STAR FORMATION HISTORY AND STELLAR METALLICITY DISTRIBUTION IN A COLD DARK MATTER UNIVERSE

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ABSTRACT

We study star formation history and stellar metallicity distribution in galaxies in a $\Lambda$ cold dark matter universe using a hydrodynamic cosmological simulation. Our model predicts a star formation rate declining in time exponentially from an early epoch to the present on a timescale of 6 Gyr, which is consistent with the empirical Madau plot with modest dust obscuration. Star formation in $L^{*}$ galaxies continues intermittently to the present, also with an exponentially declining rate on a similar timescale, whereas in small galaxies star formation ceases at an early epoch. The mean age of the extant stars decreases only slowly with increasing redshift and exceeds 1 Gyr at $z = 3$. Normal galaxies contain stars with a wide range of metallicity and age: stars formed at $z < 1$ have metallicity of $0.1 - 1.0 Z\odot$, while old stars take a wide range of values, from $10^{-6}$ to $3.0 Z\odot$. The mean metallicity of normal galaxies is in the range $0.1 - 1.0 Z\odot$. Dwarf galaxies that contain only old stars have a wide range of mean metallicity ($10^{-4}$ to $1.0 Z\odot$), but on average they are metal-deficient compared with normal galaxies.

Subject headings: cosmology: theory — galaxies: formation — methods: numerical — stars: formation

1. INTRODUCTION

Over the last 15 years, cold dark matter (CDM) models have served as basic frameworks to study the formation of cosmic structure and have been successful in delineating a scenario of galaxy formation (Davis et al. 1985; Blumenthal et al. 1984). We now understand the formation of large-scale structure reasonably well in terms of a CDM model dominated by a cosmological constant $\Lambda$ (Efstathiou, Sutherland, & Maddox 1990; Ostriker & Steinhardt 1995; Turner & White 1997; Balbi et al. 2000; Lange et al. 2000; Hu et al. 2000).

When and how galaxies formed, however, is a far more complicated problem as a result of nongravitational physical processes operating on small scales. Many authors use semianalytic models to study galaxy formation, where dark matter halo formation under hierarchical structure formation is supplemented heuristically with physical processes for baryons (White & Frenk 1991; Baugh et al. 1998; Kauffmann et al. 1999; Somerville & Primack 1999; Cole et al. 2000). These models have succeeded in presenting a picture of galaxy formation roughly consistent with observations but have the disadvantage that one has to assume a set of simplified model equations, often associated with additional free parameters, for each physical process included in the model. The advantage of semianalytic models is, on the other hand, that they are computationally light, and therefore one can search for a viable model with a small amount of cost.

An alternative but computationally much more expensive approach is direct cosmological hydrodynamic simulations. So far, intergalactic medium and overall galaxy formation processes have been well studied with a hydrodynamic approach (e.g., Cen & Ostriker 1992, 1993, 2000; Katz, Weinberg, & Hernquist 1996; but see Pearce et al. 1999). Much effort invested in improving the accuracy of simulations has brought the hydrodynamic mesh to approaching 1000$^3$, with which we may hope that we obtain meaningful results on some aspects of galaxy properties. It is certainly impossible to resolve the internal structure of galaxies with the present simulations. Nevertheless, we would expect that global properties such as a global star formation rate (SFR) are described reasonably well with a few adjustable parameters, since they primarily depend on thermal balance of the bulk of clouds, such as how gas cools, or how surrounding gas is reheated by feedback by star formation. The fact that we obtain a reasonable amount of baryonic mass frozen into stars and a global metal abundance with reasonable input parameters justifies, at least in part, our expectation.

In this paper, we primarily discuss the star formation history of galaxies and the evolution of stellar metallicity, which are the direct output of the simulation. The aspects that require additional use of a stellar population synthesis model, such as luminosity function and colors of galaxies, will be discussed in a separate publication by Nagamine et al. (2001; hereafter Paper II). Since the hydrodynamic approach is computationally demanding, we do not attempt to make a fine-tuning of input parameters, but our aim here instead is to make qualitative predictions that can be used to either verify or falsify the $\Lambda$CDM model by future observations with only a limited number of assumptions, treating the dynamics of baryons more accurately than in semianalytic models.

Our results will provide insight into how galaxies are assembled from an early epoch to the present. Observationally interesting questions include the following: (1) How old are stars in normal and dwarf galaxies, and what is
Their age distribution? A relevant question is whether star formation takes place continuously or intermittently. (2) What is the stellar metallicity distribution in normal and dwarf galaxies? A relevant old problem is the paucity of metal-poor stars in the solar neighborhood (the G dwarf problem: van den Bergh 1962; Schmidt 1963). (3) Is there a unique age-metallicity relation for stars in normal galaxies? (4) Is there a relation between the mass of galaxies and average metallicity? How these aspects evolve with redshift is also an observationally relevant problem, although the observational studies could answer only for global properties for high-redshift objects. Our simulation yields unambiguous predictions to these problems, at least qualitatively.

In § 2, we describe our simulation. In § 3 we first present the global star formation history of the entire simulation box. We then discuss in § 4 the star formation history of individual galaxies. The mean age of the stars and the formation epoch of galaxies are discussed in § 5. We discuss the stellar metallicity distribution and the mean metallicity of galaxies in § 6 and conclude in § 7.

2. SIMULATION AND PARAMETERS

We use a recent Eulerian hydrodynamic cosmological simulation with a comoving box size of 25 h⁻¹ Mpc with 768³ grid cells and 384³ dark matter particles of mass $2.03 \times 10^7 h^{-1} M_\odot$. The comoving cell size is 32.6 h⁻¹ kpc, and the mean baryonic mass per cell is $3.35 \times 10^5 h^{-1} M_\odot$ (h is the Hubble constant in units of $H_0 = 100$ km s⁻¹ Mpc⁻¹).

The cosmological parameters are chosen to be $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b h^2 = 0.016$, $h = 0.67$, and $\sigma_8 = 0.9$, and the spectral index of the primordial power spectrum $n = 1.0$. The present age of the universe is 14.1 Gyr. The structure of the code is similar to that of Cen & Ostriker (1992, 1993) but has significantly improved over the years.

The Eulerian scheme we use here has higher mass resolution than other hydrodynamic approaches, such as smoothed particle hydrodynamics (e.g., Katz et al. 1996; Dave, Dubinski, & Hernquist 1997) and the adaptive mesh refinement (e.g., Bryan & Norman 1995; Kravtsov, Klypin, & Khokhlov 1997), while smoothed particle hydrodynamics and the adaptive mesh refinement usually have higher spatial resolution than the Eulerian method. We remark that our code is specially designed to capture the shock region well, using the total variation diminishing method (Ryu et al. 1993). The higher mass resolution means more resolving power at higher wavenumbers for a given power spectrum, and hence a better treatment of early structure formation.

The baryons are turned into stars in a cell of overdensity $\delta/\rho > 5.5$ once the following three conditions are satisfied: (1) contracting flow $V \cdot v < 0$, (2) fast cooling $t_{cool} < t_{dyn}$, and (3) Jeans instability $m_{gas} > m_j$. Each stellar particle has a number of attributes at birth, including position, velocity, formation time, mass, and metallicity. Upon its formation, the mass of a stellar particle is determined by $m_\star = c_{\star} m_{gas} \Delta t/t_{dyn}$, where $\Delta t$ is the current time step in the simulation and $m_{gas}$ is the baryonic gas mass in the cell. We take $t_{dyn} = \max(t_{dyn}, 10^7 \text{yr})$, where $10^7 \text{yr}$ is the shortest timescale of star formation for O stars. We assume the star formation efficiency to be $c_{\star} = 0.25$. The fraction of baryonic mass that collapses into a dense state is fairly well defined by our code, nearly independent of the detailed values of $c_{\star}$ and the minimum value of $t_{dyn}$, as confirmed by a recent numerical experiment by M. L. Norman (2000, private communication).

The mass of the stellar particles ranges from $10^{3.5}$ to $10^{10.3} h^{-1} M_\odot$, with the mean $\langle m_\star \rangle = 10^{6.9} h^{-1} M_\odot$ at $z = 0$. An aggregation of these particles is regarded as a galaxy. The stellar particle is placed at the center of the cell after its formation with a velocity equal to the mean velocity of the gas and followed by the particle mesh code thereafter as collisionless particles gravitationally interacting with dark matter and gas.

Feedback processes such as the ultraviolet (UV) ionizing field, supernova (SN) energy, and metal ejection are also included self-consistently. The SN and the UV feedback from young stars are treated as follows: $\Delta E_{SN} = m_\star c^2 \epsilon_{SN}$ and $\Delta E_{UV} = m_\star c^2 \epsilon_{UV} g_s$, where $g_s$ is the normalized spectrum of a young, Orion-like stellar association taken from Scalo (1986) and the efficiency parameters are taken as $(\epsilon_{SN}, \epsilon_{UV}) = (10^{-3}, 3 \times 10^{-4})$ (cf. Cen & Ostriker 1993). The $\Delta E_{SN}$ is added locally in a cell and the $\Delta E_{UV}$ is averaged over the box. Extra UV is co-added for quasars as $\Delta E_{AGN} = m_\star c^2 \epsilon_{AGN} f_\nu$, where $f_\nu$ is an active galactic nucleus spectrum taken from Edelson & Malkan (1986) and $\epsilon_{AGN} = 5 \times 10^{-6}$ is adopted. The proportionality between $\Delta E_{AGN}$ and $m_\star$ is an assumption, and our ignorance is included in $\epsilon_{AGN}$, which is adjusted to fit the hard X-ray background observed by ASCA (see Phillips, Ostriker, & Cen 2000). Metals are created according to $m_\star = Y m_\odot$, where $m_\star$ is the mass of metals and $Y$ is the yield. The fraction 25% ($f_{\epsilon} = 0.25$) of the initially collapsed baryons is ejected back into the intergalactic medium in the local grid cell. This ejected gas is polluted by metals, and 2% ($Y = 0.02$; Arnett 1996, p. 496) of the initially collapsed baryons are returned to intergalactic medium as metals, which are followed as a separate variable by the same hydrocode that follows the gas density. The values of the three parameters ($\epsilon_{SN}$, $\epsilon_{UV}$, and $Y$) are proportional to the amount of high-mass stars for a given amount of collapsed baryons. The results presented in this paper are insensitive to the assumed value of $f_\epsilon$ provided the value is not zero. Thus, all our ignorance concerning star formation is parameterized into essentially one free parameter, the efficiency of cooling, i.e., collapsing mass that is transformed into high-mass stars, and this value is empirically calibrated so that one obtains a final cluster gas metallicity of $Z = \frac{1}{3} Z_\odot$, where $Z_\odot = 0.02$ is the solar metallicity.

We use the HOP grouping algorithm (Eisenstein & Hut 1998) to identify galaxies with threshold parameters $(\delta_{\text{outer}}, \delta_{\text{infall}}, \delta_{\text{peak}}) = (80, 200, 240)$. We set the minimum number of grouping particles to five; changing this to two does not modify the catalog. We identify 2097 galaxies in the entire box at $z = 0$, the minimum galaxy stellar mass being $10^{9.7} h^{-1} M_\odot$. The total mass of stars corresponds to $\Omega_\star = 0.0052$; i.e., 15% of baryons are collapsed into stars (including the ejected gas). This is consistent with the upper limit of an empirical estimate of Fukugita, Hogan, & Peebles (1998). The average metal density is $10^{-5.1} M_\odot$ Mpc⁻³, which is also close to the empirical estimate of $10^{-5.2} M_\odot$ Mpc⁻³ (M. Fukugita & P. J. E. Peebles 2000, unpublished), justifying our choice of parameters.

We examine the merger history of galaxies and find that 93% of the galaxies at $z = 0.5$ preserve more than 80% of their stellar mass to $z = 0$: i.e., most of the constituent stellar particles are not lost upon merging or tidal shredding. This tells us that the galaxies identified in our simula-
tion are dynamically stable enough to obtain meaningful results for the evolution of individual galaxies.

3. GLOBAL STAR FORMATION RATE

We first present in Figure 1a the global SFR as a function of time, from right to left. The prediction of global SFR in the CDM model has been discussed in the literature (Baugh et al. 1998; Nagamine, Cen, & Ostriker 2000; Somerville, Primack, & Faber 2001).1 This quantity is observationally known up to uncertainties associated with dust obscuration, and the agreement with observations can be used as a verification of the calculation. This quantity does not receive the effect of the grouping procedure but gives a measure of the efficiency of gas cooling, which depends on the thermal balance. We also indicate a boxcar-smoothed histogram with a 10-point running average with the dotted curve. The dashed line is a least-squares fit to the exponential decay function, corresponding to a timescale of $\tau = 5.9$ Gyr.

The same information is presented in Figure 1b, but using a logarithmic scale for the SFR and redshift as a time scale in accordance with the Madau plot. In this diagram the meaning of the solid and dotted curves is reversed: the dotted curve follows the raw data, and the solid line is the smoothed data. The observation is corrected for dust extinction correction according to the prescription of Steidel et al. (1999): we assume highly uncertain extinction correction factors to be 1.3 ($z < 2$) and 2.5 ($z > 2$) to obtain a better fit, while Steidel et al. (1999) used the higher values 2.7 ($z < 2$) and 4.7 ($z > 2$). With a rather large error in the empirical estimate of SFR, a global agreement is seen between our calculation and the observation. We do not observe a peak of SFR at low redshift, as often found by semianalytic models of galaxy formation (Baugh et al. 1998; Somerville et al. 2001).2 The SFR is, on average, a smooth function of redshift and nearly levels off at $z > 4$. Note that this behaviour is consistent with an exponential decay of the SFR in time. This means that the bulk of stars have formed at a redshift higher than 2: 25% of stars formed at $z > 3.6$, and another 25% were added between $z = 3.6$ and 1.8 (by $z = 1$, 68% of stars were formed). We consider our result to be reliable up to $z = 5$–6 from a mesh-effect consideration, whereas that at a yet higher redshift may suffer from the effect of poor resolution. Observationally, it is an unsettled problem whether the SFR levels off at high redshift (Steidel et al. 1999) or still increases beyond $z > 3$ (Lanzetta et al. 1999). It is an interesting observational problem to find out how the SFR behaves at high redshifts, but this can be done only with proper knowledge of dust extinction or with observations that are not subject to the effects of extinction. For now, it is sufficient for us to know that the calculation of global SFR is grossly consistent with the observation.

4. STAR FORMATION HISTORY IN GALAXIES

In Figure 2, we present the star formation histories of galaxies in the simulation divided into three samples according to their stellar mass at $z = 0$. Note that the starbursts at high redshift may have taken place in smaller progenitors that later merged into a massive object that is classified in the largest mass bin. The galaxies that fall into each mass interval are co-added in the histogram. Most of the mass resides in large galaxies, which are represented in

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1 The simulation used by Nagamine et al. (2000) assumed too high a yield of metals ($Y = 0.06$), which resulted in overproduction of stars compared with the empirical estimate. In addition, the simulation mesh was coarser and one may suspect the effect of low resolution above $z > 4$. We consider the result presented in this paper to supersede that of Nagamine et al. (2000).

2 In semianalytic models, one may suppress star formation at high redshift by taking a larger SN energy feedback parameter. In general, these models require a strong SN feedback to fit the faint end of the galaxy luminosity function (see Cole et al. 2000). See Paper II for the luminosity function in our simulation.
the top panel. This histogram can also be interpreted as the age distribution of stars in galaxies. The dashed lines show the least-squares fits to the exponential function given in Table 1. Massive galaxies (top) continue to form stars until the present epoch, while less massive galaxies (bottom panels) stop forming stars at higher redshift.

![Graph showing star formation history](image)

**Fig. 2.**—Star formation history of the three different samples of galaxies divided by their stellar mass at $z = 0$. Note the different scales on the ordinate. The dashed lines are the least-squares fits to the exponential function given in Table 1. Massive galaxies (top) continue to form stars until the present epoch, while less massive galaxies (bottom panels) stop forming stars at higher redshift.

The mean stellar age at each epoch in the history of the universe is also interesting. In Figure 3, we plot the median (filled squares) and the mass-weighted mean (open squares) of the age of all stars at each epoch. The median was calculated from the cumulative distribution of stellar mass at each epoch. The solid bars indicate the quartiles, which almost coincide with the 1σ ranges, shown with dotted bars. The average age of the extant stars decreases only slowly with increasing redshift. The mean stellar age today is 4–5 Gyr, and the age becomes smaller than 1 Gyr only at $z = 3$. The age 4–5 Gyr is slightly younger than the observed median stellar age of $\approx 6$ Gyr in the Milky Way (Rocha-Pinto et al. 2000b). We show in Paper II that the distribution of $B - V$ colors of simulated galaxies agrees with that of the local galaxy sample. The median age of 1 Gyr at $z = 3$ means that the majority of galaxies at this redshift are dominated, in addition to star-forming activities, by Balmer absorption features of A stars, which would be observed with near-infrared spectroscopy for Lyman break galaxies.

Figure 4 gives the mean formation redshift of galaxies versus their stellar mass at $z = 0$. The mean formation red-

### Table 1: Parameters of Exponential Fit for the SFR

| Mass Range | $A$ | $\tau$ |
|------------|-----|--------|
| ($M_\odot\ h^{-1}$) | ($h^2 M_\odot\ yr^{-1}\ Mpc^{-2}$) | (Gyr) |
| All | 0.24 | 5.9 |
| $M_{\text{stellar}} > 2 \times 10^9$ | 0.23 | 6.1 |
| $2 \times 10^9 < M_{\text{stellar}} < 2 \times 10^9$ | 0.021 | 0.83 |
| $M_{\text{stellar}} < 2 \times 10^9$ | 0.011 | 0.55 |

Note.—Parameters given above are the least-squares fit of the SFR in Figs. 1 and 2 to the exponential function SFR [$h^2 M_\odot\ yr^{-1}\ Mpc^{-2}$] = $A \exp(-t/\tau)$, where $A$ is the SFR at $t = 1$ Gyr and $\tau$ gives the e-folding time of star formation. The rise in the first 1 Gyr is neglected upon fitting.

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3 We note in passing that in the warm dark matter scenario, low-mass galaxies form primarily by “top-down” fragmentation rather than the “bottom-up” accumulation process and so are found later than in the standard CDM picture (Bode, Ostriker, & Turok 2001).
stellar mass of galaxies at increasing redshift and exceeds 1 Gyr at obtained from the cumulative distribution of the stellar mass as a function squares quartiles, and the dotted bars show 1 found at con-irms the result we saw earlier that less massive galaxies and solid bars are the quartiles, in each mass bin. This Ðgure represents an individual galaxy. The squares are the median, and the particles and then converting it to redshift. Each dot rep-
shift was calculated by taking the mass-weighted mean of the formation epoch (in time units) of constituent stellar particles and then converting it to redshift. Each dot re-
that formed at high and intermediate redshift merge into more massive systems at lower redshift. The mean formation redshift mostly decreases with increasing galaxy stellar mass, but it turns over slightly at the very massive end: this is a result of the oldest dwarfs merging into very massive galaxies.

6. METALLICITY DISTRIBUTION

The metallicity of stars as a function of their formation time is plotted in Figure 5 (right to left) for the same subsamples as in Figure 2. Each point in the Ðgure corresponds to one stellar particle in the simulation. Equally spaced logarithmic contours in number density are used where the density of data points is large. The plot shows that the stars that formed at low redshift (z < 1) do not show unique metallicity but distribute from 0.1 to 1.0 Z⊙. The width of the distribution slowly increases with redshift, while the upper envelope stays at 1.0 Z⊙ up to z ≈ 1. The widening trend of the age dispersion is conspicuous at redshift z > 2. Note that the widening takes place predominantly toward lower metallicity, while the upper envelope slightly increases to supersolar values. At z > 3, the distribution ranges from 10^{-6} to 3.0 Z⊙. It is interesting to observe that the median of metallicity changes very little at z < 2. The mass-weighted mean metallicity also varies slowly as 0.55, 0.45, 0.61, 0.24, and 0.22 Z⊙ for z = 0, 1, 2, 3, and 5, respectively. The decrease of mean metallicity above z = 2 is clear, whereas we cannot determine the change of mean metal-
llicity for z < 2 because of small statistics.

It is known that stars in the Milky Way do not obey a unique age-metallicity relation but show a signiÐcantly wide distribution, ranging from 0.1 to 3 Z⊙. Whether the dispersion increases with redshift, however, is still a matter of debate. Edvardsson et al. (1993; see also McWilliam 1997) argued that the dispersion increases as stellar age increases, while the metal-rich stars form an envelope that is about solar metallicity independent of stellar age. On the other hand, Rocha-Pinto et al. (2000a) argued that age and metallicity show a stronger correlation, earlier stars being metal-poor. Our result agrees with Edvardsson’s result, but not with Rocha-Pinto’s.

The result we discussed above means that early galaxies are not necessarily metal-deÐcient. Kobulnicky & Zaritsky (1999) show that emission-line galaxies at z = 0.1–0.4 have metallicity only slightly lower than solar, which is not uncommon in local galaxy samples. Pettini et al. (2000) show that Lyman break galaxies at z ≈ 3 have Z⊙, only modestly subsolar. The strength of metal lines in the highest redshift quasar (Fan et al. 2000) is also suggestive of normal metallicity at z = 5.8. These observations are all consistent with our simulation.

It is also our prediction that the Milky Way contains highly metal-poor stars. We expect that 1% of stars have Z⊙. Those stars are necessarily old. Another interesting result is that most super–metal-rich stars are from high-redshift epochs. This would be consistent with the fact that most of super–metal-rich stars are in the bulge rather than in the disk (Frogel & Whitford 1987; Rich 1988) if the bulge contains more old stars than the disk, as usually conceived. At the same time, our calculation predicts that the mean metallicity of the old population is lower than that of

4 A contradictory view is presented by Rocha-Pinto et al. (2000a), who claim that super–metal-rich stars are young.
the younger population, which is also consistent with the observations (Edvardsson et al. 1993; McWilliam & Rich 1994; Rocha-Pinto et al. 2000a).

We may ascribe the change of scatter in metallicity from high to low redshift to the following cause: Metallicity is a strong function of local overdensity, as shown by Gnedin (1998) and Cen & Ostriker (1999). Both authors have shown that the metallicity distribution in high-density regions is narrower than that in low-density regions. As time progresses, the universe becomes more clumpy, and star formation takes place only in moderate- to high-overdensity regions where gas is already polluted by metals, resulting in a narrower scatter of metallicity at late times as seen in the top panel of Figure 5.

Let us now consider the G dwarf problem: the fact that there are too few metal-poor stars in the solar neighborhood compared with the closed-box model (van den Bergh 1962; Schmidt 1963). In our model, a large fraction of stars formed at an early epoch, and such a population contains a significant fraction of metal-poor stars. A histogram analysis of the metallicity distribution at \( z = 0 \) shows that 50% of stars have \( Z < 0.3 \) \( Z_\odot \) in our simulation. This is roughly the same as the prediction of the closed-box model, whereas the observations show the fraction of these stars to be only a few percent (Pagel & Patchett 1975; Sommer-Larsen 1991). The qualitative trend of our prediction does not seem to be easily modified. We ascribe, however, the presence of large numbers of metal-poor stars in our simulation to our inability to resolve the internal structure of galaxies (i.e., disk from bulge). If the disk is a later addition to the bulge as the observations suggest (Fukugita, Hogan, & Peebles 1996), it would contain few metal-poor stars, as is clear from Figure 5. The material accreted onto galaxies at low redshift is already polluted by metals from bulge stars (Ostriker & Thuan 1975). A high fraction of metal-poor stars could occur in the CDM model, if we do not distinguish the disk and the bulge components. This view is consistent with the work by Kauffmann (1996), who provides a natural explanation to the G dwarf problem, using a semianalytic model, by pre-enrichment by early outflows from dwarf progenitors.

Finally, in Figure 6 we show the mean metallicity of galaxies as a function of their stellar mass in the simulation. The mean metallicity of each galaxy is calculated by taking
the mass-weighted average of constituent stellar particles. Squares are the median, and the solid bars are the quartiles in each mass bin. Massive galaxies ($M_{\text{stellar}} > 10^{10} h^{-1} M_\odot$) at $z = 0$ have a mean metallicity of 0.1–1.0 $Z_\odot$, while less massive galaxies have a wide range of mean metallicity, ranging from $10^{-4}$ to 1.0 $Z_\odot$. There are a few dwarf galaxies that have even $10^{-6} Z_\odot$ outside of the figure. The star formation in less massive galaxies (identified at $z = 0$) took place with a wide range of metallicity at high redshift, as we saw in the bottom panel of Figure 5, while larger galaxies at $z = 0$ had star formation continuing up to the present epoch with normal metallicity of 0.01–1.0 $Z_\odot$. The two solid lines in Figure 6 were obtained from a fit to the observational data of spiral and irregular galaxies given in Figure 4 of Kobulnicky & Zaritsky (1999). We converted the absolute $B$ magnitude to the stellar mass using the relation $\log M_{\text{stellar}} = -0.4 M_B + (2.75 \pm 0.20)$, which the majority of galaxies in our simulation follow before dust extinction (see Paper II), and scaled the metallicity by $\log (Z/Z_\odot) = 12 + \log (O/H) - 8.89$. A good agreement is seen between the simulated result and the observation in the range $10^7 h^{-1} M_\odot < M_{\text{stellar}} < 10^{10} h^{-1} M_\odot$. We note that Kauffmann (1996) obtained a result similar to ours, which again suggests that the reason we are not seeing a similar cumulative distribution to her result and the solar neighborhood observation is simply because we cannot resolve the bulge and the disk into separate components.

7. CONCLUSIONS

We have studied predictions of the ΛCDM universe with regard to the star formation history and the stellar metallicity distribution in galaxies. Our purpose has been to clarify what observations would test the validity of the model of galaxy formation based on ΛCDM. We have first shown that the global SFR averaged over all galaxies declines with a characteristic timescale of $\tau \approx 6$ Gyr. About a quarter of stars formed by $z \approx 3.5$ and another quarter by $z \approx 2$. This star formation history is consistent with the empirical Madau plot if modest dust obscuration is assumed.

Our calculation indicates that star formation in $L^{*}$ galaxies continues intermittently to the present epoch as they accrete gas and merge with smaller systems with a decline rate corresponding to an $e$-folding time of $\tau \approx 6$ Gyr. Star formation in less massive galaxies ceases earlier with an $e$-folding time of $\tau \lesssim 1$ Gyr. In particular, dwarf galaxies cease their star formation by $z = 2$. We cannot exclude the possibility that minor star formation activity at low redshift is missed in our calculation as a result of still-insufficient resolution, but it is unlikely that the global trend would be modified. We believe this is a feature generic to the CDM structure formation scenario, and observational tests would provide a vital test.

Stars formed in the CDM galaxy formation scenario do not follow a unique age-metallicity relation but show a considerable spread of metallicity for a given age of stars. Metallicity of very young stars spreads from 0.1–1.0 $Z_\odot$. The spread gradually increases toward high redshift. It takes 0.01–1.0 $Z_\odot$ at $z = 2$. At $z = 3$, the distribution spreads over from $10^{-6} Z_\odot$ to super–metal-rich (3 $Z_\odot$). Young stars are necessarily metal-rich, but old stars are not necessarily metal-poor. The variation of the mean metallicity with cosmic time is only gradual. The average metallicity for galaxies at $z \approx 1$ differs little from that of local galaxies.

On the other hand, mean metallicity varies as a function of the mass of galaxies. For less massive galaxies are metal-poor. Another interesting prediction is that mean metallicity of dwarf galaxies today ranges widely ($10^{-4}$ to 1 $Z_\odot$), which reflects the large scatter of metallicity of stars formed at high redshift.

The G dwarf problem in the solar neighborhood offers an interesting insight for formation of galactic structure. If we apply the prediction of the metallicity distribution to solar neighborhood, we encounter the G dwarf problem; the prediction of the metallicity distribution does not differ much from that of the closed-box model. In our case, however, the G dwarf problem would be solved if bulges were early entities and disks were later additions.

We have briefly discussed observational tests for each item of the predictions. In many aspects the predictions are supported by observational evidence, but for some aspects the predictions do not seem to agree with the current interpretation of the observations. The currently available observations, however, are sometimes controversial among authors or do not offer unique interpretations free from various working assumptions. We believe decisive tests will be a task for the future.

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