Where are the First Stars now?

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Abstract. We use high-resolution simulations to show that the current standard paradigm for the growth of structure in the Universe predicts the formation of a galaxy like our own to differ substantially from the classic ELS and Searle/Zinn pictures. On scales larger than the Local Group, the earliest star formation was extremely inhomogeneous, suggesting that the high redshift intergalactic medium should have large-scale abundance variations. The very oldest stars should be found today in the central regions of rich galaxy clusters. In the Milky Way's bulge and stellar halo little correlation is expected between age and metallicity. Some of the lowest metallicity stars may be relatively young. Many of the oldest stars may have high metallicity. Spheroid stars were formed before and during halo assembly, the oldest now lying preferentially at small radii, while low metallicity stars lie preferentially at large radii. The bulk of the Milky Way's stellar spheroid came from a small number of progenitors. It should show little spatial structure in the inner 5 to 15 kpc, but consist at each point of a superposition of hundreds of 'cold' streams. Such streams have been detected in the Solar neighborhood.

1 Introduction

Over the last two decades a standard paradigm has emerged for the origin and evolution of structure in the Universe. The basic ingredients of this picture are the following.

• The Universe has expanded from a hot, dense and smooth state. This Hot Big Bang is observed directly in the CMB at an age of 300,000 years. It is checked by the Planckian nature of the CMB spectrum back to an age of a few months, and by the abundances of the light elements back to an age of a few minutes.

• The observed near-homogeneity and isotropy were produced by an early phase of inflationary expansion.

• The dominant matter component today is some unseen form of nonbaryonic, weakly interacting dark matter.

• All observed structure originated from quantum zero-point fluctuations during inflation. These produced a gaussian field of density fluctuations with a near-Harrison-Zel'dovich power spectrum showing no characteristic features on scales relevant to galaxies and larger structures.

• Present structure grew by gravitational amplification of these small initial fluctuations.

• Galaxies formed by cooling and condensation of gas in the cores of heavy halos produced by nonlinear hierarchical clustering of the dark matter.

The current "consensus" version of this model imagines a flat Universe in which baryons contribute a few percent of the closure density, cold dark matter contributes about one third, and an effective cosmological constant contributes the rest. This model is consistent with current data on the distance scale, acceleration, large-scale structure and galaxy populations of the Universe. It should be definitively tested by the next generation of CMB experiments, in particular by the MAP and Planck Surveyor satellites.

Strong points of such CDM models are that they provide fully specified initial conditions, and that the nonlinear growth of structure in the dominant component, the dark matter, can be simulated accurately on scales larger than a kiloparsec or so. Below this scale nongravitational processes undoubtedly play a major role in shaping galaxies. Recent work has grafted phenomenological modelling of gas cooling, star-formation, feedback, and stellar evolution onto high resolution N-body calculations of dark matter clustering [8]. This has made it possible to simulate cosmologically representative volumes with sufficient resolution to follow the formation and evolution of individual galaxies. Here we present preliminary results from an extension of this work to much higher resolution. We trace the detailed formation history of individual objects and of their immediate environment, showing results for a rich galaxy cluster and for a system like the Milky Way. A much more detailed account of the results for clusters will be published shortly as Springel et al (in preparation).

2 The Simulations

The simulations discussed here were carried out using a parallel tree-code called Gadget [13] on the Cray T3E at the Garching Computing Centre of the Max Planck Society. Initial conditions were taken from a ΛCDM simulation already analysed by Kauffmann and collaborators [8]. This simulation assumes $\Omega_o = 0.3$, $\Lambda = 0.7$, $h = 0.7$ and $\sigma_8 = 0.9$. The second most massive cluster ($M_{vir} = 5.6 \times 10^{14} h^{-1} M_\odot$) at $z = 0$ was placed at the origin of coordinates and a surrounding spherical region of radius $70h^{-1}$Mpc was isolated for resimulation with Gadget. The initial mass distribution between 21 and $70h^{-1}$Mpc was represented at relatively low resolution by 3×10^6 particles. In the inner region, where the original simulation had 2.2×10^5 particles, we created new initial conditions with 4.5×10^5, 2.0×10^6, 1.3×10^7 and 6.6×10^7 particles. With increasing mass resolution along this sequence we included extra initial fluctuations on scales beyond the Nyquist frequency of the original simulation, and we decreased the force softening to give improved spatial resolution. We then ran all four simulations to $z = 0$ and compared results with each other and with the original simulation. In the largest resimulation there are about 20 million particles within the virial radius of the final cluster and the gravitational softening radius is $0.7h^{-1}$kpc. This is the highest resolution simulation of a rich galaxy cluster ever carried out.

The particle data for all these simulations were dumped at intervals of 0.06 in $\ln(1+z)$. We then implemented the semianalytic galaxy formation recipes of Kauffmann et al [8] on merging trees constructed from these outputs. A major improvement is possible as a result of the increased resolution of the present simulations. The dark halos of most of the more massive galaxies remain identifiable as self-bound substructures within the cluster. In the highest resolution simulation there are almost 5000 such “galaxy halos” within the virial radius of the final cluster. By keeping track of such substructures we are able to follow the dynamical evolution of galaxies within clusters and it is no longer necessary to use semianalytic recipes to track galaxy merging. Apart from this change we follow the procedures of Kauffmann et al exactly, using their “ejection” prescription for the fate of reheated gas, and setting the parameters regulating star formation and feedback so that the observed I-band Tully-Fisher relation and cold gas fraction are reproduced for spiral galaxies outside the cluster. This requires parameter choices very similar to those used by Kauffmann et al.

3 Cluster Results

We begin by showing that our modelling of galaxy formation, although adjusted to reproduce the properties of spiral galaxies outside the cluster, also reproduces well the observed properties of the galaxy populations within clusters. The uppermost panel of Fig. 1 compares the observed Tully-Fisher relation [3] with the predicted relation for isolated Sb/Sc galaxies; the linewidth and Hubble type are defined here as in Kauffmann et al [8]. The star formation and feedback efficiencies were tuned to reproduce this relation as well as possible, but it is still striking that adjusting two parameters can produce an excellent fit to the slope and scatter of the observations. It is much more remarkable, however, that with *no* additional parameters the model produces a cluster luminosity function which is similar in normalisation and shape to observed luminosity functions, and a morphology-radius relation within the cluster which is also like that observed. Note that in contrast to earlier work, this latter success is achieved without tuning any parameter related to merging rates.

Given that this simulation produces a reasonably good fit to the galaxy populations in and around rich clusters, it is interesting to examine in detail its predictions for the history of star formation. In our highest resolution simulations the smallest resolved objects have a total mass of about $5 \times 10^8 M_\odot$, corresponding to a total initial baryon mass of $5 \times 10^7 M_\odot$ although their mass in stars is at least 10 times smaller. The latter difference arises because feedback is assumed to make star formation inefficient in low mass objects. Thus we resolve the formation of stellar systems similar in mass to large globular star clusters.

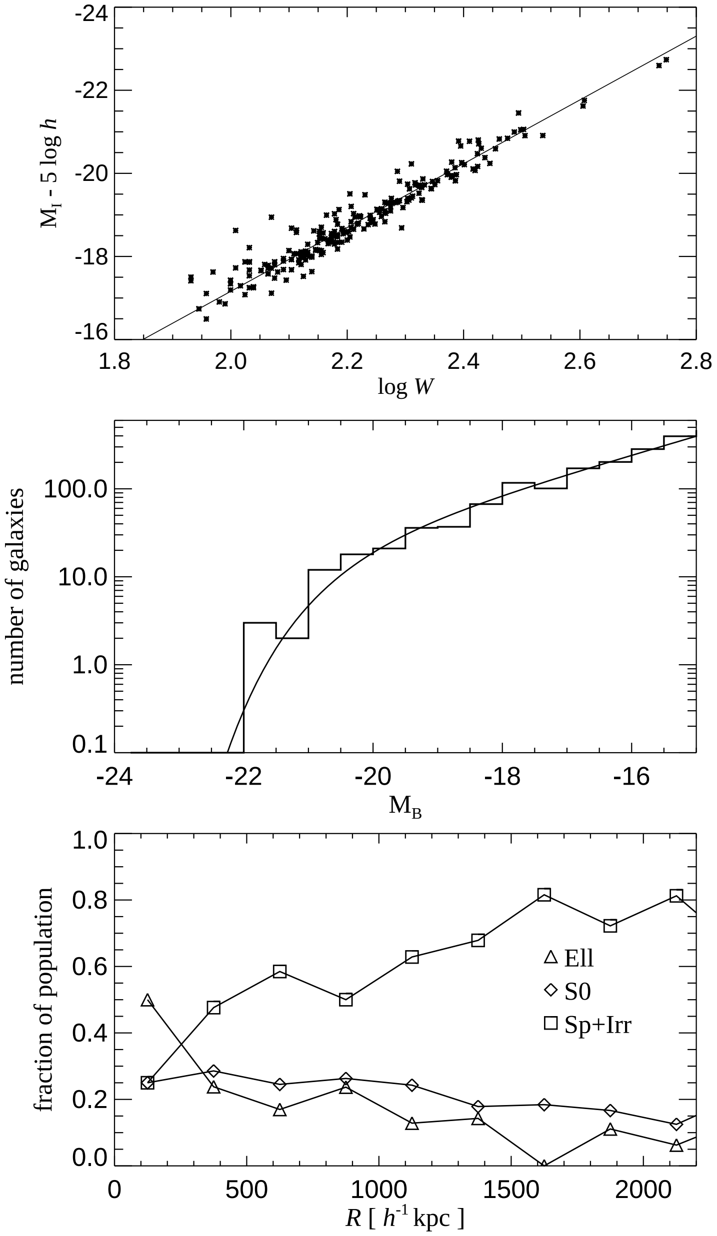

Fig. 1. *Top* I-band Tully-Fisher relation for isolated Sb/Sc galaxies outside the cluster. The straight line is the mean observed relation from [3]. *Middle* Number of galaxies within the virial radius of the cluster as a function of their absolute magnitude in the B-band. The Schechter fit shown has a faint end slope, $\alpha = -1.2$. *Bottom* Fraction of galaxies brighter than $M_B = -16.5$ in each of three morphology classes as a function of distance from cluster centre.

A first striking effect is the bias towards earlier formation for stars which end up inside the cluster. Thus half the stars which lie within the final virial radius form before $z = 4$ while half the stars outside this radius form after $z = 2$. The first 1.5% of stars in cluster galaxies have already formed by $z = 13$ while one has to wait until $z = 7.5$ to form a similar fraction of the stars outside the cluster. Note that formation is still biased in the cluster's vicinity but outside its virial radius [9]. Thus the first 1.5% of the stars in a "typical" region of the Universe would form even later.

In the upper right panel of Fig. 2 we show a projection at $z = 13$ of the galaxies in a cube of comoving side $10h^{-1}$Mpc centred on the barycentre of the material of the future cluster. The area of each symbol is proportional to the stellar mass of the galaxy. This distribution is clearly extremely inhomogeneous, with almost all the stars lying on or close to a single filament of comoving scale about $10h^{-1}$Mpc. Clearly the heavy elements produced by these "first stars" are very unlikely to be well mixed through the IGM. In the lower left panel we show where these same stars are at $z = 0$; the area of each symbol is here proportional to the mass of "first stars" which the corresponding galaxy contains. This can be compared to the plot at upper left which shows the distribution of all the stars at the end of the simulation, symbol area now corresponding to total stellar mass. Clearly the first stars are concentrated in a relatively small number of galaxies and these galaxies tend to lie close to the cluster centre. In fact, at $z = 0$ more than half of all the "first stars" lie within $100h^{-1}$kpc of cluster centre, whereas fewer than 10% of all cluster stars lie at such small radii.

Because of these strong bias effects the first stars in different regions of the Universe are predicted to form at very different times; some may still be forming today in weak structures in "voids". For many purposes it is more interesting to define the first stars not as those which formed first in time, but as those which formed from the least processed gas. In hierarchical cosmogonies the degree of processing of gas is closely related to the mass of the object in which it is found. For example, in the simulations analysed here gas which has never been part of a virialised object at all, or never part of an object with virial temperature exceeding $\sim 10^4$K, has never been associated with star formation and could plausibly have zero heavy element abundance. Such effects may be reflected in the strong observed correlation between the mean metal abundance of galaxies and their stellar mass. We illustrate the possible distribution of the "lowest metallicity" stars in the lower right panel of Fig. 2. This shows the distribution at $z = 0$ of the 1.5% of cluster stars which formed in the lowest mass dark halos. These stars are still primarily part of the lowest mass galaxies and their radial distribution within the cluster is similar to that of all the stars. Half of this subset of stars formed after $z = 3.9$, and their age distribution is very similar to that of clusters stars as a whole. Low metallicity stars in clusters are no older than the average.

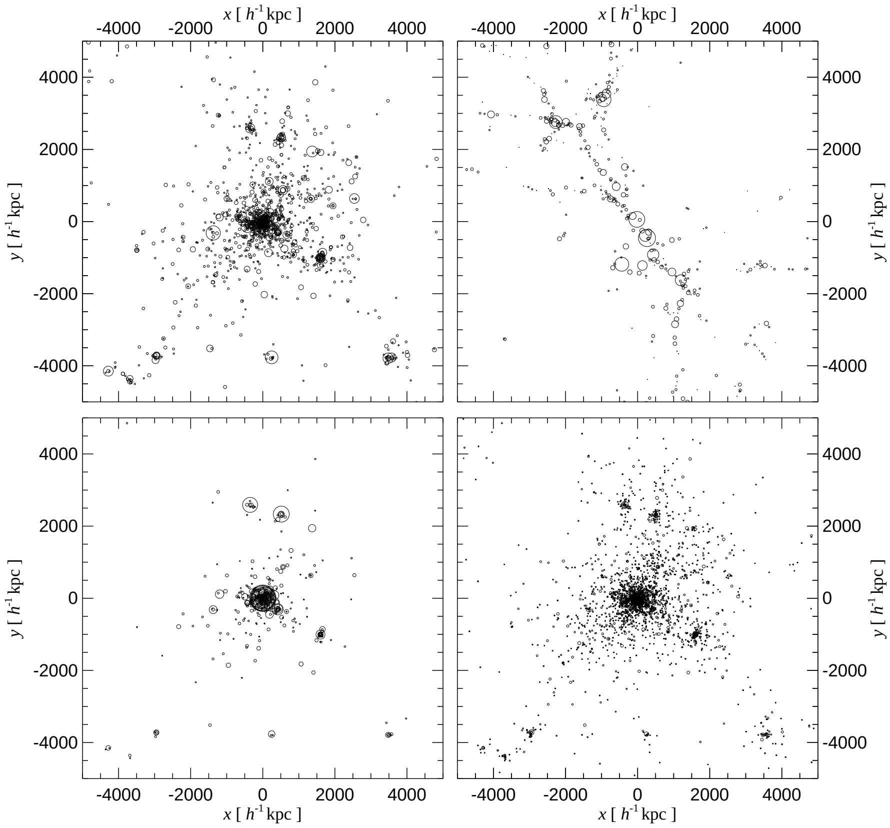

Fig. 2. Projections of the galaxy distribution in a cube of comoving side $10h^{-1}$Mpc. The upper right image is at $z = 13$ when 1.5% of the stars in final cluster have formed. The other three images are at $z = 0$. The upper images show all galaxies in the cube with symbol area proportional to stellar mass. The lower two images show only galaxies containing stars which were among either the first 1.5% (left) or the 1.5% formed in the lowest mass halos (right). In these lower images symbol size is proportional to the mass of the relevant stellar population.

4 "Milky Way" Results

Rather than running a new simulation of the assembly of a "Milky Way" halo, we here take a short cut by scaling our cluster simulations down by a factor of 7 in both size and velocity, corresponding to a factor of 343 in mass and to unchanged dynamical times. Both theoretical [**?**] and numerical [10] results suggest that such a scaling should give a good approximation to the dark matter evolution of a "typical" halo, except that assembly is shifted to somewhat lower redshifts. We run our semianalytic machinery on these rescaled simulations (using the same parameters as before) to obtain predictions for the star formation history within a "Milky Way" halo.

The results are illustrated in Fig. 3 which can be compared directly with Fig. 2. The shift in temperature (by a factor 49) caused by our rescaling produces large changes in cooling and feedback. Most star formation occurs at late times in the central disk. Within the final galaxy's halo about 80% of all stars are in the disk, 16% are in the bulge, and only 3% are part of other objects, more than half of those in a single satellite. Only by $z = 6.9$ has our model Milky Way made 1% of its stars. Figure 5 of ref. [11] suggests that this should be increased to $z \sim 10$ to account for the bias towards late assembly just noted. Despite the much higher effective resolution of the rescaled simulation, this redshift is still well below the 1% formation redshift of stars in the cluster of the last section.

The upper right panel of Fig. 3 shows the initial distribution of these "first" stars to be very inhomogeneous – most are in a handful of progenitor galaxies. By $z = 0$ they are quite centrally concentrated; 60% are within 10 kpc, with even older stars being even more centrally concentrated. On the other hand, if low metallicity stars are identified as those formed in the lowest mass dark halos, only 16% of the lowest metallicity 1% lie within 10 kpc, and lower metallicity stars are predicted to be even less centrally concentrated. These "low metallicity" stars have a median formation redshift of $z = 5.5$, much higher than the formation redshift of "typical" stars. Most are part of intact (60%) or disrupted (30%) dwarf satellites; only 10% are part of the central bulge. We return to these numbers in the next section.

5 Discussion

The results shown above demonstrate that if current structure formation theories are correct, the oldest stars should be found at the centres of rich clusters. Furthermore the distribution of the first stars was inhomogeneous on the (comoving) scale of *present-day* large-scale structure. As a result, enrichment of the intergalactic medium at high redshift must have been extremely patchy. If we want to find the oldest stars in the local universe we should look near the centre of M87, not in our own Galactic halo or in intergalactic space. Unfortunately they may be indistinguishable from the enormous background of slightly younger stars. On the other hand, the lowest metallicity stars (assumed here to be those that formed in the lowest mass objects) are distributed on large scales in a similar way to the general stellar population.

On smaller scale, similar effects imply that the classic monolithic collapse [2] and inhomogeneous assembly [12] pictures are of little help in interpreting the age and metallicity distribution within the Galactic bulge and halo. The oldest stars are predicted to be in the inner halo or bulge, and will be very difficult to distinguish from the dominant, somewhat younger population. Lower metallicity populations are expected to have more extended distributions, but there is no strong correlation between metallicity and age. Some

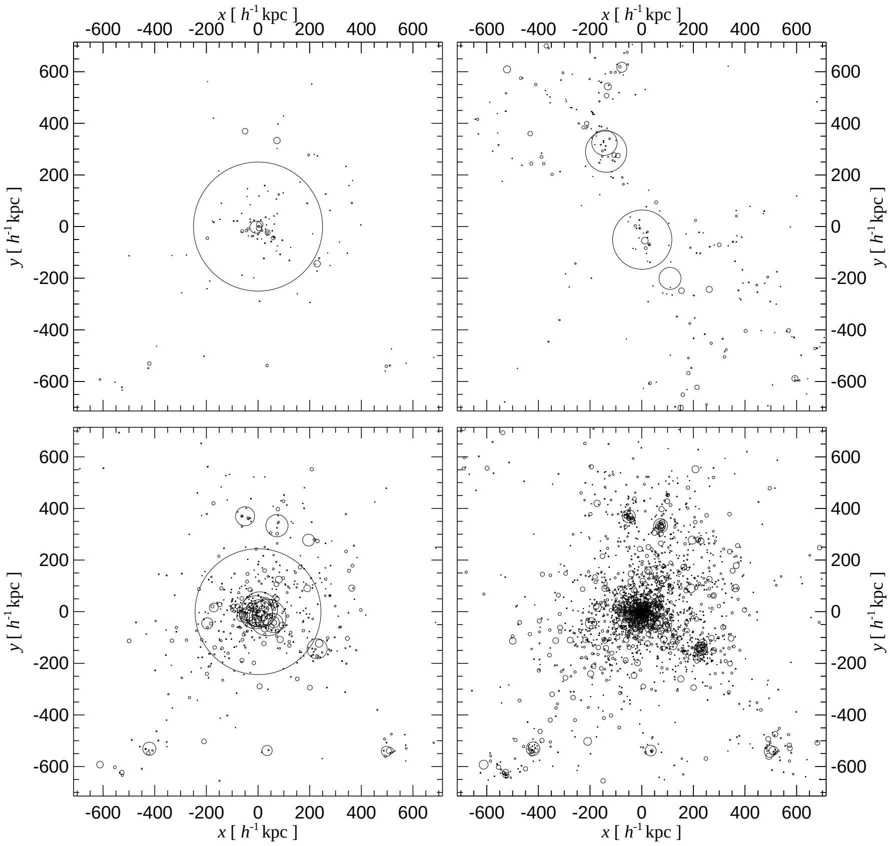

Fig. 3. Projections of the galaxy distribution in a cube of comoving side $1.4h^{-1}$ Mpc around a "Milky Way" halo. The upper right image is at $z = 5.4$ when 1% of the final stars have formed. The other three are at $z = 0$. The illustrated quantities are as in Fig. 2 except that the lower plots show the 1% "earliest" and 1% "lowest metallicity" stars.

low metallicity stars may be quite young, and indeed may continue to form today in low mass, isolated dwarf galaxies.

The rich internal structure predicted for dark matter halos in these CDM models is, as Fig. 1 demonstrates explicitly, in very satisfying agreement with the observed galaxy populations in rich clusters. Ben Moore and his collaborators [10] have emphasised that the situation is less clear for the Milky Way. Most of the low metallicity stars in our simulation are in the stellar halo rather than the bulge, but twice as many reside in satellites as in the diffuse component. In the real Galaxy more are in the diffuse halo than in satellites. This may be because the cores of many low mass halos survive undisrupted in our model, while the Milky Way can disrupt dwarfs even from relatively weakly bound orbits, as the example of Sagittarius clearly shows

[6]. It is uncertain whether this is a serious shortcoming of CDM models or may be resolved by more detailed dynamical modelling of the formation and evolution of satellites. The luminosity function we predict for satellites is *not* in obvious conflict with observation.

In our Milky Way model most of the spheroidally distributed stellar mass is contributed by the bulge of the central galaxy. As in other hierarchical models, these stars formed in the gaseous disks of a small number of relatively massive progenitors prior to or during their merger, and before the formation of the present disk [7]. The disruption of Sagittarius-like dwarfs contributes relatively few stars to the bulge.

If the stellar spheroid of the Milky Way was indeed assembled in this way, one may ask whether its current structure should retain any trace of its inhomogeneous origin. Inside the Solar circle, where most of the spheroid stars reside, orbital times are so short that the spatial distribution of debris from a 10 Gyr old merger is expected to show few sharp features. In phase-space, however, it may still occupy a small fraction of the accessible region, being confined to a kinematically cold sheet which wraps many times around the Galaxy. Such structure may be detectable with sufficiently good kinematic data; the stars in the neighborhood of any given point will not be distributed uniformly through velocity space but will be confined to a few hundred cold streams [4]. A recent analysis of the velocities of nearby metal-poor giants, based on combined ground-based and Hipparcos data, has detected two such streams in the Solar neighborhood [5]. These appear to be debris from a galaxy like Fornax or Sagittarius, destroyed roughly 10 Gyr ago. This is, perhaps, the first direct evidence for hierarchical assembly of the stellar halo.

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