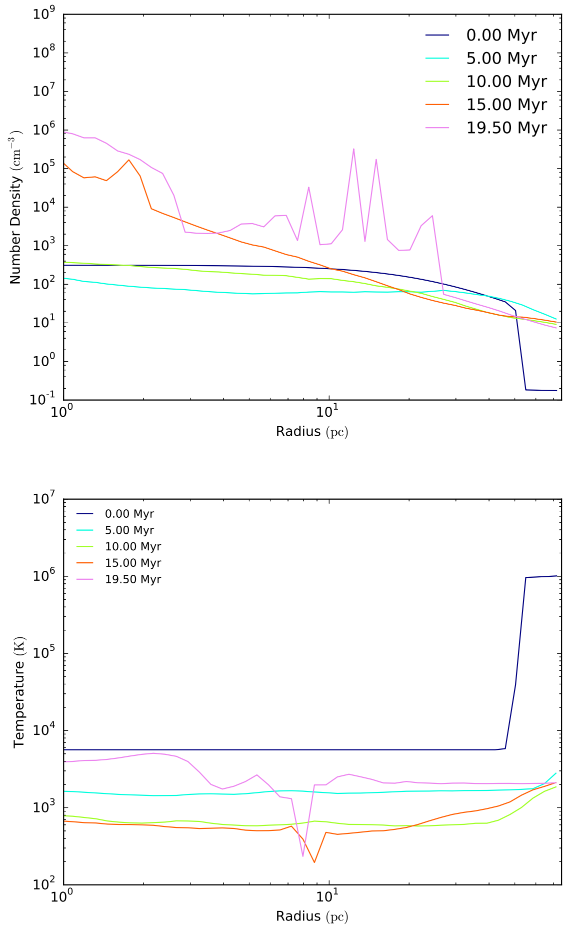

Figure 4.

Cell weighted profiles for density and temperature at give output times for run with cooling, turbulence, and metallicity of $Z = 10^{-3} Z_{\odot}$.

agree with our simple one zone models. Moreover, we find that there is a critical metallicity between $10^{-3} - 10^{-2} Z_{\odot}$ that seperates the evolution of gas cloud into either global gravitational collapse or local fragmentation.

4.2 Heating Runs

5 DISCUSSION

5.1 Analytic Model

5.2 Implications

5.3 Caveats

6 SUMMARY

ACKNOWLEDGMENTS

REFERENCES

Bonnor W. B., 1956, MNRAS, 116, 351
Haardt F., Madau P., 2012, ApJ, 746, 125
The Enzo Collaboration et al., 2013, ArXiv e-prints

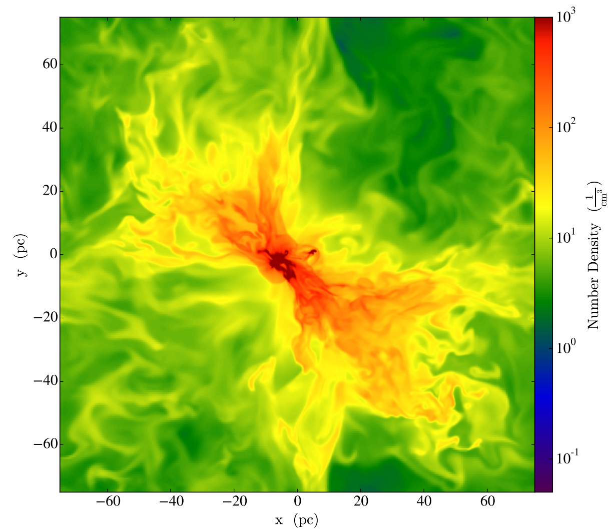

Figure 5.

Density slice at $t = 19.4$ Myr for run with cooling, turbulence, and metallicity of $Z = 10^{-3} Z_{\odot}$. In this run cooling is not efficient and gravity takes over forming a dense core.

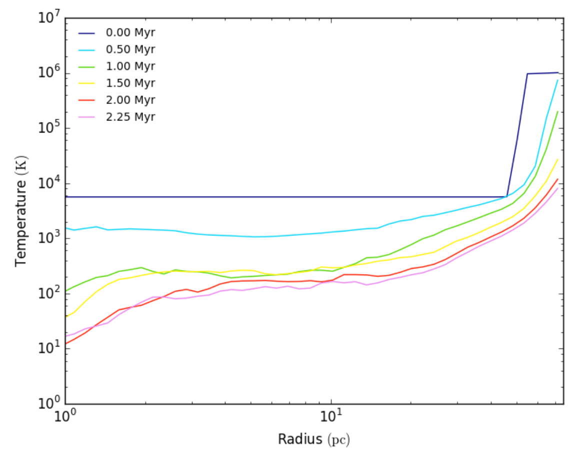

Figure 6.

Cell weighted temperature profiles at given output times for run with cooling, turbulence, and metallicity of $Z = 10^{-2} Z_{\odot}$.

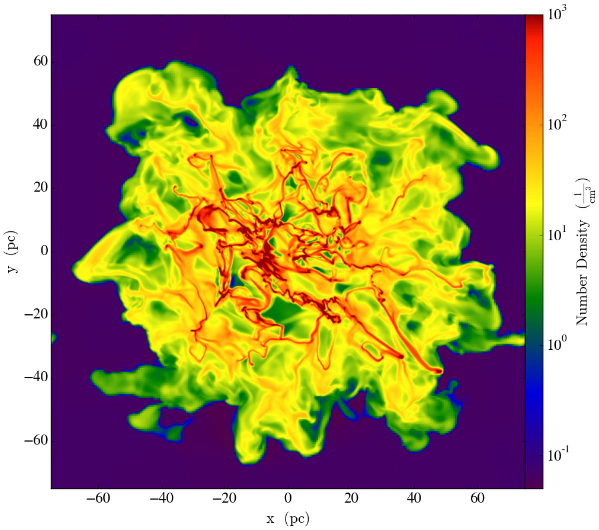

Figure 7.

Density slice at t = 2.25 Myr for run with cooling, turbulence, and metallicity of $Z = 10^{-2} Z_{\odot}$. In this run cooling is efficient causing local fragmentation.