FIRST STARBURSTS AT HIGH REDSHIFT: FORMATION OF GLOBULAR CLUSTERS

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Abstract  Numerical simulations of a Milky Way-size galaxy demonstrate that globular clusters with the properties similar to observed can form naturally at $z > 3$ in the concordance ΛCDM cosmology. The clusters in our model form in the strongly baryon-dominated cores of supergiant molecular clouds. The first clusters form at $z \approx 12$, while the peak formation appears to be at $z \sim 3 - 5$. The zero-age mass function of globular clusters can be approximated by a power-law $dN/dM \propto M^{-2}$ in agreement with observations of young massive star clusters.

For the first time it has been possible to include the formation of globular clusters self-consistently into the hierarchical galaxy formation model [Kravtsov and Gnedin, 2003]. The simulations used in our study were performed using the Eulerian gasdynamics+$N$-body ART code which uses an adaptive mesh refinement approach to achieve high dynamic range [Kravtsov et al., 1997]. Several physical processes critical to various aspects of galaxy formation are included: star formation; metal enrichment and thermal feedback due to supernovae type II and type Ia; self-consistent advection of metals; metallicity- and density-dependent cooling and UV heating due to the cosmological ionizing background. The simulation follows the early ($z > 3$) stages of the evolution of a Milky Way-type galaxy, $M \approx 10^{12} h^{-1} M_\odot$ at $z = 0$.

Although the resolution achieved in the disk region is very high by cosmological standards, $\Delta x \approx 50$ pc at $z = 4$, it is still insufficient to resolve the formation of stellar clusters. The resolution, however, is sufficient to identify the potential sites for GC formation. The natural candidates are cores of giant molecular clouds in high-redshift galaxies [Harris and Pudritz, 1994]. Accordingly, we complement the simulations with a physical description of the gas distribution on a subgrid level. It assumes an isothermal structure of the unresolved core and a universal density threshold of cluster star formation, $\rho_{\text{st}} = 10^4 M_\odot$ pc$^{-3}$. The gas
Figure 1. Projected gas density in the most massive disk at $z = 4$. A nearly face-on disk has prominent spiral arms and is in the process of very active accretion and merging. The globular clusters identified at this epoch are shown by circles.

at densities above $\rho_{sf}$ is converted into a star cluster with the efficiency $\epsilon = M_\star/M_{core} = 60\%$. The size of the cluster after the gradual loss of the remaining gas is $R_\star = R_{core}/\epsilon$.

The first globular clusters formed around $z \approx 12$ and cluster formation continued at least until $z \approx 3$. The preferred epoch of globular cluster formation ($z \sim 3 - 5$) corresponds to the cosmic time of only $1 - 2$ Gyr, when the gas supply is abundant in the disks of the progenitor halos and the merger rate of the progenitors is high. All old globular clusters thus appear to have similar ages.

Most globular clusters in our model form in halos of mass $> 10^9 M_\odot$. Within the progenitor systems, globular clusters form in the highest-density regions of the disk. In the most massive disk in the simulation (Figure 1), the newly formed clusters trace the spiral arms and the nucleus, similarly to the young star clusters observed in merging and interacting galaxies [Whitmore et al., 1999].

Note that although the high-redshift globular clusters form in gaseous disks, the subsequent accretion of their parent galaxies would lead to
Formation of globular clusters

Figure 2. The build-up of the initial mass function of globular clusters at four epochs. The straight dashed line shows a power-law, \( N \propto M^{-2} \). The slope \( \alpha \) becomes shallower with decreasing redshift and saturates at \( \alpha = 2.05 \pm 0.07 \) for \( z < 4 \).

Tidal stripping and disruption. The clusters are likely to share the fate of the stripped stars that build up the galactic stellar halo and should have roughly spherical spatial distribution at \( z = 0 \).

The total mass of clusters within a parent galactic halo correlates with the total galaxy mass \( M_h \): \( M_{GC} = 3.2 \times 10^6 M_\odot (M_h/10^{11} M_\odot)^{1.13\pm0.08} \). The global efficiency of cluster formation, \( M_{GC}/M_h \), therefore depends only weakly on the galaxy mass. The mass of the globular cluster population in a given region also strongly correlates with the local average star formation rate density: \( M_{GC} \propto \Sigma_{SFR}^{0.75\pm0.06} \) at \( z = 3.3 \). A similar correlation, albeit with a significant scatter, was reported for the observed present-day galaxies \[Larsen, 2002\]. In our model the correlation arises because both the star formation rate and mass of the globular cluster population are controlled by the same parameter, the amount of gas in the densest regions of the ISM.

The metallicities, which the clusters acquire from the gas in which they form, are remarkably similar to the metal-poor part of the Galactic cluster distribution. Note that at all epochs the dynamical time of the molecular cores is very short (\( \sim 10^6 \) yrs), which means that the galactic gas is pre-enriched even before the first clusters form. Thus the oldest globular clusters do not contain the oldest stars in the Galaxy.
The mass function of the model clusters at all output epochs (Figure 2) is well fit by a power-law $dN/dM \propto M^{-2}$ for $M > 10^5 \, M_\odot$, in agreement with the mass function of young star clusters in normal spiral and interacting galaxies [Zhang and Fall, 1999]. The power-law slope at high masses also resembles that of the high-redshift mass function of dark matter halos in the hierarchical CDM cosmology [Gnedin, 2003]. We find that although the most massive cluster in each galaxy correlates with the parent galaxy mass, $M_{\text{max}} \propto M_\text{h}^{1.3\pm0.1}$, a significant scatter around this relation implies that for a given halo the masses of individual clusters can vary by a factor of three. Therefore, the overall shape of the mass function of globular clusters in our model does not follow directly from the mass function of their parent halos, but depends also on the mass function of molecular cloud cores within individual galaxies.

The slope of the mass function steepens with increasing mass. We find a relatively shallow, $\alpha \approx 1.7$, mass function for the small-mass clusters forming in lower-density cores and the steep, $\alpha \approx 2$, mass function for massive globular clusters forming in the densest regions of the disk. The steepening of the luminosity function with increasing luminosity is also observed for young star clusters in starbursting galaxies [Whitmore et al., 1999; Larsen, 2002]. Thus over the range of masses typically probed in observations, $M > 10^5 \, M_\odot$, the mass function can be approximated by a power-law because the expected curvature over this range is rather small.

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