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MIXING OF PRIMORDIAL GAS IN LYMAN BREAK GALAXIES

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ABSTRACT

Motivated by a recent interpretation of $z \sim 3$ objects, we examine processes that control the fraction of primordial ($Z = 0$) gas, and so primordial stars, in high star formation rate Lyman break galaxies (LBGs). A primordial fraction different from 1 or 0 requires microscopic diffusion catalyzed by a velocity field with a timescale comparable to the duration of star formation. The only process we found that satisfies this requirement for LBGs without fine-tuning is turbulence-enhanced mixing induced by exponential stretching and compressing of metal-rich ejecta. The time dependence of the primordial fraction for this model is calculated. We show that conclusions for all the models discussed here are virtually independent of the initial mass function (IMF), including extremely top-heavy IMFs.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: high-redshift — galaxies: ISM — ISM: evolution — turbulence

1. INTRODUCTION

Galaxies begin their lives with entirely primordial ($Z = 0$) gas. As they age, metal production and mixing can only reduce the primordial gas fraction. We have explored the expected time dependence of the primordial fraction for various types of mixing and chemical evolution processes using a kinetic equation for the evolution of the abundance distribution. The present Letter addresses the narrower question of whether any models for mixing and chemical evolution predict this transformation occurs at an accessible redshift.

Jimenez & Haiman (2006, hereafter JH) showed that several UV properties of a variety of objects, mostly Lyman break galaxies (LBGs), at redshift $z \sim 3$, can all be understood if these objects contain a substantial fraction, about 10%–50%, of massive stars with essentially zero metallicity ($Z \lesssim 10^{-5}\, Z_{\odot}$; we use Z and metallicity indiscriminantly here). These UV properties cannot together be explained by a top-heavy initial mass function (IMF) and require $Z = 0$ stars; a top-heavy IMF is not required. Massive stars have short lifetimes, so their metal abundances reflect that of the concomitant gas. Thus, if JH are correct, a substantial fraction of the interstellar medium (ISM) of these galaxies, with star formation (SF) ages a few hundred million years, has not been polluted by any products of nucleosynthesis.[1]

Motivated by JH and other suggestions for $Z = 0$ stars (Malhotra & Rhoads 2002; Shimasaku et al. 2006), and the fact that during some early period in the lives of *all* galaxies a transformation from primordial to nonprimordial must occur, leaving spectrophotometric signatures (JH; see Schaerer 2003), we examined the viability of a number of models for this transformation.

A change in the primordial fraction requires microscopic diffusion enhanced by a complex velocity field, such as instabilities in swept-up supernova (SN) shells or a turbulent ISM, along with dispersal of nucleosynthesis products over many kiloparsecs, involving a scale range of $\sim 10^5$. Existing hydrodynamic simulations in a cosmological context (e.g., Governato et al. 2004; Scannapieco et al. 2005) therefore cannot represent the transition of the primordial gas or mixing in general, since they adopt mixing rules that arbitrarily spread metals among nearest neighbor cells or SPH particles. The only hydrodynamic simulations of true mixing of tracers in galaxies were concerned either with turbulent dispersal of mean metallicity, not mixing (Klessen & Lin 2003), or mixing of initial spatially periodic inhomogeneities by numerical diffusivity in a turbulent galaxy with no continuing source of metals (de Avillez & Mac Low 2002).

Instead of simulations, the arguments given here are phenomenological, in order to clarify the essentials for each physical process. A detailed discussion is given elsewhere (L.-B. Pan & J. Scalo 2007, in preparation, hereafter PS) using a formal probability distribution evolution equation. Here we report that most processes we examined are either far too fast or slow to partially erase the primordial fraction (§ 2), except for mixing by turbulence-enhanced diffusivity based on exponential stretching of blobs of nucleosynthesis products, discussed in § 3.[2]

2. ESTIMATES OF TIMESCALES FOR MIXING PROCESSES

2.1. *Star Formation Age*

The existence of a primordial gas fraction $P(t)$ that is not nearly unity or zero, i.e., both $P(t)$ and $1 - P(t)$ are significantly larger than zero, a condition we refer to as a "significant" or "intermediate" primordial fraction, requires a mixing or depletion process whose characteristic timescale is comparable to the SF age, the time since SF began. If the mixing timescale is much smaller, $P(t)$ will be nearly zero; if it is much larger, $P(t)$ will remain near unity. SF ages for LBGs and likely related objects at somewhat different redshifts have been estimated by Papovich et al. (2001), Shapley et al. (2001), Erb et al. (2006), and others, using galaxy evolution models that assume an exponentially decreasing star formation rate (SFR) that began at some time in the past. Although there is much variation, median SF ages are $\sim 3 \times 10^8$ yr.

These SF ages cannot be significantly different for a number

[1] The existence of $Z = 0$ gas requires an IMF deficient in stars with $M \lesssim 1\, M_{\odot}$. Otherwise, the number of low-mass stars observable today would be large, contradicting observational limits on the star fraction with very small Z (see Oey 2003) by several orders of magnitude. We discuss the effects of different IMFs below, where we show that all our conclusions are independent of the IMF as long as it satisfies the requirement $M \gtrsim 1\, M_{\odot}$.

[2] A recent estimate of the effect of SN mixing (§ 2.4) on the primordial fraction at high redshift (Tumlinson 2006) apparently used a shell mass much larger than found in analytical and numerical calculations of supernova remnant evolution (see Thornton et al. 1998; Hanayama & Tomisaka 2006).

of reasons. The look-back times of about 11.5 Gyr for $z = 3$ imply a strict upper limit to the SF age of 2 Gyr, and a more likely upper limit of 1.5 Gyr (corresponding to $z \sim 8$). The irregular morphologies of the LBGs (Giavalisco 2002) suggest that LBGs are in the process of formation, accumulating large fragments of gas and stars through mergers (Conselice 2006), and probably undergoing one of their first major bursts of SF; starburst populations have durations, estimated from statistics (Kennicutt et al. 1987; Nikolic et al. 2004), modeling of integrated light features (Marcillac et al. 2006), and theoretical arguments (see Leitherer 2001), that are similar to the estimates in LBGs. Finally, ages much greater than 3×10^8 yr would produce greater metallicity than observed (see Giavalisco 2002).

We assume SF has been a continuous function of time. If instead the SFR preceding or during the present episode consists of bursts of shorter duration, most of our arguments remain unchanged if the SF age is replaced by the accumulated duration of SF.

2.2. *Depletion of the Primordial Fraction by Sources*

The JH result of 10%–50% primordial gas at $z \sim 3$ seems surprising, but actually galaxies should remain almost completely primordial for billions of years in the absence of microscopic diffusivity. SN metal production slowly depletes primordial gas by transferring it from a $Z = 0$ delta function in the Z probability density function (pdf) to another delta function at a much larger Z, the source metallicity Z_s averaged over the IMF (∼0.1 assuming the hot ejecta are well mixed). Intermediate values of Z cannot be reached without diffusivity.

This suggests the simplest explanation for an intermediate primordial fraction in LBGs: 50%–90% of the primordial gas passed through stars that became SNe. The timescale for this process is the source timescale, $\tau_{\rm src} = M_{\rm gas}/BR_{\rm SN}$, where B is the SFR and $R_{\rm SN}$ is the returned fraction from SNe averaged over the IMF. We take the total gas mass $M_{\rm gas}$ as $5 \times 10^{10}\ M_\odot$, extrapolated from gas masses estimated in the $z \sim 2$ UV-selected sample of Erb et al. (2006). From a number of studies, we adopt a median SFR of 100 $M_\odot$ yr^{-1} for LBGs at $z \sim 3$, assuming the IMF lower limit $M_l = 0.1$ (Papovich et al. 2001; Shapley et al. 2001; Giavalisco 2002; Erb et al. 2006; Yan et al. 2006). For this M_l, we calculate $R_{\rm SN} \approx 0.1$ for various IMFs using the ejected masses given in Woosley & Weaver (1995), Meynet & Maeder (2002), and Nomoto et al. (2006), finding little dependence on metallicity, including $Z = 0$, and 20%–30% variation between studies. Variations in the form of the IMF change the SFR by ∼50%, with only a slight effect on $R_{\rm SN}$. The source timescale is then $\tau_{\rm src} = 5$ Gyr, within a factor of a few considering the uncertainty in the SFR and $M_{\rm gas}$, too large to affect the primordial fraction.

We examined the IMF dependence of $\tau_{\rm src}$. There are two nonstandard IMFs that are especially relevant. (1) Intermediate primordial fractions require that the IMF lower limit $M_l \gtrsim 1\ M_\odot$ to avoid too many $Z = 0$ stars observable today. Such a cutoff does not affect the source timescale: the empirical SFRs are based on integrated light from massive stars corrected for the rest of the IMF, and the resulting decrease of the SFR due to the cutoff is exactly compensated by the increase of the mass ejected by SNe per unit mass of stars formed $R_{\rm SN}$. This IMF independence of $\tau_{\rm src}$ holds for any cutoff smaller than the lower mass limit for SNe, ∼8 $M_\odot$. By the same argument, such a cutoff does not overproduce metallicity. (2) A perennially popular IMF for $Z = 0$ SF consists of only very massive stars (VMSs) due to the Jeans mass resulting from H_2 cooling (Hutchins 1976; see Bromm & Larson 2004), although it has been questioned on a number of grounds (Silk & Langer 2006). Comparing Hα emission per unit SFR for a VMS IMF 50–500 $M_\odot$ of $Z = 0$ stars in Schaerer (2003) with the same quantity for a 0.1–100 $M_\odot$ IMF in Kennicutt (1998), both for a Salpeter IMF (for illustration only), the SFR for a VMS IMF is 26 times smaller. Assuming only stars in the range 130–260 $M_\odot$ explode as pair instability SNe (Woosley et al. 2002), we find $R_{\rm SN} = 0.27$, so $\tau_{\rm src} =$ 50 Gyr, an order of magnitude larger than the normal IMF case.

These results strengthen our conclusion that the formation of massive stars is far too slow to deplete primordial gas significantly in the available time.

2.3. *Filling the Gap by Diffusion*

Without a process to spread metals into the "gap" between the Z_s peak and the primordial $Z = 0$ peak, $P(t)$ would remain near unity for billions of years. The only physical process that can fill this gap is microscopic diffusivity. However, an estimate of the rate at which diffusivity from random sources could pollute primordial gas in LBGs, using diffusion lengths for the cold neutral, warm neutral, and warm ionized ISM similar to those in Oey (2003), shows that the fraction of the mass of a galaxy mixed in time t is only $\sim 10^{-5}(t/0.5\ {\rm Gyr})^{5/2}$, so diffusivity by itself cannot pollute more than a tiny fraction of the primordial gas over the estimated SF ages.

To reduce the primordial fraction, a velocity field is required to catalyze diffusivity. However, a velocity field cannot by itself affect the global metallicity distribution or primordial fraction, or mix at all: displacement of fluid parcels of different Z by the velocity field conserves their volumes and thus volume fractions (or mass fractions for compressible flows), replacing one by another in space, having no effect on the Z distribution. This can be shown rigorously using a metallicity pdf equation (PS). A velocity field can only enhance mixing by spatially ramifying the Z field for diffusion to operate on small scales. Models that mix by sweeping of gas by SN or superbubble (SB) shells, cloud motions, differential rotation, or "turbulent diffusion" are unphysical without recognition that they are implicit models for microscopic diffusion.

2.4. *Several Catalyzing Velocity Fields*

Expanding supernova remnants (SNRs) and SBs are the main agents of mixing in many sequential enrichment inhomogeneous chemical evolution models (Reeves 1972; see Tsujimoto et al. 1999; Oey 2000; Argast et al. 2000; Saleh et al. 2006). Shells can mix, but only if instabilities allow diffusion to mix swept-up gas with new products of nucleosynthesis. Assuming this occurs, each SNR sweeps up and mixes a mass $M_{\rm sw} \sim 2 \times 10^4\ M_\odot$ for $Z = 0$ gas (Thornton et al. 1998; Hanayama & Tomisaka 2006). The time to sweep up primordial ISM is $\tau_{\rm sw} = M_{\rm gas}/\nu_{\rm SN} M_{\rm sw}$, where the SN rate $\nu_{\rm SN} = \epsilon B/\langle M_* \rangle$. For an IMF with mass range (0.1, 100) $M_\odot$ and indices (-0.4, -1.7) below and above 1 $M_\odot$, the number fraction ϵ of stars that become SNe is 0.004 and the average stellar mass $\langle M_* \rangle =$ 0.6, so $\nu_{\rm SN} = 0.7$ yr^{-1} and $\tau_{\rm sw} = 3 \times 10^6$ yr. Equivalently, the accumulated volume filling factor $NQ = t/\tau_{\rm sw}$ (Oey 2000), so $P = \exp(-t/\tau_{\rm sw}) = \exp(-NQ)$ and it is impossible to preserve primordial gas in LBGs for longer than ∼1% of the observed SF ages $\sim 3 \times 10^8$ yr, unless the mixing efficiency is artificially tuned to 1%, in which case the model predicts too large a present-day scatter in metallicity compared to observations. SBs have a smaller frequency, but sweep up more gas, producing an almost identical result. Spatial clustering and infalling $Z = 0$ gas also do not affect the conclusion. These points are discussed in detail in a separate publication (PS). Using the same argument as for τ_{src} in § 2.2, an IMF cutoff at 1 $M_\odot$ does not affect the SN rate, giving the same τ_{sw}. Unexpectedly, τ_{sw} for a VMS IMF is also nearly unchanged, because of the cancellation of the decrease of ν_{SN} (by a factor of 100) and the increase of M_{sw} by a factor of ~50 due to the large explosion energy of pair instability SNe (up to 10^{53} ergs; see Woosley et al. 2002). Therefore, our conclusion that SN or SB sweep-up mixing is so fast that LBGs should have zero primordial gas is virtually independent of the IMF. The mixing would be 100 times faster using the mixed mass per event adopted by Tumlinson (2006).

Unmixed pockets of metals in SBs could blast out of a galactic disk, later showering the disk with "droplets" of pure metals, diffusively mixing once they land in the disk (Tenorio-Tagle 1996). Fine-tuning of the number of droplets, or equivalently the mixed mass, per SN, is required to give the desired timescale but is unspecified by the model.

Differential rotation could stretch the products of nucleosynthesis deposited in a ~100 pc SN blob into long thin annuli until the scale of diffusivity is reached. The shear rate in LBGs, or whether they differentially rotate, is unknown. We used the rate ~10 km s^{-1} kpc^{-1} in our Galaxy as an illustration and found that the timescale to reach the diffusive scale derived in § 3 is about 8 Gyr, which is too slow.

Another stretching process, turbulence, produces exponential, rather than linear, stretching, with strain rates 10 times larger than Galactic differential rotation.

3. TURBULENCE-ENHANCED DIFFUSIVE MIXING

Turbulence deforms large-scale fluid elements and the tracers they contain into filaments and sheets, bringing tracers closer together until scales are reached on which diffusivity can homogenize faster than the strain timescale of the fluid. The process is described by the general equation for the evolution of the metallicity field in an arbitrary velocity field $\boldsymbol{u}(\boldsymbol{x}, t)$,

$$\frac{\partial Z(\boldsymbol{x}, t)}{\partial t} + \boldsymbol{u}(\boldsymbol{x}, t)\cdot\boldsymbol{\nabla} Z(\boldsymbol{x}, t) = \frac{1}{\rho}\boldsymbol{\nabla}\cdot[\rho\kappa\boldsymbol{\nabla} Z(\boldsymbol{x}, t)] + S, \quad (1)$$

where κ is the diffusivity and S denotes the sources.

In our model, a straining event on the scale of the sources L_s takes Z to a critical scale, $L_{\rm diff}$, small enough for diffusivity to operate, at constant mean strain rate in a single step, by exponential stretching of line elements (Batchelor 1952; Voth et al. 2002). This "short circuit" of the scalar cascade (Villermaux et al. 2001) is supported by experiments (Villermaux 2004; Voth et al. 2002) and simulations (Girimaji & Pope 1990; Goto & Kida 2003) and is similar to the scalar turbulence field theory of Shraiman & Siggia (2000). We assume that in supersonic turbulence compressions are analogous to stretching in the sense of bringing tracers to the critical scale $L_{\rm diff}$.

The scale $L_{\rm diff}$ below which the diffusivity term exceeds the advection term in equation (1) is obtained by equating the two terms and replacing spatial derivatives by $L_{\rm diff}^{-1}$ and $\boldsymbol{u}$ by the velocity at the scale of $L_{\rm diff}$. If we assume $u_l \sim l$ scaling appropriate for exponential stretching, the result is $L_{\rm diff} = [\kappa/(U/L_s)]^{1/2}$, where U is the rms turbulent velocity on the scale of the sources. A residence-time average diffusivity, assuming the warm neutral medium contains more than 20% of the ISM mass, is $\kappa \sim 10^{20}$ cm^2 s^{-1}. Then the average diffusivity scale in the ISM is $L_{\rm diff} \sim 0.06(L_{100}/U_{10})^{1/2}$ pc, where L_{100} is L_s/100 pc and U_{10} is U in units of 10 km s^{-1} (Kulkarni & Heiles 1987). We assume the same scale for $z \sim 3$ LBGs, noting that $L_{\rm diff}$ only enters the mixing time (below) logarithmically.

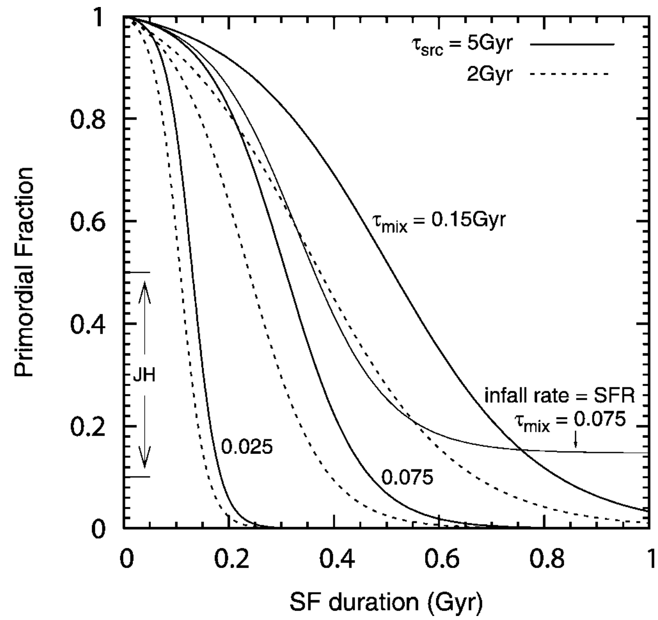

FIG. 1.—Primordial fraction as a function of SF duration for combinations of the mixing timescale τ_{mix} and the source timescale τ_{src} (see § 2.2). The empirical value for τ_{src} is about 5 Gyr within a factor of a few for an IMF with $M_l = 0.1$. The value of τ_{src} is independent of M_l if it is smaller than the mass limit for SNe. For a VMS IMF, τ_{src} is much larger but does not affect the result significantly, as discussed in the text. The range suggested for $z \sim 3$ LBGs (JH) is indicated by the arrow. Also shown is an infall model with infall rate equal to the SFR.

The mixing time follows from the assumed exponential stretching, in which scales change as $dl/dt = -\gamma l$, where $\gamma = U/L_s$ is the large-scale strain rate. This gives a time to bring tracers from L_s to $L_{\rm diff}$ as $\tau_{\rm mix} = (L_s/U)\ln(L_s/L_{\rm diff}) = (L_s/2U)\ln(UL_s/\kappa)$. The quantity UL_s/κ is the diffusivity analog of the Reynolds number, called the Peclet number Pe. Numerically, Pe $\sim 3 \times 10^7(U_{10}L_{100}/\kappa_{20})$, giving $\tau_{\rm mix} = (L_s/2U)\ln {\rm Pe} \sim 75$ Myr. The result could be smaller if the velocity dispersion increases with the SFR, as for turbulence driven by SNe (e.g., Dib & Burkert 2005).

The primordial fraction is the cumulative pdf of the gas metallicity $\int_0^Z f(Z', t)dZ'$, where $f(Z, t)$ is the differential pdf of metallicity, as the integration limit Z approaches zero. We can obtain the equation for $P(t)$ heuristically, without details of the integral closure (Janicka et al. 1979) we used to derive the full pdf equation corresponding to the advection-diffusion equation (1) (PS), a turbulent mixing closure that gives the same timescale for exponential variance decay as found in simulations by de Avillez & Mac Low (2002, eq. [17]), and the same dependence of mixing time on initial size and SN rate (their Fig. 7), if velocity dispersion U scales as the square root of the SN rate (Dib & Burkert 2005).

The primordial fraction decreases whenever fluid elements with primordial mass fraction P and gas that has been polluted by sources or previous mixing events, with mass fraction $1 - P$, are stretched sufficiently to result in diffusive mixing. This interaction occurs with an average frequency $\tau_{\rm mix}^{-1}$. The primordial fraction P is also gradually depleted by cycling through massive stars that inject metals when they explode, on a timescale τ_{src} (§ 2.2), which we assume is constant for the times of interest. The equation for the primordial fraction is then

$$dP/dt = -P(1 - P)/\tau_{mix} - P/\tau_{src}, \tag{2}$$

whose solution is, using the fact that $\tau_{mix} \ll \tau_{src}$,

$$P = [1 + (\tau_{mix}/\tau_{src}) \exp (t/\tau_{mix})]^{-1}. \tag{3}$$

The primordial fraction decreases exponentially on timescale τ_{mix}, but only after a delay time $\sim\tau_{mix} \ln (\tau_{src}/\tau_{mix})$, which is $\sim 3 \times 10^8$ yr for $\tau_{mix} = 75$ Myr and $\tau_{src} = 5$ Gyr, assuming an IMF with $M_l \lesssim 8\ M_\odot$. The delay time is the time for sources to provide enough nonprimordial gas to make P depart from unity, but the dependence on τ_{src} is only logarithmic, and so is nearly independent of the IMF, even for the extreme case of a VMS IMF (see § 2.2).

The behavior of P as a function of time for different τ_{mix} and τ_{src} is illustrated in Figure 1. The smallest mixing timescale shown, 0.025 Gyr, corresponds to a larger velocity dispersion ~ 30 km s^{-1}, not unreasonable for galaxies with large SFRs. Our major result is that $P(t)$ declines on a timescale similar to SF ages inferred from empirical modeling, without adjustment of parameters.

The effect of $Z = 0$ infall can be understood by adding to equation (2) a term $(1 - P)/\tau_{in}$, where $\tau_{in} = M_{gas}$/infall rate is the infall timescale. An example is shown in Figure 1. Infall allows intermediate values of $P(t)$ for a longer time, but only for infall timescales close to τ_{mix}, implying a huge infall rate. Therefore, it is unlikely that infall modifies the primordial fraction predicted by turbulent mixing. Galactic winds with large rates (Erb et al. 2006) have no effect if the winds sample the full pdf of metallicity. If the galaxies have undergone previous episodes of SF with an accumulated duration as large as $\sim$1 Gyr, even the turbulent model cannot explain the intermediate primordial fractions claimed by JH.

4. DISCUSSION

Most mixing processes predict a primordial fraction $P(t)$ that is either unity or zero at $z \sim 3$ because they mix on a timescale that is much larger or smaller than the empirical SF ages. The primordial fraction $P(t)$ should be zero in almost all galaxies if stellar explosions mix as efficiently as assumed in sequential enrichment models (or much more efficiently, as in Tumlinson 2006). Our turbulence-enhanced diffusivity model naturally preserves primordial gas from rapid mixing for a few times the mixing timescale, which itself depends only weakly on parameters, in particular, the assumed IMF or the averaged diffusivity, and gives an intermediate primordial fraction in galaxies with SF ages $\sim(1\text{–}3) \times 10^8$ yr. That this timescale happens to match the SF ages of these galaxies is no coincidence if SF is driven by turbulence (Mac Low & Klessen 2004) powered by stellar explosions. Future systematic investigations of the spectrophotometric signatures of primordial gas in galaxies could distinguish these possibilities.

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