Signatures of the First Stars in the Universe

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Abstract. We calculate the observable signatures of the first generation of stars at high redshifts ($5 < z < 10^3$). We determine the cosmic star–formation history, using an extension of the Press–Schechter formalism for Cold Dark Matter (CDM) cosmologies, and calibrate the fraction of gas converted into stars so as to reproduce the C/H ratio observed in the intergalactic medium at $z = 3$. We find that the Universe is typically reionized at $z = 10 - 20$. Deep infrared observations with future space telescopes (SIRTF or NGST) will be able to detect bright star clusters and early quasars at $z > 5$. The redshift of these sources can be inferred from the redshifted Lyman–limit or Lyα breaks in their infrared spectrum. Finally, we calculate the signatures of intergalactic dust produced by the first supernovae. We find that the dust opacity of the intergalactic medium (IGM) to infrared sources at $z > 10$ could be of order unity.

1 Introduction

The nature of the transition between the nearly smooth initial state of the Universe and its highly clumpy state today remains one of the outstanding problems in cosmology. COBE observations of the cosmic microwave background (CMB) have quantified the linear density fluctuations at $z \gtrsim 10^3$, and recent deep observations with HST and ground-based telescopes, such as Keck, have constrained the evolution of galaxies and their stellar content at $z \lesssim 5$. But current observations had not yet probed the intermediate transition epoch, during which the first astrophysical objects started to appear.

Popular bottom-up CDM cosmologies predict that the first objects condense at redshifts as high as $z \sim 10$–40, and their masses are close to the cosmological Jeans–mass, $\sim 10^6 M_\odot$. A fraction of the gas in these objects might fragment into stars, or be accreted onto a massive black hole. In either case, the resulting sources would have a dramatic effect on the subsequent evolution of the ionization and temperature of the rest of the gas, despite the fact that they contain only a small fraction of the total gaseous content of the Universe. The reason for this is simple: nuclear burning releases 5×10^6 eV per hydrogen atom, and thin-disk accretion onto a Schwarzschild black hole releases ten times more energy. In comparison, the ionization of a hydrogen atom requires only 13.6 eV. It is therefore sufficient to convert a fraction of $\sim 10^{-5}$ of the baryonic mass into either stars or black holes in order to ionize the rest of the Universe.

Indeed, a number of observational clues already constitute strong evidence for an early population of stars that had formed at $z \gtrsim 5$: (1) the Gunn–Peterson effect implies that the IGM was highly photoionized by $z \sim 5$, and several authors have noted that UV radiation from the declining bright quasar population at $z \gtrsim 3$ is insufficient to reionize the universe [13], [18]; (2) Recent detections [19], [20] of metals in the Lyα forest show a remarkable universality of the mean metal abundance in absorbers, spanning a range of six orders of magnitude in HI column density, indicating an early phase of metal pre–enrichment by stars; and (3) microlensing surveys [2] argue that $\sim 50^{+30}_{-20}\%$ of the mass of the halo of the Milky Way galaxy might be in the form of Massive Compact Halo Objects (MACHOs) with a mass $\sim 0.5^{+0.3}_{-0.2} M_{\odot}$.

Our work on the formation of the first stars has been motivated both by the theoretical expectation that the first objects collapsed at high redshifts ($z \sim 10$–40), and the observational clues that already hint at their existence. Future observations might probe more direct signatures of these early stars: (1) damping of the CMB anisotropies on small angular scales by the free electrons produced during reionization, detectable by future satellites such as the Microwave Anisotropy Probe (MAP), or the Planck Surveyor; (2) distortion of the CMB spectrum by starlight absorbed and reemitted by dust produced by the first supernovae; and (3) direct imaging and spectroscopy of numerous early star clusters by future space telescopes such as SIRTF or NGST. To quantify these signatures, we have used a semi–analytic approach that combines the popular CDM cosmology and star–formation in the most straightforward way.

2 Model Ingredients

The essential tools we use are the Press–Schechter formalism, and a one–dimensional lagrangian hydrodynamics code, supplemented by a chemical network [7]. The 1–D code tracks the dynamical, thermal, and non-equilibrium chemical evolution of a mixture of gas (composed of $H, H^-, H^+, He, He^+, He^{++}, H_2, H_2^+$, and e^-) and dark–matter. Our approach is complimentary to more detailed, but computationally expensive 3–D numerical simulations [3], [1], which have not yet been able to resolve the entire dynamic range of relevant mass–scales.

The Collapsed Fraction of Baryons vs. Redshift. We use the Press–Schechter formalism to find the abundance and mass distribution of virialized dark matter halos. However, we take into account the effect of pressure on small mass–scales by obtaining the exact collapse redshifts of spherically symmetric perturbations with the 1–D hydrodynamics code [5]. 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 $z{\sim}10$. We also take into account the feedback on the collapsed fraction from the photoionization of the IGM.

Star Formation in Collapsed Clouds. We calibrate the fraction of the gas which is converted into stars in each virialized cloud based on the inferred C/H ratio in the Lyα forest. We use tabulated ^{12}C yields of stars with various masses [15], and consider three different initial mass functions (IMFs) [12], [16]. In addition, we include a negative feedback on star–formation due to the photodissociation of molecular hydrogen by photons with energies in the range 11–13.6 eV. We find that soon after the appearance of the first few stars, molecular cooling is suppressed even inside dense objects [8]. Due to the lack of any other cooling agent in the metal–poor primordial gas, the bulk of the pre–galactic stars form due to atomic line cooling and fragmentation inside massive objects ($\gtrsim 10^8 M_{\odot}$) with virial temperatures $\gtrsim 10^4$K.

Propagation of Ionization Fronts. The composite spectrum of ionizing radiation which emerges from the star clusters is determined by the stellar IMF and the recombination

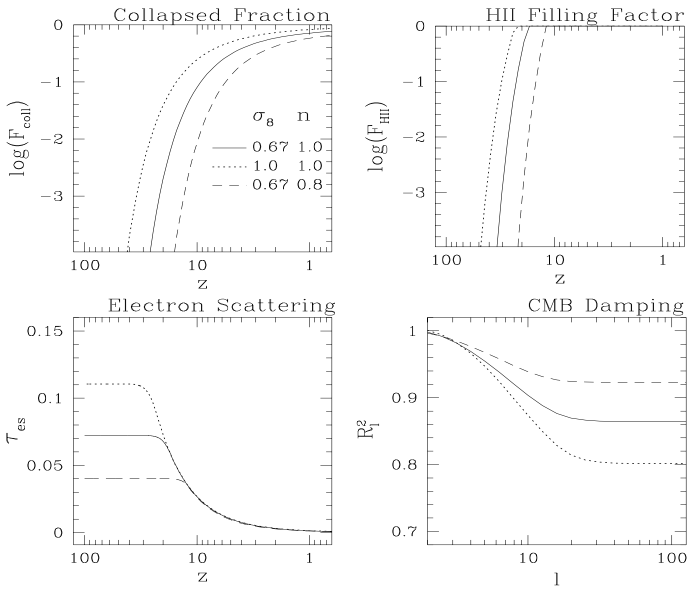

Figure 1: Reionization history and corresponding CMB damping.

rate inside the cluster. We follow the time-dependent spectrum of a star of a given mass based on standard spectral atlases [9] and the evolution of the star on the H–R diagram as prescribed by theoretical evolutionary tracks [17]. To calculate the fraction of the ionizing photons lost to recombinations inside their parent clouds, we adopt the equilibrium $1/r^2$ density profile of gas inside each cloud according to our spherically–symmetric simulations. We then use the time–dependent composite luminosity of each star–forming region and the radiative transfer equation in an expanding universe, to obtain the propagation of a spherical ionization fronts into the surrounding IGM.

3 Results

Reionization and Damping of CMB Anisotropies. The reionization histories obtained with three different power spectra are shown in Figure 1. The four panels show, in each case, the evolution of the collapsed fraction, the volume–filling factor of HII regions, and the electron scattering optical depth, as well as the damping factor for the CMB anisotropies as a function of the spherical harmonic index l. In addition to the power spectrum, we varied the baryon density, the star formation efficiency, the escape fraction of ionizing photons, the stellar IMF, and whether or not the negative feedback due to H_2 is present. For almost the entire range of parameters, the universe is reionized by a redshift $10 \lesssim z \lesssim 20$. The optical depth to electron scattering is in the range ~ 0.1–0.2. The corresponding damping of the amplitude of CMB anisotropies is ~ 10–20%, which will be detectable with the MAP or the Planck satellites, especially if a polarization of the CMB is measured [22]. The only qualitative exception to

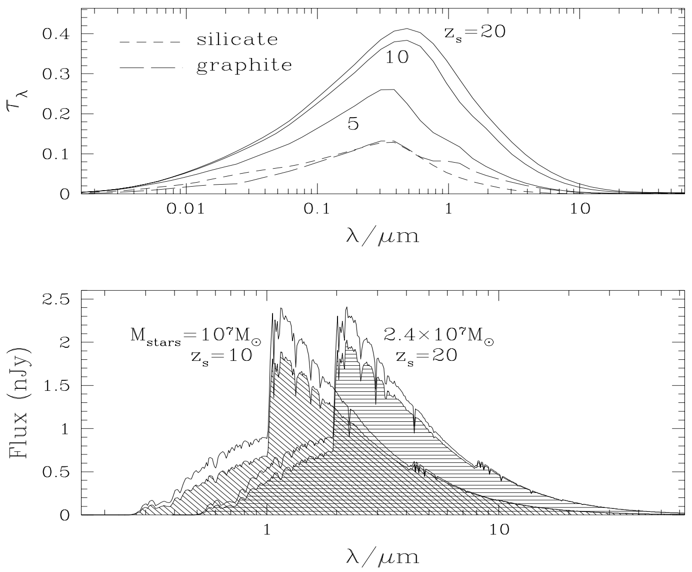

Figure 2: Lower panel: spectra of high-redshift star clusters. Upper panel: optical depth of intergalactic dust as a function of observed wavelength, λ, and source redshift, z_s. The separate contributions from silicate and graphite are also shown.

this occurs when the IMF is strongly tilted towards low–mass stars (by a power law index of 1.7), and reionization is suppressed due to the absence of massive stars which ordinarily dominate the ionizing flux. In this case, the large density of low–mass stars could account for the MACHO events detected towards the LMC.

Effects of Dust from the First Supernovae. The early epoch of star formation and metal enrichment is inevitably accompanied by the formation of dust in Type II supernovae. This dust has two important observational signatures. First, the absorption of starlight and its re–emission at long wavelengths distorts the spectrum of the CMB [21]. We find [10] in our models, assuming a uniform mix of metals and dust with the IGM, that dust distorts the microwave background spectrum by an equivalent "y–parameter" in the range $(0.02\text{–}2) \times 10^{-5}(M_{\rm SN}/0.3{\rm M}_\odot)$, where $M_{\rm SN}$ is the average mass of dust produced per supernova. This range is just around the current COBE limit of 1.5×10^{-5} [4], so that models with a high $\Omega_{\rm b}$ are already ruled out. Second, the opacity of the intergalactic medium to infrared sources at redshifts $z \gtrsim 10$ could be significant. We find $\tau_{\rm dust} \sim 0.3(M_{\rm SN}/0.3{\rm M}_\odot)$ at $\lambda \sim 1\mu$m. Figure 2 shows the dust opacity and the corresponding effect on the theoretical spectra of high–redshift star clusters. Figure 2 also illustrates that the redshift of these sources can be found from the redshifted Lyman–limit break (or the Lyα break if intergalactic absorption is strong [14]) in their infrared spectrum.

Direct Imaging with NGST. Deep observations with future infrared telescopes, such as the Space Infrared Telescope Facility (SIRTF) or the Next Generation Space Telescope (NGST) [11], will be able to image the hypothesized small pre–galactic star clusters. NGST's projected sensitivity is ~ 1 nJy in the range 1–3.5μm, and its angular resolution is $0.06''$. Based on the expected luminosity function of star clusters in our models, we find [5] that, with its proposed specifications, NGST will probe $\sim 10^3$ star clusters per square arcminute at $z > 10$. The characteristic separation between such sources is a few arcseconds, much larger than their typical size of $\lesssim 0.1''$. If the stars occupy a region comparable to the virial radius of the cluster, then $\sim$1% of these clusters might be resolved [6]. NGST's angular resolution might therefore be sufficient to distinguish a resolved star–forming cloud at $z = 10$ from a point–like low–luminosity quasar.

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