Dynamical Evolution of Dense Stellar Systems
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Dynamical Evolution of Globular Clusters in Hierarchical Cosmology

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Abstract. We probe the evolution of globular clusters that could form in giant molecular clouds within high-redshift galaxies. Numerical simulations demonstrate that the large and dense enough gas clouds assemble naturally in current hierarchical models of galaxy formation. These clouds are enriched with heavy elements from earlier stars and could produce star clusters in a similar way to nearby molecular clouds. The masses and sizes of the model clusters are in excellent agreement with the observations of young massive clusters. Do these model clusters evolve into globular clusters that we see in our and external galaxies? In order to study their dynamical evolution, we calculate the orbits of model clusters using the outputs of the cosmological simulation of a Milky Way-sized galaxy. We find that at present the orbits are isotropic in the inner 50 kpc of the Galaxy and preferentially radial at larger distances. All clusters located outside 10 kpc from the center formed in the now-disrupted satellite galaxies. The spatial distribution of model clusters is spheroidal, with a power-law density profile consistent with observations. The combination of two-body scattering, tidal shocks, and stellar evolution results in the evolution of the cluster mass function from an initial power law to the observed log-normal distribution.

Keywords. globular clusters: general

1. Giant Molecular Clouds at High Redshift

The outcomes of many proposed models of globular cluster formation depend largely on the assumed initial conditions. The collapse of the first cosmological 10^6 $M_\odot$ gas clouds, or the fragmentation of cold clouds in hot galactic corona gas, or the agglomeration of pressurized clouds in mergers of spiral galaxies could all, in principle, produce globular clusters, but only if those conditions realized in nature. Similarly, while observational evidence strongly suggests that all stars and star clusters form in molecular clouds, the initial conditions for cloud fragmentation are a major uncertainty of star formation models.

The only information that we actually have about the initial conditions comes from the early universe, when primordial density fluctuations set the seeds for structure formation. These fluctuations are probed directly by the anisotropies of the cosmic microwave background radiation. Cosmological numerical simulations study the growth of these fluctuations via gravitational instability, in order to understand the formation of galaxies and all other structures in the Universe. The simulations begin with tiny deviations from the Hubble flow, whose amplitudes are set by the measured power spectrum of the primordial fluctuations while the phases are assigned randomly. Therefore, each particular simulation provides only a statistical description of a representative part of the Universe, although current models successfully reproduce major features of observed galaxies.

Kravtsov & Gnedin (2005) attempted to construct a first self-consistent model of star cluster formation, using an ultrahigh-resolution gasdynamics cosmological simulation

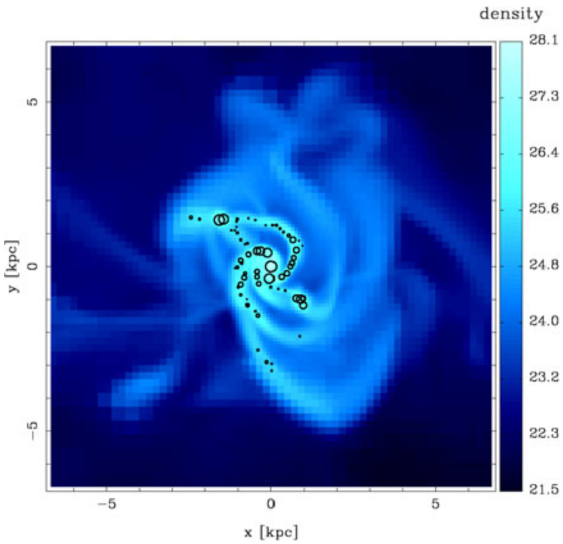

Figure 1. A massive gaseous disk with prominent spiral arms, seen face-on at redshift $z = 4$ in a process of active merging. The gas density is projected over a 3.5 kpc slice. In our model star clusters form in giant gas clouds, shown by circles with the sizes corresponding to the cluster masses. From Kravtsov & Gnedin (2005).

with the Adaptive Refinement Tree code. They identified supergiant molecular clouds in high-redshift galaxies as the likely formation sites of globular clusters. These clouds assemble during gas-rich mergers of progenitor galaxies, when the available gas forms a thin, cold, self-gravitating disk. The disk develops strong spiral arms, which further fragment into separate molecular clouds located along the arms as beads on a string (see Fig. 1).

In this model, clusters form in relatively massive galaxies, with the total mass $M_{\rm host} > 10^9$ M$_\odot$, beginning at redshift $z \approx 10$. The mass and density of the molecular clouds increase with cosmic time, but the rate of galaxy mergers declines steadily. Therefore, the cluster formation efficiency peaks at a certain extended epoch, around $z \approx 4$, when the Universe is only 1.5 Gyr old. The host galaxies are massive enough for their molecular clouds to be shielded from the extragalactic UV radiation, so that globular cluster formation is unaffected by the reionization of cosmic hydrogen. As a result of the mass-metallicity correlation of progenitor galaxies, clusters forming at the same epoch but in different-mass progenitors have different metallicities, ranging between 10^{-3} and 10^{-1} solar. The mass function of model clusters is consistent with a power law $dN/dM \propto M^{-\alpha}$, where $\alpha = 2.0 \pm 0.1$, similar to the observations of nearby young star clusters.

2. Orbits of Globular Clusters

We adopt this model to set up the initial positions, velocities, and masses for our globular clusters. We then calculate cluster orbits using a separate collisionless N-body simulation described in Kravtsov, Gnedin & Klypin (2004). This is necessary because the original gasdynamics simulation was stopped at $z \approx 3.3$, due to limited computational resources. By using the N-body simulation of a similar galactic system, but complete to $z = 0$, we are able to follow the full dynamical evolution of globular clusters until the present epoch. We use the evolving properties of all progenitor halos, from the outputs with a time resolution of $\sim 10^8$ yr, to derive the gravitational potential in the whole

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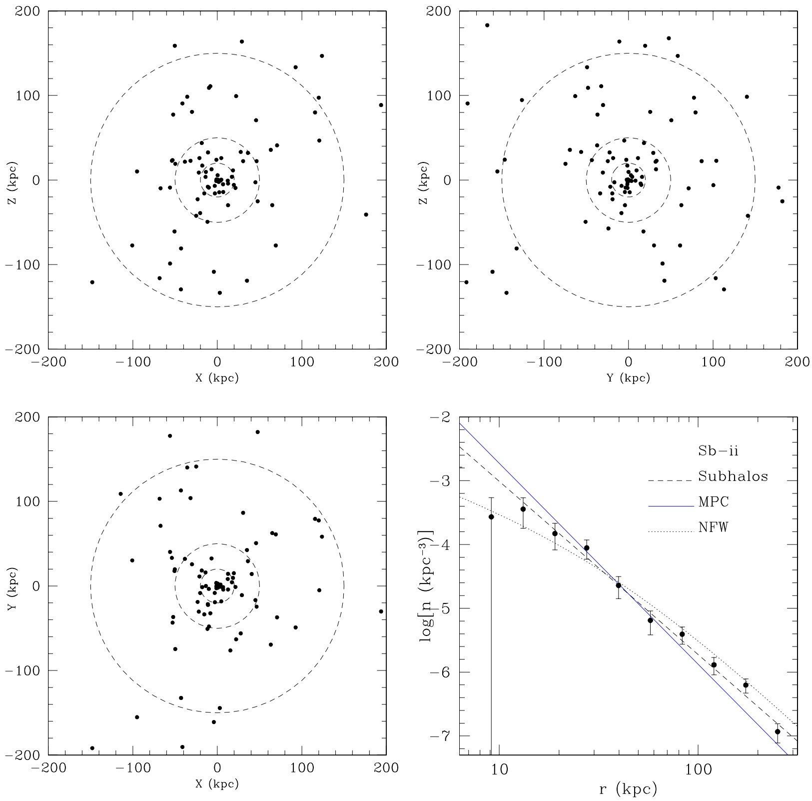

Figure 2. Spatial distribution of surviving model clusters in the Galactic frame. Dashed circles are to illustrate the projected radii of 20, 50, and 150 kpc. The number density profile (*bottom right*) can be fit by a power law, $n(r) \propto r^{-2.7}$. The distribution of model clusters is similar to that of surviving satellite halos (*dashed line*) and smooth dark matter (*dotted line*). It is also consistent with the observed distribution of metal-poor globular clusters in the Galaxy (*solid line*), plotted using data from the catalog of Harris (1996).

computational volume at all epochs. We convert a fraction of the dark matter mass into flattened disks, in order to model the effect of baryon cooling and star formation on the galactic potential. We calculate the orbits of globular clusters in this potential from the time when their host galaxies accrete onto the main (most massive) galaxy. Using these orbits, we calculate the dynamical evolution of model clusters, including the effects of stellar mass loss, two-body relaxation, tidal truncation, and tidal shocks.

We consider several possible scenarios, some with all clusters forming in a short interval of time around redshift $z = 4$, and others with a continuous formation of clusters between $z = 9$ and $z = 3$. Below we discuss the spatial and kinematic distributions of globular clusters in the best-fit model with the synchronous formation at $z = 4$.

In our model, all clusters form on nearly circular orbits within the disks of progenitor host galaxies. Depending on the subsequent trajectories of the hosts, clusters form three main subsystems at present time. *Disk clusters* formed in the most massive progenitor that eventually hosts the present Galactic disk. These clusters, found within the inner 10 kpc, do not actually stay on circular orbits but instead are scattered to eccentric orbits by perturbations from accreted galactic satellites. *Inner halo clusters*, found between 10 and 60 kpc, came from the now-disrupted satellite galaxies. Their orbits are inclined with respect to the Galactic disk and are fairly isotropic. *Outer halo clusters*, beyond 60

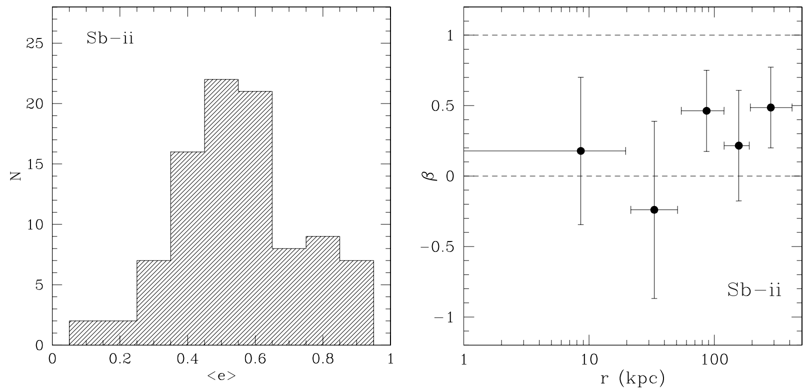

Figure 3. *Left:* Average eccentricity distribution of the surviving model clusters. *Right:* Anisotropy parameter β as a function of radius. Vertical error bars represent the error of the mean for each radial bin, while horizontal error bars show the range of the bin. Horizontal dashed lines illustrate an isotropic ($\beta = 0$) and a purely radial ($\beta = 1$) orbital distributions.

kpc from the center, are either still associated with the surviving satellite galaxies, or were scattered away from their hosts during close encounters with other satellites and consequently appear isolated.

Mergers of progenitor galaxies ensure the present spheroidal distribution of the globular cluster system (Fig. 2). Most clusters are now within 50 kpc from the center, but some are located as far as 200 kpc. The azimuthally-averaged space density of globular clusters is consistent with a power law, $n(r) \propto r^{-\gamma}$, with the slope $\gamma \approx 2.7$. Since all of the distant clusters originate in progenitor galaxies and share similar orbits with their hosts, the distribution of the clusters is almost identical to that of the surviving satellite halos. This power law is similar to the observed distribution of the metal-poor ([Fe/H] < -0.8) globular clusters in the Galaxy. Such comparison is appropriate, for our model of cluster formation at high redshift currently includes only low metallicity clusters ([Fe/H] $\leqslant -1$). Thus the formation of globular clusters in progenitor galaxies with subsequent merging is fully consistent with the observed spatial distribution of the Galactic metal-poor globulars.

Fig. 3 shows the kinematics of model clusters. Most orbits have moderate average eccentricity, $0.4 < \langle e \rangle < 0.7$, expected for an isotropic distribution. The anisotropy parameter, $\beta = 1 - v_t^2/2v_r^2$, is indeed close to zero in the inner 50 kpc from the Galactic center. At larger distances, cluster orbits tend to be more radial. There, in the outer halo, host galaxies have had only a few passages through the Galaxy or even fall in for the first time.

3. Evolution of the Globular Cluster Mass Function

Using these orbits, we now calculate the cluster disruption rates. Sophisticated models of the dynamical evolution have been developed using N-body simulations as well as orbit-averaged Fokker-Planck and Monte Carlo models. Several processes combine and reinforce each other in removing stars from globular clusters: stellar mass loss, two-body scattering, external tidal shocks, and dynamical friction of cluster orbits. The last three are sensitive to the external tidal field and therefore, to cluster orbits. While a general framework for all these processes has been worked out in the literature, the knowledge of realistic cluster orbits is essential for accurate calculations of the disruption.

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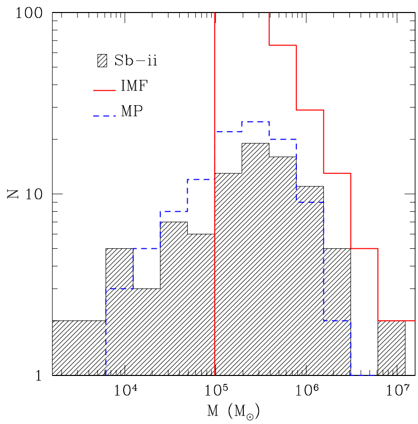

Figure 4. Evolution of the mass function of clusters in our best-fit model from an initial power law (*solid line*) to a peaked distribution at present (*histogram*), including mass loss due to stellar evolution, two-body relaxation, and tidal shocks. For comparison, dashed histogram shows the mass function of metal-poor globular clusters in the Galaxy.

Fig. 4 shows the transformation of the cluster mass function from an initial power law, $dN/dM \propto M^{-2}$, into a final bell-shaped distribution. In this model all globular clusters form at the same redshift, $z = 4$, or about 12 Gyr ago. The half-mass radii, R_h, are set by the condition that the median density, M/R_h^3, is initially the same for all clusters and remains constant as a function of time. Over the course of their evolution, numerous low-mass clusters are disrupted by two-body relaxation while the high-mass clusters are truncated by tidal shocks. The present mass function is in excellent agreement with the observed mass function of the Galactic metal-poor clusters.

This result by itself is not new. Previous studies of the evolution of the cluster mass function have found that almost any initial function can be turned into a peaked distribution by the combination of two-body relaxation and tidal shocks. However, the efficiency of these processes depends on the cluster mass and size, $M(t)$ and $R_h(t)$. *The new result is that we find that not all initial relations $R_h(0) - M(0)$ and not all evolutionary scenarios $R_h(t) - M(t)$ are consistent with the observed mass function.*

Consider two examples. (i) If the half-mass radius R_h is kept fixed for clusters of all masses and at all times, the median density $M(t)/R_h^3$ decreases as the clusters lose mass. Two-body scattering becomes less efficient and spares many low-mass clusters, while tidal shocks become more efficient and disrupt most high-mass clusters. The final distribution is severely skewed towards small clusters. (ii) If the size is assumed to evolve in proportion to the mass, $R_h(t) \propto M(t)$, the cluster density increases with time. As a result, all of the low-mass clusters are disrupted by the enhanced two-body relaxation, while the high-mass clusters are unaffected by the weakened tidal shocks. The final distribution is skewed towards massive clusters.

Only our best-fit model with $M(t)/R_h^3(t) = const$ successfully reproduces the mass function and spatial distribution of metal-poor globular clusters in Galaxy. We are now investigating the formation of metal-rich clusters in galactic mergers at lower redshifts.

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