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PROTOGALACTIC MERGERS AND COSMOCHRONOLOGY *

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Abstract

We construct a schematic model for chemical evolution and cosmochronology within the expanding and collapsing protogalactic halo followed by formation of the local disk. Star formation is associated with both the rate of protogalactic mergers and the intrinsic gas density of protogalactic clouds and the disk. This leads naturally to a scenario in which star formation in the disk can be delayed by several billion years relative to the formation of the oldest globular clusters. We analyze various cosmochronometers in the context of this model and show that the apparent differences between the maxiumum globular-cluster ages, the white-dwarf cooling age, and nuclear chronometric ages can be understood. The merger models which satisfy the age constraints imply a relatively late forming peak in luminosity and therefore may be consistent with the observed peak in galaxy number counts at intermediate redshifts. Variants of the model could even yield significant dark baryonic halos.

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1. Introduction

In models for the galactic chemical evolution of the disk, star formation is usually described (*e.g.* Audouze & Tinsley 1976; Gusten & Mezger 1986; Larson 1986; Clayton 1987; Pagel 1989) as a continuous process after the disk has formed, possibly after a prompt initial enrichment of metals. However, it has been apparent for some time (*e.g.* Searle 1977; Searle & Zinn 1978) that the early evolution of galaxies may also be characterized by bursts of star formation perhaps associated with the formation and merging of protogalactic fragments. Among the more recent evidence for this picture are observations of [O II] emission-line objects near heavy-element absorbers seen in the spectrum of background QSO's. These objects may be merging protogalaxies (York, *et al.* 1986; Yanney, *et al.* 1987, 1989, 1990; Yanney 1990). Furthermore, ages of stars in members of the Local Group (*e.g.* Carney & Seitzer 1986) may indicate episodic bursts of star formation. Similarly, deep-sky CCD images (Tyson & Seitzer 1988) and faint galaxy counts (Broadhurst *et al.* 1992) indicate an increase in the density of objects at relatively early times suggesting that the density later decreased as objects merged, although such models need to be reconciled with the lack of observed spatial clustering (Efstathiou *et al.* 1992). In any event, the existence of objects like star-burst galaxies and quasars is probably evidence that galactic mergers occur at least to some extent as part of the galaxy formation process (*cf.* Thuan 1988). This picture is also supported by theoretical models for galaxy formation (*e.g.* Silk & Wyse 1986; Silk & Szalay 1987; Frenk, *et al.* 1988; Zurek, Quinn, & Salmon 1988; Katz 1989; Larson 1990; White 1990) in which galaxies assemble from merging clumps.

However, some additional clues to the dynamics of galaxy formation may also be evident in the apparent disparity between Galactic ages determined by different means. The observed cut off in the white-dwarf luminosity function (Winget, *et al.* 1987) implies an age for the disk, $T_{disk} = 9.3 \pm 2.0$ Gyr. This is near the lower limit of the model independent nuclear age of Meyer & Schramm (1986) for which $T_{nuc} \sim 15 \pm 5$ Gyr, and is consistent with the prompt-enrichment-plus-exponential model of Fowler & Meisl (1986) and Fowler (1987) which gives $T_{nuc} \sim 10 \pm 2$ Gyr. However, this value is somewhat below the values derived from various galactic chemical evolution models, (*e.g.* Yokoi, *et al.* 1983; Cowan *et al.* 1987; Clayton 1988; Thielemann, *et al.* 1989) all of which tend to give higher Galactic ages, $T_{nuc} \sim 14 \pm 2$ Gyr (*cf.* Cowan, Thielemann, & Truran 1991a,b). The white-dwarf age is also significantly less than the ages of the oldest globular clusters, $T_{gc} \sim 15 \pm 3$ Gyr (*e.g.* Sandage 1982; Janes & Demarque 1983; Iben & Renzini 1984; VandenBerg 1988; Buonanno, *et al.* 1989; Deliyannis, Demarque, & Pinsonneault 1989; Lee, Demarque, & Zinn 1990; Sandage & Cacciari 1990; Schramm 1990). All of this supports a picture in which the bulk of star formation in the disk responsible for the local white dwarf population and nucleosynthesis may have occurred considerably later than the time at which the oldest globular clusters formed. The focus of this paper will be to construct a simple schematic model to explore how such time delays may have occurred in the processes of halo formation and collapse, and how these processes may be reflected in the various cosmochronometers.

In our proposed model, this delay is a consequence of the dynamics of the expanding and collapsing protogalaxy. Star formation is divided into several phases which affect the chronometers in different ways. The oldest globular clusters would arise shortly after recombination as protogalactic clouds and some stars begin to form from the gravitational clustering of an initial distribution of seed fluctuations (Press & Schechter 1974). As that particular overdensity which led to the formation of the Galaxy and Galactic halo expanded, however, this star formation rate is diminished both because of the a slower merger rate as the density of protogalactic clouds decreases, and because the density of gas within the clouds themselves decreases. As the halo expanded to its maximum radius it would perhaps have resembled a low-surface brightness galaxy or a Lyman-α absorption system. As the system then collapsed, collisions among the virialized distribution of protogalactic fragments produced further bursts of star formation and a sequence of binary mergers reminiscent of hierarchical clustering (*e.g.* Peebles 1965; 1980). The stellar population in the disk would be able to form only after the last major mergers when gas could begin to settle into the disk without disruption. If this picture is appropriate for galaxy formation in general, then the last collisions prior to disk formation may have induced sufficient star formation to produce a second luminosity peak in galaxy number counts at intermediate redshifts (Cowie 1991). The time scale for the formation and collapse of the halo will depend upon the amplitude of the initial density fluctuation which ultimately formed the Galaxy and could easily have taken a few Gyr or more.

The main point of this paper is to construct a simple schematic model to explore the consequences of such a picture on Galactic cosmochronology. We will show that within this simple model there is a natural explanation for the disparity of different age determinations. It is also consistent with a paucity of low-metallicity G-dwarfs in the Solar neighborhood, a spread in globular cluster ages and metallicities, and a distribution of metallicity among objects of different mass in the Local Group as observed. Such a model for star bursts may even be a source for the production of baryonic dark-matter halos, depending upon the stellar initial mass function for the early bursts.

2. Protogalactic Merger Model

For the purpose of our cosmochronology analysis, we will deduce a simple schematic model which incorporates features of N-body simulations of mergers and gas dynamics leading to galaxy formation, and satisfies the constraints from galactic chemical evolution models. N-body simulations of galactic-halo formation (*e.g.* Carlberg 1988a,b; Carlberg & Couchman 1989) have been shown to follow well the Press Schechter (1974) theory for the decoupling of protogalactic halos from the Hubble expansion. The timescale for the evolution of star formation within that particular expanding and collapsing halo which led to the formation of the Galaxy is the focus of the present work.

Our analysis begins from Press-Schechter (1974) theory in which mergers are described by the gravitational clustering of an initial distribution of fluctuations in density. However, within the expanding and contracting protogalaxy, we presume that the protogalactic fragments eventually obtain sufficient virial velocities that the clustering process can be described as the result of random cloud-cloud collisions. Since the collision velocities will often be greater than the escape velocity for the merged system, the stellar component will be dispersed into the present day Galactic halo as a result of collisions. However, we will presume that the gas component can sufficiently cool to remain as a merged protogalactic cloud for subsequent mergers.

For the present purposes, our particular assumptions about the evolution of the gas and stars are not important, as long as the gas somehow merges to form the present Galaxy and that during this process the stellar component is dispersed into the Galactic halo before the merging epoch ceases. An equivalent description might have the gas ejected via explosive processes from star forming regions. The gas could then cool and fall into the disk (Burkert, Truran, & Hensler 1992). Our purpose is only to present a schematic picture which parameterizes the Galaxy formation process in a way that the different chronometers can be analyzed. The critical ingredient is a dynamical time scale which accounts for differences between initial star formation (Pop II) versus disk formation (Pop I). Traditional single-zone models necessarily equate the build up of Pop II to Pop I abundances with evolutionary time differences rather than this new dynamical time.

2.1 Protogalactic merger rate

For the purposes of the present schematic model we start the description with a mean fragment mass of $\sim 10^6\ M_\odot$. In the calculations of Carlberg (1990) this would have occurred soon after recombination when the Galactic halo was still expanding. For the purpose of describing protogalactic mergers we will also presume that the fragments form and are virialized within a short time (~ 0.2 Gyr).

Within this virialized velocity distribution of protogalactic clouds, the collision rate per cloud can be written,

$$\lambda_m = (n-1)\sigma v/V \quad , \tag{1}$$

where n is the number of protogalactic clouds within a volume V, σ is an average collision cross section, and v is the virial velocity ($v \sim \{0.4GM/R_h\}^{1/2}$, where M is the total halo mass and R_h is the halo radius).

The merging probability for stellar systems could be estimated (*e.g.* Carlberg 1990) from the fraction of a Maxwellian velocity distribution less than the escape velocity from the half-mass radius of the colliding protogalaxies (Aarseth & Fall 1980). Since the average virial velocity of the clouds considered in our schematic models are large compared to the internal cloud escape velocities, stars within the clouds will on average not be bound to the merged system after a collision. Hence, we assume after each collision that stars within the merging clouds are dispersed into the Galactic halo. As mentioned above, it does not really matter whether this dispersion occurs early or near the end of the merging process as long as it happens.

Although the stellar component can be dispersed during the collisions, it is perhaps reasonable to suppose that the gas within the clouds can dissipate the energy of the collision and remain to form a new protogalactic cloud depleted of stars. In our simple schematic picture these clouds are represented by average spherical protogalactic fragments moving along virial orbits. Collapse of these clouds to a disk is inhibited by merger-induced disruption until near the end of the merging epoch.

With the above considerations, we take the rate of change of the average cloud mass, m, during the merging epoch to be,

$$\frac{dm(t)}{dt} \sim (m_g - m_*)\lambda_m \quad , \tag{2}$$

where m_g is the average mass of gas and m_* is the average mass in stars and stellar remnants within the clouds.

2.2 Star formation rate

The present work differs from previous N-body work in which star formation is presumed to begin simply when the density within the halo exceeds some threshold (*e.g.* Carlberg 1988ab), or recent applications of Press-Schechter theory (*e.g.* Carlberg 1990) to quasars in which star formation is presumed to occur only for mergers which are of sufficiently low relative velocity to result in merged *stellar* systems. Instead, we allow some star formation to be induced by each merger. Since clouds are presumed to form by mergers on all scales, this term implicitly approximates any burst of star formation due to the initial collapse of clouds under self gravity. We also allow for *normal* star formation to occur within the clouds at a rate proportional to a power of the density of gas within the clouds.

Our total stellar birthrate function is thus written,

$$\psi(t) = \alpha\psi_m + \beta\psi_c \ , \tag{3}$$

where, the fraction of material per unit time induced by protogalactic mergers into star formation, ψ_m, is taken as proportional to the fraction of gas mass participating in mergers per unit time, *i.e.*,

$$\psi_m \propto \frac{1}{m_g}\left(\frac{dm_g}{dt}\right)_{merge} = \lambda_m \ , \tag{4}$$

and the fraction, ψ_c, of material participating in quiescent star formation within the clouds is written,

$$\psi_c \sim \rho_g^x \ . \tag{5}$$

A slightly better fit to the white-dwarf luminosity function and the nuclear chronometers was possible for values of $x < 1$. We therefore adopt a value of $x = 1/2$.

Note, that it is necessary to consider both possible modes of star formation for our cosmochronology studies. It is necessary to follow the quiescent rate in order to keep track of stellar abundances and remnants in the disk after the merging ceases, whereas the merger-induced star formation is necessary to provide sufficient star formation prior to disk formation. Also, note that our definition of the stellar birthrate function differs from the usual convention which specifies the total number of stars formed per unit volume or surface area. The total star formation rate per volume or surface area is obtained by multiplying our star formation rate by the gas density or surface density. Thus, $x = 1/2$ in equation (5) would correspond to a Schmidt (1963) $n = 3/2$ stellar birthrate function.

2.3 Evolution of mass in gas and stars

The equations governing the mass in gas and stellar remnants in the merging protogalaxies in the instantaneous recycling approximation are simply,

$$\frac{dm_g(t)}{dt} = m_g\lambda_m - (1-R)\psi m_g \ , \tag{6a}$$

and

$$\frac{dm_*(t)}{dt} = (1-R)\psi m_g - m_* \lambda_m \quad , \tag{6b}$$

so that,

$$m_g(t) = m_g(0) e^{\int_0^t (\lambda_m - (1-R)\psi) dt'} \quad , \tag{7a}$$

and,

$$m_*(t) = e^{-\int_0^t \lambda_m dt'} \int_0^t (1-R)\psi m_g e^{\int_0^{t'} \lambda_m dt'} dt \quad , \tag{7b}$$

$$m(t) = m_g(t) + m_*(t) \quad . \tag{7c}$$

Here, $(1-R)$ is the usual factor describing the fraction of material which remains in stellar remnants (Tinsley 1980). Note that since we use the instantaneous recycling approximation we do not need to specify an initial mass function. The initial mass function during the merging epoch is, however, a subject of interest in the context of generating baryonic dark matter halos. This will be discussed in §6.

The total mass, M_*, of stars and remnants which will end up in the Galactic halo from the merging process will be,

$$M_*(t) = M - n(t)m(t) \ . \tag{8}$$

We define the input quantities for equations 1 through 8 as follows: The number of protogalactic clouds decreases exponentially with the integral of the merger rate,

$$n(t) = n(0) e^{-\int_0^t \lambda_m dt'} \quad , \tag{9}$$

where the initial number of clouds, $n(0)$, is given by the ratio of the total Galaxy-plus-halo baryonic mass to the initial fragment mass (taken here to be $10^6 M_\odot$). In the version of the model reported on here we will assume that the local Galactic dark matter is baryonic. Thus, we take $\sim 4 \times 10^{11} M_\odot$ (Fich and Tremaine 1991) for the baryonic mass, so that $n(0) \sim 4 \times 10^5$.

For the merger cross section we use a geometrical cross section, $\sigma = \pi r_t^2$, where, r_t is the tidal radius and $r_t \sim (m/M)^{1/3} R_h$, (Binney & Tremaine 1987) where, R_h is the radius of the expanding and collapsing halo which we approximate as a homogeneous sphere.

2.4 Halo expansion and collapse

The time evolution of the radius, R_h, of the collapsing system is needed both for the cloud tidal radius and the volume factor in the merger rate, Eq. (1). We assume a homogeneous spherical overdensity, for which the time evolution of R_h in the expanding Hubble background can be written analytically (Weinberg 1972),

$$t(R_h) = \int_0^{R_h} \left[\frac{2GM}{r} - \frac{2GM}{R_{max}} \right]^{-1/2} dr \ , \tag{10}$$

$$= \left(\frac{R_{max}^3}{2GM}\right)^{1/2} \arcsin(R_h/R_{max})^{1/2} - \left[\frac{R_h}{R_{max}} - (\frac{R_h}{R_{max}})^2\right]^{1/2} \quad ,$$

where, R_{max} is the maximum expansion radius of the overdense region before collapse. It is roughly related (Press & Schechter 1974) to the amplitude, δ, of the overdensity when it forms, *i.e.* $R_{max} \sim R_i\delta^{-1}$, where for small δ, R_i is just the radius of a region containing a mass, M at the epoch when galaxies begin to form. In the present context, R_{max} is a free parameter which specifies the timescale for the collapse. For the purposes of cosmochronology, it is convenient to specify R_{max} by the timescale to reach the maximum expansion and then collapse, $t_{coll} = \pi(R_{max}^3/(2GM))^{1/2}$.

The actual time evolution of R_h will of course be much more complicated than that given in Eq. (10). The evolution can begin shortly after recombination when the cosmological density and associated radius were about the same as that of the present Galactic halo. Near the end of the collapse, the combined effects of conservation of angular momentum and heating will dissipate the collapse for material which will ultimately be incorporated into the disk. In our schematic model, we approximate these effects by beginning and ending our description of the collapse when the Galactic halo has a size of the present dark-matter halo, (~ 35 *kpc*, Fich & Tremaine 1991). After this point, we turn our attention to the evolution of material which gradually settles into the disk in the local Solar neighborhood and is no longer substantially mixed by the merging process. For the purposes of this schematic study, it is important that we halt the collapse for material which will be incorporated into the local disk so that we can model chemical evolution in the Solar neighborhood. It is somewhat arbitrary as to when we halt the collapse. The choice of 35 *kpc* is because we assume that the dark matter halo is baryonic. Of course, in a model for the entire Galaxy most stars and gas continue to collapse and concentrate in the center, eventually producing the present half light radius of the halo of only 3 *kpc*.

We also presume in the beginning that the protogalactic fragments form and virialize with an exponential time scale of 0.2 Gyr. That is, we multiply Equation (1) by an additional factor of $[1 - exp\{-(t-t_0)/t_{vir}\}]$, where $t_{vir} = 0.2$ Gyr and $t_0 = t(R_h = 35kpc)$. This time scale roughly corresponds to the time (Press & Schechter 1974) for the decoupling of $10^6 M_\odot$ clouds from the Hubble expansion, assuming that the variance of the fluctuation amplitude on different mass scales varies as $(m/M)^{-1/6}$ (Carlberg 1990).

To estimate the gas density for the quiescent star formation rate (Equation (5)) in the Solar neighborhood and for determining the fraction of the local mass in gas, we follow the evolution of the height, z_g, of gas in a cylindrical homogeneous disk. During the merging process we set the height to the tidal radius. Once the merging process has ceased at $t = t_{coll}$, we allow the gas to settle into the thickness of the present disk. We chose a disk formation timescale of ~ 4 Gyr derived from Figure 5 of Burkert, Truran & Hensler (1992). This timescale results from the competition among various energetic processes like supernova-heating, planetary-nebula ejection, gas ionization by UV photons, evaporation and condensation of molecular clouds, as well as metallicity-dependent radiative cooling of gas components at different temperatures.

We approximate the collapse of the disk scale height by,

$$\frac{dz_g(t > t_{coll})}{dt} = \Big(r_t(t) - z_g(t)\Big)\lambda_m(t) + \Big(z_{disk} - z_g(t)\Big)/\tau_{disk} \ , \tag{11}$$

where, z_{disk} is the present height for the disk which we take to be 0.25 kpc, and $\tau_{disk} = 4$ Gyr. During the expansion and collapse of the halo, z_g is set equal to r_t. After the collapse is halted, equation (11) is solved numerically.

We approximate the local gas density by $\rho_g \sim m_g/(\pi z_g r_t^2)$. As the height of the disk decreases, we assume that the stars do not collapse with the gas. The star formation rate at some height above the disk will, therefore, cease once the gas has collapsed below that height. These stars will remain as part of the thick disk as gas continues to collapse into the thin disk. Within the thin disk the local density of stars and stellar remnants, ρ_s, will be given by an integral of the star formation rate as the gas collapses to increasing density, *i.e.*

$$\frac{d\rho_s}{dt} = \psi\rho_g - \rho_s\lambda_m \quad . \tag{12}$$

The fraction, μ_g, of local mass in stars is given by the ratio of the local gas density to total local density, $\mu_g = \rho_g/(\rho_s + \rho_g)$.

3. Nucleocosmochronology

To model the dependence of the nuclear chronometers on the star formation history we again make use of the instantaneous recycling approximation (*e.g.* Tinsley 1980; Clayton 1984) whereby in our model, the evolution of the mass fraction, Z_i, of a nuclear species, i, can be written,

$$\frac{d(Z_i\rho_g)}{dt} = \left[Z_i\frac{1}{\rho_g}\frac{d\rho_g}{dt} + y_i R\psi - \lambda_i Z_i\right]\rho_g \quad , \tag{13}$$

where y_i is the mass fraction of newly synthesized material in the stellar ejecta, and λ_i is the nuclear decay rate for species, i. From Equations (6a) and (13) and the chain rule, the abundance of a radioactive species at the time the Solar system condensed ($T = T_0 - 4.6$ Gyr) is just,

$$Z_i(T) = y_i R e^{-\lambda_i t}\int_0^T \psi(t)e^{\lambda_i t}dt \quad . \tag{14}$$

The ratio of actinide chronometers can therefore be written;

$$\frac{Z_i}{Z_j} = \frac{y_i}{y_j}\frac{e^{(\lambda_j-\lambda_i)T}\int_0^T \psi(t)e^{\lambda_i t}dt}{\int_0^T \psi(t)e^{\lambda_j t}dt} \quad . \tag{15}$$

For the ratio of cosmoradiogenic ^{187}Os to ^{187}Re, we similarly derive;

$$\frac{[Z_{Os}]_c}{Z_{Re}} = \lambda_{Re}\frac{\int_0^T e^{-\lambda_{Re}t}dt\int_0^t \psi(t)e^{\lambda_{Re}t'}dt'}{e^{\lambda_{Re}T}\int_0^T \psi(t)e^{\lambda_{Re}t}dt} \quad . \tag{16}$$

For the ^{232}Th/^{238}U and ^{235}U/^{238}U actinide chronometers, we use production ratios, y_i/y_j, of 1.60 ± 0.10 and 1.24 ± 0.10, respectively (Cowan, Thielemann, & Truran 1991b). The abundances when the Solar system condensed were derived from Anders & Grevesse (1989) for an age since the last nucleosynthesis event of 4.6 ± 0.1 Gyr. We thus obtain abundance ratios of 2.32 ± 0.23 and 0.33 ± 0.03 for $^{232}Th/^{238}U$ and $^{235}\mathrm{U}/^{238}\mathrm{U}$, respectively. Most of the abundance uncertainty is due to the uncertainty in the time since the last nucleosynthesis event.

There is a major uncertainty in the Re/Os chronometer due to the fact that the beta-decay rate for ^{187}Re can be considerably faster in stars than in the terrestrial laboratory environment (Takahashi & Yokoi 1982; Yokoi, Takahashi, & Arnould 1983). As in Meyer & Schramm (1986) we therefore take the age derived for the Re/Os chronometer using the terrestrial decay rate to be an upper limit to the Galactic age. From the Anders & Grevesse (1989) abundances and the analysis in Meyer & Schramm (1986) we take the ratio of cosmoradiogenic ^{187}Os to ^{187}Re when the Solar-system condensed to be, $[^{187}\mathrm{Os}]_c/^{187}\mathrm{Re} = 0.08 \pm 0.03$. With this constraint we find that the upper limit to the Galactic age from this chronometer is not particularly useful, $T_0 \leq 30$ Gyr.

4. White Dwarf Luminosity Function

We can compute the present density of stars in the disk from the comoving mass density, $B(t)$, incorporated into stars per unit time,

$$B(t) = \psi(t)\tilde{\rho}_g(t) \quad , \tag{17}$$

where $\tilde{\rho}_g$ denotes that the gas density is comoving with respect to the expansion and contraction of the halo. The fraction, $B_{eff}(m_{wd}, t)$, of local stellar mass density in the form of white dwarfs born at time, t, from progenitor stars of mass, m_{ms}, which remain in the disk and have survived the merging process to the present time, T_0, is,

$$B_{eff}(m_{wd}, t) = B(t-\tau)\phi(m_{ms})e^{-\int_{t-\tau(m_{ms})}^{T_0} \lambda_m(t')dt'} \quad , \tag{18}$$

where ϕ is the relative initial mass function for a progenitor main-sequence star which forms a white dwarf of mass m_{wd} after a main sequence life time, τ. The exponential factor accounts for the fact that the merging process will have removed progenitor stars and remnants from the present local mass density.

The local density of white dwarfs observed at a particular luminosity, L, will then be given by,

$$N(\frac{L}{L_\odot}) \propto \int_{m_{min}}^{m_{max}} dm_{ms} \int_{L}^{L_{max}} B_{eff}(m_{wd}, t(L)) \frac{dt_{cool}}{d\ log(L/L_\odot)} d\ log(\frac{L}{L_\odot}) \quad . \tag{19}$$

For the present study we use polynomial fits to the cooling curves, $dt_{cool}/d\ log(L/L_\odot)$, given as a function of m_{wd} in Winget *et al.* (1987). We use values of τ, $\phi(m_{ms})$, m_{min}, and m_{max}, and L_{max} from Tamanaha *et al.* (1990). Our models are then constrained by the data of Liebert, Dahn, & Monet (1988). The distinguishing feature of fits to the white-dwarf luminosity function is a drop off in the number of white dwarfs with faint luminosities (large ages). In our model this is produced by the fact that most stars formed during the merging epoch are swept into the Galactic halo, and only those formed since the end of the bulk of the merging epoch could have remained to become a part of the local Galactic disk.

5. Results

The variable parameters which we choose for this schematic merger model are t_{coll}, α, β, and T_0, the age of the universe. In our analysis, T_0 was fixed by the age of the oldest metal-poor globular clusters which we take to be 15 $\pm$ 3 Gyr (Schramm 1990; Lee, Demarque, & Zinn 1990; Cowan Thielemann, & Truran 1991a). The time for the halo to expand and collapse, t_{coll}, was determined by the difference between the oldest globular-cluster ages and the white-dwarf cooling age. This timescale was determined by optimizing the χ^2 for the fit to the observed white-dwarf luminosity function while requiring consistency with the nuclear chronometers and the age-metallicity relation.

The merger star formation rate parameter α was adjusted to give the correct nuclear chronometric ratios. Since the nuclear chronometers are sensitive to the difference between the past and recent star formation rates (Meyer & Schramm 1986), they can be used to fix the amount of star formation in the merging process relative to the present rate. The quiescent star formation rate parameter, β, mainly affects the present fraction of the Galactic mass which is in gas, and the time dependence of the star formation rate in the disk. Larger values of β correspond to a more rapid rate of gas consumption. Since the quiescent star formation rate depends upon the gas density, a larger gas consumption rate also corresponds to a more rapid rate of decrease of the star formation rate. We therefore adjust β to agree with the present value of the local interstellar gas fraction, $\mu_g \sim 0.28 \pm 0.09$, (Gilmore, Wyse, & Kuijken 1989).

Equations (1) - (9) were solved iteratively for each time step until self consistency and the parameters, t_{coll}, α, β, and T_0, were varied to satisfy the constraints. An example of a parameter set which fits the available constraints is given in Table 1. Note that the quiescent star formation rate is obtained by multiplying β by an additional factor of $\rho_g^{1/2} \sim 10^{3-4} (M_\odot kpc^{-3})^{1/2}$, so that although β is much smaller than α in Table 1, the quiescent star formation rates and merger induced star formation rates are comparable for this model.

Figure 1a shows the evolution of the halo radius R_h until it reaches the present dark-matter radius of $35 kpc$, after which time we follow the collapse of local stellar gas into the thin disk. Figure 1b shows the average stellar birthrate, $B(t)$, and the effective stellar birthrate, $B_{eff}(t)$ for material which is ultimately incorporated into the local disk. Figure 1c shows the evolution of metallicity compared with the age metallicity relation of Twarog (1980). The comparison in Figure 1c is not precise since our metallicity is derived from massive star evolution whereas the data are for iron which is contributed to by the slower rate of Type Ia supernovae. Nevertheless, it has been shown (Mathews, Bazan, and Cowan 1992) that the early evolution of iron is dominated by production in massive stars, and that a large fraction of Type Ia supernovae probably occur on a time scale sufficiently short that the age-metallicity relation is not significantly different when corrected for the Type Ia contribution to iron. Hence, the comparison in Figure 1c is justified.

Several epochs are identified on Figure 1b. In our model there should be an initial burst of mergers and star formation within the protogalactic clouds simply due to the fact that the clouds are initially more compact (higher internal gas density) and there are many of them per unit volume. The Hubble expansion, however, quickly halts this initial burst.

This first burst of star formation should be responsible for the oldest and most metal-poor globular clusters and halo stars (Lee, Demarque, & Zinn 1990). It may also be the source of the observed $[Z] <$ -1 metal-poor component of the Galactic globular cluster metallicity distribution function (Armandroff & Zinn 1988).

As the halo continued to expand the protogalactic system would have spent considerable time near the maximum expansion radius (Fig. 1a). During this epoch, the Galaxy may have appeared like a system of Lyman α absorbers, or as a low surface brightness galaxy. In this schematic model we can make no prediction of tracers of this epoch, perhaps represented by stars on orbits with large apocenters. By fiat, all material collapses more or less along radial trajectories except for that which is incorporated into the disk.

Although there continued to be some star formation even during the period of maximum expansion due to quiescent star formation within the clouds, the next significant burst of star formation did not occur until near the end of the halo collapse. This would have produced a second component of globular clusters with $[Z] \sim -.6$ as observed (Armandroff & Zinn 1988). If this sort of evolution is typical for other galaxies, then this second burst of star formation might also be the source of the observed luminosity peak in galaxy counts at intermediate redshifts (Cowie 1991). In our model this peak would occur for a Milky Way-sized galaxy at a redshift of $z \sim 0.9$. For more massive galaxies for which the mean fluctuation was smaller than that which produced the Milky Way, the peak would occur for even smaller redshifts, and may be responsible the observed peak in the galaxy redshift distribution at $z \sim 0.4$ (Cowie 1991).

The dashed line on Figure 1b shows the fraction of stars formed which would have survived the merging process to be a part of the present local disk population. The white-dwarf luminosity distribution derived from this effective star formation rate is shown in Figure 2. A reasonable reduced chi-squared is obtained for $t_{coll} = 6.1 \pm 0.4$ Gyr (see Table 1). The best fit is for a star formation rate which varies little after the merging process ceases. This is consistent with studies (Rana 1991) which show that the white-dwarf luminosity function constrains the local star formation rate in the disk not to have varied much for the past 10 Gyr. In our model, this relative constancy of the star formation rate is due to the fact that the rate at which gas settles into the disk roughly compensates the rate of depletion of gas by star formation once the merging has ended. This probably reflects the self regulation caused by supernova heating of the gas which slows the rate of settling into the thin disk (Burkert & Hensler 1987; Burkert, Truran, & Hensler 1992). It is during this phase of gradual settling that the thick disk could have formed. There would also be some disruption of thin-disk stars into the thick disk as the last few mergers occurred. Thus, thick disk stars are predicted to have a maximum age comparable to and perhaps slightly older than the oldest thin disk stars, but much younger than the oldest globular clusters.

In a sense, our schematic star formation rate is similar to a prompt initial enrichment model like that of Fowler & Meisl (1986) and Fowler (1987) who postulated an early spike of nucleosynthesis to enrich metals before the evolution of the disk. Although a prompt initial enrichment model like this also gives the correct white dwarf age, (10 ± 1.6 Gyr, Fowler 1987), it is not consistent with the globular cluster ages unless the bulk of star formation is delayed by ~ 5 Gyr relative to the initial spike responsible for the formation of the first globular clusters. Furthermore, in our model there is a second burst of star formation associated with the collapse of the halo to its present size. This second burst is broader than a delta function. There is also non-negligible star formation between the bursts due to quiescent star formation within the clouds, and there is an additional delay from the second burst to the end of the merging process when the thin disk can begin to form. Thus, our model is not equivalent to a prompt initial enrichment model, but could be approximated with a modified prompt enrichment model with two spikes preceding the bulk of nucleosynthesis in the disk and a constant rate of nucleosynthesis between the spikes to approximate the quiescent star formation within the clouds. Delayed constant rates could describe star formation within the collapsing disk and the surviving fraction within the present thin disk. A more accurate analytic approximation to our star formation rate, however, would be a sum of a constant rate plus exponentials. From a fit to Figure (1b) we obtain;

$$B(t) = 0.0224 + 0.199e^{-(t-0.2)/0.202}\ \Theta(t-0.2) + 0.0908e^{-(t-6.1)/16.1}\ \Theta(t-6.1) \tag{20a}$$

and

$$B_{eff}(t) = \left[B(t) - 0.0988e^{-(t-6.1)/0.794}\right]\Theta(t-6.1) \quad , \tag{20b}$$

where $\Theta(t) = 1$ for $t \geq 0$ and zero elsewhere.

The first term in Eq. (20a) describes the minimum quiescent star formation rate within the clouds. The second term describes the initial burst which starts after a virialization time of 0.2 Gyr and exponentially damps out as the halo expands. The third term of Eq. (20a) describes the rate of mergers and intrinsic star formation after the halo has collapsed at $t_{coll} = 6.1$ Gyr.

6. G-dwarfs, Baryonic Halos, and the Local Group

This model also provides some insight into the G-dwarf problem (*e.g.* Gilmore & Wyse 1986) by dispersing the oldest metal-poor stars into the Galactic halo during the merging process. As can be seen in Figure 1c, by the time the merging process is complete and the disk can form, the metallicity has already grown to more than $0.1Z_{\odot}$. Hence, few low metallicity stars should be observable in the local disk population. Although this gives a qualitative description of the G-dwarf distribution, we have found that the parameters which best fit the chronometers do not give an optimum fit to the observed G-dwarf distribution (Pagel 1991). The resolution of this discrepancy may require an initial mass function which is significantly skewed to low mass stars during the merging epoch. It is amusing to speculate that if the early low-metallicity mass function (Adams & Walker 1990) or the mass function due to cloud collisions were to preferentially produce brown dwarfs or massive stars which became black holes this could lead to the dark baryonic halo as assumed here. This possibility will be further explored in a later paper. For the models considered here $\sim 61\%$ of the total initial mass ended up as halo stars or remnants. Observationly, only a small fraction of this halo can be in visible stars which again requires an IMF for the merging epoch to be in skewed to brown dwarfs or black holes. If most of the halo mass is dark then our model corresponds to a mass-to-light ratio ~ 3. However, within the parameters of the model it is possible that a much larger fraction could presently reside in the halo as a dark matter component. We also note that models like this with merger-induced star formation (e.g. Tinsley & Larson 1979; Struck-Marcell 1981; Silk & Wyse 1986) are consistent with the observed mass-metallicity relation of the Local Group.

7. Conclusion

We have shown that a simple schematic model can be constructed to describe the star formation and nucleosynthesis associated with galaxy formation by merging protogalactic fragments within a virialized expanding and collapsing halo followed by subsequent gradual settling of gas into a thin disk in the Solar neighborhood. We have further shown that all of the chronometeric ages can be made consistent in this picture if the timescale for the collapse is $\sim$ 6 Gyr, and the stars and remnants produced during the merging process have remained in the Galactic halo. If this picture is correct, then the nuclear chronometers are most useful for constraining the amount of star formation during the merging process, and the white-dwarf luminosity function is most useful for constraining the time since the completion of the merging process when the thin disk could begin to form. The true age of the universe since the first star formation, however, is best determined from the oldest globular clusters.

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Table 1. Summary of parameters and calculated quantities for the protogalactic merger model. The times, T_0 and t_{coll} are in units of Gyr. The parameter α is in units of Gyr^{-1} and β is in units of $(M_\odot\, kpc^{-3})^{-1/2}\, Gyr^{-1}$, and M_* is in units of $4 \times 10^{11} M_\odot$. The reduced chi-squared is for a fit to the white-dwarf luminosity function.

	T_0	t_{coll}	α	β	μ_g	M_*	χ^2_r	$^{232}Th/^{238}U$	$^{235}U/^{238}U$
Model	15	6.1 ± 0.4	0.12	5.04×10^{-4}	0.28	0.61	1.45	2.27	0.32
Obs.	15 ± 3	5.7 ± 3.6[a]	-	-	0.28 ± 0.09	-	-	2.32 ± 0.23	0.33 ± 0.03

[a] For $T_{wd} = 9.3 \pm 2.0$ Gyr (Winget et al. 1987), and $T_{gc} = 15 \pm 3$ Gyr (Schramm 1990).

Figure Captions

Figure 1. Example of a model which satisfies all of the chronometric constraints: a) Halo radius, R_h, as a function of time; b) Local average comoving stellar birthrate, $B(t)$, as a function of time (solid line) normalized such that $\int_0^{T_0} B(t)dt = 1$. Various epochs of the galaxy formation process are labeled. The dashed line shows the effective stellar birthrate, $B_{eff}(t)$, for stars and remnants which would have survived the merging process to remain as part of the present local disk population; c) Metallicity $[Z]$ as a function of time compared with the age-metallicity relation of Twarog (1980).

Figure 2. Calculated white-dwarf luminosity function for the model given in Table 1, compared with the data of Liebert, Dahn, & Monet (1988).

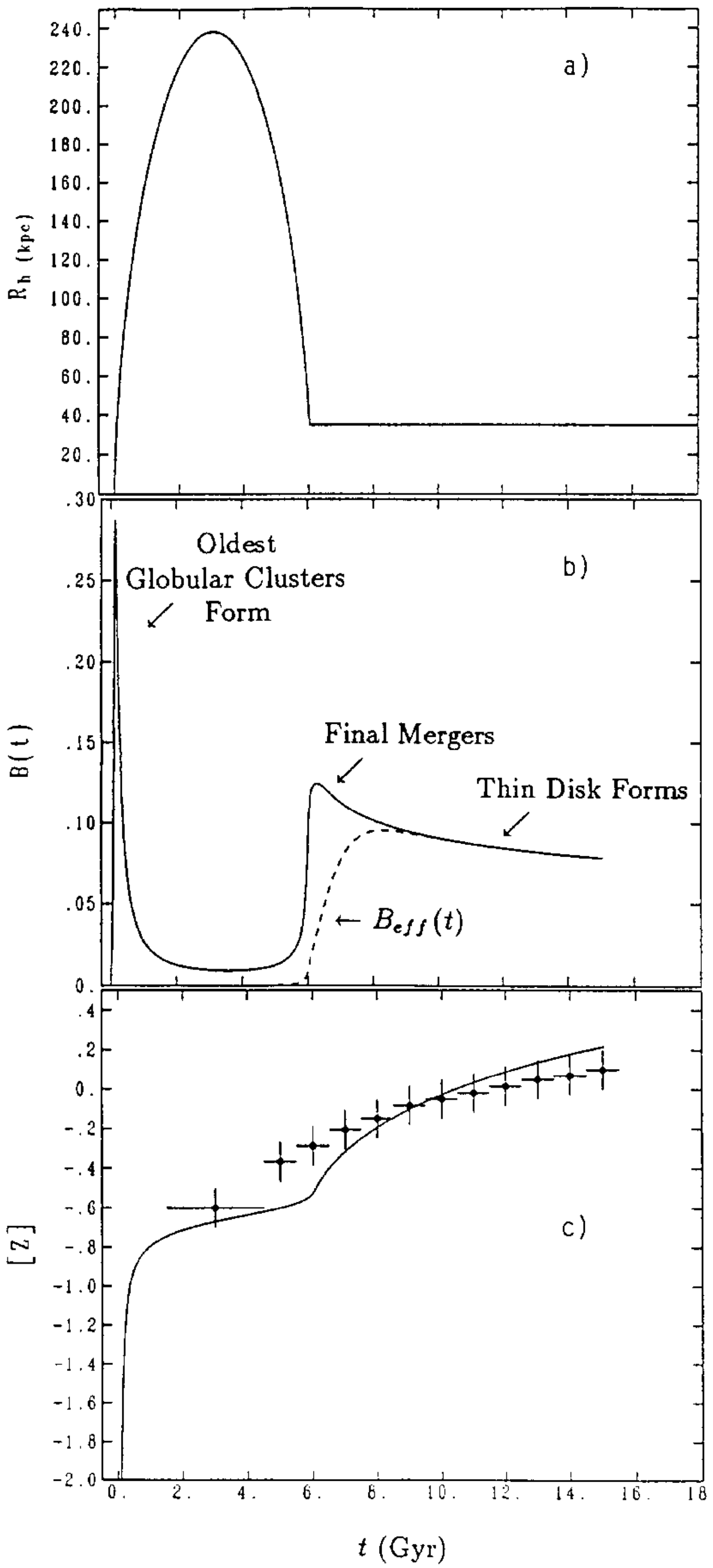
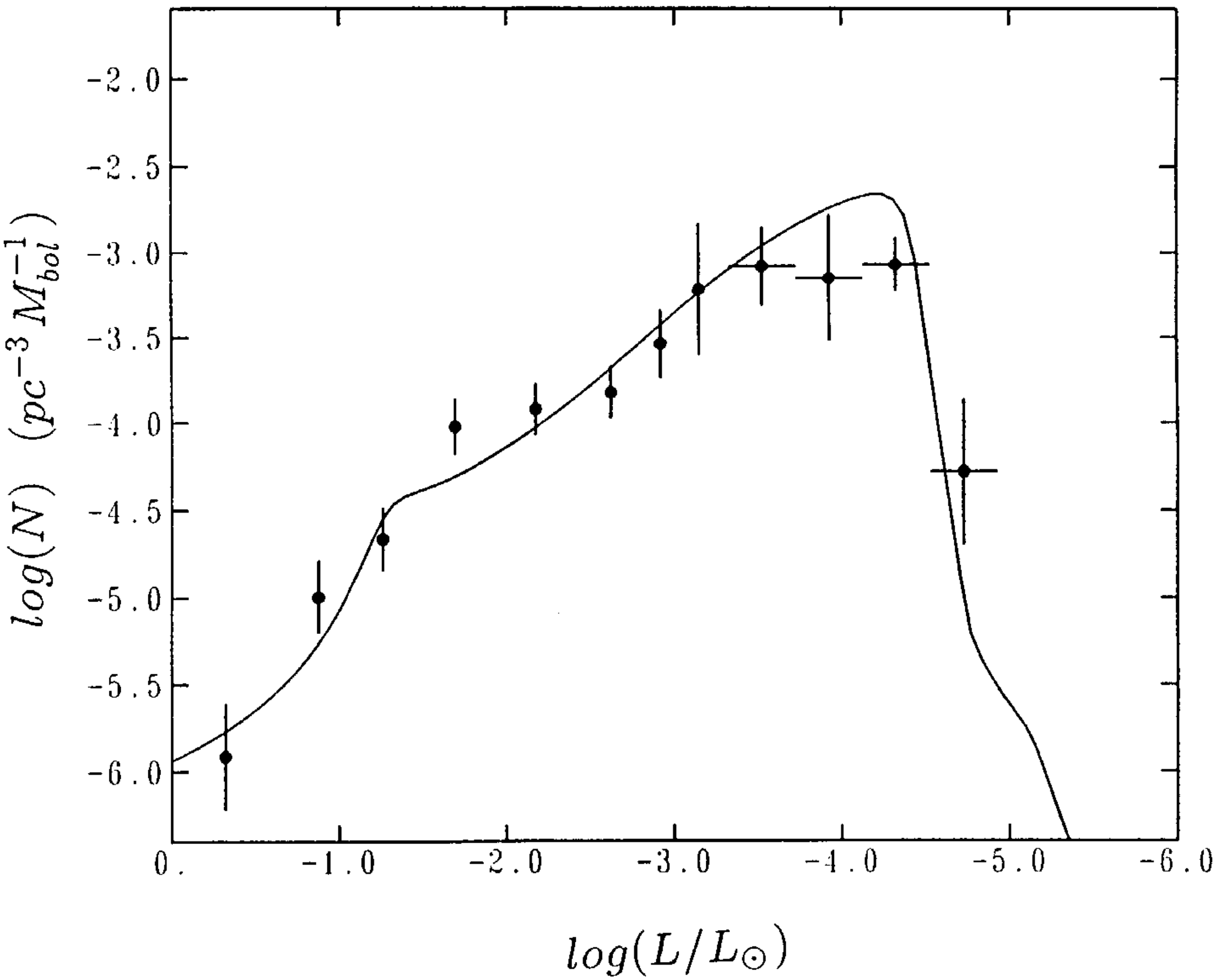

a)
R_h (kpc)
240.
220.
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
b)
B(t)
Oldest
Globular Clusters
Form
Final Mergers
Thin Disk Forms
$\leftarrow B_{eff}(t)$
.30
.25
.20
.15
.10
.05
0.
c)
[Z]
.4
.2
0.
-.2
-.4
-.6
-.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
0. 2. 4. 6. 8. 10. 12. 14. 16. 18.
t (Gyr)

Fig. 1



-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
0.
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
$log(N) \quad (pc^{-3}\, M_{bol}^{-1})$
$log(L/L_\odot)$

Fig. 2