Identifying the Reionization Redshift from the Cosmic Star Formation Rate

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IDENTIFYING THE REIONIZATION REDSHIFT FROM THE COSMIC STAR FORMATION RATE

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ABSTRACT

We show that the cosmic star formation rate per comoving volume should exhibit a distinct drop around the reionization redshift, when the H II regions in the intergalactic medium around individual ionizing sources first overlapped. The drop results from the increase in the temperature of the intergalactic medium as it was photoionized, and the consequent suppression of the formation of low-mass galaxies. We show quantitatively that the detection of this drop, which is marked by a corresponding fall in the number counts of faint galaxies, should become feasible over the coming decade with the *Next Generation Space Telescope*.

Subject headings: cosmology: theory — galaxies: formation

1. INTRODUCTION

Current observations reveal the existence of galaxies out to redshifts as high as $z \sim 6.7$ (Chen, Lanzetta, & Pascarelle 1999; Weymann et al. 1998; Dey et al. 1998; Spinrad et al. 1998; Hu, Cowie, & McMahon 1998) and bright quasars out to $z \sim 5$ (Fan et al. 1999). The detection of transmitted flux at rest-frame wavelengths shorter than Lyα in the spectrum of some of these sources implies that most of the intergalactic medium (IGM) is ionized at $z \sim 5$ (Songaila et al. 1999), and that a substantial population of ionizing sources should exist at higher redshifts (Madau, Haardt, & Rees 1999). This inference is consistent with theoretical expectations in cold dark matter (CDM) models of galaxy formation (Shapiro, Giroux, & Babul 1994; Gnedin & Ostriker 1997; Haiman & Loeb 1998, 1999a; Valageas & Silk 1999; Miralda-Escudé, Haehnelt, & Rees 2000; Chiu & Ostriker 2000; Gnedin 2000).

One of the major goals of the study of galaxy formation is to achieve an observational determination and a theoretical understanding of the cosmic star formation history. By now, this history has been sketched out only to a redshift $z \sim 4$ (see, e.g., the compilation of Blain et al. 1999). The *Next Generation Space Telescope* (*NGST*),[3] planned for launch in 2008, is expected to reach an imaging sensitivity of better than 1 nJy in the infrared, which will allow it to detect galaxies and hence determine the star formation history at $z \gtrsim 10$.

The redshift of reionization, $z_{\rm reion}$, defines the epoch at which the H II regions surrounding individual sources in the IGM overlapped. At this time, the cosmic ionizing background increased sharply, and the IGM was heated by the ionizing radiation to a temperature of $\gtrsim 10^4$ K (see, e.g., Gnedin 2000). In this article, we explore the distinct signature that this heating process is expected to have left on the global star formation rate in the universe. Because of the substantial increase in the IGM temperature, the intergalactic Jeans mass increased dramatically, changing the minimum mass of forming galaxies (Gnedin & Ostriker 1997; Miralda-Escudé & Rees 1998). Reionization is therefore predicted to cause a drop in the cosmic star formation rate (SFR) at $z_{\rm reion}$. This drop is accompanied by a dramatic fall in the number counts of faint galaxies. Detection in future galaxy surveys of this fall in the faint luminosity function could be used to identify $z_{\rm reion}$ observationally. This method for inferring $z_{\rm reion}$ is more straightforward than alternative proposals that rely on high-resolution spectroscopy of individual sources (Miralda-Escudé 1998; Haiman & Loeb 1999b; Loeb & Rybicki 1999) or on the detection of faint spectral features in the background radiation (Gnedin & Ostriker 1997; Shaver et al. 1999).

In § 2 we describe the galaxy formation model used to calculate the cosmic SFR and the luminosity function at high redshift. The results from this model, including the reionization signature, are described in § 3. We dedicate § 4 to a detailed comparison with previous semianalytic models and numerical simulations. Finally, we summarize our main conclusions in § 5.

2. GALAXY FORMATION MODEL

We model galaxy formation within a hierarchical CDM model of structure formation. We obtain the abundance of dark matter halos using the Press-Schechter (1974) model. Relevant expressions for various CDM cosmologies are given in, e.g., Navarro, Frenk, & White (1997). The abundance of halos evolves with redshift as each halo gains mass through mergers with other halos. If $dp(M_1, t_1 \to M, t)$ is the probability that a halo of mass M_1 at time t_1 will have merged to form a halo of mass between M and $M + dM$ at time $t > t_1$, then in the limit where t_1 tends to t we obtain an instantaneous merger rate of $d^2p(M_1 \to M, t)/(dM\,dt)$. This quantity was evaluated by Lacey & Cole (1993, their eq. [2.18]).

Once a dark matter halo has collapsed and virialized, the two requirements for forming new stars are gas infall and cooling. Gas of primordial composition can cool through atomic transitions in halos with virial temperatures $T_{\rm vir} \gtrsim 10^{3.8}$ K (Haiman, Abel, & Rees 2000), and through molecular hydrogen (H_2) transitions in smaller halos. However, H_2 molecules are fragile, and could have been easily photodissociated throughout the universe by trace amounts of starlight (Stecher & Williams 1967; Haiman, Rees, & Loeb 1996) that were well below the level required for complete reionization of the IGM. We therefore assume that, in the redshift interval covered by our models, efficient cooling can only occur with atomic transitions, in halos above a circular velocity of $V_c \sim 13.3$ km s^{-1}. Haiman et al. (2000)

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showed that if quasars contributed significantly to the UV background before reionization, their soft X-rays produced free electrons in small halos and may have catalyzed the formation of molecular hydrogen. In this case, smaller halos than we assume could have formed stars prior to reionization, down to $T_{\rm vir} \gtrsim 10^{2.4}$ K. However, the same X-rays may also have begun to heat the IGM before reionization, hindering gas infall into the smallest halos. Even if this heating mechanism was ineffective, most of the additional galaxies would be too faint to detect with *NGST*. Regardless of the effectiveness of H_2 cooling, the formation of new galaxies after reionization would still be greatly suppressed, since it is limited by gas infall.

Gas infall depends sensitively on the Jeans mass. When a halo more massive than the Jeans mass begins to form, the gravity of its dark matter overcomes the gas pressure. Even in halos below the Jeans mass, although the gas is initially held up by pressure, once the dark matter collapses, its increased gravity pulls in some gas (Haiman, Thoul, & Loeb 1996). Before reionization, the IGM is cold and neutral, and the Jeans mass plays a secondary role to cooling. After reionization, the Jeans mass is increased by several orders of magnitude due to the photoionization heating of the IGM, and hence begins to play a dominant role in limiting the formation of stars. Gas infall in a reionized and heated universe has been investigated in a number of numerical simulations. Thoul & Weinberg (1996) found a reduction of $\sim 50\%$ in the collapsed gas mass due to heating, for a halo of circular velocity $V_c \sim 50$ km s^{-1} at $z = 2$, and a complete suppression of infall below $V_c \sim 30$ km s^{-1}. Kitayama & Ikeuchi (2000) also performed spherically symmetric simulations, but they included self-shielding of the gas, and found that it lowers the circular velocity thresholds by ~ 5 km s^{-1}. Three-dimensional numerical simulations (Quinn, Katz, & Efstathiou 1996; Weinberg, Hernquist, & Katz 1997; Navarro & Steinmetz 1997) found a significant suppression of gas infall in even larger halos ($V_c \sim 75$ km s^{-1}), but this was mostly due to a suppression of late infall at $z \lesssim 2$. Thus, we adopt a prescription for the suppression of gas infall based on the spherically symmetric simulations. Each of these simulations follows an isolated halo, rather than a set of merging progenitors, and the halo is followed for longer than it would typically survive before merging into a larger halo. Therefore, we adopt slightly higher V_c thresholds than indicated by the spherically symmetric simulations.

When a volume of the IGM is ionized by stars, the gas is heated to a temperature of $T_{\rm IGM} \sim 10^4$ K. If quasars dominate the UV background at reionization, their harder photon spectrum leads to $T_{\rm IGM} \sim 2 \times 10^4$ K. Including the effects of dark matter, a given temperature results in a linear Jeans mass (see, e.g., § 6 in Peebles 1993), corresponding to a halo circular velocity of

$$V_{\rm J} = 93\left(\frac{T_{\rm IGM}}{2 \times 10^4\ {\rm K}}\right)^{1/2}\left[\frac{1}{\Omega(z)}\frac{\Delta_c}{18\pi^2}\right]^{1/6} {\rm km\ s}^{-1}\ , \quad (1)$$

where Δ_c is the mean collapse overdensity (Bryan & Norman 1998) and $\Omega(z)$ is the total density in units of the critical density, evaluated at redshift z. In halos with $V_c > V_{\rm J}$, the gas fraction is equal to the universal mean of Ω_b/Ω_0. We assume that the gas fraction is suppressed by 50% at a circular velocity of $V_c = V_{\rm J}(55/93)$ and that a complete suppression occurs below $V_c = V_{\rm J}(35/93)$. We set $T_{\rm IGM} = 2 \times 10^4$ K, although a lower temperature would result in a slightly weaker suppression of gas infall.

Recent semianalytic models (Miralda-Escudé et al. 2000) and numerical simulations (Gnedin 2000) show that the process of reionization is gradual. When stars or quasars form in galaxies, each source must first ionize gas in its host object (Wood & Loeb 2000). Individual ionization bubbles then grow for about a Hubble time at the relevant redshifts, until they begin to overlap. Since overlapping H II regions are filled with radiation from several sources, the ionizing intensity increases rapidly at each overlap, and this leads to a quick ionization of almost the entire volume of the universe. Only the highest density gas remains neutral and is gradually ionized subsequently.

The reionization feedback for galaxy formation depends on the fraction of the IGM that is ionized at each redshift. Thus, we focus on the overlap stage of reionization. We refer to the redshift at which 50% of the volume of the universe is ionized as the reionization redshift, $z_{\rm reion}$, and assume that a significant volume is first ionized at the starting redshift, $z_{\rm start}$, and that most of the volume has been ionized by the ending redshift, $z_{\rm end}$. We take the Gnedin (2000) simulation as a guide for the redshift interval of reionization, adopting $z_{\rm start} = 11$ and $z_{\rm end} = 6.5$ for the case of $z_{\rm reion} = 8.2$. When we vary $z_{\rm reion}$, we scale the values of $z_{\rm start}$ and $z_{\rm end}$ in order to keep the reionization era equal to a constant fraction of the age of the universe at $z_{\rm reion}$.

At each redshift, we thus obtain the fraction of the universe that is ionized, and in both the neutral and ionized IGM we obtain the gas mass that falls and cools into halos as a function of the halo mass M. If the cold gas mass is denoted by $f_{\rm cold}(M, z)M\Omega_b/\Omega_0$, then $f_{\rm cold}(M, z) = 0$ in halos below a minimum mass $M_{\rm min}(z)$, set by the minimum circular velocity. Given $f_{\rm cold}(M, z)$, we then derive the SFR directly from halo mergers, and the luminosity of each galaxy directly from its SFR.

New star formation in a given galaxy can occur either from primordial gas or from recycled gas that has already undergone a previous burst of star formation. Consider first a region with neutral IGM, in which $M_{\rm min}(z)$ is set by the need for gas to cool. In this case, halos below $M_{\rm min}(z)$ contain roughly the universal fraction Ω_b/Ω_0 of primordial gas, which collapsed along with the dark matter but could not cool. Halos with $M > M_{\rm min}(z)$ contain the same gas fraction, but this gas *is* able to cool [i.e., $f_{\rm cold}(M, z) = 1$]. Consider halos of mass M_1 and M_2 merging to yield a halo of total mass M. We assume that the merger triggers star formation only if $M > M_{\rm min}(z)$. If $M_1 < M_{\rm min}(z)$, then the merger will trigger star formation in the primordial gas contained in this halo. Assuming a star formation efficiency η, we obtain a starburst with a total stellar mass of $\eta M_1 \Omega_b/\Omega_0$. Similarly, if $M_2 < M_{\rm min}(z)$, then the starburst has an additional contribution equal to a mass of $\eta M_2 \Omega_b/\Omega_0$. If $M_1 > M_{\rm min}(z)$, we assume that the gas in this halo has already undergone a previous burst of star formation, and thus, before the merger, the gas fraction is only $(1 - \eta)\Omega_b/\Omega_0$. We assume that the merger triggers another episode of star formation in this gas if M_2 is sufficiently massive. Numerical simulations of starbursts in interacting $z = 0$ galaxies (e.g., Mihos & Hernquist 1994, 1996) found that a merger triggers significant star formation even if M_2 is a small fraction of M_1. Preliminary results (R. S. Somerville 2000, private communication) from simulations of mergers at $z \sim 3$ find that they remain effective at triggering star formation even when the initial disks are dominated by gas. We adopt a conservative threshold mass ratio of $r_{\rm merge} = 1/2$ and assume that if $M_2 > r_{\rm merge} M_1$, then star formation is triggered in M_1, producing a stellar mass of $\eta(1-\eta)M_1 \Omega_b/\Omega_0$ (where we take the same efficiency, η, for star formation from primordial and from recycled gas). Similarly, if $M_2 > M_{\rm min}(z)$, then a stellar mass of $\eta(1-\eta)M_2 \Omega_b/\Omega_0$ is produced as long as $M_1 > r_{\rm merge} M_2$.

Star formation proceeds along similar lines in a region with ionized IGM, except that the value of $M_{\rm min}(z)$, the lowest mass of a halo that can accumulate gas from the IGM, is set by gas infall. An additional complication in this case is that some galaxies in halos below $M_{\rm min}(z)$ could have survived photoionization heating (Barkana & Loeb 1999) and kept their cold gas reservoir after reionization. Although gas infall into these galaxies was subsequently suppressed, they may have continued to merge and thus form stars. In order to be conservative about the suppression of star formation, we assume that all gas that cooled before reionization settled into dense gas disks and did not subsequently photoevaporate. We estimate the contribution of this gas to merger-induced star formation as follows. At a given redshift z after reionization has started, we find the redshift $z_{\rm half}$ at which the filling factor of ionized regions was equal to half its value at z. Thus, roughly half of the volume that is ionized at z was ionized after $z_{\rm half}$. We compute the gas fraction $f_{\rm coll}$ that had collapsed into halos in neutral regions by redshift $z_{\rm half}$. This gas lies in halos that will have merged into larger halos by redshift z. To approximate the resulting gas content of halos, we assume that at redshift z, all halos down to a mass $M_{\rm merge}(z)$ contain a gas fraction equal to the cosmic mean of Ω_b/Ω_0, where $M_{\rm merge}(z)$ is set by requiring the total gas fraction in these halos to equal $f_{\rm coll}$. Since $M_{\rm merge}(z)$ may be lower than $M_{\rm min}(z)$, we include by this prescription halos that had formed prior to reionization but could not have begun to form in a fully ionized universe. As discussed above, if we only considered infall in an ionized region, then halos with $M < M_{\rm min}(z)$ would contain no gas, and the gas fraction would increase gradually up to $f_{\rm cold}(M, z) = 1$ for all M greater than the Jeans mass at z. We modify this prescription by increasing $f_{\rm cold}(M, z)$ to unity whenever $M > M_{\rm merge}(z)$. Thus, when two halos with masses M_1 and $M_2 = M - M_1$ merge, the resulting halo accretes from the IGM an additional primordial gas mass of $[f_{\rm cold}(M, z)M - f_{\rm cold}(M_1, z)M_1 - f_{\rm cold}(M_2, z)M_2](\Omega_b/\Omega_0)$ and turns a fraction η of it into stars. In addition, the initial stellar content of the two halos may undergo merger-induced recycled star formation, as discussed above in the pre-reionization case.

In order to determine the typical SFR in a halo of mass M, we average the SFR over all halos $M_1 < M$ that can merge to produce a halo of fixed total mass M. We use the Press-Schechter (1974) abundance of halos of mass M_1, and the halo merger rate $d^2p(M_1 \rightarrow M, t)/(dM\,dt)$ introduced above. By averaging the SFR over all possible mergers, we neglect the possibility of episodic star formation in individual galaxies, with merger-triggered peaks reaching star formation rates well above the average. However, for the halo mass scales relevant to galaxy formation at high redshift, the slope of the primordial power spectrum approaches $n = -3$, which implies that the merger rate is high and galaxies double their mass in a short time compared to the age of the universe. Galaxies can be brighter than we calculate only if they undergo star formation on a timescale much shorter than the merger timescale. We expect that at each redshift, galaxies observed during an exceptional burst of star formation would, on the whole, account for only a small fraction of the total cosmic SFR.

Having obtained the average SFR for a halo of mass M, we calculate the luminosity of this halo self-consistently from this SFR. At a given redshift, we assume that the halo contains a total stellar mass of $\eta f_{\rm cold}(M, z) M \Omega_b/\Omega_0$, which has formed at a steady rate equal to the calculated average SFR. The total stellar mass in each halo may be slightly different from a fraction η of the cold gas mass, but the luminosity depends mostly on the number of young, bright stars, and this number depends only on the SFR at the time that the galaxy is observed.

3. RESULTS

We assume a ΛCDM cosmology, with matter and vacuum density parameters $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$, respectively. We also assume a Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}, and a primordial scale-invariant ($n = 1$) power spectrum with $\sigma_8 = 0.9$, where σ_8 is the root-mean-square (rms) amplitude of mass fluctuations in spheres of radius 8 h^{-1} Mpc. We adopt a cosmological baryon density of $\Omega_b = 0.04$.

In calculating the stellar emission spectrum, we assume a universal Salpeter initial mass function with a metallicity $Z = 0.001$, and use the stellar population model results of Leitherer et al. (1999).[4] We also include a Lyα cutoff in the spectrum due to absorption by the dense Lyα forest. We do not, however, include dust extinction, which is expected to be less significant at high redshift, when the mean metallicity was low. We describe the sensitivity of *NGST* by $F_\nu^{\rm ps}$, the minimum spectral flux at wavelengths 0.6–3.5 μm required to detect a point source. The detection threshold of extended sources is higher, and we therefore incorporate a probability distribution of disk sizes at each value of halo mass and redshift (see Barkana & Loeb 2000 for details). We adopt a value of $F_\nu^{\rm ps} = 0.25$ nJy,[5] assuming a very deep 300 hr integration on an 8 m *NGST* and a spectral resolution of 10:1. This resolution should suffice for a $\sim 10\%$ redshift measurement, based on the Lyα cutoff.

Figure 1 shows our predictions for the star formation history of the universe, with $\eta = 10\%$. We show the SFR for $z_{\rm reion} = 7$ (Fig. 1, *solid curves*), 10 (*dashed curves*), and 13 (*dotted curves*). In each pair of curves, the upper shows the total SFR, and the lower the fraction detectable with *NGST*. As noted in § 2, if star formation is episodic, then halos are much brighter than average a small fraction of the time, and the detectable SFR could be somewhat higher than shown in the figure, although it would always lie below the total SFR. As discussed above, photoionization directly suppresses new gas infall after reionization, but it does not immediately affect mergers, which continue to trigger star formation in gas that had cooled prior to reionization. Indeed, we find a stronger suppression of primordial star formation (which declines by a factor of 3.4 for $z_{\rm reion} = 10$) than recycled star formation (which only declines by a factor of 1.7 for $z_{\rm reion} = 10$). The contribution from merger-induced star formation is comparable to that from primor-

[4] Model spectra of star-forming galaxies were obtained from: http://www.stsci.edu/science/starburst99/.

[5] We obtained the flux limit using the *NGST* calculator at http://www.ngst.stsci.edu/nms/main/.

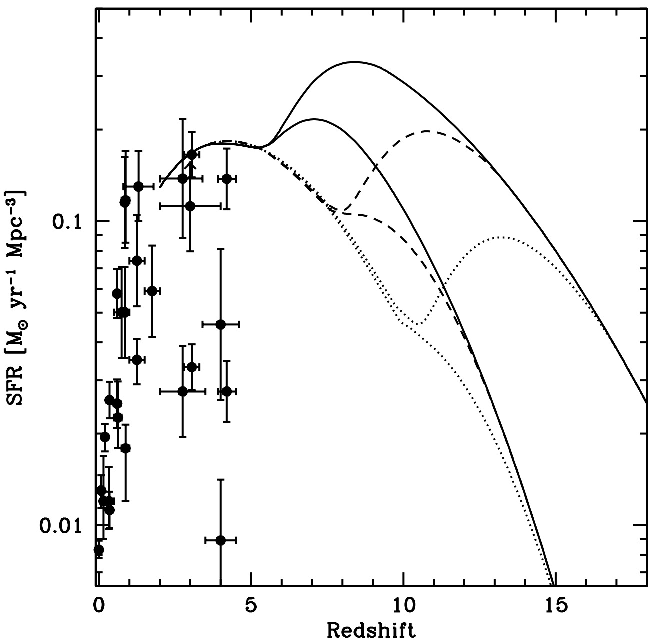

FIG. 1.—Redshift evolution of the SFR (in $M_\odot$ yr^{-1} per comoving Mpc^3). Points with error bars are observational estimates (compiled by Blain et al. 1999). Also shown are model predictions for a reionization redshift $z_{\rm reion} = 7$ (*solid curves*), 10 (*dashed curves*), and 13 (*dotted curves*), with a star formation efficiency of $\eta = 10\%$. In each pair of curves, the upper shows the total SFR, and the lower the fraction detectable with *NGST* at a limiting point-source flux of 0.25 nJy.

dial gas at $z < z_{\rm reion}$, and it is smaller at $z > z_{\rm reion}$. However, the recycled gas contribution to the *detectable* SFR is dominant at the highest redshifts, since infalling halos more massive than $M_{\rm min}(z)$ dominate the star formation in the most massive halos, and only these most massive halos are bright enough to be detected from the pre-reionization era. Although most stars at $z \gtrsim z_{\rm reion}$ form out of primordial, zero-metallicity gas, a majority of stars in detectable galaxies may form out of the small gas fraction that has already been enriched by the first generation of stars.

Points with error bars in Figure 1 are observational estimates of the cosmic SFR per comoving volume at various redshifts (see Blain et al. 1999 for the original references). The highest SFR estimates at $z \sim 3$–4 are based on submillimeter observations or on extinction-corrected observations at shorter wavelengths, and all are fairly uncertain. We choose $\eta = 10\%$ to obtain a rough agreement between the models and these observations. The SFR curves are roughly proportional to the value of η. Note that in reality, η may depend on the halo mass, since the effect of supernova feedback may be more pronounced in small galaxies.

Figure 1 shows a sharp rise in the total SFR at redshifts higher than $z_{\rm reion}$. Although only a fraction of the total SFR can be detected with *NGST*, the detectable SFR displays a definite signature of the reionization redshift. As noted in § 2, if quasars were abundant before reionization, then stars may have formed in smaller halos through H_2 cooling[6] (Haiman et al. 2000). In this case, the SFR rise would be even larger than in the cases shown in Figure 1, but the detected SFR would be essentially unchanged, since the additional galaxies would be extremely faint.

Most of the increase in SFR beyond the reionization redshift is due to star formation occurring in very small, and thus faint, galaxies. This evolution in the faint luminosity function constitutes the clearest observational signature of the suppression of star formation after reionization. Figure 2 shows the predicted luminosity function of galaxies at various redshifts. The curves show $d^2N/(dz\, d \log F_\nu^{\rm ps})$, where N is the total number of galaxies in a single field of view of *NGST*. Results are shown at redshift $z = 7$ (Fig. 2, *solid curves*) or 13 (*dashed curves*). In each pair of curves, the upper curve at 0.1 nJy assumes a permanently neutral IGM (i.e., $z_{\rm reion} \ll z$), and the lower one assumes a permanently fully ionized IGM (i.e., $z_{\rm reion} \gg z$). Although our models assign a fixed average luminosity to all halos of a given mass and redshift, in reality such halos would have some dispersion in their merger histories and thus in their luminosities. We thus include smoothing in the plotted luminosity functions, assuming that the flux of each halo can vary by up to a factor of 2 around the mean for the set of halos with its mass and redshift. As noted in § 2, if star formation is episodic, then the distribution of fluxes about the mean could have a significant tail toward high luminosities. Note the enormous increase in the number density of faint galaxies in a pre-reionization universe. Observing this dramatic increase toward high redshifts would constitute a clear detection of reionization and of its major effect on galaxy formation. The effect is greatest below a flux limit of 1 nJy, and detecting it therefore requires the capabilities of an 8 m *NGST*. In the case of effective H_2 cooling before reionization, the luminosity functions in a neutral IGM would follow the corresponding curves in Figure 2 down to their peaks, but they would continue to rise toward even

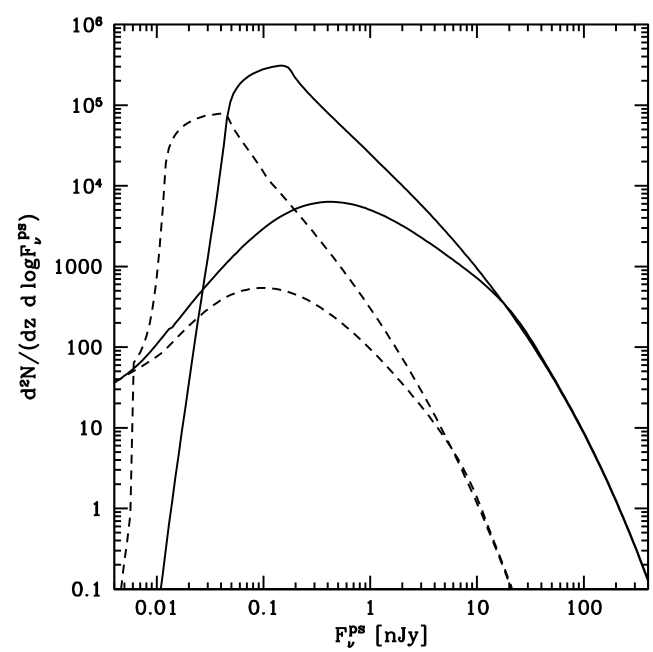

FIG. 2.—Predicted luminosity function of galaxies at a fixed redshift. With $\eta = 10\%$, the curves show $d^2N/(dz\, d \log F_\nu^{\rm ps})$, where N is the total number of galaxies in a single field of view of *NGST*, and $F_\nu^{\rm ps}$ is the limiting point source flux at 0.6–3.5 μm for *NGST*. Results are shown at redshift $z = 7$ (*solid curves*) or 13 (*dashed curves*). In each pair of curves, the upper one at 0.1 nJy assumes a permanently neutral IGM (i.e., $z_{\rm reion} \ll z$), and the lower one assumes a permanently fully ionized IGM (i.e., $z_{\rm reion} \gg z$).

[6] Note, however, that the harder quasar spectra may lead to broader ionization fronts and to preheating of the neutral IGM that would suppress gas infall into the lowest mass halos. This negative effect was not considered by Haiman et al. (2000).

fainter fluxes. This additional rise, however, would occur well below the detection limit of *NGST*.

4. COMPARISON WITH PREVIOUS WORK

The reionization of the IGM has been explored in the past, based on semianalytic models as well as numerical simulations (see § 1). In this section we discuss the relation between our work and previous models that considered the evolution of star formation history through the epoch of reionization.

The key physical ingredient that leads to the SFR drop after reionization is the temperature gap between the warm ionized regions (where the Jeans mass is high) and the cold neutral regions (where the Jeans mass is low). During reionization, the IGM consists of these two physically independent phases, which maintain their temperature gap even as the filling factor of the ionized regions increases. This temperature gap was not included in the semianalytic models of Shapiro et al. (1994) and Valageas & Silk (1999), who assumed a single-phase IGM with a uniform temperature. Gnedin & Ostriker (1997) also assumed a uniform photoheating of the IGM in their simulation.

A recent numerical simulation by Gnedin (2000) accounted for the inhomogeneous distribution of the ionizing sources, with individual ionization fronts surrounding each source. For a stellar spectrum, most ionizing photons are just above the ionizing threshold of 13.6 eV, where the absorption cross section is high and the mean free path is correspondingly short. Therefore, the ionization fronts have a sharp edge, and the reheating of the IGM occurs nearly simultaneously with reionization (see Fig. 3 of Gnedin 2000). Once reheating occurs, the subsequent formation of low-mass galaxies is suppressed as predicted by our semianalytic model (see Fig. 8 of Gnedin 2000). The suppression occurs more gradually in Gnedin (2000) than in our model, because of a difference in the assumptions about star formation. In the simulation of Gnedin (2000), gas that cools can continue to form stars for much longer than a dynamical time, until all of it has turned into stars. In our model, we assume that 10% of the gas turns into stars, and that feedback heats or expels the rest of the gas and thus halts star formation. We assume that additional star formation in the gas that is left over requires another trigger, such as a merger. Our assumption of an upper limit on the efficiency of star formation appears to be required by observations. Local galaxies contain a mass fraction in stars and stellar remnants of up to $\sim 1\%$ of the total halo mass (e.g., Fukugita, Hogan, & Peebles 1998), which is an order of magnitude smaller than the cosmic baryon fraction of $\gtrsim 10\%$ indicated by observations of X-ray clusters (White & Fabian 1995; Arnaud & Evrard 1999). Feedback is expected to have been most effective at limiting star formation in the shallow potential wells that characterize high-redshift galaxies.

Chiu & Ostriker (2000) included a two-phase IGM in their semianalytic model of reionization, and our results are generally consistent with theirs. While we have focused on the star formation rate and the faint luminosity function, Chiu & Ostriker focused on the reionization process itself and did not explicitly highlight the suppression of star formation or the evolution of the luminosity function.

5. CONCLUSIONS

We have shown that the reionization of the IGM is expected to have left a clear signature on the history of the cosmic star formation rate. In particular, the photoionization heating of the IGM resulted in a suppression of the formation of low-mass galaxies, and in a fairly rapid drop in the average SFR by a factor of ~ 3 relative to the case of no reionization.

Most of the additional star formation in the pre-reionization era occurred in low-mass, faint galaxies. This means that *NGST* can detect only a fraction of this additional star formation, but this should still suffice to identify the reionization redshift. Even more striking is the substantial increase (by 1–2 orders of magnitude) in the number density of faint galaxies before reionization. These high-redshift galaxies are expected to appear highly irregular because of their high merger rates. Although the precise shape of the luminosity function depends on the detailed model assumptions, the increase in the number density is dramatic and robust. Much of this increase occurs at a flux limit of $\lesssim 1$ nJy and should be detectable with an 8 m *NGST*.

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