Detection of the First Star Clusters With NGST

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Abstract. We calculate the observable signatures of the first generation of stars at high redshift ($5 < z < 100$). To determine the cosmic star–formation history, we use an extension of the Press–Schechter formalism for Cold Dark Matter (CDM) cosmologies that incorporates gas pressure. We calibrate the fraction of gas converted into stars to be 6% so as to reproduce the 1% solar C/H ratio observed in the intergalactic medium (IGM) at $z = 3$.

With this star–formation efficiency, we find that NGST would be able to image more than 10^4 star clusters from high redshifts ($z > 10$) within its $4' \times 4'$ field of view. If stars occupy a region comparable to the virial radius of the cluster, then $\sim$1% of these clusters could be resolved. We calculate the expected number–flux relation and angular size distribution for these early star clusters. We also describe the reionization of the IGM due to the first generation of stars, and the consequent damping of the CMB anisotropies on small angular scales. This damping could be detected on $\lesssim 10°$ angular scales by MAP and PLANCK.

1. Introduction

In this contribution, we describe calculations of the signatures of the first generation of stars from high redshifts ($z > 5$). Our approach is to combine current data on CDM cosmologies and star–formation in the most straightforward way. The standard hierarchical structure formation models predict the abundance of virialized clouds as a function of mass and redshift. The first of these clouds appear with a low mass ($M \sim 10^5 \mathrm{M}_\odot$) at redshifts as high as $z \sim 50$; objects with successively higher masses assemble later (cf. Haiman, Thoul, & Loeb and references therein). Such objects are the most natural sites for the formation of the first generation of stars.

Although it is not known how star–formation in these objects proceeds, a necessary requirement for continued post–virialization collapse and fragmentation is that the gas can cool efficiently. In the metal–poor primordial gas, the only coolants available are neutral atomic hydrogen (H) and molecular hydrogen (H_2). However, it has been found (Haiman, Rees, & Loeb 1996, 1997; Gnedin & Ostriker 1997) that the H_2 molecules are fragile, and are photodissociated throughout the universe. Accordingly, we assume that clouds form stars if and only if they are massive enough to cool via atomic H transition lines ($T \gtrsim 10^4$K).

The total number of stars formed can be fixed using the recent observations (Songaila & Cowie 1996, Tytler et al. 1995) of the near universal carbon to hydrogen (C/H) ratio in Lyman–α forest clouds at redshifts as high as $z = 3$. These observations yield the value C/H $\sim$ 1% solar for systems with a large range of column–densities. The fact that (i) the scatter in the metalicity from one system to another is only an order of magnitude, and (ii) the overdensity of the lowest column density system is only a few (i.e., too tenuous to form its own stars) supports the hypothesis of uniform metal enrichment by an early generation of stars.

Based on this star–formation efficiency, the redshift evolution of the abundance of star–forming clouds, and a detailed composite model spectrum for a low–metalicity stellar population with the local Scalo (1986) initial mass function (IMF), we derive the expected number–flux relation and angular size distribution of these star clusters. We find that NGST would be able to image more than 10^4 of these star clusters at $z > 10$ within its $4' \times 4'$ field of view, with $\sim$1% of these clusters possibly resolved.

In addition, we show that the pre–galactic population of stars reionize the universe by a redshift of $z = 10 - 20$. The consequent damping of microwave anisotropies on small angular scales is $\sim 10\%$, detectable on $\lesssim 10°$ angular scales by MAP and PLANCK[1]. The pre–galactic low–mass stars could also account for some of the microlensing events observed in the halo of the Milky Way (Alcock et al. 1997), and could also be detected in the future through their lensing of distant quasars (Gould 1995).

2. Description of Model

To quantify the observational signatures of the first stars in CDM cosmologies, we use a simple semi–analytic approach that is complimentary to more detailed, but computationally expensive and therefore less versatile, 3–D numerical simulations (e.g. Gnedin & Ostriker 1997). The main ingredients of our model are:

The Collapsed Fraction of Baryons. We use the Press–Schechter formalism to find the abundance and mass distribution of virialized dark matter halos. Since initially most of the collapsed baryons are in low–mass systems near the Jeans mass, the pressure of the baryons has a significant effect on the collapsed fraction. Effectively, the collapse of the baryons is delayed relative to the dark matter in these low–mass objects (Haiman, Thoul & Loeb 1996). We obtained the exact collapse redshifts of spherically symmetric perturbations by following the motion of both the baryonic and the dark matter shells with a one dimensional hydrodynamics code (Haiman & Loeb 1997). We find that because of shell–crossing with the cold dark matter, baryonic objects with masses $10^{2-3}\mathrm{M}_{\odot}$, well below the linear–regime Jeans mass, are able to collapse by $z{\sim}10$.

Another important effect is the feedback on the collapsed fraction from the photoionization of the IGM. As the first stars form, they ionize a fraction $F_{\rm HII}$

[1] See the homepages for the MAP (http://map.gsfc.nasa.gov) and PLANCK (http://astro.estec.esa.nl/SA-general/Projects/Cobras/cobras.html) experiments.

of the gas in the universe. In these regions condensation of objects is strongly suppressed; to be conservative we assume that only a fraction $(1 - F_{\rm HII})$ of the gas participates in forming new virialized objects.

Star Formation. We calibrate the fraction $f_{\rm star}$ of the condensed gas converted into stars in each virialized cloud using the inferred C/H ratio in the Lyα absorption forest. We use tabulated ^{12}C yields of stars with various masses, and consider three different initial mass functions (IMFs). The uncertainty in the total carbon production is a factor of $\sim$10; a factor of $\sim$3 is from the uncertainty in the carbon yields of $3 - 8{\rm M}_\odot$ stars due to the unknown extent of hot bottom burning (Renzini & Voli 1981), and another factor of $\sim$3 is due to the difference between the Scalo and Miller–Scalo (1979) IMFs. To be conservative, we assume inefficient hot bottom burning, i.e. maximum carbon yields. Under these assumptions, we find $f_{\rm star} = 13\%$. [2]

We also include a negative feedback on star–formation due to the photodissociation of molecular hydrogen by photons with energies in the range 11.2–13.6 eV. These photons are not absorbed by neutral H and travel freely across the IGM. We find (Haiman, Rees & Loeb 1997) that the masses required to self-shield H_2 against photodissociation by the Solomon process (cf. Field, Somerville & Dressler 1966) are exceedingly high ($M > 10^{20}{\rm M}_\odot$ for a spherical object with an overdensity of 200 at $z = 25$). As a result, soon after the appearance of the first few stars, H_2 is universally destroyed, and molecular cooling is suppressed even inside dense objects. Due to the lack of any other cooling agent in the metal–poor primordial gas, the bulk of the pre–galactic stars must form via atomic line cooling inside massive clouds with virial temperatures of at least $\sim 10^4$K, or $M_{\rm tot} \gtrsim 10^8[(1+z)/10]^{-3/2}{\rm M}_\odot$. We therefore allow star–formation only inside clouds with at least this mass.

Propagation of Ionization Fronts. To determine the ionization history of the universe, we need to follow the evolution of the ionization (Strömgren) front around each star cluster. The composite spectrum of radiation which emerges from each star cluster is determined by the stellar IMF and the recombination rate inside the cluster. We follow the time-dependent spectrum of a star of a given mass based on standard spectral atlases (Kurucz 1993) and the evolution of the star on the H–R diagram as prescribed by theoretical evolutionary tracks (Schaller et al. 1992).

To calculate the fraction of the ionizing photons lost to recombinations inside their parent cloud, we adopt the equilibrium $1/r^2$ density profile of gas inside each cloud according to our spherically–symmetric simulations (Haiman, Thoul & Loeb 1996). We assume that stars are distributed with the same $1/r^2$ profile across the cloud, and obtain the number of recombinations under the assumption of ionization equilibrium. We then use the time–dependent composite luminosity of each star–forming region to calculate the propagation of a spherical ionization front into the surrounding homogeneous IGM. The ionized fraction of the universe is given by the volume–filling factor $F_{\rm HII}$ of the

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[2] Since the collapsed fraction at $z = 3$ is $\sim$50%, the fraction of all baryons in stars is $\sim$6%. A factor of $\sim$3 is included in this number due to the average time required to produce carbon inside the stars; i.e. only a third of the total stellar carbon is produced by $z = 3$.

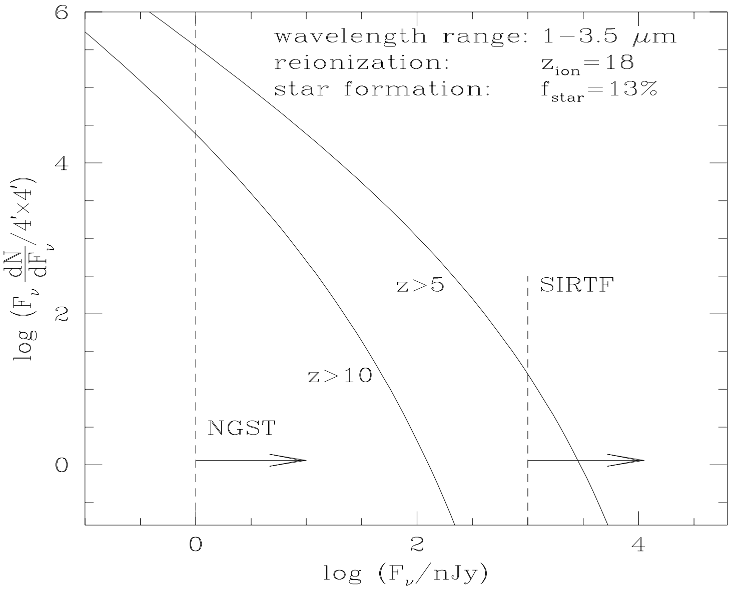

Figure 1. Predicted number counts in the 1–3.5μm range.

ionized bubbles, and the universe is reionized when these bubbles overlap so that $F_{\rm HII} = 1$.

3. Predictions for NGST

Figure 1 shows the predicted number of high–redshift star–clusters at $z > 10$ and $z > 5$, per logarithmic flux interval, in the wavelength range of 1–3.5μm. The number of clusters that could be probed by future space telescopes depends on their sensitivity; the vertical dashed lines show the proposed imaging thresholds of the Space Infrared Telescope Facility (SIRTF) and the Next Generation Space Telescope (NGST). NGST would be able to image $\gtrsim 10^4$ star clusters at its flux limit from high redshifts ($z > 10$) within its $4' \times 4'$ field of view.

Figure 2 shows the predicted angular diameter ($\theta_{\rm vir}$) distribution of the star clusters. $\theta_{\rm vir}$ is taken to be twice the angle subtended by the virial radius $r_{\rm vir}$ of each star–cluster; $r_{\rm vir}$ is calculated based on a spherically symmetric $1/r^2$ density profile, with a factor of 50 overdensity at the surface $r_{\rm vir}$ of the cloud, assuming $\Omega_{\rm b} = 0.05$ (based on the 1–D simulations). Note that stars in present–day galaxies form in a much smaller central region; however, the early star clusters may behave differently and form stars at their outskirts, since they are denser, and we have imposed the requirement of efficient atomic line cooling throughout the cloud. With its proposed $0.06''$ angular resolution, NGST could resolve ∼100 virialized star–clusters at $z > 10$, and $\sim 10^4$ clusters at $z > 5$ per field of view.

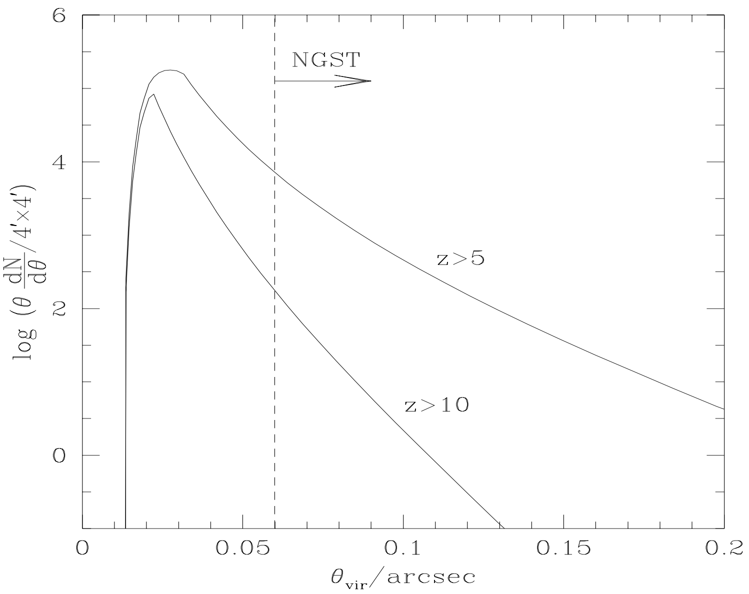

Figure 2. Predicted distribution of virial angular diameters.

4. Reionization

Table 1 summarizes the reionization redshifts and resulting electron scattering optical depths that we obtain in our models for a range of parameters. We varied the cosmological power spectrum ($\sigma_{8h^{-1}}$, n), the baryon density ($\Omega_{\rm b}$), the star formation efficiency ($f_{\rm star}$), the escape fraction of ionizing photons ($f_{\rm esc}$), the IMF, and whether or not the negative feedback due to H_2 is included. For almost the entire range of parameters, the universe is reionized by a redshift $\gtrsim 10$. The only exception occurs when the IMF is strongly tilted towards low–mass stars. We considered an unconventional tilt of this kind by adding a constant 1.7 to the power–law index, while keeping the IMF fixed at $M = 4{\rm M}_{\odot}$. With this tilt, the increased number of low–mass stars could account for the observed microlensing events. In this case, however, reionization is strongly suppressed due to the absence of massive stars which ordinarily dominate the ionizing flux.

The redshift evolution of the ionized fraction $F_{\rm HII}$ can be directly converted into the optical depth τ to electron scattering to high redshifts. For the range of parameters in Table 1, we find $\tau \sim$ 0.05–0.1. The corresponding damping factor for the CMB anisotropies (Hu & White 1997) is $\sim$ 5–10%. Such a damping could be detected by the MAP and PLANCK satellites, especially if the polarization of the CMB is measured (Zaldarriaga 1996).

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Table 1. Reionization redshift and electron scattering optical depth for a range of parameters.

Parameter	Standard Model	Range Considered	Reionization Redshift	Optical Depth
$\sigma_{8h^{-1}}$	0.67	0.67–1.0	18–22	0.07–0.11
n	1.0	0.8–1.0	13–18	0.04–0.07
$\Omega_{\rm b}$	0.05	0.01–0.1	17–19	0.02–0.13
$f_{\rm star}$	13%	1%–40%	12–24	0.05–0.09
$f_{\rm esc}$	$f_{\rm esc}(z)$	3%–100%	11–18	0.05–0.07
IMF tilt (β)	0	0–1.69	18–1	0.01–0.07
H_2 feedback	yes	yes/no	18–20	0.07–0.11

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