History of Star Formation in the Universe

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Abstract. The cosmic history of star formation is briefly reviewed, starting with the Milky Way and then discussing observations relevant to the closed box and hierarchical build-up models. Observations of local star formation are reviewed for comparison. The halo globular clusters appear to have formed in about the same way as today’s clusters, with the same IMF and stellar densities, and with a larger mass reflecting the higher pressures of their environments. The bulge of the Milky Way appears to have evolved according to the dissipational collapse model, but other bulges may differ.

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1. Overview

Surveys of the Hubble Deep Field and other regions have demonstrated over the last few years that galaxies at high redshift are mostly spheroidal until approximately $z \sim 2$, and then disks form more recently (Madau et al. 1996; Steidel et al. 1996; Giavalisco, Steidel & Macchetto 1996; Cowie et al. 1997; Franceschini et al. 1998; Rodighiero et al. 2000). Theory suggests that dark matter halos also formed early, perhaps at $z \geq 3$ (Percival, Miller & Peacock 2000).

The star formation rate during the spheroid epoch is about constant and higher than during the average disk epoch by a factor of $\sim 3$. The star formation rate today is smaller still, perhaps by another factor of 3. Figure 1 shows the cosmic history of star formation according to Boselli et al. (2001), compiled from various sources. Cosmological models explain the general trends in this diagram by having more galaxy interactions and triggered starbursts at high $z$, and more isolated disk star formation at low $z$ (e.g., Rowan-Robinson et al. 1997; Baugh et al. 1998; Tan, Silk, & Ballard 1999; Cole et al. 2000; Nagamine, Cen & Ostriker 2000).

2. Milky Way Formation

The sequence of events during the formation of the Milky Way gives a consistent picture. The ages of the oldest halo globular clusters are $12.9 \pm 2.9 \text{ Gy}$ (Carretta
et al. 2000), corresponding to \( z \sim 3 - 4 \) in standard ΛCDM cosmologies. The age of the solar neighborhood is \( \sim 11 \) Gy (Binney et al. 2000), which corresponds to \( z \sim 2 \), and the bulge formed between these two times, at \( z \sim 2 - 3 \).

Most of what we know about the earliest star formation comes from studies of globular clusters in our Galaxy and other galaxies. We have learned, for example, that the oldest globular clusters probably formed before the galaxies condensed. These blue globular clusters, which have the lowest metallicities, have spatial distributions and velocity dispersions that correlate better with the group potentials around elliptical galaxies than with the potentials of the galaxies themselves (e.g., Blakeslee et al. 1997; Minniti et al. 1998; Harris, Harris, & McLaughlin 1998; Kissler-Patig et al. 1999; see review in Elmegreen 2000a). This is unlike the red globular cluster populations, which correlate well with the host galaxies. Milky Way globular clusters are even bluer than the blue globulars in ellipticals, and may have formed before the elliptical globulars or in more metal-free regions. Perhaps these globulars formed in low mass dwarf-like galaxies at \( z > 4 \), and then came together when our halo potential appeared (e.g., Searle & Zinn 1978).

After the globular clusters and spheroid stars collected into the Milky Way, 90% of the gas that made them was left over, as inferred from their low metal abundances. This and other gas presumably cooled and condensed, forming the bulge (Zinn 1990; Carney, Latham, & Laird 1990; Wyse & Gilmore 1992). Such dissipational collapse includes the possible formation of new globular clusters (Zinn 1990), bar/disk self-regulation (van den Bosch 1998), the formation of giant disk clumps (Noguchi 1999), continued satellite accretion (Aguerri, Balcells

Figure 1. Cosmic history of star formation from Boselli et al. (2001), taking data from various sources and fitting a closed-box model to it.
& Peletier 2001; Hammer et al. 2001), super starbursts (Koppen & Arimoto 1990; Elmegreen 1999), superwinds (Efstathiou 2000), and multiphase structure (Molla, Ferrini, Gozzi 2000). A comprehensive model for the Milky Way was in Samland, Hensler, & Theis (1997).

There is good evidence for dissipational collapse in our Galaxy bulge. In a survey of bulge K giant stars, Minniti (1996) found that as the metallicity increased for presumably younger stars, the random speed decreased and the rotation speed increased. This directly shows the time sequence of collapse and spin-up for successive generations of stars during bulge formation. In addition, Aguerri, Balcells & Peletier (2001) found that bulge growth by accretion changes an initial exponential light profile to an \( r^{-1/4} \) profile, yet the Milky Way bulge profile is best fit by an exponential (Kent et al. 1991). Thus the Milky Way bulge probably did not form by accretion or coalescence of smaller spheroids, but by dissipational collapse from the halo. Other galaxy bulges may have formed by accretion (Hammer et al. 2001), so there could be several formation mechanisms for bulges.

Following the formation of the bulge, the Milky Way disk gas presumably built up from continued infall and minor-merger accretions (at \( z < 2 \)). Stars formed in the disk by gravitational processes like what we see today, involving a threshold column density, dynamical timescales, a predominance of clusters, and a “Universal” IMF (e.g., Fall & Efstathiou 1980).

3. Closed Box versus Hierarchical Models

Closed box or monolithic collapse models (e.g., Eggen, Lynden-Bell & Sandage 1962) have often been used to model the evolution of metallicity and galaxy luminosity functions. Usually there is an epoch of high mass accretion, possibly until \( z \sim 2 \) or 3, and then a quiescent, semi-isolated period which is the “closed box.” Recent models like this are in Guiderdoni et al. (1998), Chiappini et al. (1999), Pei et al. (1999), Somerville & Primack (1999), Bell & Bower (2000), Bell & de Jong (2000), Buonomo et al. (2000), Boissier & Prantzos (2000), van den Bosch (2000), Springel (2000), Devriendt & Guiderdoni (2000), Prantzos & Boissier (2000), Boselli et al. (2001), Buchalter et al. (2001), Boissier et al. (2001), and Rowan-Robinson (2001).

The line fitting the data in Figure 1 is from a closed box model (Boselli et al 2001). As part of this model, Boselli et al. also explain why the ratio of the present star formation rate to the past average rate correlates with the galaxy mass, as does the current gas mass fraction. The primary assumption is that the star formation time is shorter in more massive galaxies (see also Boissier & Prantzos 2000).

The observation of hyperluminous infrared galaxies requires early star formation and suggests approximate closed box evolution in subsequent times. Hyperluminous galaxies have star formation rates of \( \sim 1000 \, M_\odot \, yr^{-1} \). Rowan-Robinson (2000) and Pearson (2001) have identified ultra-luminous infrared galaxies at high \( z \) with \( L \sim 10^{12} - 10^{13} \, L_\odot \). If a galaxy forms stars on a dynamical time, which is about as fast as it can, then for \( \rho \sim 1 \, cm^{-3} \), which is the tidal density limit, and velocity dispersion \( c \sim 250 \, km \, s^{-1} \) from the potential, the mass of \( M \sim \rho \times Vol \sim 10^{11} \, M_\odot \) forms in about a crossing time, \( (G\rho)^{-1/2} \),
and this gives a star formation rate of $\sim c^3/G \sim 1000 \, M_\odot \, \text{yr}^{-1}$. Triggers for such rapid and global star formation could be interactions between giant gas clouds that leave elliptical galaxies after the stars mix (see review in Sanders & Mirabel 1996).

Observations of galaxies with such high star formation rates imply that the mass was assembled quickly, not slowly from pieces that already formed their stars at lower rates. Benitez et al. (1999) claim, for example, that ellipticals formed at $z > 5 - 10$. We have not seen these proposed young galaxies yet, but extinction corrections implied by infrared observations could be large enough to hide them (e.g. Blain et al. 1999; Ramirez-Ruiz et al. 2000). If there is a significant population of massive bright galaxies at high $z$, forming the ellipticals and S0’s, for example, then these galaxies would presumably evolve thereafter according to the closed box models. The fraction of galaxies that evolve this way, and the fraction of the total time most galaxies spend in semi-isolation, is not yet known.

Indirect evidence for early galaxy formation is that elliptical galaxies correlate with QSOs. The redshift evolution of QSOs and bright AGN’s is the same as for elliptical galaxies, and the evolution of weak AGNs is the same as for spiral galaxies (Boyle & Terlevich 1998; Franceschini et al. 1999; Cen 2000). Thus, ellipticals formed quickly and early, perhaps by rapid interactions, and not slowly by hierarchical building over several billion years.

A further test of the closed box model is disk fading with decreasing $z$. From $z = 1.2$ to $z = 0.5$, disks fade by 1.2 mag in blue passbands (Schade et al. 1995; Brinchmann et al. 1998). If disks fade at $z < 1$, then they are not growing much by hierarchical accretion. Hierarchical buildup requires evolution of the galaxy number density, but at $z < 1$, such evolution is observed primarily for low mass or blue galaxies (Glazebrook et al. 1995; Lilly et al. 1995; Ellis et al. 1996; Brinchmann et al. 1998). In general, peculiar galaxies show more evolution at $z < 1$ than spirals or ellipticals (Brinchmann & Ellis 2000). Steidel et al. (1999) found no change in the general galaxy luminosity function out to $z = 4$, and Shanks et al. (2001) found no change in the number density of bright galaxies out to $z = 6$. There is apparently no change in the density of elliptical galaxies either, out to at least $z \sim 2$ (Benitez et al. 1999).

These observations support the case for early galaxy formation followed by nearly closed-box evolution. They contrast with some predictions of big bang models in a $\Lambda$CDM cosmology. These models form small dark matter clumps early on, and then rely on prolonged coalescence to get $L^*$ galaxies. The hierarchical models are extremely successful in some respects: they get the galaxy luminosity function, the DLA distribution, and the observed level of galaxy interactions at high $z$. However, the galaxy and cluster core densities are often too large in these models (which need SF feedback or dynamical heating), and the model disks are too small. Recent studies are in Mo, Mao & White (1998), Weil, Eke, & Efstathiou (1998), Colín et al. (1999), Navarro & Steinmetz (2000), Firmani & Avila-Reese (2000), Koda, Sofue, & Wada (2000), and Hatton & Ninin (2001).

Observational evidence for hierarchical build-up comes from the metallicity, which is too low at high $z$ to have had most star formation take place at a very early time (Madau et al. 1998). If most galaxies formed early and had a decaying
star formation rate thereafter, then the metal abundance in DLA absorbers should be much higher than observed (Pettini et al. 1997). A hierarchical model with smaller star formation rates at high z fits the metallicity observations better. We cannot be sure, however, that the DLA metallicities represent the average in the Universe at their redshifts. Elliptical galaxies could have formed early and produced a lot of metals that did not get into the DLA systems.

The K-band luminosity function at high z (Songaila et al. 1994; Cowie et al. 1996) also agrees with the hierarchical model better than a model with pure luminosity evolution (Kauffmann & Charlot 1998). This implies there are too few galaxies at high z for pure luminosity evolution. There is some uncertainty about extinction at high z, though. Extinction can hide galaxies and decrease the luminosity function.

Other evidence for hierarchical build-up is that the brightest cluster galaxies, which are mostly ellipticals, get bluer but not brighter with increasing z. This requires half the mass at z=1 for these galaxies compared with their masses today (Aragon-Salamanca et al. 1998; McCracken et al. 2000). Alternatively, there could be a low-mass bias to the stellar IMF (Broadhurst & Bouwens 2000; McCracken et al. 2000).

In summary, the Milky Way roughly fits into the cosmological formation scenario observed at high z: the spheroid and globular clusters formed at z > 3, the bulge at z ~ 2 – 3, and the disk at z < 2. The closed box and hierarchical models are debated because of unknown extinction corrections at high z, possible IMF variations, high z selection effects, and field-to-field variations. Apparently, some galaxies, particularly the ellipticals and maybe also some giant spirals, formed quickly and early, perhaps in a hierarchical fashion, and then decayed in semi-isolation as in the closed box models. The Milky Way bulge and disk may be examples of closed box evolution, perhaps because of the low density of other galaxies in our neighborhood. Smaller galaxies continued to coalesce or merge with larger galaxies up to modern times. Implicit in this closed-box scenario is the requirement that the metallicity distribution in the early Universe was not uniform: metals forming early in elliptical galaxies could not have dispersed very far. The DLA absorbing clouds then have to be more primordial than the average cosmic matter.

4. What can we Learn from Local Star Formation?

The 2MASS survey suggests that 90% of local star formation is in dense clusters (e.g., Lada et al. 1991; Carpenter 2000), having ~ 10^4 stars pc^{-3}. Approximately 0.5% of the gas participates in this cluster formation inside a molecular cloud (e.g., McLaughlin 1999). The gas structure is hierarchical and fractal prior to collapse, presumably as a result of turbulence and self-gravity (e.g., Falgarone & Phillips 1990), and the stars form in fractal patterns (Motte, Andre & Neri 1998; Testi et al. 2000; Elmegreen & Elmegreen 2001) in only a few crossing times (Ballesteros-Paredes, Hartmann, & Vazquez-Semadeni 1999; Elmegreen 2000b).

Hierarchical and fractal structure can explain the cluster mass function, \( n(M) dM \propto M^{-2} dM \) (Fleck 1996; Elmegreen & Falgarone 1996; Elmegreen & Efremov 1997). This mass function is appropriate for galactic clusters (Bat-
tinelli et al. 1994), OB associations (from the HII region luminosity function: Kennicutt, Edgar, & Hodge 1989; Comeron & Torra 1996; Rozas, Beckman & Knapen 1996; Feinstein 1997; McKee & Williams 1997; Oey & Clarke 1998), super-star clusters (Whitmore & Schweizer 1995; Zhang & Fall 1999), and high mass halo globular clusters (Ashman, Conti, & Zepf 1995).

The structure can give the stellar mass function too if the clumps turn into stars at the local dynamical rate (Elmegreen 1997; Sánchez & Parravano 1999). This stellar function is

\[ n(M) dM \propto M^{-2.35} dM \]

down to the thermal Jeans mass, which is

\[ M_J \sim 0.3 M_\odot \left( \frac{T}{10 \text{ K}} \right)^2 \left( \frac{P}{10^6 \text{ km cm}^{-3}} \right)^{-1/2} \]

for temperature \( T \) and pressure \( P \).

The difference between a globular cluster and an open cluster is primarily in the mass. Their average densities are about the same. Pressure is an important consideration for cluster mass. A virialized cluster with \( c^2 \sim GM/R^3 \) has a pressure

\[ P \sim \frac{GM^2}{R^4} \]

and a cluster mass

\[ M \sim 6 \times 10^9 M_\odot \left( \frac{P/10^8 \text{kB}}{n/10^5 \text{ cm}^{-3}} \right)^{3/2} \]

(1)

The normalization here is from the Orion core (Lada, Evans, & Falgarone 1997), considering a stellar density of \( 10^4 M_\odot \text{ pc}^{-3} \) at 50% efficiency. Evidently, in higher pressure environments, the cluster masses are larger. This goes a long way toward explaining the primary differences between halo globular clusters and modern disk clusters: the pressure in the halo when these globulars formed was very high as a result of the high gas density and the high velocity dispersion from the galaxy potential and big bang turbulent motions.

Pressure is also related to the star formation rate. For a general disk,

\[ P \sim G \Sigma_{\text{gas}} \Sigma_{\text{stars}} \propto \Sigma_{\text{gas}}^2 \]

(Kennicutt 1989, 1998). Thus \( P \propto \text{SFR}^{1.4} \). Also, from the previous expression for maximum cluster mass as a function of pressure, \( M_{\text{max}} \propto P^{1.5} \propto \text{SFR}^2 \) when clusters all have about the same stellar density. The total cluster luminosity is the integral over \( Mn(M) dM \), which, for

\[ \int_{M_{\text{max}}}^{\infty} n(M) dM = 1, \]

equals

\[ M_{\text{max}} \ln \left( \frac{M_{\text{max}}}{M_{\text{min}}} \right) \propto \text{SFR}^2 \]

Thus the fractional SF luminosity in the form of clusters is proportional to the star formation rate, as found by Larsen & Richtler (2000).

The high pressure of star formation in the early Universe contributed to three major differences compared to today’s star formation: the maximum cluster mass increased, forming globular clusters at the high mass end, the star formation rate increased, perhaps giving the observed increase in the star formation rate history (Fig. 1), and the fraction of all star formation in the form of dense massive clusters increased, giving a prominent population of halo globulars. These changes are observed in modern starbursts too because of the same high pressures. There should also be halo field stars along with the old halo globulars, and intergalactic blue field stars corresponding to the blue globulars near elliptical galaxies.

Aside from this pressure difference, halo globular cluster formation looked pretty normal: the globulars have a normal mass distribution function for stars (Paresce & De Marchi, 2000), normal masses for the expected halo pressure, a normal cluster mass function (at the high mass end where most of the clusters
survived), a normal efficiency of cluster formation in gas clouds (0.25%-0.5% – see McLaughlin 1999), and normal cluster core densities.

There is a feature of modern star formation that has not yet been seen at high z, and that is a threshold gas column density. For modern disks, \( \Sigma_{\text{gas}} \geq 5 \ M_\odot \ pc^{-2} \) for a cool phase of interstellar matter (Elmegreen & Parravano 1994), and \( \Sigma_{\text{gas}} \geq 0.7k c/\pi G \) for self-gravity to be important (Toomre 1964; Kennicutt 1989). Modern disks also have a \( \text{SFR/Area}\sim 0.033\Sigma_{\text{gas}}\Omega_{\text{orb}} \) (Kennicutt 1998) for orbital angular rate \( \Omega_{\text{orb}} \). This areal rate along with \( Q = 1 \) gives a total rate of star formation equal to \( \text{(SFR/Area)} \times \pi R^2 \sim 0.04V^2c/G \sim 5 \ M_\odot \ yr^{-1} \) in a typical disk. This rate corresponds to a lower efficiency than the value of \( c^3/G \) found above for a spheroid (where \( c = V \)).

5. Summary

Cosmological star formation is observed directly for \( z < 5 \), although extinction problems, selection effects and survey limitations are probably important at high \( z \). What is observed to be forming at \( z > 3 \) are primarily spheroidal systems, and these correlate well with the onset of the QSO phase. The galaxy buildup process is still uncertain, however; it could have been hierarchical or monolithic, or some of each, depending on epoch, environment, galaxy mass, and local density. Galactic bulges can apparently form by either closed-box or hierarchical scenarios, although the Milky Way bulge seems to have formed as a closed box. Disks require quiet environments in order to survive, and this tends to limit them to \( z < 2 \). The source of the disk gas is not known.

Globular clusters look normal in comparison to observations of present day star formation. The primary difference seems to have been the high pressure of their environment, which is expected for galactic halo conditions. These high pressures increased the maximum cluster mass, the star formation rate, and perhaps the cluster formation efficiency.

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